Improving concrete quality by using an expert system

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BHDSC no: DX 174669
IMPROVING CONCRETE QUALITY
BY USING AN EXPERT SYSTEM

By

TAHIR ÇELIK, BSc., MSc., MIED.

A Doctoral Thesis submitted in partial fulfillment of the Requirements for the Award of Doctor of Philosophy of Loughborough University of Technology.

April 1989

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DEDICATION

To my son Tolga Çelik,
who was born at the first stages of this research
and,
to the soul of my father Ibrahim Çelik,
who passed away during the research.
DECLARATION

No portion of the research referred to in this thesis has been submitted in support of an application for another degree or qualification at this or any other university or other institution of learning.
SUMMARY

There is great scope for problems and deficiencies in the workmanship of concreting operations namely, batching, mixing, transporting, placing, compacting, finishing, and curing. These problems will adversely affect the quality of the finished concrete. Improving the knowledge and experience of the supervisory staff and workmen on construction sites is essential if these deficiencies are to be minimized. It has been observed that specifications for concreting activities contain insufficient information regarding workmanship. This causes difficulties in controlling the concreting operations. This thesis addresses the problems associated with the transfer of knowledge from acknowledged experts in concreting operations to site practitioners. It is proposed that an appropriate tool for this information transfer is the use of computer based expert systems. Therefore, an expert system, called ESCON, has been developed to advise on concreting activities. The knowledge of this system was acquired from technical literature, site visits, self experience, and by interviewing experts in the domain. ESCON is capable of:

1) defining and diagnosing concreting problems;
2) giving expert recommendations for the solution of these problems, including the reasons behind the solution;
3) educating inexperienced staff by improving their appreciation of the domain;
4) preparing comprehensive specifications including information on the workmanship requirements of concreting procedures;
5) calculating the expected loss in the strength of concrete when recommendations are ignored.
Experimental work was undertaken at CITB (Construction Industry Training Board), Bircham Newton, Norfolk, to assist in the verification of the model. The model was tested by undertaking five evaluation methods, including comparison of the result with an objective standard, sensitivity analysis, expert's experience, novice users, and a real life case study.
ACKNOWLEDGEMENTS

This research has been completed within the subject area of construction Technology and Management in the Civil Engineering Department, at Loughborough University of Technology.

The author wishes to extend his gratitude to the following individuals and organisations:

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* All my friends and fellow research students for their encouragement and good cheer.

Above all I would like to thank my supervisor Mr. Tony Thorpe for his valuable guidance, support, and patience, without which this work would have not been completed.
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Concrete is produced from four basic materials, namely, water, cement, fine aggregate, and coarse aggregate, and sometimes an admixture may also be used. The quality of the concrete is affected by its constituent materials, the equipment used, and the workmanship in concreting operations. In this research concreting operations include batching, mixing, transporting and placing, compacting, finishing of unformed concrete surfaces, and curing of concrete. The required quality of concrete making materials is normally well defined in the standards and specifications. So their quality control comprises a straightforward job which is testing the quality of them against the standards with a predefined procedure. Therefore, the influence of materials on the quality of concrete is left out of the scope of this research.

Given that the materials and proportions of ingredients are suitable and properly selected, the quality of concrete depends on the knowledge of the person(s) responsible for the concreting operations. If these people have insufficient knowledge and experience, they are likely to be unaware of the concreting problems which may seriously affect the quality. Thus, the quality of the concrete produced will be poor and may not meet the requirements of the specifications. Repairing poor quality concrete structure is costly, undesirable, time consuming, and in many cases not possible. Therefore, every effort should be made to avoid the production of a poor quality concrete structure.

In order to observe the deficiencies and mistakes in concreting operations, a total of 84 concreting sites were visited in Northern Cyprus in 1986. During these visits, a total of 19 major different mistakes or deficiencies were noted. It was also noted that there was 6 major causes of these mistakes and deficiencies. Partial supervision was available on only 25 of these sites. On the other 59 sites there was no supervision. The length of the specifications used on these sites was between 1 to 2 pages and contained very little information on the workmanship requirements. Tests were
undertaken on 70 of these sites, and a standard deviation ($\sigma$) of 78.3 kg/sq cm (7.7 MPa) was obtained for the compressive strength of the concrete placed to its final location in the form. The mean strength ($\bar{X}$) was 151.7 kg/sq cm (14.9 MPa), and the coefficient of variation ($\sigma / \bar{X} \times 100$) was 51.6%. This variation is far outside the acceptable limits given in section 2.3 (g). Excluding the two sites where a crushed aggregate was used, the source of the natural aggregates used was the same on all the sites. Although the variations in the cement and mixing water can affect the quality of the concrete, the major cause of this high coefficient of variation in the strength of the concrete is due to the variation in:

i) the standard of workmanship; and

ii) the applied concrete production methods and equipment.

Whilst in some large projects concrete production methods and plant are included in the specification, in other projects, especially small to medium size projects they are often left unspecified. Contractors decide on which concrete production method and plant to select, depending purely upon their past knowledge and experience. The contractor will obviously have many different criteria affecting his choice: availability of the plant and labour; cost; quality; time; prevailing site conditions etc. Thus quality will normally only be one of many factors considered. Different concrete production methods will produce concrete at different qualities. This point is especially important on concreting sites where there is no proper quality control, particularly in many developing countries.

The standard of workmanship plays the most important part in the overall quality of finished concrete [1,2]. However, the workmanship appears to have received little attention in past studies [3,4]. For example, in a survey of specifications on 85 sites very little information on the workmanship requirements of the concreting operations was included. But the materials were relatively better defined. Since compliance with workmanship requirements depends on the standard of inspection and supervision [5], the appreciation of supervisory staff need to be maintained and improved if disputes are to be avoided. This can be achieved by
improving their knowledge and awareness of the influence of bad workmanship on the quality of concrete. Therefore, the supervisors and workmen should be trained beforehand to appreciate the necessity of a good workmanship [6,7].

In the literature there are few books aimed at improving the knowledge of supervisory staff on the site [1,8,9,10,11,12]. These appear unsuccessful in transferring knowledge to the site staff to improve the standard of workmanship and consequently, the quality of concrete. Their main weaknesses are:

a) they mainly give general information and are not comprehensive,

b) reading and learning from a book needs patience and takes time,

c) they mostly require a background knowledge.

Thus, the quality of concrete is affected by the lack of uniformity in materials, selection of improper concrete production methods, and poor workmanship in concreting operations. In the specifications the required quality of the materials are normally well defined. But the selection of concrete production methods, and the standard of workmanship are not specified adequately. Therefore, to obtain the required concrete quality the on-site staff must be both knowledgeable and experienced in correct concreting procedures which sadly is not always the case.
1.2. HYPOTHESIS

Excluding defects in basic concreting materials, the variations in the quality of concrete can be attributed to:

i) Poor workmanship in concreting operations

ii) Selection of incorrect methods or equipment.

Both of these are primarily caused through a lack of detailed knowledge and training in concreting operations by both supervisory staff and workmen on the site. This can be alleviated by:

i) Improving the knowledge of the supervisory staff on
   a) the choice of method and equipment; and
   b) the use of the method and equipment on site.

ii) Preparing a detailed specification stating exactly how the concreting work should be carried out.

To improve the knowledge of the supervisory staff may involve in-company or external training courses, or seminars, or exposure to other forms of condensed information such as manuals, guides etc. However, this often proves uneconomical especially in developing countries where training facilities are scarce and general education levels are low. Inevitably the site staff gain experience of different methods through practice and mistakes.

Similarly the designers who produce the specifications often have much greater information to hand on materials performance and quality than on actual construction operations. This bias is evident in the emphasis placed on material specifications at the expense of workmanship requirements.

What is required is a simple, quick, and cheap method of providing the best expertise and advice on a number of subjects to the people who require it. The expert system appears to provide a good vehicle for this.

Expert Systems (Knowledge Base Systems) contain the knowledge and experience of many experts. This knowledge and experience can
be used to give the supervisory staff a greater awareness of the factors influencing the choice and use of equipment and methods. Having obtained the knowledge through the Expert System on a personal computer, the supervisor or engineer may transfer the necessary knowledge to the workmen. In this way the workmen can be trained on the site. The distilled knowledge stored in the knowledge base of the expert system can also be used to prepare detailed specification on the workmanship. Therefore, it is hoped that, the use of an Expert System will provide an efficient and effective medium to transfer knowledge to the staff on site, and through them to the workmen. This should then create an environment in which the workmanship and quality of concrete can be improved.

Thus this thesis set out to demonstrate that the creation of such an expert system is viable and that it can be shown to be an effective means:

a) in communication information on selected use of methods and equipment in concrete practice; and
b) in the creation of specifications.

1.3. OBJECTIVES

To test the hypothesis outlined above, the main objectives of this research are to:

a) Explore concrete production, handling, placing, compacting and curing methods and plant;
b) Analyse and define the mistakes and deficiencies occurring in concreting operations;
c) Define the causes of these mistakes and deficiencies;
d) Develop a computer program (expert system) for batching, mixing, transporting, placing, compacting, finishing, and curing of concrete, which is capable of:
   i) defining, predicting and diagnosing the problems mentioned above and giving expert recommendations
for the solution of the problems including the reasons behind the solutions;
ii) educating inexperienced staff by improving their appreciation of the domain;
iii) preparing comprehensive specifications containing all the necessary requirements for the workmanship and supervision of concreting operations;
iv) quantifying bad workmanship in terms of loss of concrete strength;
e) Evaluate the developed expert system to prove its reliability and effectiveness in communication information on concreting operations.
f) Undertake experiments to test the accuracy of the calculations explained in (iv) above.

1.4. WORK UNDERTAKEN:

To meet these objectives, the following work was undertaken:
Firstly, previous literature in concrete practice was carefully reviewed. 5 major concreting sites were visited in Turkey and concrete production methods, plant used, and concrete practice techniques were defined and their influence on the quality of concrete were determined.

Secondly, sources of mistakes and deficiencies in batching, mixing, transporting, placing, compacting, finishing of unformed surfaces, and curing of concrete were investigated by both visiting 84 concreting sites in Cyprus, and with the help of the previous literature. It was found that, the major causes of mistakes and deficiencies is the lack of appreciation of concrete production practices by supervisory staff and workmen on the concreting site. It was proposed that, these mistakes could be minimized by improving both the knowledge and awareness of the staff about the influence of bad workmanship on the quality of concrete. During the visits of 84 sites in Cyprus, and 1 site in UK, the specifications were also
examined. The specifications on these 85 sites included insufficient information on the workmanship requirements.

Thirdly, a computer program, a knowledge based (expert) system, was developed to transfer information to the site by producing advice on the problems in the concreting operations. This expert system covers the practices of batching, mixing, transporting, placing, compacting, finishing of unformed surfaces, and curing of concrete. To develop this system, knowledge was acquired from technical literature, self experience, site visits, and by interviewing 6 experts in the domain. These experts were selected from different areas of industry such as, contractors, training centres, consultants, the Concrete Society, the British Ready Mixed Concrete Association (BRMCA), and the British Cement Association (BCA). The model is also capable of calculating how much strength loss is expected when a number of selected recommendations are ignored.

Fourthly, two series of experiments were undertaken at CITB (Construction Industry Training Board) to verify the strength loss predicted by the model when some of its recommendations are ignored. These experiments included testing 16 cube samples and 2 cores drilled from two different structures.

Finally, the developed expert system was tested on an ongoing concreting project by undertaking a case study. This indicated that, the model is a good tool to transfer the necessary knowledge to the staff on the site. In this way, the model can help to improve the quality of concrete providing all its recommendations are followed.
1.5. MAIN ACHIEVEMENTS:

The main achievements of this work are:

a) Having undertaken a critical review of concreting methods, a total of 120 points that may create mistakes, or deficiencies in concreting operations were defined. These 120 points include all of the cases possible in concreting operations.

b) The 6 major causes of these mistakes and deficiencies are stated;

c) A computer program (an Expert System) was developed for the concreting operations defined in section 1.1. This expert system includes 234 questions, 139 variables, 622 actions, and 22 groups which make a total of 1017 items (see chapter 3). The total size of the model is about 510000 bytes. The model is capable of:

   i) Having defined, predicted, and diagnosed the possible mistakes and deficiencies in concreting operations, expert recommendations are given for the solution of these problems;

   ii) Improving the knowledge of concrete supervisory staff by defining the problem, giving the solution and stating why such a solution is recommended;

   iii) Preparing comprehensive specifications about the workmanship of concreting operations which is useful in supervision.

   iv) Evaluating the influence of bad workmanship on the quality of concrete produced by calculating the expected strength of the concrete when a number of the recommended solutions are ignored;

d) The system was evaluated using five different methods: comparison with an objective standard; sensitivity analysis; experience of experts; novice users; and a case study. It was concluded that, the system is reliable and effective in transferring knowledge to the concreting staff on the site.
Defining the Mistakes and Deficiencies
To achieve (a), a lengthy literature review was undertaken and 84 concreting sites were visited in Northern Cyprus. A total number of 120 points were explored throughout the concreting operations. The documentation of these are:

<table>
<thead>
<tr>
<th>Concreting operation</th>
<th>Number of the points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batching</td>
<td>10</td>
</tr>
<tr>
<td>Mixing</td>
<td>18</td>
</tr>
<tr>
<td>Transporting and placing</td>
<td>38</td>
</tr>
<tr>
<td>Compacting</td>
<td>25</td>
</tr>
<tr>
<td>Finishing of unformed concr. surfaces</td>
<td>8</td>
</tr>
<tr>
<td>Curing</td>
<td>21</td>
</tr>
<tr>
<td>Total</td>
<td>120</td>
</tr>
</tbody>
</table>

Causes of the Mistakes and Deficiencies
After discussions with the contractors, supervisors, and workers on the 84 sites visited in Cyprus, the 6 causes of the mistakes and deficiencies were determined as follows: economical considerations; technological considerations; insufficient specifications; lack of supervision; and lack of appreciation of concreting problems by supervisors with insufficient knowledge, and workmen with insufficient training and experience.

Developing Expert System
To achieve (c), the problems, their causes and solutions have been incorporated into an expert system computer program. The system includes the views of 6 UK domain experts.

Again from the literature survey, and the assessment of the site visits, it was concluded that, one of the reason why the quality of concrete suffers is the lack of knowledgeable and competent staff on concreting sites. Therefore, to improve the quality of concrete produced, it is necessary to upgrade the knowledge of the supervisory staff on the site. This can be achieved by using an expert system. So achievement (c) (ii) is accomplished from the
characteristics of expert systems. As a characteristic of expert systems, the model developed contains a corpus of expert knowledge. This knowledge can be used to educate inexperienced, or insufficiently experienced concreting staff on the site.

It is necessary to provide all the necessary requirements in the specification for better supervision [13]. The model developed provides the expert knowledge on the workmanship of the concreting operations. If this knowledge appears in the specification, then the supervisor will readily be able to control the job. To achieve (c) (iii), a computer printout is provided for any particular case. The system keeps the recommendations, that will appear in the specification, and at the end of the session, these recommendations are printed.

During the visits in Cyprus, it was noticed that, sometimes a concrete supervisor knows that the applied concreting procedure is not right. However he does not always take it seriously and consider the precautions to correct the mistake. Therefore a means of motivation is necessary to make the supervisory staff correct the mistakes on the site. This motivation could be a reminder that, each mistake will result a reduction in the quality of concrete produced. Therefore, to achieve (c) (iv) the developed expert system can check some of the previously given recommendations to see if they have been obeyed or not. These selected recommendations are those that can be quantified in terms of strength loss when they are ignored. Consequently, the system calculates and displays the expected strength loss.

**Evaluating the System**

The reliability and effectiveness of the system was determined by the use of five evaluation methods: comparison with an objective standard; sensitivity analysis; experience of experts; novice users; and a real life case study. To compare the system with an objective standard, experiments were undertaken at CITB. At the end of these experiments it was concluded that, the accuracy of the figures given by the system on expected strength loss when some of its
recommendations are ignored was about 89%. The sensitivity analysis showed that, the model is highly sensitive to any change in its variables. This indicates that the model is reliable. The experts examined the model critically and found it a useful and applicable tool for transferring knowledge to site. Testing the model by 4 novice users (post graduate civil engineers) showed that, the recommendations of ESCON are understandable and the system can be used in transferring information to the novice users. Having undertaken a real life case study for an ongoing concreting job, it was indicated that the system is successful in transferring the necessary information to the site staff. In this way, an environment can be created in which both the workmanship and quality of the concrete can be improved.

1.6. **GUIDE TO THE THESIS:**

The thesis is divided into three sections as shown in fig. 1.1. The first section includes the chapters 1, 2, and 3. This section defines the problems addressed by the research, and discusses the background to the problems. A literature review on expert systems is presented and the developed system, ESCON, is described.

The second section includes the chapters 4, 5, 6, 7, 8, and 9. In this section, the effects of concreting operations on the quality of the finished concrete structure are explained, and the methods by which ESCON improves the workmanship of these operations are described. Finally, a conclusion of application of ESCON on these concreting operations is given.

The third section comprises chapters 10 and 11. In this section, ESCON is evaluated using 5 different methods, and the general conclusions of the research are discussed. A short description of the chapters are shown in fig. 1.2, as follows.
Fig. 1.1 - Sections of the Thesis.
The first part of chapter 2 reviews the literature on concrete quality. The quality of concrete is explained in terms of strength, durability, and appearance. It is pointed out that, the quality of concrete is affected by materials used, production procedures, and workmanship. The present situation of concrete quality, its major problems resulting from bad workmanship, and the reasons for these problems are discussed, and the proposals to improve the quality of concrete are given. In the second part, a general introduction to expert systems, and the general features of expert system are given. Finally, the reasons for selecting an expert system approach for this work are explained.

The first part of chapter 3 reviews the literature on knowledge based expert systems. The differences of expert systems and conventional programs, advantages and disadvantages of expert systems are explained and a comparison of expert systems and human experts is given. The stages of building an expert system, available expert system shells and the application of expert systems in construction industry are critically reviewed. In the second part, the expert system developed (called ESCON) is introduced, and its general features and achievements are explained.

The first part of chapter 4 briefly reviews concrete batching methods and how the quality of concrete is affected by the choice of batching procedure. In the second part, the rules of ESCON about off-site batching, on-site volumetric batching, and on-site weigh batching are explained and the ideas behind these rules are described. The problems in maintaining accurate batching in both individual and successive batches, and the way of solving these problems by ESCON are explained.

Chapter 5 contains a brief review of concrete mixing methods and equipment. The effects of loading the mixer, minimum mixing time, discharging of the mixer, capacity of the mixer, formation of cement balls and head packs, and mechanical conditions and design of the mixer are briefly explained. In the second part, the rules of ESCON about mixing of off-site and on-site batching methods are presented
and the reasons for selecting these rules are explained. The method of ESCON to provide information to the concreting staff to maintain a uniform mixing is given.

The first part of chapter 6 briefly reviews concrete transporting and placing equipment, and their effect on the quality of concrete. Then concrete placing techniques into columns, walls and slabs are explained. In the second part, the rules of ESCON about transporting and placing concrete, and the principles behind these rules are given. The way of ESCON in providing the necessary information on workmanship and for the choice and use of the methods and equipment are explained.

The first part of chapter 7 briefly reviews concrete compaction methods and compaction techniques, and the effects of compaction on the quality of concrete. In the second part, the rules of ESCON about concrete compaction, and the principles behind these rules are explained. The way of transferring information of ESCON to maintain a well compacted concrete is also described.

The first part of chapter 8 briefly reviews the finishing techniques of unformed concrete surfaces, and their effect on the quality of concrete. In the second part, the rules of ESCON about finishing techniques, and the reasons for selection of these rules, are given. In this chapter, how ESCON provides knowledge to overcome the finishing problems is also explained.

The first part of chapter 9 reviews the literature on concrete curing methods, and the effect of curing on the quality of concrete. In the second part, the rules of ESCON about curing of concrete, and the principles behind these rules are presented. The necessary information to maintain a good curing, and how ESCON transfers this information to the site is also explained.

Chapter 10 explains the evaluation of the model in five parts. In the first part, the results of the experiments undertaken at CITB are compared with the figures given by the system on the strength loss
when a number of its recommendations are ignored. In the second part the model is evaluated by using sensitivity analysis. The model was demonstrated and discussed with experts, and in the third part of the evaluation, the comments of an expert about the model are discussed. In the fourth part of the evaluation, the model was tested by 4 novice users unfamiliar with ESCON and inexperienced in concrete technology. In the fifth part of the evaluation, ESCON was tested with a real life application as a case study. Finally, the results of the evaluation methods are discussed.

Chapter 11 contains the discussions, and conclusions of the research. In this chapter, recommendations and future works are proposed.

1.7. SUMMARY:

The quality of concrete mainly suffers from the lack of uniformity in materials, selection of improper concrete production methods, and lack of appreciation by both supervisory staff and workmen on the site. Almost in every specification, the required quality of materials and the procedure to control their quality are very well defined. So, controlling the quality of materials is often a relatively straightforward task and in many cases it does not require the contractor to be expert in that area. But, the contractor relies upon the knowledge and experience of this staff for both selection of concrete production methods, and in meeting the required standard of workmanship in concreting operations. If this is inadequate the required concrete quality in a finished structure is unlikely to be attained.
Fig. 1.2 - Schematic structure of the thesis.
CHAPTER 2: BACKGROUND

2.1 Introduction
2.2 Definition of Concrete Quality
2.3 Factors Affecting the Quality of Concrete
2.4 Concrete Quality - Present Situation
2.5 Reasons for Mistakes and Deficiencies
2.6 Proposals to Improve the Quality of Concrete
2.7 Introduction to Expert Systems
2.8 General Features of an Expert System
2.9 Reasons for the Selection of an Expert System
2.1. INTRODUCTION

The quality of a finished concrete structure is affected by the quality of the freshly mixed concrete and the standard of workmanship in handling, compacting, finishing, and curing the concrete. The standard of workmanship throughout the concreting operations is therefore extremely important in construction a good quality concrete structure. Unfortunately although materials are regularly checked, monitored and tested the workmanship, being harder to specify and quantify is often given little attention or ignored completely. This is supported by Newman [3,4,14] that, workmanship in concrete construction has received little attention.

In order to see the quality of the concrete produced, and the mistakes in concreting operations, a total of 84 concreting sites were visited in Northern Cyprus in 1986. The standard of workmanship on these sites was observed, and it was concluded that, Newman's observation was right. The workmanship received little attention, and the quality of the concrete suffered because of it. The specifications on these sites were also found to include very little information on the workmanship requirements for the concreting operations.

In the first part of this chapter, the concept of concrete quality and the major factors affecting the quality are defined. The present situation of concrete quality is described including the results of 84 sites visited in Cyprus. The observed mistakes, the reasons for the mistakes, and the proposed solutions are also explained. In the second part of the chapter, expert systems are introduced as a proposed solution. Finally, the reasons for selecting expert systems to alleviate mistakes in concreting operations are discussed.
2.2. DEFINITION OF CONCRETE QUALITY

Scanlon [15] defined concrete quality as the "degree of excellence", which is generally established in the project specifications. Tipler [16], and Gunning [17] stated that quality is not perfection but, merely fitness for the purpose. So the best concrete for any given purpose is the one that does the job satisfactorily at the lowest cost. The author agrees with Herman [18], and C&CA [19] that, quality concrete is that which is capable of meeting the requirements of the job in terms of strength, durability, and appearance. Strength is often the major feature in defining the quality because strength is both easy to define and to measure. Therefore in many cases, strength is the unique measurement of concrete quality.

Durability of concrete is not a constant characteristic, since it depends on the environmental conditions [20]. The durability of concrete is defined by ACI Committee 201 [21] as the ability of concrete to resist weathering action, chemical attack, abrasion, or any other process of deterioration. Durability requirements for concrete are still expressed mainly in terms of limits on the mix proportions, e.g. minimum cement content, and/or maximum water/cement ratio, or requirements of admixture. However, there are no simple rapid tests to measure either cement content or water/cement ratio of finished concrete. Therefore, there has been a trend towards specifying durability requirements in terms of strength grades [22].

The appearance of concrete is important if the concrete is to be left exposed as an architectural feature. Unfortunately, there is again no objective testing method for measuring the appearance of concrete. It largely depends upon the subjective inspection of the client's representatives on the site.

Concrete is a variable material, and to meet the requirements described, its production, handling, compaction, finishing, and curing procedures must be controlled, as well as its ingredients. This
can only be undertaken by skilled supervisors and well trained workers. The workmanship of concreting operations is therefore paramount in maintaining the required concrete quality. The specifications should also contain sufficient information on the workmanship requirements as well as on materials to maintain satisfactory supervision. A good level of supervision helps to improve the standard of workmanship on the site [34].

2.3. FACTORS AFFECTING THE QUALITY OF CONCRETE

In-situ concrete quality is affected by the quality of the freshly mixed concrete and by the standard of workmanship of construction. See Fig. 2.1. Freshly mixed concrete quality is influenced by its constituent materials, procedures of production, and equipment used. Here, the term "materials" includes both the quality of concrete making materials, and the proportions. However, a discussion of materials is outside the scope of this research. The influence of materials on the quality of concrete is well documented [23,24,25,26,27,28,29,30,31,32]. Whilst the effects of production procedures and workmanship on the strength, durability, and appearance of concrete is discussed in detail in other chapters, a summary is given below.

To obtain a good quality concrete structure, attention should be paid to all aspects of concreting operations. It does not only depend on the quality and uniformity of the concrete discharged from the mixer, but also on the skill and knowledge shown on the site in carrying out the various operations including batching, mixing, transporting and placing, compacting, finishing, and curing the concrete. The adverse effects on quality of a mistake in one of the concreting operation can not be rectified even if all the other operations are performed perfectly. Therefore, from a quality point of view, every aspect of the concreting operation is important and should receive equal attention.
Fig. 2.1- Factors affecting in-situ concrete quality
Concrete production procedures include batching and mixing of concrete. In order to produce good quality concrete, it is essential to place the correct amount of the ingredients in the mixer. This is possible by accurate batching. A uniform concrete can only be produced if the required accuracy is maintained in individual and successive batches. The factors that affect the accuracy of batching are explained in chapter 4.

Having placed the correct amount of materials into the mixer, a uniform mixing can produce good quality fresh concrete. Uniform mixing is affected by the method of loading the mixer, mixing time, discharging the mixer, capacity of the mixer, formation of cement balls and head packs, mechanical conditions and design of the mixer, and retempering. The effects of these factors on the quality of concrete are explained in chapter 5.

However, having good quality concrete discharged from the mixer is insufficient to produce a good quality concrete structure. Plastic concrete is subject to segregation during transporting and handling. Segregated concrete contains one portion with insufficient coarse aggregate, and one portion with a lack of mortar. The first portion is less durable and provides less resistance to shrinkage effects. The second portion inevitably contains some air voids. So, segregated concrete is weaker than the prescribed mix. During transporting and handling concrete, two other points that require consideration are: slump loss; and loss of ingredients. If the loss of slump exceeds the permissible amount, it creates construction problems during placing and compacting. Loss of ingredients, mainly grout, also reduces the quality of the concrete, and should be avoided. The effects of segregation, slump loss, and ingredient loss are discussed in detail in chapter 6.

After the concrete has been mixed, transported and placed, it contains entrapped air in the form of voids. The amount of voids depends on the workability of the concrete. For example, a concrete with a 75 mm slump contains about 5% air, while a concrete of 25
mm slump contains about 20% [33]. It is well established that, one percent of voids in the concrete reduces its strength by as much as 5-6%. Therefore, after placing the concrete, thorough compaction is essential. The compaction methods are explained in chapter 7.

If the concrete is required for a slab, floor, or pavement construction, proper finishing of the unformed concrete surfaces should be performed after compaction. During the finishing procedure, the most important point is not to perform any finishing work if there is excessive moisture or bleeding water on the surface of the concrete. The finishing procedures of unformed concrete surfaces are explained in detail in chapter 8.

The last concreting operation is curing and protection. In its early age, concrete needs water and favorable temperatures to complete the hydration of the cement. A high level of hydration produces a better concrete quality. Therefore, every effort should be provided to ensure maximum hydration. Concrete should be protected against frost in cold weather. In hot weather, rapid evaporation of water from the surface of concrete should be minimized. Keeping the concrete in a humid medium is essential to maintain the hydration process. The curing and protection of concrete is discussed in detail in chapter 9.

2.4. CONCRETE QUALITY - PRESENT SITUATION

Every party involved in concrete construction (client, designer, and contractor) wants to produce good quality concrete [34]. The client wants to have a good quality concrete structure since his money is in the project and he has to live with what he gets. The designer wants to produce good quality concrete structures since his reputation and professional satisfaction depend on it. The contractor also wants to produce good quality concrete. Although he sometimes has adverse influences such as time and money, his reputation and professional satisfaction again depend on it [35].
If this is the case, why is the quality of concrete still variable? The answer may not be the same for all concreting sites, but it is deemed that it will be similar. Some of the defects of concreting operations were reported by Arioglu [36], Blackledge [37], and Birt [38]. According to a survey on the features of reinforced concretes in Istanbul in 1972, Arioglu stated that, the risk of reinforced structures collapsing in Istanbul was 14.47%. This was reported as being due to: lack of effective standards and specifications; the use of improper materials; the selection of incorrect concreting methods; providing insufficient supervision and poor workmanship. Blackledge [37], reported that, poker vibrators were incorrectly used as explained in section 7.3.3. Birt [38], reported that, in a survey in UK it was observed that: 24% of the contractors had very little interest in any form of curing or its implications; and although 50% of the contractors were moderately concerned with curing and its effect, because of practical and economical considerations, they gave limited attention to its application.

Newman [39] stated that, in UK there is a continuing risk of concrete of inadequate quality. He mentioned that, there is a greater risk than ever before of concrete being specified, supplied, by ready mix concrete producers, and used which is not suitable for the purpose intended. His approach was that, the specifications should be changed to exclude the nominal mix proportionings, and an approved procedure should be adopted through the UK for the selection of concrete mixes. Newman also stated that, throughout the UK a practical guidance on the placing, compacting, and curing of the concrete should be adopted to reduce the risk of inadequate concrete quality.

Paterson [40] reported that, in a survey in France on 10000 building defects between 1968-1978, the construction faults was 43% in terms of the repairing costs. He also stated that, the frequency of occurrence of the defects relying on construction was 51%. Of course these defects were the results of mistakes in many construction activities not just concrete construction.
In order to determine the quality of concrete produced, and the reasons for not achieving the desired concrete quality on sites, a total of 84 sites were visited in Northern Cyprus between October, 1986 and January, 1987. During each visit, the concreting operations, namely, batching, mixing, transporting, placing, compacting, finishing, and curing were carefully observed; slump tests were made; and samples were taken to measure the standard compressive strength of concrete as defined in BS 1881 [41].

Unfortunately, due to the limited facilities, on many sites only one cube specimen (150X150X150)mm could be prepared. The mistakes and deficiencies in concrete practice observed during these visits are explained in below.

a) **Batching of Concrete**
   
i) **Aggregates** : The mistakes in batching of aggregates were: (1) selection and use of the batching method; (2) omitting the bulking of the sand; (3) no moisture adjustments. Aggregates were volumetrically measured on all the sites visited. Measurement of aggregates was by the shovel on 17 sites, and wheelbarrows on 67 sites. Neither of these methods is acceptable for producing good quality concrete. The bulking of the sand can increase its volume by about 50\% depending on the size and moisture content of the sand [42]. This was not considered on the sites visited. Since a volumetric batching method was used, the adjustment of the moisture of the aggregates was meaningless, and omitted. Thus the water/cement ratio relied completely on the observation of the mixer operator.

ii) **Cement** : Cement was measured as full bags on 26 sites out of 75 sites. On the other 49 sites, cement was measured volumetrically either in buckets, or by using "hand scales". In the "hand scales" method, the top of the bag was torn and either half or 3/4th portion of the cement was poured directly into the mixer or into the skip of the mixer. However, volumetric measuring of cement is not accurate
and should always be avoided.

iii) **Water:** On the sites visited, water was measured volumetrically by using plastic buckets, capacities were about 10 kg. The consistency of the concrete largely depended on the observation of the mixer operator. It was observed that, on 31 out of 81 sites the mixer operators failed to produce uniform concrete in successive batches.

b) **Concrete Mixing**

i) **Order of Loading:** On the sites visited, all the mixing water was placed into the mixer, and then the solids were added. This affected the uniformity of the concrete discharged from the mixer.

ii) **Mixing Time:** On all the sites visited, the minimum concrete mixing time should be 1 min., since the capacities of the mixers were all less than 0.76 cu m (1 cu yd). However, on only 3 sites was the mixing time 1 min or above. On the other 60 sites, the mixing time was less than 1 min. Less mixing time promotes non-uniformity in batches, and causes a higher variation in the strength of concrete [23]. The histogram of the observed concrete mixing times on the sites visited is shown in Fig. 2.2.

iii) **Capacity of the Mixer:** On 17 sites the rated capacity of the mixer was exceeded. To prevent spillage, the axis of the tilting drum mixer was tilted upwards by more than the recommendation of its manufacturer. This caused poor mixing.

iv) **Discharging the Mixers:** On 32 sites the total batch of the concrete was split into two or three fractions while the mixer was discharged. The number of the fractions depended on the capacity of the concrete transporting equipment. It was observed that, this caused nonuniform concrete amongst the fractions of the batch.
c) Transporting and Placing of Concrete

i) **Slope of the Chute**: The slope of the chute depended on the site conditions. On some sites the slope of the chute was so flat that, it was necessary to produce higher slump concrete than specified to enable the concrete to flow.

ii) **Wheelbarrows**: Concrete was transported by wheelbarrows on 32 of these sites. On 21 of them the path of the wheelbarrow was so rough, or muddy that, a very wet mortar accumulated on the top of the concrete in the wheelbarrow at the destination point. Meanwhile, the coarser particles settled causing segregation.

iii) **Depositing the Concrete**: On all sites visited, concrete was not dumped into the face of concrete already placed. The usual procedure was to dump concrete away from that already placed. This procedure promotes segregation since the larger aggregate particles may roll further.
iv) **Lateral movement of the concrete:** On some sites, concrete was moved about 3 m away from where it was deposited using shovels. This also increases the non-uniformity of the concrete [1] and should be avoided where possible.

v) **Dropping the Concrete:** On these sites concrete was dropped freely into the reinforced columns or walls. Normally, the small size of the columns was about 200 to 300 mm, which was not suitable for dropping the concrete freely into the form. On some sites the height of the columns or walls was up to 6 m, and dropping concrete this distance causes segregation as is shown in Fig. 2.3.

d) **Compacting of Concrete**
Compacting concrete was usually omitted on the sites visited. Concrete was compacted on 1 site by internal vibrator, and on another 4 sites by manual rodding. On the other 79 sites concrete was not compacted at all. Fig. 2.3 shows a typical uncompacted concrete column.

e) **Finishing of unformed concrete surfaces:**
The finishing procedures of concrete slabs were generally wrong. On all of the sites visited floating was started before the bleeding water had evaporated. This caused the mixing of the bleeding water into the surface of the concrete. So, the water/cement ratio at the surface was high, hence, the strength and durability of the concrete was low and the risk of spalling increased.

f) **Curing of Concrete**
During these visits, the ambient temperature was about 18-24C (64-75 F), and a drying wind was common.

i) **Formed Surfaces:** The formwork material for walls and columns was timber. Usually, the formwork was removed 1-2 days after casting. Neither the formwork, nor the concrete surface was cured or protected against the weather after removing the formwork.
Fig. 2.3 - A segregated and improperly compacted concrete column.
ii) **Unformed Surfaces:** Slab surfaces were cured by spraying water. This was commonly done twice in a day, once in the morning, and once in the evening.

iii) **Duration of Curing:** Although the appropriate duration of curing on the sites visited should be a minimum of 7 days, the curing was maintained for only 3 days.

g) **Concrete Quality**
The appearance of concrete was not important on the sites visited. The quality of concrete was measured only in terms of strength. The required compressive strength was standard, 160 kg/sq cm (15.7 MPa). During the visits, compressive strength of concrete was tested on 70 sites, and the mean strength ($\bar{X}$) was found to be 151.7 kg/sq cm (14.9 MPa). But the standard deviation of the compressive strength ($\sigma$) was astonishingly high, at 78.3 kg/sq cm (7.7 MPa). This equals a coefficient of variation ($\sigma/\bar{X}$) of 51.6 %, which is far outside acceptable limits. ACI Committee 318 [43] specifies that, the concrete strength is considered satisfactory when the averages of any three consecutive tests remain above the design strength and no individual test falls below the design strength by more than 35 kg/sq cm (3.5 MPa). If the strength is low, as in this case, the Committee requires that, the probable frequency of the tests more than 35 kg/sq cm (3.5 MPa) below the design strength will not exceed 1 in 100. Kocataskin [44], stated that, if the variation in the strength of concrete is more than 30% for concrete with an average strength of below 250 kg/sq m (24.5 MPa), then, the degree of the quality control is "poor". The histogram of the strength on 70 sites is shown in Fig. 2.4.
h) **Supervision and Quality control**  
There was only partial supervision on 25 out of 84 sites visited. On the other 59 sites there was no supervision. The quality of concrete making materials were not controlled at all. Only on 4 out of 84 sites the quality of the concrete was tested by a control engineer. Lack of supervision and quality control obviously causes a great variation in the strength of concrete. Sparkes [6] estimated that, the lack of control causes a standard deviation in the strength of concrete by more than 84 kg / sq cm (8.3 MPa).

i) **Specifications**  
The length of the specifications used on these sites was between 1 to 2 pages including the requirements on both materials and workmanship. Whilst the information on the materials requirements was insufficient, the workmanship requirements were even less. For example, the whole requirements on the compaction of the concrete was explained in a sentence such as "After placing in the form the concrete should be compacted with proper equipment". This statement did not provide enough information to the supervisor.
(when available) to maintain satisfactory compaction especially when the supervisor has insufficient knowledge and experience.

2.5. REASONS FOR MISTAKES AND DEFICIENCIES

As explained above, there were many mistakes and deficiencies in the concreting operations on the sites visited. Having talked to the staff and contractors, and observed their activities, it was concluded that the main reasons for these mistakes and deficiencies were:

i) **Technical Considerations:** Many of the technical facilities were either scarce or not available. For example, poker vibrators were scarce, and a ready mix concrete producer was not available.

ii) **Economical:** The contractors always preferred to finish the job in the cheapest way. Therefore not enough attention was given to the quality of concrete produced.

iii) **Specifications:** The specifications for concreting operations were of a "prescription" type, and they didn't include the necessary requirements to maintain the specified quality.

iv) **Quality Control:** Lack of the quality control for both concrete making materials, and for the concrete produced.

v) **Supervision:** There was insufficient supervision on the sites and where supervision was available the supervisors often lacked technical knowledge.

vi) **Lack of Appreciation:** Probably the major deficiency was the lack of the appreciation of both workmen and supervisory staff (when available) of the effect of workmanship on quality. This was caused by:

- supervisors having insufficient knowledge and experience about the job; and
- workmen with insufficient training and experience.
2.6. **PROPOSALS TO IMPROVE THE QUALITY OF CONCRETE**

The proposals given here to improve the quality of concrete are not only for the sites visited in Cyprus, but are also valid for every concreting site where concrete quality needs to be improved. The proposals are:

i) Prepare a strong and clear specification including all necessary requirements to improve quality and reduce variability [45]. The task of inspection will be much easier and more effective if specifications are available for individual sites and projects.

ii) Provide careful and effective quality control for both concrete making materials and for the concrete produced.

iii) Provide knowledgeable supervision and trained workmen for all concreting operations.

iv) Improve the appreciation of both the workmen and the supervisory staff by transferring distilled knowledge to the site. Make sure that, they appreciate how much the quality of concrete will be affected by bad workmanship.

2.7. **INTRODUCTION TO EXPERT SYSTEMS**

In practice many problems require judgements based on experience to generate potential solutions. So, the typical algorithmic approach is not easily applied to the complex, nonuniform and ill-structured situations involved in construction. Normally, problems such as these are solved by experts in the field. Using their knowledge and experience, experts solve problems which a novice has no knowledge of.

These problems are well suited to the application of knowledge based systems or simply expert systems. Expert systems have recently emerged (in the last decade) from research in artificial intelligence as a practical problem solving tool. The standard definition of expert systems can be stated as "knowledge based expert systems are interactive computer programs incorporating
judgement, experience, rules of thumb, intuition, and other expertise to provide knowledgeable advice about a variety of tasks" [46]. Expert systems use the knowledge of the domain to simulate the reasoning of an expert in the field in order to solve an ill-structured problem at or near to the performance level of an human expert.

Expert systems are not applicable to every problem. Trimble [47], has defined the key criteria to judge the suitability of expert systems as follows:

1) can the problem be stated in a form that leads to goals?
2) can all the goals be predefined so that the system has only to select from the set of possibilities?
3) can rules be written that link the answer to practical questions with the predefined set of goals?

An expert system computer program asks a series of questions to the user, and the user answers these questions as "YES", "NO", "I DON'T KNOW", or by inputing a NUMBER. These answers lead the program to display one or more recommendations with their reasons. The running of an expert system computer program is quite simple and does not require the user to have a vast amount of computer knowledge. Expert systems are explained in detail in chapter 3.

2.8. **GENERAL FEATURES OF AN EXPERT SYSTEM**

The general features of an expert system (see fig. 2.5) can be summarised as [48]:

a) A corpus of knowledge
b) High level expertise
c) Predictive modelling
d) Institutional memory
e) Training facility
Fig. 2.5 - General features of an expert system
a) Corpus of Knowledge
The heart of an expert system is a powerful corpus of knowledge that is accumulated during the building of the system. The accumulation and organisation of knowledge is one of the most important aspects of an expert system. The knowledge that fuels the expert system has the following characteristics:

i) Flexibility of Expression: The knowledge base is able to embody both the rules of thumb that expert practitioners never write down, and well known expressions.

ii) Uncertainty: The knowledge base can contain uncertainty cases, where knowledge is not complete and judgement is required.

iii) Ease of Expression: The knowledge base is formed by normal statements of facts and rules instead of program steps in conventional programs. Therefore, expert systems are more easily understood by practitioners in the domain who might not be computer literate.

iv) Updating: The knowledge of an expert system is explicit and readily accessible. So it is easy to change or update by the end user when he becomes an expert in the domain.

b) High Level Expertise
One of the most important characteristics of an expert system is the high level expertise it provides in problem solving. This expertise can represent the views of the best known and most competent experts in the domain.

c) Predictive Modelling
The system can act as an information model to solve problems in the given field, providing the desired answers show how they would change for new situations. The expert system can predict by diagnosing and explaining in detail how a particular situation will lead to new changes. This lets the user evaluate the potential effect of the new facts or data, and understand their relationship to the solution.
d) **Institutional Memory**

If the knowledge was acquired from the key people in an organisation, department, or office, it represent the current policy or operating procedures of that expert group. This compilation of knowledge is a permanent record of the strategies and methods used by the staff of that institution. When the key people leave, their expertise is retained.

e) **Training Facility**

Expert systems can be designed to provide training, since they already contain the necessary knowledge and the ability to explain their reasoning processes. As a training device, expert systems can be used to train novices in a specific task. Expert systems can also be used to train new staff members about the recommended policy and method by using high experience and strategies of the institution.

2.9. **REASONS FOR THE SELECTION OF AN EXPERT SYSTEM**

As was proposed previously in 2.6, to improve the quality of concrete it is necessary to prepare comprehensive specifications; to provide careful quality control for both concrete making materials, and for the concrete produced; to provide knowledgeable supervision and trained workmen; and to improve the appreciation of both supervisors and workmen on the site.

Assuming that the concrete ingredients and the proportions are suitable, the quality of concrete is a function of workmanship in concreting operations, and the degree of inspection for the workmanship. The more knowledgeable the supervision and the more trained and skilled the workers, the scope of attaining the specified quality is increased. A detailed specification which includes all necessary requirements helps to improve the efficiency of the supervision. This promotes a better and less variable quality.
An expert system provides a corpus of knowledge that can be consulted by an inexperienced supervisor or engineer to obtain specialist advice to define predict, and diagnose the problems, and to get solutions for them. Having obtained the knowledge through the expert system, the supervisor or engineer can transfer it to inexperienced workmen involved in concrete practice. In this way the workmen can be trained cheaply and their appreciation can be improved.

The knowledge base of an expert system of the domain includes a distilled knowledge in concreting operations. This knowledge can readily be used to prepare comprehensive specifications on the workmanship of concreting operations.

The features of expert systems satisfy all the proposals given in section 2.6, except the proposal (ii). An expert system can help contractors to produce a knowledgeable supervisory staff easily and cheaply. Therefore an expert system could be used as a tool to assist improving the quality of concrete on many sites.
3.1 Introduction
3.2 Definitions of Expert Systems
3.3 History of Expert Systems
3.4 Differences Between Expert Systems and Conventional Programs
3.5 Functions of Expert Systems
3.6 Roles of Expert Systems
3.7 Components of Expert Systems
3.8 Knowledge Representation
3.9 Architectural Variations of Expert Systems
3.10 Building an Expert System
3.11 Major Problems of Expert Systems
3.12 Expert Systems and Construction Industry
3.13 ESCON
3.1. **INTRODUCTION**

Expert systems have emerged recently and have been applied to many different human disciplines. This has led to expert systems with different emphases. Expert systems evoke great expectations in professional problem solving which at present is too optimistic a view.

The first part of this chapter defines and clarifies what an expert system is, and explains what it can achieve.

The second part of the chapter introduces the developed expert system, called ESCON.

3.2. **DEFINITIONS OF EXPERT SYSTEMS**

Expert systems have been variously called knowledge based systems, ruled based systems, intelligent based systems, and expert or intelligent assistants [49]. A general definition of an expert system is, "a computer program in the field of Artificial Intelligence which plays an important role in decision making to solve a problem". A wider definition of expert systems has been suggested by The Expert System Group of British Computer Society [50] as:

"An expert system is a mean of capturing the knowledge of experts in the form of programs and data where disagreement among the experts are settled by mediation and results refined so as to extract the essence of their knowledge in such a way that it can be used by less experienced people within the field. The usage of such a system can be monitored so that adjustments may be made semi-automatically under the guidance of the experts. The expert system is a tool and means of coherent communication of the latest views of the experts to the users who may well be the experts.
themselves. The use of the system combined with a measure of importance provided by experts gives a measure of the utility of what is being communicated. This recorded utility may then be used by a program to vet the knowledge so that the channel does not get closed with redundant material".

Because of the wide research developments that have taken place on expert systems, it is difficult to give a single strict definition. However, for the purpose of this thesis the following definition is suggested by the author.

"An expert system is a computer program that intelligently manipulates the encoded expertise knowledge in a specific domain to assist a novice user to solve a problem."

The key expression in this definition is "to assist a novice user to solve a problem". A novice user requires mainly two types of assistances: (1) knowledge and experience to handle the problem; and (2) when the problem is complicated or the human brain is too slow or insufficient, a computer to solve the problem. Many expert systems have been developed, but unfortunately few of them have been practically used in industry as a professional problem solving tool. So, it is believed that, this technology requires more development and time to find wide acceptance in industry. But expert systems can be used in teaching and training of inexperienced people by transferring knowledge and experience to them. The second type of assistance, the necessity of using computer, (valid for experienced people also), is fulfilled automatically, since the expert systems are computer programs.
3.3. **HISTORY OF EXPERT SYSTEMS**

Artificial intelligence (AI) is a branch of computer science that is concerned with a broad range of topics that are related to simulating human intelligence in a computer. Some of the known areas of AI are speech understanding, machine vision, and robotics. Expert systems are also one of the branches of AI which started in early seventies [48]. The original goal of artificial intelligence researchers was to develop computer programs that could solve problems in a similar way to a human. In the sixties AI scientists tried to create general-purpose computer programs to solve a broad class of problems. Developing general-purpose programs proved too difficult at that time.

In the seventies, AI scientists realised that, the problem-solving power of a program comes from the knowledge it possesses. Then, a conceptual breakthrough was made, which was simplified by Waterman [48] as: "to make a program intelligent, provide it with lots of high quality, specific knowledge about some problem area". This realisation lead researchers to develop special-purpose computer programs to do this. These programs were expert in one domain only. Here domain refers to particular area of discourse, for example, concrete production. These programs were called "expert systems", and are the result of many years of attempting to simulate intelligent problem-solving behavior in a computer program. The first successful expert systems were MYCIN, in mid seventies for diagnosing infection deaseses; PROSPECTOR, late seventies, for interpreting geological information; and MOLGEN, for planning molecular genetic experiments [51]. In the eighties many other expert systems have been developed [52,53,54].

The historical development of expert systems is shown in fig. 3.1.
3.4. **DIFFERENCES BETWEEN EXPERT SYSTEMS AND CONVENTIONAL PROGRAMS**

The differences between expert systems and conventional programs are given in many articles, such as, Fenves [46], Waterman [48], Maher [51], Adeli [52], Fenves et al [55], and Sodipo [56]. These differences are summarised in Table 3.1.
TABLE 3.1 - Differences between conventional programs and expert systems (with some additions to reference 51).

<table>
<thead>
<tr>
<th>Conventional Programs</th>
<th>Expert Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Representation and use of data</td>
<td>Representation and use of knowledge</td>
</tr>
<tr>
<td>Knowledge and control integrated</td>
<td>Knowledge and control separated</td>
</tr>
<tr>
<td>Algorithmic (repetitive) process</td>
<td>Heuristic (inferential) process</td>
</tr>
<tr>
<td>Effective manipulation of large data base</td>
<td>Effective manipulation of large knowledge base</td>
</tr>
<tr>
<td>Programmer must ensure uniqueness and completeness</td>
<td>Knowledge engineer inevitable relaxes uniqueness and completeness restraint</td>
</tr>
<tr>
<td>Midrun expression is impossible</td>
<td>Midrun expression is desirable and achievable</td>
</tr>
<tr>
<td>Sequential</td>
<td>None sequential</td>
</tr>
<tr>
<td>Oriented towards numerical expressions</td>
<td>Oriented towards symbolic expressions</td>
</tr>
</tbody>
</table>

One of the basic differences between expert systems and conventional programs is that, expert systems manipulate knowledge, while conventional programs manipulate data. Knowledge is defined by Hayes-Roth et al [57] as descriptions, relationships, and procedures to manipulate these descriptions and relationships. Data is often the first output of an experiment or study, and needs to be refined to become knowledge. However, in many conventional programs knowledge is also used, such as, matrix manipulation. But, the amount of knowledge used in algorithmic programs is relatively small [46]. Heuristics is the study or practice of procedures that are valuable but are incapable of proof. In expert
systems the manipulation of knowledge, such as, display, searching, and modifying is separate from the control (inference engine) which executes the knowledge base. But this is not true for conventional programs. In expert systems, a given set of facts may lead to one or more conclusions. Some are designed so that, the various possible conclusions can be ranked on the basis of their likelihood or certainty. But in conventional programs, for a given set of data the conclusion is unique.

Completeness need not be guaranteed in expert systems, at least not in the development stages. The prototype model can be demonstrated to experts in the domain and rules can be added into the knowledge base. Even the user can add or change the rules in the knowledge base.

Normally every expert system has a facility to explain the reasons behind each goal or question that has been asked. This facility helps the user to understand why a question has been asked and how it affects the goal.

Unlike the instruction set in conventional programs, the rules in an expert system are not executed sequentially. The sequencing is the responsibility of control strategy used. The control strategies of expert systems are explained in section 3.8.1.

When a human expert solves a problem, normally he does not do it by solving sets of equations or performing other laborious mathematical computations. Instead, he choses symbols to represent the problem concept and applies various strategies and heuristics to manipulate these concepts. Expert systems also represent knowledge symbolically and they may fire a goal without making mathematical calculations. For example, "if a mortar layer appears on the top of the concrete while compacting", then, it fires a goal that "the compaction is completed, and hence vibration should stop".
3.5. FUNCTIONS OF EXPERT SYSTEMS

Expert systems have been developed for many different types of problems in different fields such as medicine, geology, engineering, military, chemistry etc. But their basic ten functions as grouped by Hayes-Roth [57] are shown in Table 3.2.

TABLE 3.2 - Generic categories of expert system applications [48]

<table>
<thead>
<tr>
<th>Category</th>
<th>Problem Addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpretation</td>
<td>Inferring situation descriptions from sensor data</td>
</tr>
<tr>
<td>Prediction</td>
<td>Inferring likely consequences of given situations</td>
</tr>
<tr>
<td>Diagnosis</td>
<td>Inferring system malfunctions from observables</td>
</tr>
<tr>
<td>Design</td>
<td>Configuring objects under constraints</td>
</tr>
<tr>
<td>Planning</td>
<td>Design actions</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Comparing observations to expected outcomes</td>
</tr>
<tr>
<td>Debugging</td>
<td>Prescribing remedies for malfunctions</td>
</tr>
<tr>
<td>Repair</td>
<td>Executing plans to administer prescribed remedies</td>
</tr>
<tr>
<td>Instruction</td>
<td>Diagnosing, debugging, and repairing the behavior of novice model user</td>
</tr>
<tr>
<td>Control</td>
<td>Governing overall system behavior</td>
</tr>
</tbody>
</table>
Interpretation systems infer situation descriptions from observables. They explain the observed data by using their symbolic meaning. Prediction systems infer the likely consequences from the given situations. Diagnosis systems use situation description, behavior characteristics to infer probable causes of system malfunctions. Design expert systems develop the configurations of objects based on a set of problem constraints. Planning expert systems design actions. They decide on the entire course of action before acting. Monitoring expert systems compare the actual system behavior to expected behavior. Debugging systems find remedies for malfunctions. Many debugging systems rely on design, planning, and prediction capabilities. Repair systems develop and execute plans to administer a remedy for some diagnosed problems. Instruction expert systems diagnose and debug student deficiencies by analysing the model and devising plans for correcting the deficiencies. Here student refers to the novice model user. They repair the student behavior by executing these plans by direct interaction with the student. Control expert systems govern the overall behavior of a system. To do this, the control systems must interpret the current situation, predict the future, diagnose the causes of anticipated problems, formulate a remedial plan and monitor its execution to ensure success.

3.6. **ROLES OF EXPERT SYSTEMS**

Basden [58] identified the five roles of expert systems as seen from the viewpoint of end users rather than AI researchers. These are:

i) **Consultancy:** An expert system can be used to give specialist advice or other forms of help to an inexperienced user to accomplish a task.

ii) **Checklist:** Humans can forget. Expert systems can serve as an intelligent assistant. The questions of an expert system in a relevant area could act as a checklist, reminding the user of all the factors to take into account.
iii) Training: Expert systems are useful in training non-specialist trainees. They can be used for continually improving the expertise of inexperienced persons.Hover [59], and Chin [60] stated that, expert systems are also useful in education. Teaching a complex and ill-defined operation is highly difficult. But when the students attempt to develop an expert system about such a task, first they have to understand the logic and technical background, and then translate this understanding to a computer code. Finally, the students can use the model in simulation processes which improves their field experience. This can be a comprehensive training tool.

iv) Refining expertise: Many experts freely admit that they have gaps in their knowledge. Expert systems can help to identify these gaps. The experts involved during the construction of the system will benefit by refining their expertise.

v) Communication medium: Unlike conventional programs, expert systems provide a variety of information, in a flexible format. In a textbook, it can be difficult to insert and maintain many cross-references, or to locate the precise information required. In an expert system these problems are reduced. The software can be used to aid searching and processing large collections of distilled rules or information. So, expert systems can be considered as an active textbook or even as an active notebook for rough notes.

3.7. COMPONENTS OF EXPERT SYSTEMS

The parties involved in the architecture of an expert system were given by Çelik, Thorpe, and McCaffer [61] as shown in Fig. 3.2. The components of an expert system are defined in many publications [55,60,62,63,64]. But the most complete one, defined by Maher [51] is as follows:
Fig. 3.2 - Parties involved in the architecture of an Expert System
i) short term working memory
ii) knowledge base
iii) inference engine
iv) explanation facility
v) knowledge acquisition
vi) user interface.

i) **Short term working memory:** This is a dynamic data base (context) which represents the current state of the system. This is the component of an expert system which stores the details of a given problem during the running of the system. As the action of the rules are executed, the facts in this memory change. Upon completion of the problem solving process, this memory contains all the intermediate results of the problem. As an example, if the rule:

**IF** The durability of concrete is important  
**THEN** use the "weight batching" method to measure concrete ingredients.

is executed, the short term memory records that, the durability of concrete is important and the batching method is "weight batching".

ii) **Knowledge base:** This part contains the key concepts in the domain which may be general information, heuristic or judgmental knowledge. In the knowledge base the rules are represented in the form of **IF** <condition>, **THEN** <action>. The rules may be certain or uncertain. The rules of uncertainty are specified by the degree of certainty. **IF** <condition> , **THEN** <action> , **WITH** <certainty>. For example.

**IF** the haul road for a concrete transporting dumper is rough and longer than 300 m, and no precaution is considered to improve the cohesiveness of the concrete,  
**THEN** probably the concrete in the dumper is segregated.  
**WITH** probability = 0.80.
iii) **Inference engine**: The inference engine contains the general procedures for manipulating the knowledge base and short term working memory [65]. This part of the expert system is responsible for the execution of the system. It controls the order of questions, manipulate the given answers, and executes an action as soon as it is satisfied.

iv) **Explanation facility**: In expert systems the explanation facility has two main functions. Firstly, it gives explanations to the user why a particular question has been asked. This helps the user to understand the question better. The second function of the explanation facility is to explain to the user how a particular decision or conclusion has been reached.

v) **Knowledge acquisition**: This component enables the knowledge to be entered into the knowledge base. With this facility the program builder can add or change any rule in the knowledge base easily.

vi) **User interface**: The expert systems user interface provides a dialogue between the system and the user. The user interface is interactive with "help" facilities. In this way, the reasoning and the process used are explained.

3.8. **KNOWLEDGE REPRESENTATION**

The knowledge engineer acquires, organises, and stores the knowledge in the knowledge base of the expert system. The storing of the knowledge in the knowledge base is possible in one of the available representation methods. The common knowledge representation methods are as follows:

1) rules
2) semantic nets
3) frames
3.8.1. **KNOWLEDGE REPRESENTATION USING "RULES"**

In this method, the knowledge of the domain is represented as sets of rules. Rules provide a way of representing recommendations, strategies, or directories. Rules are represented as IF-THEN statements, as shown below.

1. If the required rate of concrete production exceeds 30 cu m per hour, then don't select a manual batching control system.
2. If a shining mortar layer appears on the surface of the concrete, then stop vibration.
3. If the temperature of air exceeds 27°C, then, do not use a clear liquid curing compound.

When the IF portion of a rule is satisfied by the facts (the current situation of the case), the action specified by the THEN portion is performed. When this happens, the rule is said to be "fired" or "executed". A rule interpreter in the inference engine (see section 3.7(iii)) compares the IF portions of the rules with the facts and execute the rule whose IF portion matches the facts as shown in fig. 3.3.

![Fig. 3.3 - The rule interpreter cycles through a match-execute sequence. (redrawn from ref. 48).](image-url)
In the rule base knowledge representation the inference engine uses two types of control strategy, *forward chaining*, and *backward chaining*.

**Forward chaining:** In forward chaining the system starts from all the known facts and searches to find a suitable conclusion or goal that fits the facts. Bottom-up, data-driven, or antecedent-driven are equivalent terms to *forward chaining* [51]. This strategy is useful in cases where there are many hypotheses or solutions, and few input data. For example, for concrete curing, the weather conditions may be "hot", "normal" or "cold". So, in this case there are three hypotheses "hot weather", "cold weather", or "normal weather".

The system needs data such as, relative humidity, air temperature, concrete temperature, and wind velocity to calculate the rate of evaporation from the surface of the fresh concrete. Once these data are fed into the system, it makes the necessary calculations and searches for a suitable conclusion for the given facts. Finally, it concludes, for example, 'the weather condition is "hot" since the rate of evaporation from the surface of concrete is more that 1 kg/ sq m.'

This method has two drawbacks [64]: (1) it requires all possible facts as input which may be wasteful in time, and sometimes all the facts may not be known; (2) the user may think that many of the questions are purposeless.

**Backward Chaining:** In backward chaining, the system starts assuming a hypothesis or goal and works backward checking to see if the known facts support the hypothesis. Top-down, goal-driven or hypothesis-driven are terms equivalent to *backward chaining* [51]. If the known facts do not support the hypothesis, then the system checks the validity of other hypotheses in the knowledge base. For example, consider that the pipeline is blocked in a concrete pump. In this case, the conclusion or the hypothesis is obvious, "the pipeline is blocked". The system goes backward for reasoning or
support for the conclusion. The required facts for reasoning might be one of the following:

- segregation occurred. (the slump of concrete is more than 125 mm, or gap graded aggregate is used, or proportioning is not suitable for pumping concrete)
- Excessive friction. (the amount of fine particles is excessive, or the pipeline was not lubricated, or there are many bends, or the pressure of the pump is not sufficient)

The system checks the reasons for segregation and excessive friction. As soon as it finds a reason or reasons, it gives a message telling the reason or reasons for the blockage of the pipeline.

In general, rule-based knowledge representing systems have the advantage of simplicity. Their main drawback is that, their ability to express relations between the various pieces of knowledge is severely restricted. However, a specialised knowledge representing architecture, blackboard is also available. Blackboard models are explained in section 3.9.

### 3.8.2. KNOWLEDGE REPRESENTATION IN "SEMANTIC NETS"

Semantic nets, also called "semantic networks" are knowledge representations based on a network structure. A semantic net comprises nodes and arcs. The nodes represent the objects, concepts, or events of the knowledge represented. The arcs are used to link the nodes and can be defined in a variety of ways depending on the kind of the knowledge being represented. The common arcs are "has-part", and "is a". If semantic nets are used to represent the natural language, the arcs can be "agent", "object", "recipient", "time", etc. A simple example of a semantic net is shown in Fig. 3.4. This is a simplified example to show a semantic net, and it does not cover the entire concept of concrete quality.
MINIMUM MIXING TIME OF 1 MINUTE FOR CONCRETE MIXERS WITH A CAPACITY LESS THAN 1 CU YD.

Fig. 3.4 - A simple semantic net for concrete quality
In fig. 3.4 it is shown that, concrete quality has parts of durability, strength, and appearance of the concrete. Durability for example has parts of proper compaction, proper curing, and use of durable materials. The use of vibrator is a proper compaction method and a poker is a vibrator.

The inference engine of a tool where the knowledge is represented in the semantic nets, has two parts. The first part deals with the rules by forward or backward chainings as in the rule based systems. The second part invokes the necessary information through the arcs. For example, when a question is asked about the quality of the concrete, the second part of the inference engine investigates that, the quality has the parts of durability, strength, and appearance.

3.8.3. KNOWLEDGE REPRESENTATION USING "FRAMES"

Knowledge representation in a frame is organised similarly to a semantic net. Sometimes both semantic nets and frames are considered to be "frame-based rules" [48]. A frame is a network of nodes and relations organised in a hierarchy. The topmost node represents the general concept and the lowest nodes more specific instances of those concepts. For example, in a frame system, the concept of concrete batching could be organized as shown in Fig. 3.5.

In a frame system, the concept at each node is defined in detail by collection of attributes, such as, name, color, size, etc. The attributes are called slots and each attribute has values such as, Tony, white, large, etc. The knowledge representation about a gauge box is shown in fig. 3.6. In this example, the necessary attributes for a gauge-box are the filling method of the box, the necessity of trimming, the plan area of the box, and the depth of the box. The values of these attributes are shown in the slots as "loose", "trimming is necessary", "small", and "deep" respectively.
The advantages of frames are encoding the knowledge with particular properties, including values, and giving the relations of the frames by identifying semantic links to other parallel concepts.

Fig. 3.5 - A "Frame" representation of batching methods
3.9. ARCHITECTURAL VARIATION OF EXPERT SYSTEMS

There are two common variations in the basic architecture of expert systems: production system models; and blackboard models. The production system models use a generic architecture, but mostly production rules [51] as explained in section 3.8.1. In production system model, the control system, inference engine, provides the strategy to identify the productions that are eligible to be executed. Blackboard models are explained below.
Blackboard models:
Blackboard models provide a mechanism for reasoning about problems including multiple sources of levels of knowledge. This model is based on the separation of the knowledge base or context called a blackboard (see Fig. 3.7). The knowledge sources are self-activating and there is not a control component specified in the blackboard model [66]. The control is in the knowledge sources. Knowledge sources produce changes to the blackboard that leads incrementally to a solution to the problem. Communication and interaction among the knowledge sources take place only through the blackboard.

The blackboard model has been applied to problems involving distributed processing, multiple levels of the knowledge, and multiple sources of knowledge [51]. The problems being solved by the use of a blackboard model tend to be complex which require splitting the overall problem into subproblems.

Fig. 3.7 - Blackboard model
3.10. **BUILDING AN EXPERT SYSTEM**

To build an expert system, the steps are:

a) to decide whether an expert system is a viable solution for that particular problem
b) choosing a tool for the expert system
c) knowledge acquisition
d) developing the expert system

**a) Is An Expert System a Solution?**

There is no general rule as to which problems are appropriate for expert systems. However, Waterman [48] summarised guidelines for expert system application as follows: "Consider expert systems only if expert system development is possible, justified, and appropriate". The parameters for "possible", "justified", and "appropriate" are summarised in Fig. 3.8.

Yazdani [67] defined the following categories of domain where developing expert systems is difficult:

1) experts do no generally agree
2) the strategies in reasoning are complicated
3) the knowledge includes temporal and/or spatial relationships
4) the problem take a long time to solve by people
5) many actions hing on many conditions
6) there are too many objects and too much reliance on commonsense concepts.

**b) Choosing a tool for an expert system**

Two general types of tools can be used to develop an expert system: (1) general purpose programming languages, such as LISP, PROLOG, C, FORTRAN, or PASCAL; (2) knowledge engineering languages (shells). A comparison of some of the available shells is given by Allwood et al [68], and Ludvigsen et al [69]. Programming languages offer more flexibility, but they usually require the developer to design
Fig. 3.8 - Characteristics to define whether an expert system is a solution for a particular problem. (adapted from ref. 48).
the knowledge base and implement the inference engine. So, developing expert systems with programming languages takes a longer time, but it may fit the needs of the problem domain more closely. Knowledge engineering languages offer less flexibility but development should be easier, faster and cheaper. Cabrera and Al-Shawi [70] reported that, using an expert system shell provides significant advantages. These authors stated that, if a knowledge engineering shell has been used, adjusting the system in the light of operational experience is relatively easy. Cullen and Bryman [71] stated that, 47% of expert systems have been developed by using knowledge engineering languages.

Waterman [48] proposed the following method for selecting an appropriate tool for an expert system:

1) select a tool that complement the strength of the knowledge engineer. (a weak or inexperienced team of knowledge engineers would be better with a powerful shell)
2) pick a tool with adequate support facilities. (explanation facility, knowledge base editor, etc.)
3) do not select a tool still under development and thus unreliable
4) select a tool that you will not have to maintain yourself during expert system development
5) pick a tool with features suggested by the problem and its application.

c) Knowledge Acquisition

Human experts can not usually code their knowledge into explicit rules accessible to a computer system [64]. "Knowledge engineers", bridge this gap and code the human expert's knowledge into a set of rules for an expert system. Knowledge acquisition is however a laborious, time consuming, and complex operation [72]. Knowledge for an expert system may be acquired from many sources, such as, textbooks, reports, case studies, empirical data, personal experience, and domain experts. Knowledge acquisition and structuring that
knowledge into a usable form is one of the major bottlenecks in developing expert systems [48,67]. The methods of knowledge acquisition from experts are explained by Trimble & Cooper [73], Welbank [74], and Ellman [75]. These methods can be classified as follows:

I) Unstructured interview: In this method general questions about the domain are asked and the experts' answers are noted. The knowledge engineer then extracts the useful information from the transcript. This method can be useful for inexperienced knowledge engineers. Sometimes, the expert may be asked to prepare a short talk on his specialism if he is willing to do so [74].

II) Structured interview: The knowledge engineer develops a prototype system based very often on his prior knowledge. The prototype is demonstrated to the domain expert who suggest modifications and amplifications. The changes are made and the revised system is demonstrated again. This iteration process continues until the domain expert is satisfied. If the initial prototype is good, this method can be productive. Its drawback is that, this method has a prejudicing effect on the expert, and may direct him from more intuitive knowledge that might be of crucial importance. When a prototype system of the domain is not available, another prototype system of a similar domain (if available) may be demonstrated to prompt the expert for the important issues. Sometimes the knowledge engineer prepares a document detailing the rules and develops this as a knowledge acquisition program. The document records the status of each rule, i.e. finalized, tentative, needs review, etc [73]. The knowledge engineer sometimes extracts questions to direct the conversation of the expert. This method is useful when the experts time is limited.

III) Observation: This method of knowledge acquisition is recommended only for experienced knowledge engineers. Inexperienced engineers may not be able to interpret what they see so well [74]. This method is useful when the expert is defensive about his knowledge.
The selection of a knowledge acquisition method depends on the following:

1) available time for the domain expert
2) whether the expert holds his experience in explicit or intuitive form
3) whether the expert is motivated to help the process
4) the experience of the knowledge engineer.

d) Developing an Expert System

Since additions to the knowledge base is possible any time, expert systems can successfully be developed by starting from a small system and enlarging it later. Weiss [76] and Buchanan [77] gave stages to develop an expert system. The stages are shown in Fig. 3.9 and are summarised below:

i) Initial knowledge base design stage: This comprises three principal substages:

Identification stage: In this stage the problems and the goals are defined. In problem identification the definition and characteristics of problems are specified, and their supporting knowledge is defined. Goal identification comprises defining the objectives of building the expert system.

Conceptualization stage: The concept mentioned in the identification stage is made explicit by drawing diagrams and breaking the problem into subproblems.

Computer representation of the problem: In this stage the problems of representing the information and the data on a computer are addressed.

ii) Prototype development: In this stage the implementation of a prototype system is performed. The prototype system should contain representative knowledge to perform the task aimed.

iii) Testing the prototype system: The testing of the prototype system involves its evaluation. In this stage, the prototype system is run and the weaknesses in the knowledge base or in the inference structure are defined. The system should be compared to an
Fig. 3.9 - Stages of developing an expert system.
available standard test set. In this stage, wrong questions, difficult questions to understand, poorly stated messages, incorrect conclusions, mistakes in sequencing of the questions etc. are found and corrected.

iv) Refinement and generalisation of the knowledge base: Refinement of the prototype system normally involves recycling through the implementation and testing stages to adjust the rules and their control structures. This stage can take a considerable time until the system reaches the expected expert level of performance.

3.11. MAJOR PROBLEMS OF EXPERT SYSTEMS

The application of expert systems technology has some general problems. These problems can be summarized as lack of resources, limitations on expert systems, and weaknesses of expert systems.

i) Lack of resources: There appear to be a shortage of personnel competent in designing and developing expert systems. The major party involved in developing expert systems is the human expert. However, human experts are either scarce or appear unwilling to share their whole knowledge. Their unwillingness may be due to the fact that, the experience they have gained over the years can now be stored on a computer which is then generally available, thus reducing their importance.

ii) Limitations: The application of expert systems is limited in areas where knowledge is inconsistent, temporal, or where performing common sense reasoning. The list of domains where expert systems are difficult to apply is given in section 3.10.(a).

iii) Weaknesses: Compared to human experts, expert systems have some weaknesses, such as: (1) updating the expert system is not as quick as for a human expert. Developing technology and research improve the knowledge in a particular area. Therefore, the knowledge base of an expert system needs to be revised frequently; (2) human expert can learn, understand, and improve their
knowledge easily, but expert system can not. Therefore, expert systems require continuous refining: (3) rules can exceptionally be broken. Human expert knows when to break the rules, but expert systems do not; (4) expert systems are developed to deal with one domain, but human expert may have knowledge in more than one domain [78]; (5) when the problem is difficult, man can call help from the other experts, but expert systems can not.

In many cases, the research environment where an expert system is developed, may differ from the user environment. This may cause a considerable reduction in the accuracy of an expert system. Feigenboum [78] stated that, the accuracy of an expert system (RI) was 90% in a research medium, but reduced to 60% in the user medium. So continuous refining and restructuring an expert system must be provided.

3.12. EXPERT SYSTEMS AND THE CONSTRUCTION INDUSTRY

Levitte [54, 79] divides construction engineering and management into three as: construction engineering; construction management; and rehabilitation, repair, and maintenance engineering.

1) Construction engineering: Construction engineering covers the activities of: design of construction methods; production, handling, compacting, finishing, and curing of concrete; geotechnical engineering decisions for temporary facilities of construction (large projects may require geotechnical engineers); constructability evaluation (the evaluation and critique of engineering designs in terms of ease and cost of construction); site layout; and surveying. Construction engineers make the decisions about these activities depending on their own judgement and experience.

2) Construction management: Construction management consists of managing the administrative, legal, financial, and behavioral aspects of construction. The activities of construction management are
project planning, scheduling, and control; contract management; and construction company management.

3) Rehabilitation, repair, and management: This branch of construction engineering and management involves diagnosing the deficiencies and recommending remedies for rehabilitation, repair and maintenance of engineering facilities.

Having defined construction engineering and management, the reasons for using expert system in construction can be summarised as follows:

a) **Construction problems are ill-structured:** The problems and solutions of the construction industry depends on the location of the work, weather conditions, available technology, time, etc. Therefore, a structured approach to decision making is difficult. Decision rules in construction management manuals -where they exist- tend to look very much like the "IF .... <condition> ..., THEN ....<action>...." rules that are employed to represent knowledge in rule based systems.

b) **Construction decisions must be fast:** In order to keep workers and machines fully utilised, construction decisions should be fast. The adage of "Any decision is better than no decision " and "Ask forgiveness, not permission " explain the attitudes of the construction industry. An expert system can contain the knowledge of an experienced manager, and can immediately be consulted in the absence of the manager. Because of those reasons, expert systems offer valuable new capabilities to provide decision in Construction Engineering and Management. A wide range of expert system applications in the construction industry is given by Adeli [53], and the report of U.S. Army Corps of Engineers [54].
3.13. **ESCON**

ESCON is an expert system (knowledge-based system) that has been developed to perform "prediction", "diagnosis", and "debugging" (see section 3.5) for mistakes and deficiencies in concreting procedures, including batching, mixing, transporting and placing, compacting, finishing of unformed concrete surfaces, and curing. The knowledge base of ESCON can also be used to prepare detailed specifications on the workmanship of the concreting operations.

**Users of ESCON**

The envisaged users of ESCON are control engineers or supervisors who have insufficient knowledge and experience in concreting operations. Having obtained the knowledge from the system, these people can transfer the knowledge to the inexperienced workmen on the site to train them. In this way, the workmen can indirectly get a benefit from the system. The other envisaged users of ESCON are engineers who are responsible for writing specifications but have insufficient site practice to fully specify equipment and methods. ESCON can prepare the specifications for them. To do this, ESCON should be run for their particular case.

ESCON is a model developed for research purposes. As discussed in detail in chapter 10, ESCON requires editing by a local expert to become a professional applicable package or adjusted by operational experience.
3.13.1. KNOWLEDGE BASE OF ESCON

Having undertaken an extensive literature survey, observing the above mentioned concreting activities of experienced practitioners, and combining the experience of the author, a prototype system was developed. In this system, knowledge has been represented as rules (see section 3.8.1.). So, the operation of ESCON consists of a series of questions linked by IF - THEN logic. The user answers the questions as YES, NO, DO NOT KNOW, or by a NUMBER. After each series of questions have been asked, the inference engine of ESCON produces a decision by comparing the answers of the facts within the knowledge base of ESCON.

This prototype system was demonstrated to, and discussed with acknowledged experts in the domain. Because of time restrictions, each expert could only be visited once. To develop the knowledge base of ESCON, six experts from different organisations (contractors; Concrete Society Advisory Service; private consultants; British Ready Mixed Concrete Association; British Cement Association; and Construction Industry Training Board) were visited. During these visits, the knowledge acquisition methods used were:

1) Prototyping: The developed prototype model was introduced or demonstrated to the experts. During the discussion with the expert, his views were noted. The model was then modified to include his views. The model was then demonstrated to the next expert, and his views were also noted. The model was again modified to include the views of this expert also. This procedure was repeated for the 6 experts visited. The recommended modifications by the experts were gradually reducing. At last, the model achieved a state where further major modifications were not required.

2) Structured interview: Sometimes the experts had limited time to discuss everything in the model. In this case, the prototype model was partly introduced, and selected questions were asked to the expert to speed up the discussion. For that purpose, a list containing
more than 70 questions were prepared. The expert described his knowledge while answering the questions. Later this knowledge was refined and included into the prototype system.

Both methods were found successful in the knowledge acquisition for ESCON.

3.13.2. TOOL FOR ESCON

Considering the limited time to develop ESCON, a knowledge engineering language (shell) was used instead of a general programming language. Having considered several available shells, the "SAVOIR" knowledge building tool (shell) was chosen. The main criteria used in the selection of SAVOIR was its proven success in other research programs undertaken at the Civil Engineering Department, Loughborough University of Technology. For example a system called ESEMPS has been developed for the selection of earth moving equipment in road construction [49], and CONPLANT [80].

The Savoir expert system shell consists of three main programs [80]: (1) rules compiler program, called SCOMP; (2) prior value checker, called PV; and (3) run time program, called RT.

The SCOMP program is used to compile the text file of the source. The SCOMP program identifies any errors in the model by line and by error number. The PV program is used to calculate and check the prior values of all questions, variables, and set the initial status and starting values of all questions, variables, and actions, and of the conditions qualifying them. The RT program is used to consult the compiled model. This program decides which goal is to be investigated, examines the model knowledge based to find the appropriate antecedent question and presents this to the model user. If the model user gives a direct answer, the value is propagated
by forward chaining through all nodes in the knowledge base for which the question was an antecedent. Instead of a direct reply to a question the model user may select an option code which allows interrogation of the state of the model or the opportunity to volunteer an answer to a question not yet asked. The options are identified by entering a single letter from the option list described below.

a: Displays an amplification of the current question if one has been provided by the model builder. This option is specially useful for the model user inexperienced in concreting technology.

b: Steps back to the previous question in order to supply a different answer. This previous question will revert to "unanswered" and "unknown", and this new status will be repropagated through the model. However, it is not permitted to step back beyond a point which triggered an action.

c: Displays the chain of reasoning being followed, i.e. the name of the goal being investigated, and the names of all intermediate nodes on the knowledge structure down to the current question at a terminal node.

d: Displays details of the integral questions, variables and actions used in the model. The model user will be asked to specify whether a display is required of the whole model, of a selected group of items, or of just a single item. (Items are identified by their serial numbers as presented in the model summary generated by the SAVOIR compiler program).

e: Displays an "essay" for each item on the chain of reasoning currently being investigated (if there have been provided by the model builder). In most circumstances this option will be used to provide an explanation to the user of why a question is being asked.

h: This option is used to trigger "help" facilities included in the system.
i: Displays a list of all those items currently appearing on the investigated list together with an identification which of these is the current goal.

j: Allows the user to switch session logging on or off. The log is directed to a file "LOG.TXT". The log is a copy of all interactions between SAVOIR and the user and may be printed after the runtime program has terminated.

q: This option is used to end the session. The session terminates and no further question will be asked.

r: This option displays the accumulated report built up by REPORT commands in actions.

s: Displays a summary of the questions which have been answered so far.

v: This option displays a list of the questions which have not been answered so far. The model user is asked if he/she wishes to volunteer the answer to one of these questions.

?: This is the option list request character and displays a summary of the options given above.

The main cycle of the inference engine consists the following phases in the Run Time program (see fig. 3.10):
- the FORWARD chain phase (update all values and execute actions)
- check for the user -or program- requested exist, leaving the main cycle
- the BACKWARD chain phase (find a question to ask)
- the INTERACTIVE phase (ask a question).

These four phases are repeated continuously. **Forward chaining** is the process by which the value of each model variable is updated (re-evaluated) as other values change, for example when a question is answered. In this stage, the effect of the new value is propagated through the network of items. When a change in values sets a goal true, this goal is fired in this phase. Once the forward chaining is complete, and no exit has been requested, the **backward chain** phase is invoked. In this phase the system tries to evaluate a goal. In order to satisfy this hypothesis goal, relevant questions are investigated.
The *interactive phase* directly follows the backward chain phase, and the discovered askable question is displayed. If there is no question to ask, the user will see a system message indicating this. The interactive phase always terminates with some new information to be inserted into the knowledge base. At this point, the run time control program calls the forward chain phase to update the system.

In Savoir, knowledge is represented in the rule base. The three major components of the Savoir knowledge representation languages are:

- **Questions**: Questions are employed to elicit information from the model user.
- **Variables**: Variables are used to store values describing the state of the model as it progresses through a consultation by the user. The values of variables are obtained from the values of other variables and from the replies of questions. Each time the user replies to a question, the RT program automatically uses the value of the reply to re-evaluate the values of all variables dependent on that question. A variable may store the value of a number, a probability, a condition, or a character string.
- **Actions**: Actions control the consultation of the model. An action is fired whenever its associated trigger condition becomes TRUE. The actions of Savoir are:

  1) **To control the display of information:**

<table>
<thead>
<tr>
<th>ACTION</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>DISPLAY</td>
<td>Display information immediately on the model user's terminal.</td>
</tr>
<tr>
<td>PRINT</td>
<td>Prints the messages given by the model.</td>
</tr>
<tr>
<td>REPORT</td>
<td>Adds a text string to the collection of reports known as reportlist.</td>
</tr>
<tr>
<td>DISPLAY REPORTLIST</td>
<td>Displays the reportlist on the screen.</td>
</tr>
<tr>
<td>PRINT REPORTLIST</td>
<td>Sends the reportlist to the printer.</td>
</tr>
<tr>
<td>CLEAR REPORTLIST</td>
<td>Empties the reportlist.</td>
</tr>
</tbody>
</table>

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2) To control evaluation of items:

INVESTIGATE: Put the variables or questions which are to be valuated on the investigate list.
STOP: Removes the variables, questions, and groups from the investigate list.
STOP ALL: Clears the whole investigate list.
STOP CURRENT: Removes just the top question or variable or group from the investigate list.
CLEAR: Reset the status of a question or list of questions to "unanswered" and "unknown".
CLEAR ALL: Clears the answers to all questions in the model allowing the consultation to restart from its prior value state.
ASK: Investigate a question immediately after clearing its value and stops the question once answered.

3) To set values

MAKE: Sets a value for a variable.

4) To save and resume a consultation

DUMP: Stores the current state of the consultation on disk, enabling sessions to be suspended until later RESTORE.
RESTORE: Replace the current state of the consultation by one previously dumped.

5) To execute external procedures

DO: Calls an external program.
Limitations of SAVOIR: Although SAVOIR is capable of making some simple calculations, it is not successful in complex calculations. In this case, it is necessary to call an external program for the calculations. SAVOIR provides access to an existing external program if it is written in Pro-Pascal. This means that, the knowledge engineer must have a good programming knowledge in Pascal to write any external program to perform complex calculations.

While running the system, the inference engine of SAVOIR does not let the user to go back and change the answer of a question which has already been asked and a goal executed. This creates difficulties in getting other alternative goals for a specific set of questions when required.

Although, SAVOIR is a general-purpose knowledge base shell and while developing an expert system a novice knowledge engineer may encounter some problems, the shell is quite flexible and easy to use.

3.13.3. STRUCTURE OF ESCON

ESCON is divided into six modules as follows:

1) Batching of concrete
2) Mixing of concrete
3) Transporting and placing of concrete
4) Compaction of concrete
5) Finishing of unformed concrete surfaces
6) Curing of concrete

The files for the batching, mixing, transporting and placing, compaction, finishing of unformed surfaces, and curing of the concrete are BATCHING.XPT, MIXING.XPT, TRANSPOR.XPT, COMPACT.XPT, FINISH.XPT, and CURING.XPT respectively. These files are explained in chapters 4, 5, 6, 7, 8, and 9 respectively.
3.13.4. ACHIEVEMENTS OF ESCON

ESCON is capable of:

a) defining, predicting, and diagnosing mistakes and deficiencies in the concreting activities given above;
b) debugging mistakes and deficiencies explained in (a) above, including the reasons;
c) helping to improve the knowledge and experience of inexperienced staff on concreting sites;
d) preparing comprehensive specifications on the workmanship of concreting operations;
e) predicting the strength loss when some of its recommendations are ignored;

a) **Defining, predicting, and diagnosing problems:**
ESCON can define, predict, and diagnose a problem depending on the facts of the given situation. For example,

**QUESTION:** Does the drum of the truck mixer rotate more than 300 times after introducing cement with water or aggregates?

**ANSWER:** YES

**DISPLAY:** Since the drum of the truck mixer is rotated more than 300 times after introducing cement with water or aggregates, the concrete is overmixed. Overmixing is undesirable because:
- extending the grinding action causes an increase in the fine particles
- more water is required to maintain the predefined consistency
- the entrained air is driven out
- the mixer wears unnecessarily.
Therefore, as a solution to overmixing, reduce the delays, speed up delivery, and rotate the drum of the truck mixer at the lower end of the range of agitation speed (2-6 rpm).

b) **Debugging of problems:**
As shown in the above example, after predicting, and defining the problem, (overmixing), ESCON suggests remedies to avoid the adverse effects of overmixing. In this case, the remedies are, to reduce the delays, speed up delivery, and to rotate the drum of the truck mixer at the lower end of the range of agitation which is 2-6 rpm.

c) **Educating the staff:**
Welfare [82] stated that, a concrete foreman must be given the knowledge and experience to ensure that the operation is performed correctly. The knowledge of the supervisory staff can be improved by training courses, or seminars, or reading manuals, guides etc. However, in many instances, these prove uneconomical or not available or impossible especially in the developing countries where training facilities are scarce and the general education levels are low. In such cases, expert systems are good teaching aids for the supervisory staff, since they contain the definitions of the problems, the solutions, and the reasons for the solutions. As shown in the example in (a) above, the system states why the concrete is overmixed, as well as, defining, and debugging the problem.

d) **Predicting strength loss:**
During the site visits in Cyprus, it was observed that, on some sites the supervisor knows that the applied concrete practice and workmanship is wrong. However, he may not appreciate the effects of bad workmanship on the quality of the finished concrete. ESCON therefore contains a file to calculate and display the effects of improper concreting operations on the strength of the concrete produced. It is hoped that, this will act as a reminder for the
supervisory staff and motivate them to avoid mistakes. However, it is impossible to quantify all of the goals of ESCON in terms of strength loss when they are ignored. Therefore, only 12 of the goals are quantified in terms of strength loss. These goals are:

- **Aggregate surface texture, shape, and grading:** The surface texture, shape and the grading of the aggregate affects the compressive strength of the concrete by up to 44%, 22%, and 20% respectively [6,23]. When off-site batching is used, these properties of the aggregate are especially important. The ready mixed concrete purchaser should specify these properties of the aggregates if he is responsible for the selection of the proportions. (see section 4.5.1).

- **Cement last loading method:** In off-site batching the delivery time may necessitate the use of the "cement last" truck mixer loading method (see Table 5.3, 5.4,and 5.5). A reduction in the strength of the concrete by up to 15% is expected if this recommendation is ignored.

- **Weight batching:** Weight batching is more reliable and accurate than volume batching. As explained in section 4.4.(a), ignoring the recommendation to use weight batching reduces the strength of the concrete from 4% to 33% depending on the water/cement ratio, and conditions of the volumetric batching method used.

- **Storage of the cement bags:** The cement bags should be stored on the site properly and the cement delivered first should be used first. "Air set" cement causes a reduction in the strength of the cement. It is expected that, a code of practice on workmanship on building sites to be published by BSI will state that, the cement in the normal 3-ply paper bags stored under good conditions on the site can lose its strength by about 20% in 4 to 6 weeks. The similar figures were also given by Blackledge [8]. If this recommendation is ignored, it is assumed that, the cement is stored on the site for about 4-6 weeks and thus "air set" will occur.
- **Aggregate moisture adjustment:** The weights of the mixing water and the aggregates should be adjusted for the changes in the moisture content of the aggregates (see section 4.4.(b)). An increase in the moisture content of aggregates by about 1% causes a reduction in the strength of the concrete by about 10%. If this recommendation of ESCON is ignored, it is assumed that the strength of the concrete is reduced by about 10%.

- **Mixing time:** In order to achieve a uniform mixture, the concrete should be mixed for a minimum duration as defined in section 5.3.2. Otherwise, the strength of the concrete is reduced. If this recommendation is ignored, in the calculations, it is assumed that the concrete is mixed only for the half of the minimum mixing time specified, and this causes a reduction in the strength of the concrete by about 10% [25].

- **Slump reduction:** As explained in section 6.3.3.3.(b), it is recommended that the slump of the concrete should be reduced as the concrete rises in the form of the columns or walls. Otherwise, a reduction in the strength of the concrete as shown in Table 6.1. is unavoidable.

- **Vibration duration:** Concrete should be vibrated for a duration as explained in section 7.3.4. Undervibration or overvibration causes strength loss. If the recommendation of ESCON about the vibration duration, or systematic penetration is ignored, it is assumed that the strength of the concrete is reduced by about 15%.

- **Revibration:** Revibration is recommended when bleeding or settlement cracks are excessive. Revibration increases the strength of the concrete by about 3-14% if it is undertaken as explained in section 7.3.4. If this recommendation is ignored, it is assumed that the expected strength of the concrete does not increase by a minimum of 3% and a maximum of 14%.
**Duration of curing:** Curing should be maintained for a minimum duration as explained in section 9.3.3. Any duration of curing less than this causes a loss of strength. If the recommendation of ESCON about the duration of the curing is ignored, it is assumed that, the strength of the concrete is reduced by 17% as discussed in section 9.3.3.

While running ESCON, if a recommendation given in the above list is executed, the system checks whether that recommendation is obeyed or not. At the end of the session, the user is asked if he/she wants to see how much the strength of the concrete is lost by ignoring a number of its recommendations. If the user answers "YES", the file QUANTIFY.XPT calculates the expected strength loss.

In some cases, the effect of ignoring a recommendation on the strength of the concrete can not be expressed with a constant number. For example, the shape of the aggregate affects the strength by up to 22%, but this does not mean that the strength reduces automatically by 22% when the shape of the aggregate is not defined during ordering ready mixed concrete. Although it is not defined, the correct aggregate shape still could be used, or the aggregates used may not cause as much as 22% reduction in the strength. However, there are some cases, where ignoring a recommendation causes a definite and constant loss in the strength. For example, if the adjustment in the weights of the mixing water and the aggregates are ignored when the moisture content of aggregates increases by 1%, then the strength of the concrete reduces by about 10%. Therefore, QUANTIFY.XPT makes two different calculations, one for a maximum, and one for a minimum expected strength. Finally, the system displays both the maximum and the minimum expected strength of the concrete in terms of the percentage of the design strength.
e) **Preparing comprehensive specifications:**

Mahaffey [83] stated that, ideal supervision is where the designer of the structure writes the specification, then supervises the construction. Mahaffey continued that, this disappeared with cottage industries. Today, normally, the writer of a specification and the supervisor of that job are not the same person. This highlights a communication problem in many specifications. Good supervision should not be expected if the supervisor does not understand the requirements of the specification.

In a survey conducted by the ASCE Task Committee on specifications, the criticism of American contractors was that, specifications were unfair, annoying, or meaningless [84]. Pittaway [85] reported that, the situation in Australia was similar. During the 84 site visits in Cyprus, and 1 in UK, it was observed that, specifications didn't contain all the necessary information required to control the workmanship of concreting operations. Mather [13] stated that, in order to provide efficient inspection on site, all the necessary requirements should be put into the specifications. In the survey of ASCE, the contractors preferred specifications that: (1) are written in clear, concise language; (2) fit to the job rather than general or standard specifications; and (3) emphasis on "performance" type specifications rather than method or "prescription" specifications. In this survey, the weighted average of the responses indicated that, the possible savings to owners was 7.8% of the construction cost if the specifications were prepared in detail as explained above.

The knowledge base of ESCON contains distilled knowledge on concreting activities. This knowledge can be used to prepare detailed specifications on the workmanship of the concreting activities. These specifications contain all the necessary information to perform the job. When the system runs for a particular case or a job, the user is asked before switching off the computer, if he/she
requires a printed specification on the workmanship of the concreting operations. If the answer is "YES", then the specification is printed. An example of specification on the workmanship for concrete operations is given in Appendix D.

3.13.5 THE STATISTICS OF ESCON

Acquiring the knowledge, developing the knowledge base, and evaluating ESCON took two and a half years. The model includes 234 Questions, 139 Variables, 622 Actions, and 22 Groups which make a total of 1017 items. The total size of ESCON is about 510000 bytes over 12000 lines. One complete run of ESCON takes about 40 to 60 minutes.
CHAPTER FOUR: BATCHING OF CONCRETE

4.1 Introduction
4.2 General Requirements
4.3 Batching Methods
4.4 Factors Affecting the Accuracy of Batching
4.5 "Concrete Batching" Module of ESCON
4.1. INTRODUCTION

Batching involves measuring the quantities of the concrete making materials (cement, water, sand, and coarse aggregate, and sometimes admixtures). The correct amount of each material must be batched if the quality of the concrete is to be maintained in both individual and successive batches. Mistake in measuring the ingredients reduces the accuracy of the batching. Poor accuracy in the batching causes variation in the properties and the quality of the concrete produced.

In the first part of this chapter, the methods of batching and the factors that affect the quality of the concrete are explained. In the second part of the chapter, the "Concrete Batching" module of ESCON is described, and the way in which ESCON handles batching problems are discussed.

4.2. GENERAL REQUIREMENTS

The accuracy of measuring the ingredients affects the quality of the concrete produced, and is largely dependent on the selected batching method. There are two main objectives of batching irrespective of the batching method selected [11,86]:

a) to obtain uniformity and homogeneity in the physical properties of the concrete, such as, unit weight, slump, air content, strength, and air free unit weight of mortar in both individual and successive batches of the same mixture proportions;

b) to maintain proper sequencing and batching of the ingredients.

To meet these objectives, proper batching plant, and adequate inspection and supervision of the batching processes are required. Specifications containing detailed requirements for concrete batching equipment can be found in several books and papers on the
subject [28, 87, 88, 89, 90].

The frequently used typical batching tolerances are given in table 1. Other commonly used batching requirements include beam or scale division of 0.1 % of total capacity, and batching interlock of 0.3 percent of total capacity at zero balance; quantities of admixture weighed for one batch (3 % of the admixture weight required per batch should not be smaller than 0.4 % of the full scale capacity); protection of automatic control from dust and weather; and frequent checking and cleaning of scale and beam pivots [10].

**TABLE 4.1 - TYPICAL BATCHING TOLERANCES [11]**

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Batch weights greater than 30 % of scale capacity</th>
<th>Batch weights less than 30 % of scale capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Individual batching</td>
<td>Cumulative batching</td>
</tr>
<tr>
<td>Cement and other cementitious materials</td>
<td>+/- 1 % of scale capacity, whichever is greater</td>
<td>+/- 0.3 % of scale capacity, whichever is greater</td>
</tr>
<tr>
<td>Water (by volume or weight), %</td>
<td>+/- 1</td>
<td>Not recommended</td>
</tr>
<tr>
<td>Aggregates %</td>
<td>+/- 2</td>
<td>+/- 1</td>
</tr>
<tr>
<td>Admixtures (by volume or weight) %</td>
<td>+/- 3</td>
<td>Not recommended</td>
</tr>
</tbody>
</table>
4.3. BATCHING METHODS

Concrete batching methods can broadly be divided into:

a) Off-site batching
b) On-site batching

4.3.1. OFF-SITE BATCHING

Off-site batching usually uses sophisticated batching devices and therefore, the accuracy of batching is higher than most of the on-site batching methods that are used on small to medium size sites. In this method, aggregates, cement or other cementitious materials, and powder admixtures (if any) are measured by weight; water and liquid admixtures are measured either by weight or by volume [88,90,91]. Depending on their batching control systems, off-site batching plant fall into three general categories [11,25,28,88,92,93,94] :

a) manual controls
b) semi-automatic controls
c) automatic controls

a) Manual Controls
These batching devices are actuated manually, and the accuracy of the batching operation is dependent on the operator's visual observation of the scales or volumetric indicators. The batching devices may be actuated by hand or by pneumatic, hydraulic, or electrical power assists.

b) Semi-automatic Controls
These batching devices are actuated by one or more starting mechanisms. The semi-automatic batcher control starts the weighing operation for each material, and stops automatically when the designated amount has been reached. Semi-automatic batching control systems can be equipped with interlock systems so that, the discharge device can not be actuated until the indicated material is
within the applicable tolerances. Visual confirmation of the scale reading for each material being weighed is essential.

c) **Automatic Controls**
Automatic batching control is actuated with a single starter switch. It then starts the weighing operation for each material and stops automatically when the designated weight for each material has been reached. This system is interlocked in such a manner that,

i) the charging device can not be actuated until the scale has returned to zero balance within +/- 0.3 % of the scale capacity,

ii) the charging device can not be actuated if the discharge device is open,

iii) the discharge device cannot be actuated if the charging device is open.

iv) the discharge device can not be actuated until the indicated amount is within the applicable tolerances.

Automatic control systems provide either cumulative batching or individual batching of materials. Electronic control systems may provide other facilities such as aggregate moisture control, or slump control systems. Automatically controlled plant are usually equipped with either a graphic or a digital recorder to record the quantities weighed for each batch [95].

4.3.2. **ON-SITE BATCHING**

On-site concrete batching can be divided into:

a) Volumetric batching;

b) Weight batching.
a) **Volumetric Batching**

This method involves batching aggregates or cementitious materials by volume [11]. Volumetric batching is suitable for the production of most concretes, provided the equipment is operated in accordance with ASTM C 685 [96]. The principal of volumetric batching comprises two distinct methods:

i) For continuous mixers: accuracy is controlled by either passing solid materials through a calibrated rotary vane feeder, or conveying materials through a calibrated gate opening, or by some other method that provides a known volume in a calibrated unit time.

ii) For site mixers (tilting or reversing drum): in this case the best aggregate measuring tool is a gauge-box with a small plan area, or hopper which is filled to a certain level. The only recommended cement batching method is the use of full bags of cement for each batch.

However the use of volumetric batching has generally been discarded in favour of weight batching. The reason for this is the two possible sources of errors in volume batching [31]:

a) variation in the amount of solids volume in a specified volume of aggregate due to changes in the physical properties of the aggregates (moisture content, grading, etc)

b) errors in the measured volume.

ASTM C 685 [96] defines the tolerances in volumetric proportioning of ingredients as follows:

- cement, weight %: 0 to + 4
- fine aggregate, weight %: + or - 2
- coarse aggregate weight %: + or - 2
- admixtures, weight or volume %: + or - 3
- water, weight or volume %: + or - 1

In order to meet these tolerances, it is necessary to give attention to:

i) the degree of compaction of the cement when not measured
as full bags,

ii) the grading and other physical characteristics of the fine and coarse aggregates,

iii) the moisture content and bulking factor of the fine aggregate,

iv) the viscosity of the admixture,

v) other factors of influence, for example, the mechanical condition of the batcher or the prevailing weather conditions.

b) **Weight Batching**

In weight batching aggregates, cementitious materials, and powder admixture (if any) are measured by weight; water and liquid admixtures are measured by volume or weight. The amount of solid granular material in a unit volume is variable; the volume of moist sand in a loose condition weighs much less than the same volume of dry compacted sand. But, a ton of aggregate is a definite quantity, which usually only requires adjustment for the moisture content. Measuring cement by weight, avoids errors, since for example, Portland cement may weigh anything from 1200 to 1522 kg/m³ (75 to 95 lb/ft³) according to the degree of compaction and aeration [97].

The factors affecting the choice of the weight batching system are [11]:

i) size of job;

ii) required production rate; and

iii) required standards of batching performance.

Different types of weight batching plant are available for use in large and small contracts. On large concrete sites, the available weight batching equipment falls into three categories: manual weight batchers, semi-automatic weigh-batchers, and automatic weight batchers. The control of these systems is explained in section 4.3.1. On smaller concrete sites, the weight batcher may be of a different type. It may for example be situated at ground level and be used as the loading skip of the mixer which is elevated to discharge the measured materials into the drum of the mixer.
4.4. FACTORS AFFECTING THE ACCURACY OF BATCHING

Inaccuracies in measuring batch quantities cause variations of concrete quality. The factors which affect the accuracy of batching are:

a) batching method
b) compensation for aggregates moisture
c) batching control systems
d) inspection and maintenance

a) Batching Methods
In volumetric batching the accuracy of measuring the batch quantities is always doubtful. Sparkes, [6] stated that, in volumetric batching, a variation in the strength of concrete up to 100% is possible. The Road Research Laboratory [42] discovered that, depending on the measuring conditions, volumetric batching method may cause a variation in the strength of concrete up to 75%, with a water/cement ratio of 0.8. The Road Research Laboratory also reported that, the use of volumetric batching reduces the strength of concrete by 4% to 33% depending on the water/cement ratio and the condition of the volumetric batching method used. In 1962, Waddel, J.J. [3] stated that, volumetric measurement of solid ingredients causes a fluctuation in the strength of concrete by as much as +/- 20%. As was explained in chapter 2, the coefficient of variation of the compressive strength of volumetrically measured concrete taken from 70 sites in Cyprus was found to be 51.3%.

However, in volumetric batching it is difficult to compensate for any changes in the physical properties of the aggregates (moisture content, bulking factor, grading, etc). Volumetric measurement of cement may cause a 20% variation in the measured amount [97] and this should be avoided.
b) compensation for Aggregate Moisture

The final batch weight of the water and aggregates should be adjusted to compensate for the moisture in the aggregates. In batching, significant errors can be introduced if this process is not undertaken consistently and correctly. Normally in mix design calculations, the moisture content is based on the Saturated Surface Dry (SSD) weight of aggregates. Therefore any variation other than the SSD condition needs to be allowed for in the weights of both aggregates and added mixing water. For example, a 1% increase in the moisture content of the aggregates will cause an increase in the water/cement ratio of the mixture, by approximately 5% when the original water/cement ratio is 0.5, and the cement content is 300 kg per cu m. A 5% increase in the water/cement ratio is enough to destroy the expected quality of the concrete by reducing both its strength and its durability.

On many sites, the adjustment of aggregate moisture is left to the mixer operator. This method of adjustment may not always be successful. Zeistman and Fulton [98] observed that, an experienced mixer operator with a large mixer and reasonably uniform aggregates can maintain the slump of concrete produced between 50 and 100 mm for two thirds of the time. For many jobs so much variation in the slump of freshly mixed concrete is unacceptable. Therefore to reduce this variation proper adjustments in the weights of water and aggregates are required regularly.

c) Batching Control Systems

From a quality point of view, the batching control systems can be divided into two: manual control systems; and others (semi-automatic and automatic control systems). The batching control system is selected depending on the required rate of concrete production. Manual control systems are good for a small rate of production, up to 30-40 cu yd (23-30 cu m) per hour [99]. Any attempt to produce concrete at a higher rate will promote inaccuracy and subsequently the quality of the concrete will suffer.
d) **Inspection and Maintenance**

Competent inspection and supervision of the batching devices and procedures prevent mistakes in batching. The sources of common batching errors are:

i) careless setting or reading of amounts on the scales, dials, or meters;

ii) material sticking in weigh hoppers, so, scales do not return to zero between batches;

iii) dirty or worn knife-edges and fulcrums on scales;

iv) careless operation that may cause overlapping of batches, or loss of materials;

v) uneven wearing of continuous mixer's vane feeders (usually, the coarse aggregate vane feeder wears out faster than others);

vi) clogging of the valves of the admixture dispensers;

vii) leakage at the closing devices of the containers.

In BS 5328 [89] it is specified that, all measuring equipment shall be maintained in a clean, serviceable condition, and shall be zeroed daily, and calibrated monthly. However, this does not always happen.

4.5. **"Concrete Batching" Module of ESCON**

As stated in section 4.1, the accuracy of measuring the ingredients affects the quality of the concrete produced. The accuracy of batching is influenced by batching methods, adjusting aggregate moisture content, batching control systems, inspection of batching procedures and maintenance of batching devices. The adverse effects of these factors on the quality of the concrete can be alleviated by knowledgeable supervisors, and experienced workmen. The production of a detailed specification on the workmanship of concrete batching can help to improve the efficiency of the supervision. The "Concrete Batching" module of ESCON is designed therefore to transfer concise, relevant information to the supervisory staff about these factors.
The flow diagram of the "Concrete Batching" part of ESCON is shown in fig. 4.1. ESCON, divides concrete batching into two: off-site batching; and on-site batching.

4.5.1. OFF-SITE BATCHING

In selecting the batching method for a particular situation, ESCON investigates the following points (see Fig. 4.2):

i) **controlling the concrete making materials:** To select off-site batching, the system requires all the concrete making materials used by the ready mix producer to be controlled regularly by the purchaser unless, there is any other means of independent control.

ii) **availability of a ready mixed concrete supplier:** Off-site batching is possible if a ready mixed concrete producer is available at a reasonable distance from the concrete site. This distance is actually measured as "delivery time" of concrete from the ready mixed concrete plant to the site. The delivery time is affected by the truck-mixer loading method, weather conditions, and the acceptable strength loss due to the effect of retempering the concrete on the job site.

iii) **maximum aggregate size:** For off-site batching, ESCON limits the maximum aggregate size to 63 mm (2.5 in). Otherwise, the discharged concrete will not have a uniform distribution of coarse aggregate throughout the batch.

iv) **rate of concrete delivery:** To select off-site batching, it is essential that, the ready mixed concrete producer is able to deliver the concrete at a rate that meets the specified rate of concrete placing and finishing.
Fig. 4.1 - Flow-chart for "Concrete Batching" module of ESCON
ARE THE CONCRETE MAKING MATERIALS USED BY READY MIXED CONCRETE PRODUCER CONTROLLED REGULARLY?

YES

IS THERE ANY AVAILABLE READY MIXED CONCRETE PRODUCER THAT CAN DELIVER CONCRETE IN SPECIFIED DELIVERY TIME?

YES

IS THE MAXIMUM AGGREGATE SIZE LESS THAN 63 mm (2.5 in)?

YES

CAN THE READY MIXED CONCRETE PRODUCER DELIVER CONCRETE AT THE PRESPECIFIED RATE OF PLACING AND FINISHINGS?

YES

YOU MAY USE EITHER OFF-SITE OR ON-SITE BATCHING METHOD

NO

NO

NO

NO

SINCE CONCRETE MAKING MATERIALS ARE NOT CONTROLLED, OR THE SPECIFIED CONCRETE DELIVERY TIME IS EXCEEDED, OR MAXIMUM AGGREGATE SIZE IS MORE THAN 63 mm, OR THE RATE OF CONCRETE DELIVERY IS LESS THAN THE SPECIFIED RATE, THEN, ON-SITE BATCHING METHOD IS RECOMMENDED.

Fig. 4.2 - Selection of ON-SITE or OFF-SITE batching
If all the above can be satisfied, ESCON permits the use of either off-site or on-site batching. The selection of the batching method then depends on other factors such as, economical considerations, capacity and location of the job and anticipated workload of the available ready mixed concrete supplier. In this case, the user can select any of the available batching methods. If any of the above points is unfavourable to off-site batching, then, only on-site batching is applicable.

If off-site batching is selected, ESCON highlights the necessity of proper ordering. Concrete ordering types fall into three categories:

a) the purchaser will be responsible for the selection of proportions for the concrete mixture.

b) the ready mixed concrete producer will be responsible for the selection of the proportions for the required concrete

c) the ready mixed concrete producer will be responsible for the selection of the proportions of the required concrete with a condition that, the minimum cement content is specified by the purchaser (when the durability of the concrete is important).

ESCON gives the items that must be specified for each of these concrete ordering types. An extract from a run of ESCON is given below which includes the items to be specified when ordering the concrete.
QUESTION ORDERING '£13£ What is the concrete ordering method of the ready mix concrete purchaser?

£13£1- The purchaser will be responsible for the selection of the proportions of the mixture,
£13£2- Ready mix concrete producer will be responsible for the selection of the proportions,
£13£3- Ready mix concrete producer will be responsible for the selection of the proportions with a minimum allowable cement content specified by the purchaser. This is applicable when the durability of concrete is important). £13£'

INTEGER 1 3

DISPLAY '£13£ It is recommended that, the purchaser should specify the following when he is responsible for the proportions of the mixture.
£13£1-properties of aggregates, (size and surface texture of coarse aggregate, and shape of aggregates)
£13£2-slump or slumps desired at the point of delivery,
£13£3-when air entrained concrete is specified, the air content at the point of discharge from truck mixer,
£13£4-cement content
£13£5-maximum allowable water content, including surface moisture on the aggregates, but excluding water of absorption,
£13£6-if admixture is required, the type, name, and dosage. £13£'

STOP ORDERING
INVESTIGATE AGGREGATE_TEXTURE
ASSOONAS (ORDERING=1)

DISPLAY '£13£ It is recommended that, the purchaser should define the following when the ready mix concrete producer is responsible for the selection of the proportions for the required concrete.
£13£1-size and shape of the aggregates,
£13£2-slump or slumps desired at the point of delivery,
£13£3-when air entrained concrete is specified, the air content at the point of discharge from truck mixer,
£13£4-requirements for compressive strength as determined on samples taken from the transportation unit at the point of discharge,
Prior to the actual delivery, the purchaser should ask for a statement from the producer that includes the dry weights of the cement and saturated surface dry weights of the coarse and fine aggregates, type, and name of the admixture (if any) and the water content.

STOP ORDERING
INVESTIGATE SUPERVISION
AS SOON AS (ORDERING=2)

DISPLAY £13£ It is recommended that, the purchaser should specify the follows when the ready mix concrete producer is responsible for the selection of the proportions for the concrete required. This ordering method is used when the durability of the concrete necessitates the defining of a minimum cement content.

1. Size and shape of the aggregates.
2. Slump or slumps desired at the point of delivery.
3. When air entrained concrete is specified, the air content at the point of discharge from truck mixer.
4. Requirements for compressive strength as determined on samples taken from the transportation unit at the point of discharge.
5. Minimum cement content
6. If admixture is required, the type, name, and amount to be used. The cement content will not be reduced when any admixture is used.

Prior to the actual delivery, the purchaser should ask for a statement from the producer including the dry weights of cement and saturated surface dry weight of coarse and fine aggregates, type, and name of admixture (if any) and water content. £13£

STOP ORDERING
INVESTIGATE SUPERVISION
AS SOON AS (ORDERING=3)
4.5.2. **ON-SITE BATCHING**

The system divides on-site batching into two as on-site volumetric batching and on-site weight batching by considering the class, durability, appearance, and the strength variation of the concrete. See fig. 4.3.

Weight batching is recommended when the concrete is required for first class work, or the grade of concrete is higher than 15CP as defined in BS 5328 [89]; or the durability or appearance of the concrete is important; or when the variation in the strength of concrete is required to be minimized due to batching inaccuracies.

**a) On-site Volumetric Batching**

ESCON, generally discourages the use of volumetric batching. However, its simplicity, cheapness, and requirements for less maintenance means, it can be recommended for small jobs. Volumetric batching is usually used with:

1) tilting drum or reversing drum site mixers
2) continuous mixers.

ESCON recommends that the bulking of the sand should be allowed for in the volumetric batching.

1) **Tilting Drum or Reversing Drum Site Mixers**

   i) **Aggregates:** ESCON recommends that guage boxes with a relatively small plan area, or hoppers marked for the level of the required amount of aggregate are used providing that the necessary allowances for the bulking of the sand is also recommended.

   ii) **Cement:** ESCON recommends that volumetric measurement of the cement should never be permitted. In volumetric batching, cement can only be measured as full bags.
Either volume or weight batching method can be used. But considering cheapness, and less maintenance, volumetric batching may be more convenient for that job.

If concrete is for a first class work, or durability, or appearance of concrete is important; or strength variation due to inaccuracies in batching is not acceptable, then, weight batching is recommended.

Fig. 4.3 - Selection of on-site VOLUME or WEIGHT batching.
iii) **Water**: ESCON recommends that the mixing water should normally be measured by volume. The recommended water measuring devices are:
   a) **Water Meter**: This is applicable when water is available at a constant pressure, and is free of sediment, dirt, or scale.
   b) **Vertical Tank**: Vertical water measuring tanks can be used in every condition providing there are no leaks through the valves.

iv) **Admixture**: ESCON recommends that the admixture is mixed with mixing water before charging the mixer to enable better dispersal. The system defines the following admixture measuring devices:
   a) **Timer Control**: This is used when the admixtures need to be measured in increments of less than one ounce. The existence of admixture in the reservoir needs to be checked regularly.
   b) **Displacement Dispencer**: This similar to the timer control.
   c) **Visual volumetric container**: only applicable on very small sites.
   d) **Admixture meter**: This is quite common and recommended when the viscosity of the admixture changes.

2) **Continuous Mixers**
   i) **Aggregates and cement**: ESCON states that aggregates and cement should be measured by adjusting the speed of the spiral conveyors which feed them into the mixer.
   
ii) **Water and Admixture**: The system states that water and admixture should be measured by separate flowmeters.

b) **On-site Weight Batching**
Having selected the weight batching method, the model highlights the importance of regular maintenance of the weighing devices.
ESCON recommends that, all weighing devices should be kept clean, zeroed daily, and calibrated monthly.

1) **Aggregates:** Aggregates may be weighed in separate batchers or cumulatively.

2) **Cement:** Cement is either weighed in a separate batcher or measured as full bags of cement. If more than one type of the cementitious materials will be measured cumulatively, ESCON recommends that, the cement should be weighed first, and then the other cementitious materials should be weighed. In this way, the possible mistakes in weighing the cement is reduced. The rules of ESCON to select the cement measuring methods are as follows:

**RULE 1**

IF the cement is delivered in bags;
AND the weights of the cement bags are checked regularly;
AND there is a proper shed to store the cement bags on the site;
AND the batch capacities can be arranged so that, only full bags of cement are used for each batch;
THEN cement can be measured as full bags.

**RULE 2**

IF cement is not delivered in bags;
OR the weights of the cement bags are not checked regularly;
OR there is not a proper shed to store the cement bags on the site;
OR the batch capacities can not be arranged to use only full bags of the cement
THEN cement should be measured by weigh batchers, but not using full bags.
3) **Water:** ESCON does not distinguish between weight or volume batching for the mixing water. However, if a weight batcher is used, its accuracy can be improved by controlling the valves to prevent leakages, and by providing a two-step water cut-off systems (fast and slow), especially when a high rate of batching is required. Volumetric water batching is discussed in 4.5.2.(a).

4) **Admixtures:** ESCON does not distinguish between weight or volume batching for admixtures. It is recommended that the admixture are added into the mixing water before charging the mixer. If more than one type of admixture is used in one batch, any possible reaction between the admixtures that nullifies their effects should be investigated. If a reaction is likely, one of the admixtures should be mixed with the mixing water, and the other with the sand or directly into the mixer. Weight batching of the admixture is the most accurate, foolproof, and positive method, but also the most expensive. Volumetric measuring of the admixture is therefore more common. Volumetric measuring of the admixture is discussed in section 4.5.2.(a).

ESCON divides batching control systems into manual control; and others (semi-automatic or automatic). When the rate of concrete production exceeds 30 cu m per hour, manual batching control systems are not recommended. Otherwise, the effects of operator fatigue will reduce the accuracy of the batching, and eventually the quality of the concrete will suffer. In semi-automatic and automatic batching control systems the installation of an interlock system, a recorder, and a slump meter will help to improve the accuracy of the batching.

ESCON strongly recommends that the adjustments in the weights of the mixing water and the aggregates be made when the moisture content of the aggregate changes. The system makes necessary calculations for the adjustments of the weights of the aggregates and
water. After inputing the original weights of the water and aggregates, and the prevailing moisture conditions of the aggregates, it gives the corrected weights of the mixing water and the aggregates.

Finally, the system recommends that knowledgeable supervision, and careful quality control are provided on the site. Otherwise the quality of the concrete produced will always be variable.
5.1 Introduction
5.2 Mixing Methods
5.3 Factors Affecting the Uniformity of Mixing
5.4 "Concrete Mixing" Module of ESCON
5.1. **INTRODUCTION:**

Having placed the correct amount of materials into the mixer, thorough mixing is essential for the production of uniform quality concrete. Thorough mixing means distributing the concrete ingredients uniformly and spreading the cement-water paste evenly onto the surfaces of the aggregates. If this is not achieved, the quality of the concrete discharged will not be the same throughout the mix.

This chapter describes the mixing methods available and discuss the factors that affect thorough mixing. In the second part of the chapter the "Concrete Mixing" module of ESCON, is described.

5.2 **MIXING METHODS:**

Concrete mixing methods can broadly be divided into:

1) Hand mixing
2) Machine mixing

5.2.1. **HAND MIXING:**

Hand mixing is only used in extremely small jobs where the provision of a mixer may not be economical [100]. Mixing concrete by hand is expensive in labour and it is difficult to maintain uniformity. For this reason, hand mixing is not consider in this research.

5.2.2. **MACHINE MIXING:**

Machine mixing is quicker, more efficient and produces much more homogeneous concrete [29,101]. Therefore, mechanical mixers have been in general use for many years. Mixers can either be stationary.
as part of central mixing plant, or mobile. Satisfactorily designed mixers have a blade arrangement and a drum shape which ensures an end to end exchange of materials parallel to the axis of rotation. The types of concrete mixing equipment are:

a) Tilting drum mixers
b) Nontilting drum mixers
c) Pan mixers (turbine mixers or vertical shaft mixers)
d) Paddle mixers (horizontal shaft mixers)
e) Split drum mixers
f) Continuous mixers
g) Truck mixers.

These are described below.

a) **Tilting Drum Mixers:**
These are revolving drum mixers, that discharge by tilting along the axis of the drum. The drum axis may be horizontal or inclined from the horizontal while charging and mixing. The efficiency of the mixing action depends on the design of the blades and the drum of the mixer, and the ability of the mixer to discharge the concrete rapidly and unsegregated [23,28]. Tilting drum mixers are preferable for mixes of low workability and for those containing large size aggregates [23,24,25,29,92]. A wide drum opening allows easy inspection of the concrete by the operator.

b) **Nontilting Drum Mixers:**
Nontilting drum mixers are revolving drum mixers which are charged, mixed, and discharged with the axis of the drum always horizontal. Depending on their discharging methods, nontilting drum mixers can be divided into two: tipping chute discharge types, and reversing drum rotation discharge types. However, the tipping chutes discharge type nontilting drum mixers have largely been superceded, since it is difficult to discharge dry or cohesive mixes. When they are used with dry or cohesive mixes, concrete tends to built up inside the drum [29,98] because of their slow rate of
discharge, nontilting drum mixers may promote segregation, of the mix [23,24]. Concrete Plant Mixer Standards [102] limit the maximum aggregate size to 2in (50 mm) for nontilting drum mixers.

c) **Pan Mixers**
In pan mixers the mixing is done with rotating blades, or paddles, mounted on a vertical shaft in a pan. The pan is either stationary or rotated in the opposite direction to the blades. Pan mixers are ideal for mixing relatively dry concretes, and are often used by concrete product manufacturers [11,23,24,24,98]. They produce a well mixed concrete in a short time varying from 30 to 60 sec [28,92,98].

These mixers are usually very sensitive to the sequence of charging the materials. The aggregates and the cement should be blended before reaching the mixer, or they should be fed into the mixer together. The water should be introduced with the cement and aggregates and it should be placed well inside the mixer.

Their main disadvantage is that, they require a more careful maintenance schedule than for other mixers [98].

d) **Paddle Mixers:**
Paddle mixers use horizontal blades and are suitable for harsh, and stiff concrete mixes for example in concrete product plant [11,25,29]. Their power requirements, liner and blade wear, are high.

e) **Split drum Mixers:**
These mixers are similar in shape to the non-tilting drum mixers but they discharge by separating or splitting the two halves of the drum by a distance of about 230mm (9in). Split drum mixers are rarely used owing to the difficulties of making the joint between the two halves watertight [29]. However, they may satisfactorily be used with dry mixes. Their main advantages are very quick discharging, and the ability to mix large aggregate sizes up to 230 mm (9in) [103].
f) Continuous Mixers:
In continuous mixers, mixing is accomplished by a spiral blade rotating in an enclosed trough, inclined at 15 to 25 deg. to the horizontal. The materials are proportioned by volume using spiral conveyors. Usually, the cement, sand, and coarse aggregate are fed into the mixer chamber by separate spiral conveyors. The measuring of these materials is possible by adjusting the speed of the conveyors. Water is added to the mixer continuously through a valve. Spirals for cement, sand and coarse aggregate wear at different rates, and must be checked regularly. In this mixing method, it is difficult to keep a check on the proportions, and in particular, to allow for the bulking of sand. The batching tolerances should not exceed the limits given in ASTM C 685-86 [96]. See Table 5.1.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Requirements. Expressed as max. permissible difference in results of tests of samples taken from 2 locations in the concrete batch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air content (% volume of concrete)</td>
<td>1.0</td>
</tr>
<tr>
<td>Average slump &lt;=4 in</td>
<td>1.0 in</td>
</tr>
<tr>
<td>Average slump= 4-6 in</td>
<td>1.5 in</td>
</tr>
<tr>
<td>Coarse aggregate content (by weight of each sample retained on No:4) (4.75 mm) sieve</td>
<td>6.0 %</td>
</tr>
<tr>
<td>Unit weight of air free mortar based on average for all comparative samples taken</td>
<td>1.6 %</td>
</tr>
</tbody>
</table>
g) Truck Mixers:
Truck mixers are designed to mix or agitate concrete while mounted on a moving truck. The truck mixers are of three types: inclined axis revolving drum; horizontal axis revolving drum; and open top revolving blade or paddle. However, the inclined axis revolving drum type truck mixers are the most common, because they have larger capacities for equal drum volumes with others, and they can also discharge at a high level, so that the concrete can be chuted easily. The fins attached to the drum mix the concrete in the mixing mode, and the same fins discharge the concrete when the drum rotation is reversed. They are not suitable for uniformly discharging the concrete with a maximum aggregate size of larger than 63 mm (2.5in), and a slump of less than 50mm (2in) [25,28]. Unless adequate precautions in loading, mixing, and discharging are taken, the quality control of truck mixed concrete presents problems that are not common to the other type mixers. Segregation and variation in the consistency of the concrete may occur to such an extent that, the control of the water/cement ratio may be completely lost [28].

There are two categories of truck mixed concrete. In the first category, concrete is first partially mixed in a stationary mixer, and then the mixing is completed in the truck mixer. This type of mixing increases the capacity of the truck mixer, and is known as "shrink-mixing". In the second category, the concrete is completely mixed in the truck mixer, and known as "truck-mixing" or "transit-mixing". In both categories, the concrete should conform with the requirements of uniformity defined in specifications, such as, ASTM C 94-86b [104], or BS 5328:1981 [89].

5.3. FACTORS AFFECTING THE UNIFORMITY OF MIXING:

Mixing procedures comprise the selection of mixing equipment and the mixing workmanship. The selection of mixing equipment depends mainly on the type of contract, economical considerations,
and the required rate and continuity of the production. The mixer type has little effect on the concrete uniformity providing that, the instruction of the manufacturer are followed. Therefore, the selection of the mixer is left outside the scope of this work.

However, the workmanship of the mixing greatly affects the uniformity of the concrete produced. (See Fig. 5.1). The factors that affect uniform mixing are:

1) loading the mixer
2) mixing time
3) discharging the mixer
4) capacity of the mixer
5) formation of cement balls
6) formation of head packs
7) mechanical conditions and design of the mixer
8) retempering.

5.3.1. LOADING OF THE MIXER:

During loading the materials should be blended as much as possible before loading into the drum. Research has been undertaken to give a relation between the order of loading and the strength of the concrete produced [105,106]. The results of this research were in divergence of opinions, because they were trying to find a specific order of loading that, produces the highest strength of the concrete. However, today it is believed that, the order of loading is important for the uniformity of concrete produced rather than the highest strength can be achieved. The order of loading can be divided into four groups, depending on the loading type of the mixer:

a) small mixers without loading skip
b) mixers with a loading skip

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a) small mixers without loading skip
b) mixers with a loading skip
a) **Small Mixers Without Loading Skip:**

Small tilting mixers without a loading skip are used in very small jobs, or in laboratories. Each ingredient is loaded separately, and in turn. To get the highest uniformity the proper sequence of loading is, water, cement, fine aggregate, and coarse aggregate [107]. With small laboratory pan mixers and stiff mixes, the sand should be fed
first, then a part of the coarse aggregate, cement, and water, and finally, the remainder of the coarse aggregate. This sequence breaks up any nodules of mortar [24].

b) Mixers With a Skip:
Tilting drum or nontilting reversing drum type concrete mixers equipped with a loading skip (bucket) are quite common on small to medium size concreting sites. For these mixers the materials should be placed into the skip in the following order: first, the coarse aggregate, then the cement, and finally the sand [98,108,109]. This order minimizes the cement lost, and dust nuisance caused by the wind. Under usual conditions, up to about 10% of the mixing water should be placed in the drum before the solid materials are added. The water, should then be added uniformly with the solids, leaving approximately the last 10% to be added after all the other materials are in the drum. When heated water (above 140°F or 60°C) is used in cold weather, addition of the cement should be delayed until most of the aggregate and water have mixed in the drum to prevent possible rapid stiffening, or formation of cement balls [1,28,110].

c) Mixers Loaded by Overhead Batchers:
In batching plants, the mixer is usually loaded by overhead batchers. The most significant factor affecting the uniformity of concrete produced in a batching plant is the sequence of loading the ingredients into the mixer [85]. The ingredients (cement, pozzolan, if any, fine aggregate, and coarse aggregate) should be fed into the mixer simultaneously and in such a manner that the period of flow of each material is about the same [1,28]. A small amount (about 10%) of the water should be fed in before the other solid materials are added. The remaining water should be added uniformly with the solids, leaving the last 10% to be added afterwards [24,28,110]. Care must be taken not to load the cement or the water too quickly, or too hot, thus preventing the formation of cement balls. The results of tests undertaken by Bozarth [86] on charging the cement and water, indicated that concrete strength uniformity is highly
sensitive to the deviations from the uniform blending of the cement and/or water during charging of the batch ingredients into the mixing drum.

d) Truck Mixers:
The uniformity of a mix in a truck mixer is greatly affected by the sequence and procedures used to charge the materials into the mixer. The common truck mixer loading methods are:

i) ribbon loading
ii) cement last loading
iii) sandwich loading
iv) slurry mixing.

However, the materials for a load are sometimes batched in two or more cycles, depending upon the capacity of the weighing system. This loading method is known as "multiple batching". Here, the "multiple batching" method will not be discussed as a separate loading method, since the loading of each cycle can use one of the methods described below.

i) Ribbon Loading:
This involves blending the coarse aggregate, fine aggregate, and the cement throughout the majority of the loading cycle. The coarse aggregate will be started before the other ingredients to prevent the formation of head pack. The mixing water theoretically should be ribboned simultaneously with the other ingredients. However, research [111] proves that, the best uniformity of concrete can be obtained when half the mixing water is added before the other ingredients, and the second half after.

ii) Cement Last Loading:
In this method, the aggregates and then the cement is loaded while the drum of the mixer does not rotate. If the drum does not rotate until the truck approaches the delivery point, only the small amount of cement that is in contact with the aggregates becomes wetted.
This can be advantageous when the concrete has to be transported long distances. Depending on the temperature of the concrete, this loading method can extend the concrete delivery time from half an hour to one and half hours [112]. This method, requires a load size to be reduced by about 10-20% to avoid cement spillage. This procedure also increases the time required to load a truck mixer [113].

iii) Sandwich Loading:
In this loading method, the cement is sandwiched between equal increments of ribboned aggregates and water. In sandwich loading, the uniformity of concrete may not be as good as in ribbon loading [111].

iv) Slurry Mixing:
In slurry mixing, water is loaded first, followed by the cement, and the slurry mixed for a short period (about 1 minute) before the aggregates are ribbon loaded. In research [111], the slurry mixing method produced an excellent strength uniformity, and an acceptable slump and air content after only 50 revolutions of the drum of the truck mixer. This method of loading appears to avoid the formation of cement balls completely.

In the UK, where the average radius of operation of the truck mixers is 8 km [18], and the weather is normally not hot, the commonly used truck mixer loading method is "ribbon loading". The "cement last" loading method is more commonly preferred in the hot weather where the loss of the slump during delivering the concrete may exceed the permissible limits.
5.3.2. **MIXING TIME:**

Mixing time affects the uniformity of concrete produced [23,112]. As shown in fig. 5.2, undermixing causes a coefficient of variation in the strength of the concrete by up to 35%. In the case of fig. 5.2, the acceptable minimum mixing time is about 60 sec. On sites, there is often a tendency to mix concrete as quickly as possible (see data collected in Cyprus on fig. 2.2). But it is important to know the minimum mixing time necessary to produce a concrete of uniform composition and consequently, of reliable strength. The optimum mixing time depends on the following: the type and the size of the mix; the speed of rotation of the drum; the quality of the blending of ingredients during charging the mixer; and the consistency of the mixture. Therefore, it is recommended that, mixer performance tests [28,96,104,114,115], are undertaken to find the optimum mixing time for a particular job. The U.S. Bureau of Reclamation [28] states that, the acceptable minimum mixing time can be fixed by using the "unit weight of air free mortar" test. The minimum mixing time is the one that satisfies the requirement that, the mortar weight of the samples taken from the first (after discharging 15%), and the last portion (after discharging 85%) of the batch will not vary more than 1.6% from the average of the two mortar weights. Similarly, the average variability of six batches should not exceed 0.5%. However, if it is not possible to perform these tests, then, the specified minimum mixing time should be used.

The specified minimum mixing time for tilting and nontilting mixers is 1 minute for a mixer capacity of 1 cu yd (0.76 cu m) or less, and an additional 15 sec for each additional 0.5 cu yd (0.38 cu m), or fraction thereof [1,24,110]. However, high speed pan mixers can mix concrete uniformly in as little as 30-35 sec [24,92]. The minimum mixing time for a padle mixer is about 180 sec. [25], and for a split drum mixer 56 sec. [103]. The minimum number of revolutions of truck mixers is specified by ASTM C 94 [104] as 70 rotations.
Overmixing is undesirable because the grinding action increases the fines, thereby requiring more water to maintain the specified consistency of the concrete. Also overmixing may drive out entrained air. Some specifications therefore state that, the mixing time should not exceed the specified minimum mixing time by more than a factor of 3 [28,116]. For the same reasons, ASTM C 94 [104] specifies a limit of 300 revolutions including both mixing and agitating in a truck mixer.

Fig. 5.2- Relation between the coefficient of variation of strength and mixing time. (Redrawn from ref. 23)
5.3.3. **DISCHARGING OF THE MIXER:**

Except in continuous mixers, the entire batch of the mixer should be discharged before the mixer is recharged. Otherwise, it becomes impossible to control the water content of the mixture. Usually, the quantity of the largest size aggregates is greater at the end of the discharge than at the start. In order to minimize the risk of stone pockets in the structure, it is advisable to discharge the whole batch capacity into a container, rather than into small separate transporting equipment [31].

While discharging, precautions should be taken to avoid the concrete becoming segregated. Nontilting mixers particularly, employing chutes should provide a baffle or hopper with a section of down-pipe at the end of the chute so that, the concrete falls vertically, or nearly so into the center of the receiving container. The length of the down-pipe should be a minimum of 600 mm (24 in). With tilting mixers, the batch usually slides out in a bulkier mass which has less opportunity to segregate [28]. As a general rule, to prevent segregation, concrete should be dropped vertically and into the centre of the receiving container rather than, letting it drop uncontrolled at the end of a chute.

Truck mixers, prior to discharge should be rotated at mixing speed for about 30 revolutions to reblend possible stagnant spots near the discharge end into the batch [11].

5.3.4. **CAPACITY OF THE MIXER:**

BS 1305 [115] specifies that the capacity of a mixer should be expressed as the volume of fully compacted fresh concrete produced by that mixer. It also specifies that the rated capacity of the mixer should be stated on an attached plate. BS 5328 [89] does not permit the mixers rated capacity to be exceeded. But, in some
specifications, this rated capacity can be exceeded by up to 10 %, providing it is proved that the mixing action is not adversely affected by doing so [28].

TMAS [117] specifies the capacity of a truck mixer as about 60-61 % of its entire drum volume. ASTM C 94 [104] imposes similar limits in that the capacity of a truck mixer is a maximum 63 % of the total volume of the drum. When the concrete is centrally mixed, the capacity of the mixer can be up to 80 % of the total volume of the drum.

5.3.5. FORMATION OF CEMENT BALLS:

Cement balls are accumulations of cement, sand, and sometimes gravel rather than cement per se [111]. See fig. 5.3. The main causes of the formation of cement balls are [2,24,98]:

1) addition of the cement too slowly or too quickly;
2) addition of a too hot water, or too slow in ribbon loading;
3) overloading the mixer;
4) worn mixer blades;
5) insufficient revolutions of the mixer; or
6) keeping the cement in contact with wet aggregate without mixing for too long.

The size of the cement balls can be anything from about 75 to 200 mm (3 to 8 in) in diameter, and they are common in ribbon loading, cement last loading, and sandwich loading. Slurry mixing appears to prevent the formation of cement balls.

The cement balls may be broken up during handling or compacting the concrete. However, the materials of these balls don't usually mix properly with the constituents and thus don't produce uniform concrete.
Fig. 5.3 - A cement ball on the grid of pump hopper
5.3.6. FORMATION OF HEAD PACKS:

Head packs mainly occur in truck mixers when sand or sand and cement lodges in the head of the drum. Once a head pack is formed, it remains lodged in the head, and does not mix into the concrete. The typical thickness of a head pack is 1 to 2 feet (300 to 600 mm) [111]. They break up after about the half of the batch has been discharged. The indications of a head pack are: changes in the colour and slump of the concrete after discharging the first half of the batch; and the occurrence of sand streaks in the concrete after discharging the first quarter of the batch.

Head packs can be avoided by placing the coarse aggregate and/or the mixing water in the hub of the truck mixer. This is possible by starting the loading of the water and/or coarse aggregate a little before the sand. The loading of about 2000 lb (900 kg) of coarse aggregate before starting the loading of the sand will help to prevent formation of the head packs.

5.3.7. MECHANICAL CONDITIONS OF THE MIXER:

Concrete mixers should be kept clean and the mixing blades should not be worn beyond certain tolerances. The ACI Manual of Inspection [1] specifies that, the blades should not be worn more than 10%. However, both the design of the mixer, and the wearing degree of the blades can be checked by one of the mixer performance tests, known as, "weight of coarse aggregate in a cubic foot of concrete". ASTM C 94 [104] requires that, the weight of the coarse aggregate in a cubic foot of concrete taken from the first and from the last portion of the batch should not vary by more than 6 % from the average of the two weights of the coarse aggregates. In this respect the Bureau of Reclamations [28] is more strict than ASTM C, and requires only 5 % variation. Excessive variation in the weights of coarse aggregate in a cubic foot of concrete indicates that the mixer is either improperly
designed, or the blades are excessively worn.

British Standards do not state any requirement for the variation of percentage of the coarse aggregate. But, BS 1305 [115] requires that the maximum percentage of variation of fine aggregate should be only 8 to 9% of its nominal value. Otherwise, the mixer fails to comply with the requirements of the mixer performance test.

5.3.8. RETEMPERING:

When fresh concrete is left to agitate in the drum of the mixer, it tends to stiffen before its initial set. This stiffening can be the result of one or more of the following [118,119]:

i) the loss of water by evaporation;
ii) insufficient water batched initially;
iii) the absorption of the water by aggregates;
iv) high rates of grinding during the agitation or mixing; or
v) the hydration of the cement.

Retempering concrete involves the addition of more water to the mix to maintain the specified workability [120]. Retempering water which is added to offset (i) or (ii) or (iii) above will not result in a lower strength than expected, whereas, extra water to compensate (iv) or (v) above will result in a lower strength [118]. (See Fig. 5.4). On site, it is difficult to determine which of the above factors caused the stiffening of the concrete. Therefore, it is better to discourage retempering. The grinding action caused during prolonged agitation and mixing is important when the aggregate is soft. The aggregate abrasion value of the bulk aggregate can be assessed by using BS 812 Part 113 [121], or ASTM 9131 [122]. But to assess any degradation of aggregates on prolonged mixing or agitating of fresh concrete, a wet attrition test is desirable to determine how much material smaller than 0.075mm (No:200 sieve) is produced. However no standard apparatus is available for this test [24].
Temperature of concrete is 90°F (32°C).

Under average conditions, where the ambient temperature is 60°F (16°C) and the relative humidity is about 60%, the hydration of the cement starts to produce significant effects after the times shown in Table 5.2. Therefore, retempering for reasons (i), (ii), (iii), and (v) could be carried out with reasonable confidence within these times, and conditions [118,123]. Many specifications permit retempering providing that: during retempering a maximum of 3% of the original water content is added [28]; the maximum allowable water/cement ratio is not exceeded; the maximum allowable slump is not exceeded; the maximum allowable time or the number of drum rotation for mixing and/or agitation is not exceeded; and the concrete is remixed for at least half of the specified minimum mixing time or number of the revolutions [110].

Fig. 5.4 - Effect of retempering water on the strength of the concrete. (Redrawn from ref. 23)
Table 5.2 - Approximate times of agitation after which the relation between strength and workability commence to deviate significantly from those for concrete placed shortly after mixing [118].

<table>
<thead>
<tr>
<th>Aggregate/Cement ratio (by weight)</th>
<th>Agitation time (h)</th>
<th>Initial slump (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>125</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>4.5</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>6</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>9</td>
<td>3.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

5.4. "CONCRETE MIXING" MODULE OF ESCON:

A thorough and uniform mixing is essential to reduce the variation in the quality of the concrete. The factors affecting the uniformity of the mixing are given in section 5.3. The staff responsible for the mixing concrete should be knowledgeable and experienced in these subjects if a uniform concrete is to be produced. A detailed specification including sufficient information on the workmanship requirements of mixing can improve the quality of the supervision.

The "Concrete Mixing" module of ESCON contains concise knowledge of these subjects. This knowledge can be transferred to the novice users of the model. The module also produces detailed specifications as mentioned above, at the end of a consultation with ESCON. The system divides concrete mixing into three groups depending on the applied batching method:
1) mixing for off-site batching;
2) mixing for on-site volume batching; and
3) mixing for on-site weight batching.

Fig. 5.5 and fig. 5.6 shows the flow diagrams of mixing procedures for off-site batching, and on-site batching respectively.
Fig. 5.5 - Flow diagram for the "mixing for off-site batching" of "CONCRETE MIXING" module of ESCON
Fig. 5.6 - Flow diagram for the "mixing for on-site batching" of "CONCRETE MIXING" module of ESCON
5.4.1. MIXING FOR OFF-SITE BATCHING:

Mixing for off-site batching includes using truck mixers either to mix or to agitate the concrete. However, here, the truck mixers are considered only as mixers. ESCON, first, selects the appropriate loading method from one of the available methods: cement last loading, slurry mixing, ribbon loading, and sandwich loading. ESCON recommends the "cement last" loading method when the concrete delivery time is extended especially in hot weather. Table 5.3, Table 5.4, and Table 5.5 (evaluated from the results of research undertaken by Meininger, R. C. [124]), help the user to decide on the loading method that fits his job best. If cement last loading is rejected, the system then selects another loading method. The slurry mixing method is recommended when the formation of cement balls and/or the uniformity of concrete produced is undesirable. Otherwise, the system allows the user to select either ribbon loading or sandwich loading. ESCON reminds the user that, the uniformity of concrete obtained by sandwich loading is not as good as that uniformity obtained by ribbon loading. The rules of ESCON to select the loading methods are as follows:

RULE 1

IF delivery time is extended as shown in tables 5.3, 5.4, and 5.5;

THEN "cement last" loading method should be used.

RULE 2

IF delivery time is not required to be extended as shown in table 5.3, 5.4, and 5.5;

AND cement balls are observed in concrete while discharging;

THEN "slurry mixing" method should be used.
TABLE 5.3 - Ready mixed concrete delivery time with a 5 % loss in the strength of concrete.

<table>
<thead>
<tr>
<th>Concrete temperature $F$ (°C)</th>
<th>Delivery time (hr) for 5 % loss in strength</th>
<th>No delay before mixing</th>
<th>Cement last loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 (18) (normal weather)</td>
<td>1.25</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>90 (32) (Hot weather)</td>
<td>1.00</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 5.4 - Ready mixed concrete delivery time with a 10 % loss in the strength of concrete.

<table>
<thead>
<tr>
<th>Concrete temperature $F$ (°C)</th>
<th>Delivery time (hr) for 10 % loss in strength</th>
<th>No delay before mixing</th>
<th>Cement last loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 (18) (normal weather)</td>
<td>2.00</td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>90 (32) (Hot weather)</td>
<td>1.25</td>
<td>2.00</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 5.5 - Ready mixed concrete delivery time with a 15 % loss in the strength of concrete.

<table>
<thead>
<tr>
<th>Concrete temperature $F$ (°C)</th>
<th>Delivery time (hr) for 15 % loss in strength</th>
<th>No delay before mixing</th>
<th>Cement last loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 (18) (normal weather)</td>
<td>2.5</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>90 (32) (Hot weather)</td>
<td>1.5</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>
RULE 3

IF delivery time is not required to be extended as shown in table 5.3, 5.4, and 5.5;
AND cement balls do not occur in the concrete;
THEN "ribbon" or "sandwich" loading method should be selected.

The system explains the features and procedures of each selected truck mixer loading method as was explained in section 5.3.1. The system also recommends the optimum mixing speed as 18 rpm.

After the selection of the loading method, ESCON gives recommendations regarding the incidents that affect the quality of concrete, such as:

a) minimum number of revolution of the truck mixer;
b) nonuniformity or segregation of concrete during discharging;
c) formation of cement balls;
d) formation of head packs;
e) retempering of concrete;
f) doubt about the quality of delivered concrete.

a) Minimum Number of Revolution:
ESCON advises that to find the minimum number of revolution for the truck mixer the "unit weight of air free mortar test" should be used. The requirements of this test were explained in section 5.3.2. If the minimum number of revolution of the mixer cannot be fixed by experiments, then the system recommends it to be 70 which is required by ASTM C 94 [104]. Otherwise, the concrete is regarded as being undermixed.

b) Nonuniformity or Segregation in Discharging:
The distribution of the coarse aggregate may not be uniform in the first and last portion of the concrete discharged from a truck mixer. Therefore, ESCON recommends that the batch capacity of the mixer should be reduced by about 1 or 2 cu yd if a nonuniformity in the
distribution of the coarse aggregate is observed while discharging. When difficulties appear to estimate the uniformity of distribution of the coarse aggregate in the concrete, then the system recommends that the mixer performance test known as "weight of coarse aggregate in a cubic foot" should be undertaken (see section 5.3.7). In the case of producing a nonuniform concrete, if reducing of the batch capacity does not maintain a satisfied concrete, the system recommends that, the concrete should be rejected.

ESCON also recommends that, prior to discharge, the mixer drum should be rotated at the mixing speed for about 30 revolutions to reblend any possible stagnant spot near the discharge end into the batch.

While discharging the truck mixer, it is recommended that, concrete should not be dropped freely from the end of the discharge chute. A down-pipe at the end of the chute with a minimum length of 600 mm (24 in) will help to minimize the segregation.

c) Cement Balls:
ESCON first defines cement balls and then states the causes of formation of the cement balls as was explained in section 5.3.5.

To avoid the formation of cement balls the system recommends that: the previously explained mixer loading procedures should be followed carefully; the mixer's performance should be tested regularly; and the concrete should not be undermixed. If cement balls still occur after these precautions then, the system advises using the "slurry mixing" method to load the mixer. However, if the "cement last" loading method has to be used, it is recommended that, the original cement content should be increased. As Waddel [2] reported, ESCON states that an amount equal to 3% of the original cement content in the batch should be added for each hours delay, starting with a 6% for a delay between 2 and 3 hours.
d) **Head Packs:**
The system defines head packs, and states their indications as was explained in section 5.3.6. The main cause of head packs is defined as charging the fine materials before the coarse aggregate and/or water. Therefore, ESCON recommends that, the coarse aggregate and/or the mixing water should be placed in the hub of the mixer as was explained in section 5.3.6.

e) **Retempering:**
ESCON permits retempering of concrete which has stiffened in the truck mixer before its initial set. The system recommends that retempering should be done under careful supervision and as was explained in section 5.3.8.

f) **Doubt About the Quality of Concrete:**
If the quality of truck mixed concrete is doubted, then, ESCON recommends that mixer performance tests should be undertaken, and the results checked against Table 5.6. The system also recommends that "delivery tickets" should be asked for each batch delivered. These tickets will contain the following information:

- a) name of the ready mix batch plant
- b) serial number of the ticket
- c) date
- d) truck number
- e) name of the purchaser
- f) specific designation of the job
- g) specific class or designation of the concrete
- h) the amount of concrete
- i) the time of loading or the first mixing of cement with the mixing water or wet aggregate.
### TABLE 5.6 - REQUIREMENTS FOR UNIFORMITY OF CONCRETE PRODUCED BY TRUCK MIXERS.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Requirements. Expressed as max. permissible difference in results of tests of samples taken from 2 locations in the concrete batch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air content (% volume of concrete)</td>
<td>1.0</td>
</tr>
<tr>
<td>Average slump &lt;= 4 in</td>
<td>1.0 in</td>
</tr>
<tr>
<td>Average slump = 4-6 in</td>
<td>1.5 in</td>
</tr>
<tr>
<td>Coarse aggregate content (by weight of each sample) retained on No: 4 (4.75 mm) sieve</td>
<td>6.0 %</td>
</tr>
<tr>
<td>Unit weight of air free mortar based on average for all comparative samples taken</td>
<td>1.6 %</td>
</tr>
<tr>
<td>Average compressive strength at 7 days for each sample, based on average strength of all comparative tests</td>
<td>7.5 %</td>
</tr>
<tr>
<td>Weight per cu ft calculated to an air free basis</td>
<td>1.0 lb/cu ft</td>
</tr>
</tbody>
</table>

When it is necessary, the following information may also be required with the tickets:

1. reading of the revolution counter at the first addition of the water
2. type and brand and amount of the cement
3. type and brand and amount of admixture
iv) total added mixing water  
v) maximum aggregate size  
vi) weight of the fine and coarse aggregates  
vii) ingredients certified as being previously approved  
viii) the signature of the ready mix representative.

5.4.2. MIXING FOR ON-SITE VOLUME BATCHING

ESCON specifies that, on-site volumetrically batched concrete can be mixed in two ways:
   a) by using continuous mixers  
   b) by using site mixers (tilting or reversing drum mixers usually up to 1 cu yd capacities).

5.4.2.1. CONTINUOUS MIXERS:

In the case of continuous mixer operation, ESCON recommends that attention is given to the following:
   i) the degree of compaction of the cement  
   ii) the grading and other physical characteristics of the aggregates  
   iii) the moisture content and the bulking of the sand  
   iv) the viscosity of admixture  
   v) the mechanical condition of the mixer  
   vi) the uniformity of the concrete produced. The uniformity of the concrete can be checked regularly by slump test, air content test, coarse aggregate content test, and unit weight of air free mortar test. ESCON recommends that, the results of these tests is checked with Table 5.1.
5.4.2.2. **SITE MIXERS:**

On site, volumetrically measured concrete is usually mixed with site mixers (tilting drum or nontilting reversing drum). The capacities of these mixers are usually less than 1 cu yd. Therefore, the mixing time for these mixers are recommended to be a minimum of 1 minute. ESCON divides their loading methods into two:

a) ingredients are loaded separately and in turn (small mixers without a loading skip)

b) ingredients are loaded by a loading skip (mixers are equipped with a loading skip)

The system explains these loading methods as discussed in section 5.3.1. (a) and (b).

After advising on the loading method, ESCON gives advice on the other mixing operations that affect the quality of the concrete. These are:

a) discharging the mixer

b) capacity of the mixer

c) formation of cement balls

d) overmixing

e) mechanical conditions of the mixer

These factors are discussed in section 5.3.

5.4.3. **MIXING FOR ON-SITE WEIGHT BATCHING:**

Mixing for on-site weight batching is undertaken by using:

1) site mixers with weighing skips; or

2) stationary mixers.

Whether site mixers or stationary mixers are used, ESCON recommends that, a separate mixer should be employed for colored concrete.
5.4.3.1. SITE MIXERS WITH WEIGHING SKIPS:

This category comprises tilting drum mixers and nontilting reversing drum mixers. ESCON recommends using tilting drum mixers when the slump is less than 50 mm (2 in), or the maximum aggregate size is larger than 50 mm (2 in). In all other cases either of these mixers can be used. The uniformity of concrete discharged from a tilting drum mixer may differ between the first and the last portion of the batch. Therefore, the system recommends that, the capacity of the concrete transporting equipment should be sufficient to receive the entire batch capacity.

The other mixing factors that affect the quality of the concrete produced are discussed in section 5.4.3.2.

5.4.3.2. STATIONARY MIXERS:

The quality of concrete is very little affected by the type of the mixer used in a batching and mixing plant providing the mixer is used according to the instructions of the manufacturer. The factors that are dominant in the selection of the mixer types are economy, suitability, availability, and the required capacity of the mixer, which are not considered in this system. Therefore, ESCON does not select a type of mixer, but if required, it gives information about the important characteristics of the mixers, including nontilting drum mixers, tilting drum mixers, pan mixers, horizontal shaft mixers, and split drum mixers. The information given contains: suitable slump range; available capacity; suitable maximum aggregate size; the range of mixing time; required time range for charging and discharging; cycle time; wearing rate; raised concrete temperature for each minute of mixing; recommended job types; and advantages and disadvantages of each mixer.
ESCON gives recommendations about the factors that affect the uniformity of the concrete. These factors include: loading of the mixer; mixing time; discharging of the concrete; capacity of the mixer; formation of cement balls; overmixing; and the mechanical conditions of the mixer. The system advises on these factors as explained in section 5.3. An extract from ESCON consultation about the loading methods of the site mixers and stationary mixers is given below.

QUESTION LOADING_TYPE '£13£ What is the method of loading the mixer?
 £13£1- by a mixer loading skip (usually with job batcher or in some small batching and mixing plant)
 £13£2- by any means of overhead batcher.£13£'
INTEGER 1 2

QUESTION HOT_WATER '£13£ Do you use hot (above 60 C) mixing water?£13£'
YESNO

GROUP MG5 LOADING_TYPE HOT_WATER

DISPLAY '£13£ The materials should be placed into the mixer loading skip in the order of coarse aggregate, cement, and fine aggregate. In this way the cement is sandwiched by the aggregates and it is placed into the mixer safely. About 10% of the mixing water should be added before introducing the solids. The addition of the water should continue simultaneously with the solids. The last 10% of the water should be placed after all solids are loaded.£13£'

STOP MG5
INVESTIGATE PERFORMANCE_TESTS
AS SOON AS (LOADING_TYPE =1) AND (NOT HOT_WATER)
Blending of the materials before placing into the mixer improves the uniformity of the mixing. Therefore, the recommended order of loading is to introduce all the solid ingredients (cement, and coarse aggregate) simultaneously, and at the same period of time. About 10% of the mixing water should be placed before the solid materials are placed into the mixer. Then, the water should be added uniformly with the solid materials leaving about 10% to be added after all the other materials are placed.

If hot mixing water (above 140 F or 60 C) is used, a rapid hardening of the concrete is likely. Therefore, when hot mixing water is used care should be taken to avoid mixing of the hot water with the cement. So, first about 10% of the hot water is placed and then the coarse and fine aggregates are ribboned with the remaining water. The loading of the cement will be started when most of the hot water and aggregates are mixed.
CHAPTER SIX: TRANSPORTING AND PLACING OF CONCRETE

6.1 Introduction
6.2 Concrete Transporting and Placing Equipment
6.3 Factors Affecting Proper Handling of Concrete
6.4 "Transporting and Placing Concrete" Module of ESCON
6.1. **INTRODUCTION**

Even though concrete may be proportioned and mixed properly, its quality may be seriously impaired by the use of improper or careless transporting and placing methods. The method used for transportation should deliver the concrete to its final location efficiently without significantly altering its properties. Mistakes in transporting and placing concrete cause segregation, slump loss, or ingredient loss of the concrete. Although there is no standard method to measure the effects of these problems on the quality of the concrete, they obviously create construction problems which are undesirable.

This chapter considers concrete transportation and placing equipment, and the associated factors that affect quality. In the second part of the chapter, the "Transporting and Placing Concrete" module of ESCON is described.

6.2. **CONCRETE TRANSPORTING AND PLACING EQUIPMENT**

The principal concrete transporting and placing equipment are:

- a) wheelbarrows
- b) buggies
- c) concrete hoppers
- d) buckets
- e) agitating trucks
- f) non-agitating trucks
- g) chutes
- h) belt conveyors
- i) dumpers
- j) concrete pumps
- k) drop chutes or elephant trunks
- l) rail cars
- m) hoists.
a) **Wheelbarrows**
Wheelbarrows are still frequently used to move small quantities of concrete over a short distance (up to 60m) [125]. Wheelbarrows are especially useful in areas which are inaccessible to other equipment. Segregation of concrete in transit can be avoided by providing well constructed and smooth borrow runs.

b) **Buggies**
Two types of buggies (concrete carts) are available: hand-operated buggies, and power-operated buggies. Buggies require pneumatic tyres and a relatively smooth path. Owing to their small capacities, they are convenient for concreting works which requires small rates of placing, compacting and finishing especially in difficult or irregular shaped situations.

c) **Concrete Hoppers**
Concrete receiving hoppers are used in combination with other equipment to provide temporary storage, or surge capacity, or to transfer the concrete from one type of the transporting equipment to another. During charging, the recommendations given in section 6.3.3.1. should be followed to avoid segregation. For concrete having a slump of more than 25 mm the hopper should be conical or near to conical having six or more sides. The valley angle of the hopper should be about 50-60 deg. to the horizontal. If the hopper has four sides, then, the valley angle should be more than 60 deg. to the horizontal. When the slump of the concrete is more than 50 mm, the gate should be equipped with rubber wipes to prevent leakage [126].

d) **Buckets**
Buckets may either be a rollover (laydown) type or a constant altitude type. Rollover type buckets have a lower filling height than the same capacity of a constant altitude type. Rollover buckets are usually used in building construction [126]. Their advantages are: they are good for discharging into narrow openings e.g. walls or columns; they occupy the least space for a given capacity while discharging. Low
slump concrete can be charged into the constant altitude buckets more easily than rollover buckets. Their advantages are: they occupy less space at the loading point; they need less space under the hook at the discharge point; and they are available for higher capacities (9cu m or even higher).

e) Agitating Trucks
Agitating trucks fall into two categories: truck mixers and open top hauling units. The truck mixers are preferable in the cases where the expected delivery time is greater than 45 min. The drum of the truck mixer rotates at a speed of 2-6 rpm during the agitation [23,126]. Their usual discharging rate is about 0.5 cu m per min. [117]. Open top agitating haul units have rotating blades to agitate the concrete en route. They are not able to remix the concrete, therefore, they are not recommended for delivery times that may require remixing at the delivery point. Their special shaped bodies can discharge the concrete in 30-40 sec [126], and in many cases they are preferred in civil engineering works.

f) Non-agitating Trucks
Non-agitating trucks can be used to transport air entrained concrete with a slump of up to 2 in (50 mm). They are convenient for haul distances up to 3 miles [28]. If they are used for long distances, it is recommended that, the concrete is protected from the sun or drying wind. Their discharging is rapid, but difficult to control. Vibrating, or frequent scraping may be required to prevent accumulations of concrete especially in the corners.

g) Chutes
Chutes are a simple and expeditious way of moving or transferring concrete to a lower elevation. They require a slope that the concrete will slide down by gravity. Effective end control that produces a vertical drop to prevent segregation must be provided. If the chute is more than a few feet long, it may be necessary to cover against the sun or wind [28].

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h) Belt Conveyors
Belt conveyors are an extremely fast method of handling concrete. Concrete can be transported about 20% faster by conveyor belts than is possible by pumping [127]. They are used to transfer concrete horizontally or a limited distance vertically. They are particularly useful in areas where space is limited, such as, tunnel construction. They are also useful in building construction for concreting large slabs. Belt conveyors have been developed in three categories: portable conveyors, for short lift-reach applications; feeder conveyors, for the carrying applications; and spreader conveyors, for side discharging or spreading applications [128,129]. The factors that affect the capacity of belt conveyors are as follows: angle of elevation - the steeper angle the less capacity; slump of concrete - the less slump the higher capacity; cement contents - the more cement content the higher capacity; and size and shape of aggregates - the bigger and rounded the particles are the less capacity. The important considerations of the belt conveyors are: a properly functioning wiper or scraper to remove the mortar and paste from the returning belt, and controlling the drop of concrete at the discharge end. To avoid excessive slump loss, it may be necessary to protect the belt from the sun or wind.

i) Dumpers
Dumpers are used to transfer concrete for a distance of up to 300 m without the risk of major segregation [29]. The dumpers equipped with hydraulic discharge facility are preferred in transporting concrete since, the discharge can be controlled.

j) Concrete Pumps
One of the most satisfactory method of transporting concrete is by pumping. The concrete discharged from the pumpline is generally free from segregation; in fact, concrete that segregates badly can not be pumped satisfactorily [28]. The normal effective pumping range varies from 90 to 300 m (300 to 1000 ft) horizontally; or from 30 to 90 m (100 to 300 ft) vertically [28,125]. But these figures are
arbitrary and subject to changes by curves, lifts, or concrete properties.

Steel, plastic, flexible hose or aluminum pipes can be used for pumplines. However the most common pipes are steel or flexible hose pipes. The internal diameter of the pipe should be a minimum of 2.5-3 times the maximum aggregate size. Therefore, concretes made of aggregates larger than 2.5 in (63 mm) are not suitable for pumping [28]. The normal pumping output varies from 15 to 76 cu m (20 to 100 cu yd) per hour [130] depending on the type and the capacity of the pump, characteristics of the concrete, and working conditions. The best pumpable slump range is from 50 to 125 mm (2-5 in). Concrete with a lower slump require more pressure to move through the pipes. Concretes with a higher slump may segregate in the pipe under the pump pressure. Concrete of poor graded or gap graded aggregates are not suitable for pumping. Before commencing the pumping, the pipes should be lubricated by grout to enable an easy flow of the concrete through the pipes.

**k) Drop Chutes (Elephant Trunks)**
Drop chutes are used for delivering concrete to a lower elevation without segregation. They also keep the reinforcement bars from becoming coated with mortar. This is especially important when the rate of placing is not high. In this case, the mortar accumulates on the steel bars and may dry out before becoming embedded into the concrete rising in the form. Drop chutes are usually made of rubber tubing, plastic tubing, sheet metal, or short sections of steel tubing fastened together, so that they are flexible and can easily be shortened [126]. The hopper for the drop chute should be large enough and steep enough to discharge the concrete readily.

**l) Rail Cars**
Rail cars are useful in tunnels, or for short distances from the mixing plant for high pickups [28]. Free water should not collect on the surface of concrete delivered, and coarse aggregate should not settle
or cake at the bottom of the load. These can be avoided by using air entrained dry concretes.

m) **Hoists**

Hoists are only used to move concrete vertically. Two types of hoists are used in transporting concrete [130]: **tip skip hoists** - tipping action is actuated manually; **automatic discharge skips** - once the skip arrives at the discharge level, the chute of the skip falls and concrete discharges automatically.

### 6.3. FACTORS AFFECTING THE PROPER HANDLING OF CONCRETE

To ensure good quality concrete proper handling is required. The transporting and placing factors which affect the quality of concrete are summarized in fig. 6.1. These include:

i) slump loss
ii) loss of ingredients
iii) segregation
i) formation of cold joints.

Some segregation of the concrete may be acceptable if for example, the coarse aggregate is recombined with the fine materials after the concrete is placed in its final location and compacted. However harmful segregation during dumping, dropping, or transporting concrete should be avoided. Agitating the concrete whilst it is moved reduces the segregation and allows it to be moved longer distances. Excessive jolting without stirring tends to segregate the concrete.

The primary causes of slump loss are the effects of elapsed time, and high temperature. Other less frequent causes of slump loss are the characteristics of the concrete making materials [131]. Slump loss is best avoided by prompt handling, and protecting the concrete from adverse weather conditions.
Fig. 6.1 - Factors affecting proper handling of concrete
Loss of ingredients, (usually grout), can be avoided by using a watertight transporting container, and gates that do not leak grout. It is a good practice to coat the inside of the transporting and placing equipment with grout before use, and also to prevent excessive built up of concrete in the container.

Concrete should be supplied to the placing point at such a rate that, formation of the cold joints is avoided. If the concrete already placed and compacted dries before placing the next layer, an unsightly cold joint will be visible on the surface of the concrete after removing the formwork.

6.3.1. SLUMP LOSS

All concretes lose slump. Otherwise, concrete would never harden. The concrete first gradually loses its slump and then proceeds to harden through the initial and final set as defined in ASTM C 403 [132]. This is known as "normal slump loss". But when concrete loses its workability before placing to such an extend that, placing and compaction can not be undertaken as specified, then, this slump loss is abnormal, and this is said to be "slump loss". In many specifications, a slump loss of up to 1 in (25 mm) or even more is permissible, if it does not raise serious problems in placing and compacting. But when the slump loss exceeds the permissible limit, it usually causes significant difficulties. The production rate and the quality of workmanship both decrease. Eventually, the cost, goes up and repair for imperfections will be unavoidable. When repairs become necessary, the appearance of the concrete is inevitably diminished. Thus, slump loss can be a serious construction problem.

Slump loss is caused by:
1) excessive delivery times
2) high temperature
3) the characteristics of the concrete making materials.
6.3.1.1. **DELIVERY TIME**

One of the most important factors in causing slump loss is the elapsed time from the mixer to the point of placing. As agitating (or mixing) proceeds, the entrapped air is gradually expelled from the concrete. Munn [133] reported that, in 25 minutes of agitating, an air entrained concrete and a non-air entrained concrete expell about 3.3% and 1.5% of entrapped air respectively. The loss of air results in a corresponding loss in the workability of the concrete. Freshly mixed concrete also loses more water by evaporation in longer delivery times. At the same time the process of hydration reduces the workability of concrete still further. If the freshly mixed concrete is continuously mixed or agitated, a grinding action, will occur in the mixer. As a result of this grinding action, the fine particle content will increase in the mixture. Production of additional fine particles reduce the workability of the concrete. For these reasons, many specifications impose time limits for the period between the mixing and the final placing and compacting of concrete. Generally, the time permitted is 30 min., but this varies from 15 min to 2 hr [119]. BS 5328 [89] gives some arbitrary delivery times and states that, "concrete will be discharged from the delivery vehicle within 2 hr after the time of loading when concrete is transported in truck mixers or agitators, or within 1 hr after the time of loading when non-agitating equipment is used". These limits may be extended in cool and humid weather, but a shorter time is essential in hot weather, especially when rich concrete, or accelerating admixtures have been used. ASTM C 94 [104] specifies a more strict time for truck mixers as either 1.5 hr or a maximum of 300 revolutions including mixing and agitating, whichever comes first. Researches on concrete delivery time by Meininger [124], Ravina [134], Klieger [135], Gaynor [136], and Beaufait [137] concluded that, acceptable concrete delivery times change with the weather conditions, admixtures used, and the truck mixer loading methods. Therefore, specifying a general delivery time is impracticeable. However, every effort should be made to keep the slump loss within the specified
limits (usually 25 mm).

If non-agitational transporting equipment is used, more attention should be paid to reduce the elapsed time as retempering will not be possible. In this case it is recommended that the following points are considered:

i) eliminating delays: Elimination of delays is possible by providing systematic preventative maintenance for all equipment. If wheeled equipment is used, the haul road should be kept in good condition.

ii) early delays: At the very start of the work, the problems that cause delays are: permitting the mixing of concrete before the work is ready for placing concrete; and having a mixture at the lowest end of the slump range.

As a result, concrete delivery times are difficult to specify in terms of hours. A better method is to specify the concrete delivery time in terms of acceptable slump loss for that particular job.

6.3.1.2. TEMPERATURE

The higher the temperature at which the concrete is mixed, transported and placed, the greater evaporation and hydration of the cement, and the more likely the occurrence of operating problems. Slump loss more often occurs in hot weather. In hot weather, the effects of all the other factors on the slump loss are increased. See Fig. 6.2. The adverse effects of higher temperature on the fresh concrete can be summarized in initial workability, rate of stiffening and rate of evaporation as follows:
i) **Initial workability**: A higher temperature of the fresh concrete will require a greater quantity of water to produce a given workability. If the mix proportions are based on the trial mixes made at a particular temperature, then a higher temperature on site will cause the concrete to be less workable than expected. In this case, compaction may be impaired, or additional water needed to control the workability. The latter increases the water/cement ratio. However, in either case, both the strength and durability of concrete are likely to be reduced.

ii) **Rate of stiffening**: The reaction between the cement and water in fresh concrete is approximately doubled for every 10°C increase in the temperature of the concrete [138]. Therefore, even if the concrete is produced at the desired initial workability, it quickly becomes stiff when the temperature of the paste is high. The higher rate of stiffening will increase the degree of heat generated as the
result of hydration. Eventually, the increased rate of hydration associated with the higher concrete temperature, reduces the workability of concrete more rapidly.

iii) rate of evaporation: When the heat generated combines with the initial concrete temperature the concrete becomes warmer. In a warmer medium, water evaporates at a higher rate. High rate of evaporation also causes a higher slump loss.

The adverse effects of higher temperature can be reduced by the following [113,132,139,140]:

1) speed up the concrete delivery, placing and compaction
2) if permissible use a retarder
3) protect the concrete from the sun and wind while handling
4) use cold mixing water
5) avoid using hot cement
6) cool the aggregates by spraying with water and/or shading
7) avoid overmixing
8) if possible perform concreting operations at the coolest time of the day.
9) wet the formwork before starting concreting
10) shade the work and use windbreaks
11) when a truck mixer is used:
   i) start the mixing as late as possible and use transit mixing
   ii) agitate the concrete at the lowest range of agitating speed (2rpm)
   iii) paint the drum of the truck mixer white
   iv) maintain a very strict and precise coordination between concrete producer and contractor
   v) study the route well in advance to provide fast and easy access to the jobsite
   vi) discourage the unloading of the delivered concrete into small units like wheelbarrows or buggies
   vii) spray water onto the drum of the truck mixer.
6.3.1.3. CHARACTERISTICS OF THE CONCRETE INGREDIENTS

Although the major causes of slump loss are the delivery time and the temperature, the concrete making materials also affect the slump loss. The effects of aggregates, cement, admixture, and water on the slump loss are explained below.

a) Aggregates:
The use of dry aggregate or aggregates having an absorption capacity of more than 2 % in one hour [135] increases the slump loss. In the case of prolonged mixing or agitating, the grinding action increases the amount of fine particles in the mixture. When the aggregate is soft the grinding action causes more severe problems. More fine particles need more water to maintain a specified workability.

However, the effects of aggregate characteristics on the slump loss are not difficult to cope with. When the aggregates are too dry or highly absorptive, spraying water on aggregate stock piles and shading will reduce these problems. If there is no other option but, to use soft aggregates, it is recommended that, the agitation time is reduced by using transit mixed concrete.

b) Cement
Cement doesn't usually play an important role in increasing the slump loss, unless hot cement or any kind of rapid hardening cement is used. An increase in the cement temperature by 8 F will cause an increase in the concrete temperature by 1 F [113]. The effects of higher temperature on the slump loss is discussed in section 6.3.1.2.

c) Admixtures
Admixtures that reduce the water requirement (WRA) slightly retard setting of the concrete. This retardation is usually less than would result from a 10 to 20 F (5 to 10 C) drop in concrete temperature. Actually as compared with plain concrete, at ordinary temperatures,
concrete containing unmodified lignin-base WRA has slightly more slump loss. But the length of the time that the concrete will respond to vibration is increased [131]. The other advantage of using an increased dosage of water-reducing, or water-reducing and retarding admixtures in prolonged mixed concrete is the need for less mixing water after retempering. Consequently, this will help to improve the strength of the concrete.

Superplasticisers can be used to produce flowing concrete or high strength concrete. But their effect is relatively short, and about 30 to 60 minutes later a rapid loss in workability is expected [110].

However, there are retarder admixtures that can be used especially in hot weather for extending the time available for delivering and placing. Thus the formation of the cold joints is avoided. These retarders slow down the hydration, but have no influence on the evaporation rate. So, the retarders do not prevent the workability, as measured by the standard slump test, from decreasing with time [141].

d) Water

The only effect of the mixing water on the slump loss may be as increasing the temperature of concrete when hot water is used. ACI Committee 305 "Hot weather concreting" [113] states that, every 4 F water temperature, increases the temperature of the concrete by about 1 F.

In truck mixed concrete operations, if the proposed precautions are not enough to keep the slump loss in the specified limits, then, controlled retempering is advisable [134]. When on-site batching is used, an adjustment to the initial slump should be made after a suitable trial on the job. This adjustment will offset any reasonable slump loss during transporting and placing the concrete. The proportions should be revised to ascertain a new workability-strength relationship.
6.3.2. **LOSS OF INGREDIENTS**

During transporting and placing the concrete ingredients may be lost normally grout. Also extraneous materials carried by wind or rain should not be allowed to contaminate the concrete. Therefore, the concrete transporting container needs to be watertight. When one of the open top wheeled transporting unit is used, especially on rough terrain, mortar spillage should be avoided. If this occurs, reducing the capacity of the transporting unit is a solution. A wiper or scraper should be provided with the belt conveyor to prevent the loss of mortar on the returning belt.

6.3.3. **SEGREGATION**

Segregation can be defined as separation of the constituents of a heterogeneous mixture so that their distribution is no longer uniform [142]. In fresh concrete, segregation is caused by differences in the size of particles and sometimes in the specific gravity of the ingredients. Fresh concrete may segregate in two ways. Firstly, the coarse particles tend to separate since they travel further along a slope or settle more than the finer particles. Secondly, the grout separates the other constituents. This is especially common in wet concretes.

Segregated fresh concrete comprises two distinct parts. One part has too little coarse aggregate, and the other too much. The first is likely to shrink, crack, and scale, having poor layers, and poor resistance to wear. The latter is too harsh for consolidation and finishing, and frequently causes honeycombing and formation of rock pockets in the concrete structure [110,143].

Segregation may not be corrected automatically in the succeeding operations, and must therefore be avoided as far as possible during handling. The selection of a good grading will improve the
cohesiveness of the fresh concrete. But even if the concrete is cohesive, improper application on the site will result in segregated concrete. So, the most effective way of controlling the segregation is to select adequate methods and equipment in transporting, placing, and consolidating concrete. Use of air entraining admixtures, and coarse aggregate that do not differ greatly in specific gravity from the fine aggregates help reduce segregation. However, on the construction site, segregation of concrete can be controlled effectively by competent supervision which covers the following operations:

1) charging concrete containers
2) moving concrete
3) discharging concrete containers
4) pumping concrete.

6.3.3.1. CHARGING CONCRETE CONTAINERS

Concrete containers such as, wheelbarrows, buggies, dumpers, hoppers, trucks, rail cars, etc., should filled so that concrete will be dropped vertically, or near to vertical, and into the center of the container thus avoid segregation.

6.3.3.2. MOVING CONCRETE

Concrete can be moved by using one of the following:

a) chutes
b) belt conveyors
c) containers.

a) Chutes

A chute is one of the most unsatisfactory method of transporting concrete [28]. In order to prevent segregation, it is necessary to meet the following requirements:
i) The slope of the chute must be sufficiently steep to handle the concrete at the specified workability. However, too high a slope may cause rolling of the larger particles. The recommended slope for the chute is between 1 to 2, and 1 to 3 [110].

ii) Effective end control that produces a vertical drop of concrete. This end control is very important, because the segregation does not result from the length of the chute, but from the lack of such an end control. An acceptable end control is a baffle or hopper attached to a down-pipe with a minimum length of about 600 mm (24 in).

b) Belt Conveyors
The slope and the end control of the belt conveyors are the two important features that should be planned beforehand to prevent segregation. A steep slope (more than 25-30 deg. with horizontal) may promote segregation of concrete [144] due to the sliding of the concrete. At the end of the chute, concrete may be segregated while dropping, this therefore, an effective end control should be provided as explained in (a) (ii) above.

c) Containers
While moving concrete in a container, especially with a wheeled transporting equipment, there is a tendency for the coarser and the heavier particles to settle, and for the finer and lighter particles, especially water, to rise. This type of segregation can be minimized by reducing the jolting of the container, by shortening the haul distance, and the most importantly by specifying a cohesive and drier concrete.
6.3.3.3. **DISCHARGING CONCRETE CONTAINERS**

Concrete container can either be discharged by gates or by dumping. In the case of a concrete hopper, it is recommended that gates are placed at the center of symmetrically shaped hoppers, and to provide a vertical flow of concrete as far as possible.

When concrete is discharged from a container into its final location, it is necessary to prevent segregation during the following operations:

a) placing slab or mass concrete

b) placing columns or walls

c) placing concrete on sloping surfaces.

**a) Placing Slab or Mass Concrete**

To place concrete in a horizontal slab or in a mass concrete placing, the points that should be noted are:

i) **dump the concrete**: Wheelbarrows, buggies, and buckets are dumped so that the concrete is discharged into the face of concrete already in place. Dumping the concrete away from the concrete in place may cause rock pockets in the structure. The concrete should be dumped as near as possible to its final location, so that lateral movement of the concrete isn't necessary. Depositing concrete in large heaps should be prevented.

ii) **start dumping from the corners**: Especially when the durability of concrete is important, it is necessary to start placing at the corners, and finishing at the center. Otherwise, it will be necessary to move the concrete laterally either by shovelling or by vibrator to fill the corners. In both cases the uniformity of the constituents may be impaired.

iii) **thickness of the layers**: The thickness of the layer should not exceed more than 15-24 in (375-600 mm) for mass concrete, and 12-20 in (300-500 mm) for structural concrete [278]. However the thickness of the concrete mainly depends on the compacting method as explained in chapter 7.
b) **Placing Columns or Walls**

In placing columns, walls, or deep beams, it is recommended that the following points are considered:

i) **unconfined free fall:** Unconfined free fall is defined as dropping concrete freely without it touching any reinforcement, form, etc. This possible in placing very large columns, walls, or caissons. There is no height limit for dropping concrete into an unconfined form [145].

ii) **drop chutes:** In placing concrete through a narrow opening like, columns, or walls, concrete will strike the reinforcement bars, form, and other obstacles. This creates two types of problems. The first problem is the segregation of concrete. When the concrete strikes the reinforcements, etc., some of the coarser particles will leave the mortar. This problem is especially important when the concrete can not be dumped into the formwork vertically. The second problem is the accumulation of the mortar on the reinforcement bars. The latter one is important when the rate of placing of the concrete is not high enough to embed the mortars before drying. To solve both of these problems, it is necessary to use a drop chute, or a hopper with a down pipe to direct between the curtains of the reinforcement bars should be used. The length of the down pipe can be about 5 ft (1500 mm) [146]. The top part of the chute may be sloped, but the bottom (min 600 mm) should be vertical to avoid segregation. Reading [147] reported that, from a compaction point of view, the drop chutes should never be spaced more than 3.0 m (10 ft) apart, but 1.8 m (6 ft) spacing is much better.

However, if the use of drop chute is not possible, extra precautions are necessary to minimize the segregation. These precautions are: trying to keep the slump in the range of 1-3 in (25-75 mm); limiting the maximum aggregate size by 3/4 in (19 mm); improving the workability by using plasticisers, or air entraining admixtures without reducing cohesiveness; and
increasing the sand content by about 6% to increase the cohesiveness and reduce the bleeding [146].

iii) **access doors:** Concreting of columns or beams which are sloped or curved in the vertical magnifies the problems explained above in section (ii). Therefore, it is recommended that, access doors are provided at about 1/2 to 1/3rd of the height. The concrete should be charged through this doors by attaching a drop chute on the outside of the formwork. A pocket under the drop chute should be formed to prevent segregation.

iv) **slump of concrete:** Due to bleeding, there is a reduction in the strength of concrete at the upper portion of a column or wall. See Table 6.1. To prevent this reduction in the strength, the height of the column or wall should be divided into 4 divisions, and the slump of the concrete should be reduced from bottom to top by 1/2 in (12 mm) for each division [25].

<table>
<thead>
<tr>
<th>Approximate cube strength of concrete lb/sq in (MPa)</th>
<th>Approximate reduction in the strength of concrete in uppermost portion of columns %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2850 (19.6)</td>
<td>5 to 10</td>
</tr>
<tr>
<td>5700 (39.3)</td>
<td>15 to 20</td>
</tr>
<tr>
<td>8550 (59)</td>
<td>25 to 30</td>
</tr>
</tbody>
</table>

TABLE 6.1 - REDUCTION IN THE STRENGTH OF CONCRETE IN THE UPPERMOST PORTION OF COLUMNS AND WALLS [146]
6.3.3.4. **PUMPING CONCRETE**

The pressure imposed on the concrete in the pipeline of a pump is in the order of 1 MPa [127]. If this pressure is capable of separating the mortar from the coarse aggregate, then, concrete will not pump easily. The pumpable mixtures need to be plastic, cohesive, and well graded. The design of pumpable concrete mixtures is explained in literature [148,149,150,151,152]. Here, the design of a pumpable concrete is not addressed, but those features that affect the segregation of concrete are discussed. The features are:

a) the slump of concrete
b) the proportions
c) downhill pumping.

a) **Slump of Concrete**

The optimum slump for pumpable concrete is 75mm +/-25mm [149]. However, any concrete with a slump range of 50-125 mm is pumpable [153]. A higher slump usually contains more water which can escape from the mixture under pressure and cause bleeding or segregation. A lower slump requires higher pressure to move the concrete in the pipeline. When this pressure requirement exceeds the capacity of the pump, then pipeline becomes blocked.

b) **Proportion**

To produce a pumpable concrete, the void ratio of combined aggregates should be less than 25%. This can often be obtained by adjusting the fine and coarse aggregate ratios. To produce a pumpable concrete, there should be a balance between the void content of combined aggregates and the cement content. The void content should not be more than the cement content by 4%, and should not be less than by 10%. In fact, in any pumping operation, the problems and the remedies can be summarized in two groups:

i) **frictional resistance is excessive:** This problem is likely to occur in high strength concrete with a compressive strength of more than 35 MPa. High frictional resistance in pipelines
necessitates too great a pressure to perform the pumping. This can be avoided by: decreasing the cement content; adjusting the aggregate coarse/fine ratio to increase the voids; increasing the water content; or the use of wetting agent admixtures.

ii) segregation and bleeding: This may occur in pumping of lean mixes or high slump concrete, and can be avoided by: increasing the cement content; adjusting the aggregate coarse/fine ratio to reduce the voids; adding fines (e.g. rock dust or pfa); or use of flocculating agent admixtures.

c) Downhill Pumping
In downhill pumping, concrete in the pipeline is likely to segregate unless there is a resistance against which to pump. Therefore, a resistance is provided by a valve at the discharge end that can be adjusted to restrict the flow of concrete, or by inclining the final length of the pipe upward [153].

6.3.4. COLD JOINTS

The rate of transporting and placing concrete should be high enough to prevent the formation of cold joints in the structure. Cold joints occur when a layer of previously placed concrete hardens or sets to such a degree that, a newly placed concrete layer does not bond to it. The rate of transporting and placing concrete are especially important in hot weather or on windy days. In addition to the lack of bonding, cold joints are also unsightly.

Cold joints may be eliminated by planning the batching, mixing, transporting, and placing procedures so that, the placed concrete is not exposed for too long before it is covered by the subsequent layer. This can be accomplished by speeding up the whole procedure. This speeding up can be achieved by using more or different equipment, more workmen, or eliminating the bottlenecks that cause delays. Precautions can be considered to delay the setting and the hardening
of the placed concrete. These precautions include, using retarders, using colder concrete, shading the work area, maintaining higher humidity by fog sprays, or placing concrete in the evenings, early mornings, or at nights in the hot weather.

However, if cold joints are inevitable, it is recommended that, a richer thin mortar layer is placed on the hardened concrete, and then, the normal concrete is placed on that mortar layer. This soft bed reduces the voids between the two layers.

6.4. "TRANSPORTING AND PLACING CONCRETE" MODULE OF ESCON

Mistakes in transporting and placing concrete promotes slump loss, segregation, ingredient loss, and formation of cold joints. These mistakes can be reduced by improving the knowledge and appreciation of the supervisory staff, and workmen on transporting and placing equipment. They should know how the mistakes in using these equipment affect the quality of the concrete produced. Detailed specification including the necessary information on the workmanship requirements about transporting and placing concrete, help to improve the efficiency and effectiveness of the supervision.

Therefore, the "Transporting and Placing " module of ESCON is aimed to give information to the novice users about concrete transporting and placing equipment and procedures. This part of ESCON also produces a detailed specification as mentioned above, at the end of a consultation.

The flow diagram for the "transporting and placing concrete" module of ESCON is shown in Fig. 6.3. This module is divided into two as:

1) transporting and placing equipment
2) placing techniques.
Fig. 6.3 - Flow diagram for "Transporting and Placing Concrete" module of ESCON.
6.4.1. TRANSPORTING AND PLACING EQUIPMENT

The selection of concrete transporting and placing equipment depends on numerous factors such as: character of the particular site; effects of permanent works; continuity of operation; site mixed or ready mixed concrete; and the season in which the work will take place. The selection of transporting equipment has little effect on the quality of the concrete, providing that the selected equipment is used correctly. Therefore, the selection of concrete transporting and placing equipment is left outside the scope of ESCON. But once a piece of equipment is selected by the user, ESCON provides the necessary information, to ensure that the concrete quality is not impaired during handling. In this respect, ESCON provides information for the equipment given in section 6.3. ESCON recommends that, during charging a concrete container, the precautions given in section 6.3.3.1. should be followed to avoid segregation.

a) Wheelbarrows

On rough or muddy run ways concrete may be segregated in wheelbarrows. In this case, to prevent the segregation, the system recommends that:

i) planks are placed to form a run way
ii) pneumatic tyres are preferred
iii) wheelbarrow are not filled to the brim
iv) wheelbarrow are not used on rough terrain for long distances (the maximum haul distance may be up to 60-70m).

b) Buggies

Concrete may be jolted in buggy when it runs on muddy or rough runway. Therefore, the system recommends that, the runway will be constructed by using planks. The buggies are not recommended for long haul distances on rough terrain. The maximum haul distance for hand-operated, and power-operated buggies may be 60-70 m and 300-350 m respectively [126].
c) Concrete Hoppers
ESCON gives advice about the charging and discharging a concrete hopper, shape of the hopper, and the rubber gate wipes as explained in section 6.2.(c).

d) Buckets
The buckets can be transported in two ways: (i) by rail cars or trucks; (ii) by cranes, cableways, or helicopters. The latter creates no problem about the segregation or slump loss. But in the first way the concrete may be segregated, and there may be a considerable slump loss. ESCON allows the first way of transporting only for the concretes where the slump is less than about 1 in (25 mm). The system limits the delivery time of this method so that, the specified slump loss will not be exceeded (usually this time may be up to 30-45 min). The system also recommends that, in hot weather the buckets are covered against the sun and wind and painted white.

ESCON also states that, the capacity of the buckets should be selected so that, the batch capacity of the mixer is not split. The system recommends that, the rollover buckets are selected when the concrete is discharged into the narrow openings, and the headroom for charging the bucket is limited. The system also recommends that, the conical heaping of the concrete is avoided since the larger aggregate particles may roll down.

e) Agitating Trucks
The systems states that, when the delivery time exceed about 45 min, the truck mixers should be selected, considering the possibility of retempering. If the delivery time is less than 45 min, then, either truck mixer or agitational truck bodies can be used. The system defines the delivery time as the time that the maximum permissible slump loss is not exceeded. If the defined slump loss is likely to be exceeded, then, the system recommends that the points given in section 6.3.1.2.(iii) should be considered.
ESCON states that, after all these practicable precautions, if the slump loss still exceeds the permissible range, then, retempering can be undertaken. The system gives the requirements of retempering as explained in chapter 5.

f) Non-agitating Trucks
ESCON states that, non-agitational trucks can be used providing the slump of the concrete is less than 2 in (50 mm), the cohesiveness and plasticity of the concrete is improved by air entraining admixtures, the haul road conditions are good enough to avoid excessive jolting, and the delivery time is not so long to cause a slump loss more than specified. The system states that, concrete is excessively jolted when clear water accumulates on the surface of the concrete in the truck. If one of the above conditions fails, then the system does not advocate the use of non-agitating trucks for haul distances of more than 300 m [29].

g) Chutes
ESCON recommends that, the chutes are used as explained in section 6.2.(g), and 6.3.3.2.(a).

h) Belt Conveyors
The system states that, belt conveyors should be loaded continuously. If continuous feeding can not be achieved, then, the system recommends that, a feeding hopper is used to regulate the feeding. Use of a corrugated belt also helps to prevent sliding on an inclined belt. The system does not recommend using a conveyor belt at an angle of more than 30-35 deg to the horizontal when the slump of the concrete exceeds 3.5 in (90 mm). On hot or windy days, the system also recommends that, the belt conveyor is covered to help to reduce the slump loss.

ESCON recommends that, an acceptable end control has to be provided as was explained in section 6.3.3.2.(a).
j) **Dumpers**
ESCON recommends that the bucket of the dumper should be watertight to avoid leakage. The system also gives advice about haul distances of the dumpers as explained in section 6.2.1.

k) **Concrete Pumps**
ESCON defines the slump of pumpable concrete, the maximum aggregate size, and the appropriate diameter of the pipes as explained in section 6.2(j), and 6.3.3.4. The system also gives information about the types of the pumping pipes, such as steel, flexible hose, aluminum, and plastic. The system does not recommend aluminum pipes particularly for long pipelines and on hot days. The reason is that, the cement and the abraded aluminum may react in the pipeline and produce hydrogen gas which increases the voids in the pumped concrete.

The system recommends that, appropriate proportioning is maintained to produce pumpable concrete. The conditions for producing pumpable concrete are explained in section 6.3.3.4.(b). The system defines the problems of concrete pumping depending on the void content of aggregates and the cement content. However, if the user has difficulties in determining the void content of the aggregates, then the system divides the concretes into three categories:

i) high strength concrete (compressive strength is more than 35 MPa)
ii) medium strength concrete (Compressive strength is 15-35 MPa)
iii) low strength concrete (compressive strength is less than 15 MPa).

Having defined the strength category, the system states the major pumping problems for each categories of concrete. Then the system propose solutions for these problems.
Finally, the system reminds the user that, lubrication of the pipeline is essential before commencing pumping. About 1 cu yd (0.76 cu m) of grout is required for lubrication of each 1000 ft (300 m) of pipeline. The effects of the lubrication may last only a few minutes in hot weather, and about 15-20 minutes in cold weather unless the pumping is continuous.

1) Drop Chutes
ESCON recommends that, the length of the drop chutes is a minimum 600 mm (2 ft) to direct the concrete to fall vertically. The diameter should be a minimum of 8 times the maximum aggregate size. If a tapering pipe is used, then the system permits the lower end of the pipe to be about 6 times of the maximum aggregate size. ESCON also states that, the lower portion (minimum 600 mm) of the pipe should be kept vertical to prevent segregation.

m) Rail Cars and Hoists
The system recommends that, the points given in section 6.3.3.1. should be followed to prevent segregation while charging the rail cars or hoists. The containers should be watertight. When slump loss is a problem, the system recommends that, the rail cars should be covered against the sun or wind.

6.4.2. PLACING TECHNIQUES
ESCON gives recommendations on the placing techniques for columns, walls, or deep beams, and slabs or mass concretes.

a) Columns, Walls or Deep Beams
Placing concrete into columns, walls, or deep beams mainly involves the "dropping" of concrete. The system defines the "unconfined free fall" as was explained in section 6.3.3.3.(b),(i), and states that, in this type of placing there is no height limit. But when concrete is placed through narrow openings, like, columns, walls etc., then the system
recommends some precautions, such as, use of drop chute, or access
door. The system recommends the use of drop chutes in cases where
the concrete would not be discharged vertically from the container,
for example from wheelbarrows or buggies. This ensures that the
cement drops vertically through the reinforcement curtains. If the
cement can be dropped vertically, as discharged from a crane
bucket or pump, then there is no need to use a drop chute. When the
structural element is curved or sloped in vertical, then, the system
recommends that, the use of access doors is essential to prevent
segregation. The system defines the dimensions and the places of
these access doors as explained in section 6.3.3.3.(b).(iii).

If for any reason the use of a recommended drop chute is not
practiceable, then, the system advises revising the proportioning as
was explained in section 6.3.3.3.(b)(ii).

b) **Slabs or Mass Concretes**
ESCON gives recommendations about the concreting techniques of:
  i) sloping slabs
  ii) monolithic placing of slabs and columns
  iii) flat slabs.

i) **Sloping Slabs:** The system recommends that, in concreting the
sloping slabs, the concreting should be commenced from the lower
end. If concrete is placed by a chute, a baffle should be placed at the
lower end of the chute.

ii) **Monolithic Placing of Slabs and Columns:** In this case, it is crucial
to let the concrete settle in the columns before starting to place the
slab. Concrete may need about 1-3 hours to settle depending on the
weather conditions and the workability of the concrete. This
duration will be the maximum duration that, the vibrator can still be
driven into the concrete with their own weight.

iii) **Flat Slabs or Mass Concretes:** The system recommends the
placing of mass concrete or flat slab should be in horizontal layers
with thicknesses explained in section 6.3.3.3.(a)(iv). ESCON gives
advice about where to start concreting, and the thickness of the layer as explained in section 6.3.3.3.(a).

When the appearance of the concrete is important, ESCON recommends that the following precautions are taken in addition to those explained above: place concrete into the formwork as continuously as possible, and at a rate of about 1.8 m (6ft) per hour to reduce the blowholes; try not to place the concrete against the form face which is to be exposed to view to reduce the number of the blowholes; keep the elapsed time between the placing and compaction a minimum and constant to prevent colour variation; and have concrete transporting equipment with enough capacity to get the whole batch in one unit.
CHAPTER SEVEN: COMPACTION OF CONCRETE

7.1 Introduction
7.2 Compacting Methods and Equipment
7.3 Factors Affecting Proper Compaction
7.4 Compaction Imperfections
7.5 "Concrete Compaction" Module of ESCON
7.1. **INTRODUCTION**

A mass of freshly mixed concrete as deposited in a form, usually contains an amount of entrapped* air. The amount of entrapped air depends on the workability of the concrete. Concrete allowed to harden in this condition is nonuniform, weak, porous, poorly bonded to the reinforcement, and unsightly. Concrete needs to be densified to remove this air and to improve its quality. Therefore, the two main objectives of compaction (also called consolidation), are:

i) to remove the entrapped air from the fresh concrete in the form

ii) to eliminate the rock pockets that may be formed during handling the concrete.

Removing the entrapped air and rock pockets will improve the strength, durability, and appearance of the concrete. The benefits of compaction are shown in Fig.7.1.

A higher concrete quality can be obtained with a lower water/cement ratio, provided that, sufficient compaction is maintained. However, insufficient compaction will reduce the quality of dry concrete at a higher rate than of wet concrete.

The first part of this chapter discusses, concrete compaction methods and the factors affecting proper compaction. In the second part of the chapter, the "Concrete Compacting" module of ESCON is described.

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*: Entrapped air needs to be distinguished from entrained air. Entrapped air is the incidental or accidental air voids in the concrete. Entrained air is the intentionally added small air bubbles which is not intended to be removed during compaction.
7.2. **COMPACTING METHODS AND EQUIPMENT**

Concrete compacting methods can broadly be divided into two:
1) manual methods
2) mechanical methods.

Concrete compacting methods should be selected depending on the workability of the concrete, degree of deaeration desired, and the placing conditions, i.e., the complexity of the formwork and the amount of reinforcement.

The entire range of concrete consistencies used in construction sites, and their values in slump and vebe time are given in Table 7.1.
Workability: The workability of fresh concrete is the ease with which concrete can be mixed, handled, compacted, and finished. Workability is affected by the grading, particle shape, and the proportions of aggregates, as well as, the cement content, admixtures, if any, and the consistency of the mix.

Consistency: Consistency is the ability of freshly mixed concrete to flow. Once the materials and the mix proportions are selected, the major control of workability is through the changes in the consistency by changing the water content [154].

Concrete should be sufficiently workable to be compacted satisfactorily. But any excess workability is undesirable, because it tends to increase the cost of the concrete. Excess workability often gives an unstable mix which is more likely to segregate while handling and compacting. The degree of workability, slump, and their suitable uses are summarised in Table 7.2 [24].
The available variety of manual and mechanical compacting methods is discussed in the next section.

7.2.1. MANUAL METHODS

Satisfactory hand compaction is possible for a plastic or a flowing concrete. Usually, the quality of these concretes is rather poor, because of their high water or sand content. Therefore the use of manual compaction methods should generally be discouraged. However on small sites manual compaction methods are still used. Of course manual compaction is better than no compaction at all. The manual compacting method can be grouped as:

i) **hand rodding**: A tamping rod or other suitable tool is thrust repeatedly into the concrete. The rod should be long enough to reach the bottom of the form, or the lift. Also the rod should be thin enough to pass between the reinforcement bars and the form. When the bottom layer is still in a plastic condition, it is necessary for the rod to penetrate about 100-200 mm into the bottom layer.

ii) **spading**: Spading is used to improve the appearance of formed surfaces. A flat spade-like tool is repeatedly inserted and withdrawn adjacent to the form. This forces the coarse particles away from the form surface, and the upward movement pulls the air bubbles upward to the top surface.

iii) **foot taping**: Tamping by foot also contributes the elimination of air voids in the concrete. Manual compaction method can also be used to compact stiff mixes. In this case, the concrete should be placed in thin layers, and each layer carefully rammed or tamped. However it is very laborious and costly to attain satisfactory consolidation.
TABLE 7.2 - Degree of workability, slump, and suitable places of concrete used in construction [24]

<table>
<thead>
<tr>
<th>Degree of Workability</th>
<th>Slump (mm)</th>
<th>Use for which concrete is suitable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>0-25</td>
<td>Roads vibrated by power-operated machines. At the more workable end of this group, concrete may be compacted in certain cases with hand operated machines</td>
</tr>
<tr>
<td>Low</td>
<td>25-50</td>
<td>Roads vibrated by hand-operated machines. At the more workable end of this group, concrete may be manually compacted in roads using aggregate of rounded or irregular shape. Mass concrete foundations without vibration or lightly reinforced sections with vibration</td>
</tr>
<tr>
<td>Medium</td>
<td>50-100</td>
<td>At the less workable end of this group, manually compacted flat slabs using crushed aggregates. Normally, reinforced concrete manually compacted and heavily reinforced sections with vibration.</td>
</tr>
<tr>
<td>High</td>
<td>100-175</td>
<td>For sections with congested reinforcement. Not normally suitable for vibration.</td>
</tr>
</tbody>
</table>

7.2.2. MECHANICAL METHODS

Mechanical compacting methods make the placement of concrete with a low water/cement ratio, and high coarse aggregate content possible. These are associated with high quality concrete. Compacting concrete by vibration does not affect the strength of concrete [155], but it does affect the removal of air voids. For instance, a reduction of water/cement ratio of 0.6 to 0.5 in a well vibrated concrete, may cause an increase in the compressive strength of concrete up to 40 % [156].
Whilst concrete can be compacted mechanically by spinning, pressure, or shock, on construction sites the most common concrete compaction method is vibration. The basic concepts of vibratory compaction include:

1) vibratory motion
2) process of compaction
3) compaction of flowing concrete
4) equipment for vibration

7.2.2.1. VIBRATORY MOTION

A concrete vibrator transmits an oscillatory motion to the fresh concrete. This motion is described in terms of frequency, (the number of oscillations or cycles per a given unit of time), and amplitude, (maximum deviation from the rest position). In many vibrators, the oscillation motion is produced by rotating an unbalanced weight or eccentric inside the vibrator casing. The acceleration which is a measure of the intensity of the vibration, can be calculated from the frequency and amplitude when they are known. The acceleration is usually expressed in terms of the acceleration of gravity, "g". The maximum aggregate size contained in the concrete affects the optimum acceleration, so that, the larger aggregate size requires less acceleration. The C&CA [157] reported that, the required acceleration for the maximum aggregate sizes of 40, 20, and 10 mm are 100, 150, and 200 g respectively. The terminology of vibratory motion is explained in Appendix A.

7.2.2.2. PROCESS OF COMPACTION

When first placed in the form, a typical concrete, (i.e. excluding those of very low or high slump) will contain between 5 and 20 % entrapped air by volume [158]. This air content depends on the workability of the mix, the size and shape of the form, the amount of reinforcement bars and the method of deposition. The purpose of compaction is to remove practically all of this entrapped air.
The behavior of fresh concrete under the effect of vibration can be expressed as a two stage process. The first stage comprises the "slumping" of the concrete, and the second the "deaeration" (removal of entrapped air bubbles) [153, 159, 160]. In the first stage, the rapid vibratory impulses "liquefy" the mortar portion of the concrete, and reduces its internal friction. This results in the consolidation of the originally honeycombed concrete by gravitational forces. This movement creates a denser packing. Thus the air filled voids are gradually removed with a decreasing speed [159]. When the vibration is stopped, the internal friction is reestablished. At the completion of this stage, honeycombing has largely been eliminated, and large voids between the coarse aggregates and reinforcement and form are filled with mortar. However, the mortar still contains many entrapped air bubbles. The amount of these air bubbles can amount to several percent of the concrete volume [154]. These air bubbles are also undesirable, and should be removed to diminish their adverse affect on the quality of the concrete. In the second stage of vibration, concrete behaves more like a dense liquid transmitting the vibratory impulses more effectively. Eventually, the entrapped air escapes to the surface to be replaced with cement paste.

To remove all the entrapped air with a conventional vibrator would take an unreasonably long vibrating time. Therefore, some air pockets - around 1% can always be expected in the concrete or on the formed surface at the end of compaction [159].

7.2.2.3. COMPACTION OF FLOWING CONCRETE

As was explained in section 7.2.2.2, the vibration process comprises two stages. The main objective of the first stage is to provide mobility for the larger aggregate particles. Therefore this stage requires a relatively high amplitude and low frequency vibration. The objective of the second stage of vibration is to fluidify the cement paste sufficiently for any entrapped air to become bouyant. Thus, the second requires a relatively low amplitude and high frequency. Since the optimum requirements of the first and the second stage are
different, it is difficult to achieve both with any given vibrator [160].

When water reducing admixtures or superplasticisers were introduced in the mid seventies, many people concluded incorrectly that, superplasticised concrete was self levelling, and hence, it was also self compacting. According to the theory of compaction explained above, in fact, the use of superplasticised concrete may eliminate only the first stage of the vibration process. The second stage, "deaeration" is still essential for the removal of about 5% [159] of the entrapped air where it exists either under the coarse aggregate particles, or along the side of the form. Thus the use of high workability concrete does not remove the need for compaction.

7.2.2.4. EQUIPMENT FOR VIBRATION

Vibrators that are used on construction sites to compact concrete can be divided into two main classes:

a) internal vibrators
b) external vibrators.

a) Internal Vibrators
Internal vibrators are also called spud, or poker vibrators. They are commonly used to consolidate concrete especially in walls, columns, beams, and slabs. The head of the vibrator is usually cylindrical, and its diameter range from 20 to 180 mm (3/4 to 7 in). Smaller diameter vibrators have high speed frequencies ranging from 10000 to 15000 vibration per minute (vpm) or (170 to 250 Hz). They have low amplitude, ranging from 0.4 to 0.75 mm (0.015 to 0.03 in). As the diameter increases, the frequency decreases, and the amplitude increases. Therefore, the effective radius of action of a vibrator increases with an increased diameter.

Internal vibrators can be grouped as:

1) **flexible shaft**: In this type of vibrator, the vibrating head is connected to a driving motor by a flexible shaft. Inside the head, an unbalanced weight rotates at a high speed causing the head to
revolve in a circular orbit.

ii) electric motor in the head: For this type of vibrator the motor is in the vibrator head. The minimum diameter of the head is 2 in (500 mm) since it is difficult to miniaturize the parts further. The motor rotates an unbalanced weight which causes the head of the vibrator to revolve in a circular orbit.

iii) air vibrators: Usually the motor which works by compressed air is in the head of the vibrator, and create the motion as explained above. Air vibrators are attractive on sites where compressed air is readily available at a constant pressure.

The effectiveness of an internal vibrator for a specific job depends on its radius of action, and its ability to perform the two stage compaction process as explained in 7.2.2.3. The best measure of performance of a vibrator is measuring its effectiveness on the job site. Knowing this, ACI Committee 309 [153] have produced recommendations for the characteristics, performance, and applications of internal vibrators excluding special purpose vibrators. These recommendations are given in Table 7.3.

b) External Vibrators

Form vibrators and surface vibrators are the two commonly used external vibrator types to compact concrete on construction sites. Surface vibrators are vibrating screeds, pan type vibrators, plate or grid tampers, and vibratory roller screeds.

i) Form Vibrators (shutter vibrators)

These vibrators are securely attached to the outside of the form. They are especially useful in cases of: compacting concrete in thin sections, or heavily reinforced sections; supplementing the internal vibrators; stiff mixes where internal vibrators can not be used. Concrete compacted by form vibrators should be deposited in layers of about 10 to 15 in (250 to 400 mm), and each layer should be compacted individually. Form vibrators should be spaced uniformly to distribute the intensity of vibration uniformly over the entire area.
<table>
<thead>
<tr>
<th>Column (1)</th>
<th>(2) Recommended frequency Vibrations per min.</th>
<th>(3) Suggested average amplitude</th>
<th>(4) Approximate values of</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of head mm (in)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-40 (0.75-1.5)</td>
<td>10000-15000</td>
<td>0.4-0.8 (0.015-0.03)</td>
<td>80-150 (3-6)</td>
<td>0.8-4</td>
<td>Plastic and flowing concrete in very thin members and confined places. May be used to supplement larger pokers.</td>
</tr>
<tr>
<td>30-60 (1.5-2.5)</td>
<td>9000-13500</td>
<td>0.5-1.0 (0.02-0.04)</td>
<td>130-250 (5-10)</td>
<td>2.3-8</td>
<td>Plastic concrete in thin walls, columns, beams thin slabs, and along construction joints. May be used to supplement larger vibrators in confined areas.</td>
</tr>
<tr>
<td>50-90 (2-3.5)</td>
<td>8000-12000</td>
<td>0.6-1.3 (0.025-0.05)</td>
<td>180-360 (7-14)</td>
<td>4.6-15</td>
<td>Stiff plastic concrete in general construction, such as walls, columns, beams, and heavy slabs. Auxiliary vibr. adjacent to forms of mass concrete and pavements. May be gang mounted.</td>
</tr>
<tr>
<td>80-150 (3-6)</td>
<td>7000-10500</td>
<td>0.8-1.5 (0.03-0.06)</td>
<td>300-510 (12-20)</td>
<td>11-31</td>
<td>Mas and structural concrete of 0 to 2 in (50 mm) slump deposited in quantities up to 3 cu m in relatively open forms of heavy constructions (power houses, heavy bridge pierd., foundations, etc.) Also auxiliary vibration in dam const. near forms and around embedded items and reinforcement bars.</td>
</tr>
<tr>
<td>130-180 (5-7)</td>
<td>5500-8500</td>
<td>1.0-2.0 (0.04-0.08)</td>
<td>400-610</td>
<td>16-24</td>
<td>Mas concrete in gravity dam, large piers, massive walls, etc. Two or more vibrators will be required to operate simultaneously to melt down and compact concrete quantities deposited in more than 3 cu m at once.</td>
</tr>
</tbody>
</table>

Notes:
Column (2) - While vibrator is operating in concrete
Column (3) - Peak amplitude operating in air
Column (4) - Distance over which concrete is fully vibrated.
Column (5) - Assumes insertion spacing is 1.5 times the radius of action, and that vibrator operates two-thirds of the time concrete is being placed.
Columns (4) and (5) - These ranges reflect not only the capability of the vibrator, but also differences in workability, degree of deaeration desired, and other conditions experienced in construction.
Normally the distance between them is within the range of 5 to 8 ft (1.5 to 2.4 m). However, the spacing is best found by experimentation. Form vibrators should not be applied within the top few feet [110]. At the top of the form, the oscillatory movement may create a gap between the form and concrete. They are more effective with steel shutterings rather than timber [159]. Concrete can be compacted by form vibrators up to a vertical distance of 18 in (450 mm) from the surface of form. If form vibrators are attached on both parallel shutterings, they can be used to compact concrete with a form opening of 30 in (750 mm) [29].

When congested reinforcement prevents the penetration of internal vibrators, and the opening of the form is too wide to use the form vibrators, the concrete can be compacted by vibrating the reinforcement. This method also improves the bond between the reinforcement and concrete. In this method, a form vibrator is attached to the reinforcement with a suitable fitting. Reinforcement vibration should not be performed by fixing the internal vibrators on the reinforcement bars, since they may be damaged [154].

ii) Surface Vibrators
These are mainly used in slab construction. Surface vibration can be applied to slabs with a thickness of up to 6 in (150 mm) which are lightly reinforced. If there is no reinforcement, then surface vibration can be used for slabs up to 8 in (200 mm) thick [154, 161].

vibrating screeds: Vibrating screeds are the most common surface vibration equipment. A vibrating screed consists of single or double beam long enough to span the width of the slab. One or two vibrators (eccentric) are attached to the top of the beam(s). For these vibrators, the range of frequency is 3000 to 6000 vpm and an acceleration of 5 g has been found to be the most satisfactory [154]. The beams are supported on the edge form or suitable rails, that can also control the elevation of the screed. They also perform the strike-off operation in slab construction. A vibrating screed is not recommended for concretes with a slump in excess of 3 in (75 mm) as surface vibration results in an excess accumulation of mortar and fine particles on the surface. This reduces the wearing resistance of
the concrete. For the same reason, this equipment should not be used after the concrete has been adequately compacted by some other means of vibrator. The intensity of the compaction is controlled by the forward speed of the screed, i.e. for more compaction the forward speed is reduced.

**Pan type vibrators:** These consist a horizontal pan or a series of pans spanning the entire width of the slab, transversely to the direction of progress. They rest on the slab without touching the form, and therefore can not be used for striking-off purposes. Pans are vibrated by eccentric weights and with a similar frequency and acceleration of the vibrating screeds explained above.

**Plate or grid vibratory tampers:** These consist of small vibrating plates or grids about 0.2 sq m which are moved over the slab surface. These vibrators are useful in compacting stiff concretes.

**Vibratory roller screed:** These are used for both strike-off and vibrating. The rollers act as an eccentric vibrator and knock down and screed the concrete. These are useful to compact plastic concretes.

### 7.3. FACTORS AFFECTING PROPER COMPACTION

The factors that affect the proper compaction of concrete are shown in Fig. 7.2. Proper compaction of concrete is essential to reduce the adverse effects of entrapped air on the quality of concrete. It is well established that, each percent of entrapped air (including the entrained air) reduces the strength of concrete by about 5 to 6 % \([24,137,156,162]\). The imperfections of compaction do not only affect the strength of the concrete, but the durability and the appearance of concrete are also drastically diminished.

To maintain the desired concrete quality, it is necessary to consider the following:

1) selection of compaction method and equipment
2) vibration duration
3) vibration techniques
4) revibration.
Fig. 7.2 - Factors affecting proper compacting
7.3.1. **SELECTION OF COMPACTION METHOD AND EQUIPMENT**

Any particular compacting method or piece of equipment may not be applicable in every situation. Manual compaction may be used to compact high workability concrete, but as explained in section 7.2.1, it is unsuitable for other concretes. In selecting a vibrator, internal vibrators as a general rule should be used in every section that are large enough for insertion. They are the most efficient compaction tool on construction sites [159,161]. The largest and the most powerful vibrator that fits the job (see table 7.3), should be used. Internal vibrators should also be used to supplement the surface or form vibrators when their compaction is not satisfactory. Table 7.3 gives a selection guide for internal vibrators.

Form vibrators are used to compact concrete, where the use of internal vibrators are impracticle, such as, in heavily reinforced or very thin walls, columns, beams, or the sidewalls or arch of tunnels. Low frequency (less than 6000 vpm), and high amplitude (more than 0.13 mm) form vibrators are normally preferred to compact concrete of stiff consistencies. High frequency (more than 6000 vpm), and low amplitude (less than 0.13 mm) vibration generally results in more efficient compaction with plastic consistencies [154].

The conditions for surface vibrators are explained in section 7.2.2.4. (b).

**7.3.2. VIBRATION DURATION**

There is no simple and reliable indicator that concrete has been compacted adequately. The duration of vibration to maintain proper compaction depends on the mixture, the capacity of the vibrator and the shape of the form. However, the principal indicators of well compacted concrete are: (1) a glistening of the surface, (2) appearance of cement paste near forms or embedded parts, (3) blending of coarse aggregate into the surface, but not completely
disappearing, (4) cessation of the rise of air bubbles, (5) changes in the speed and/or the sound of the vibrator. The two possible errors that affect the quality of concrete are, undervibration and overvibration.

a) Undervibration
On construction sites, undervibration is far more common than overvibration [154,159]. Undervibrated concrete is not compacted to the maximum practiceable level of compaction. It causes honeycombing, reduced bonding between the reinforcement and concrete, and does not remove all the entrapped air. The experiments undertaken at CITB (see chapter 10) indicated that, reducing the normal compacting time by 50% resulted in approximately a 7% reduction in the strength of the concrete with a slump of 50 mm. Normally on construction sites, full compaction of concrete is not expected, but it is necessary to reduce the percentage of unwanted entrapped air to less than 1% [37]. To avoid undercompaction, it is necessary to maintain compacting until the sign(s) of sufficient compaction are observed. (See section 7.3.2).

b) Overvibration
Normal weight concretes which are well proportioned and with a normal slump are not readily susceptible to overvibration. Overvibration can occur due to careless operation such as, leaving the vibrator operating in the concrete for a long period, or by using oversized equipment. Overvibration may result in [154]:

i) settlement of coarse aggregate: On the top surface of concrete (usually wet concrete) a layer of mortar is formed containing practically no coarse aggregate.

ii) sand streaks: These are most likely with harsh, and lean mixes.

iii) loss of almost all of the entrained air: This reduces the resistance of the concrete to freezing and thawing when air entrained admixtures are used.

iv) excessive form deflection or form damage: This is most likely with form vibrators.
To avoid overvibration, the vibration should be halted when the indications of sufficient compaction are observed. (see section 7.3.2.)

7.3.3. VIBRATION TECHNIQUES

In a survey investigation [37] it was observed that, internal vibrators are used inefficiently for about 70% of their operating time. This is made up as follows:

- 15% out of the concrete and running
- 35% wrongly positioned in the concrete
- 20% vibrating already compacted concrete.

This means that, the internal vibrators were being used in useful work for only 30% of their time. Therefore, to improve the efficiency of internal vibrators the following points should be considered:

a) insertion method;

b) pulling out rate;

c) thickness of the layer.

a) Insertion Method

Internal vibrators can be used successfully when the newly placed concrete is compacted by considering these points:

1) **vertical penetration:** When the concrete layer is thick enough to embed the entire head of the vibrator, it should be held vertically. However, if the concrete layer is not thick enough, the vibrator can be penetrated at a slope to embed the entire head.

2) **systematic penetration:** The head of the vibrator will be inserted at frequent and at regular spacings over the entire area of placement. Haphazard random penetration of the head may cause segregation of the concrete. The recommended spacings of penetration are about 1.5 times the radius of action of the vibrator. (See Table 7.3).

3) **quick penetration:** The head of the vibrator should be penetrated quickly. If penetration is too slow, then, the upper part will be compacted first, and the entrapped air in the
lower part of the layer will not escape easily.

(4) **insertion into the bottom layer:** The head of the vibrator should be penetrated rapidly into the bottom layer if possible under its own weight. To prevent cold joints, the penetration into the bottom layer should be approximately 100 to 200 mm [29].

(5) **starting melting around the perimeter of the heap:** Although heaps should be avoided during the placing of concrete, they are sometimes unavoidable or caused by mistake. In this case, first, the "flattening" or "melting" of the heap is performed by inserting the vibrator around its perimeter. If melting is started from the top of the pile, then, the entrapped air at the bottom will be difficult to remove [163]. During this procedure, segregation should be avoided by moving the concrete laterally. The real compaction starts after flattening is completed. In large jobs where one vibrator is not sufficient, one vibrator is employed for melting and one or two for compacting.

(6) **Avoid touching to the reinforcement or form with vibrator:** Touching the reinforcement with a vibrator is not so undesirable providing that, the reinforcement is not embedded into the already hardened concrete. When the appearance of concrete is important, care should be taken not to touch to the formwork with the poker. It is advisable to keep the vibrator about 75-100 mm from the formwork [37].

**b) Pulling Out Rate**

The vibrator should be withdrawn slowly, at the rate of about 80 mm/sec (3 in/sec) [154]. The concrete should cover the space vacated by vibrator. In compacting dry mixes sometimes the hole may not be closed during the withdraw of the vibrator. In this case, reinserting the vibrator several centimeters away may solve the problem. If this is not effective, the mix or the vibrator should be changed; probably a thinner vibrator will be required.
c) Thickness of the Layer

In compacting structural concrete, the thickness of each layer should normally be about 300-450 mm (12-18 in), depending on the length of the vibrator head. However, when the bottom layer is still compactable, the vibrator should be inserted into it about 100-200 mm. In this case, the thickness of the layer should be the length of the vibrator head minus a length of about 100-200 mm. In the case of mass concrete consolidation, the thickness of the layers are normally 400 to 500 mm (15 to 20 in) [154].

7.3.4. REVIBRATION

Revibration is an application of vibration to compact concrete after placing and initial compaction, but preceding initial setting of the concrete. The unintentional vibration of the bottom layer while placing and compacting the successive layer is not considered to be revibration. Revibration is beneficial if the concrete is again brought to a plastic condition. It may be accomplished by internal vibrators or form vibrators and should be done as late as possible after placing the concrete, providing that, the concrete still can be liquified momentarily by revibration. Revibration generally results in improving the 28 day compressive strength of concrete by about 14%, when it is carried out about 1-2 hr after placing [164]. It also improves the reinforcement bond strength, reduces the content of entrapped air, and relieves plastic shrinkage stresses [153]. Revibration is particularly beneficial for the top 500 to 1000 mm of a placement, where the water voids are the most prevalent. Wetter concretes can be improved considerably by revibration.

However, revibration is not common on construction sites since, it increases the cost of compaction, and if applied too late can damage the concrete.
7.4. **COMPACTION IMPERFECTIONS**

Improper compaction can cause troublesome imperfections. The most common compaction imperfections are:

1) honeycombing
2) excessive entrapped air voids
3) sand streaking
4) "pour" lines

The major portion of these imperfections are the result of too short a duration of vibration, improper vibration, inadequate equipment, and lack of experience of the vibrator operator.

7.4.1. **HONEYCOMBING**

Honeycombing occurs when the mortar does not fill the space between the coarse aggregate particles. Honeycombing shows that the first stage of compaction (see section 7.2.2.2.) has not been completed at these locations. Honeycombing is generally caused by using improper vibrators, or by poor vibration procedure such as inserting the poker at haphazard angles, and unsystematically (see Fig. 7.3). Other factors may also cause honeycombing, such as, inadequate proportions of ingredients, and improper placing methods.

7.4.2. **EXCESSIVE ENTRAPPED AIR VOIDS**

As a general rule, a formed concrete surface contains voids (commonly called bugholes) of various sizes. To reduce air voids on concrete surfaces the following points are recommended:

a) reduce the spaces between inserting the poker
b) increase the vibration duration at each insertion
c) provide a row of insertion close to the form (but without touching it) If touching is unavoidable, the vibrator should be rubber tipped.
d) avoid the application of high viscosity or thick form coating
e) use form vibrators in combination with internal vibrators
f) spade next to the form with a spade-like flat tool
g) arrange the mixture so that, the consistency is not too stiff, an air entrained admixture is used, and a deficit of aggregate finer than 0.25 mm is avoided [165]
h) reduce the thickness of the layer to 150 mm for the form vibrators, and to 300 mm for the internal vibrators [154].

7.4.3. **SAND STREAKING**

Sand streaking is caused by heavy bleeding along the form. Sand streaking is the result of proportioning the materials and the procedures of placing and compacting concrete. Dropping concrete through the reinforcing steel and depositing it in thick lifts without adequate vibration may cause sand streaking. Another cause of sand streaking is the use of form vibrators attached to loose forms. This enables fines to be lost through the joints.

7.4.4. **POUR LINES**

Pour lines are dark lines showing on the formed surfaces, marking the boundaries between adjacent batches of concrete. They are the result of not lowering the internal vibrator sufficiently to penetrate into the layer below.
7.5. "CONCRETE COMPACTION" MODULE OF ESCON

Mistakes in selection and using compaction equipment causes the imperfections as mentioned in section 7.4. These imperfections adversely affect the quality of the finished concrete structure, and must be avoided. They can be avoided by knowledgeable supervisors and experienced workmen who can appreciate the influence of bad compaction on the quality of the concrete. A well prepared specification including all the necessary information on the workmanship requirements on the compaction of the concrete helps to improve the quality of the supervision.

The "Concrete Compaction" module of ESCON therefore, produces advice on the selection and procedures of compaction methods and equipment. This module also prepares a specification as mentioned above, at the end of a consultation of ESCON.

Fig. 7.3, fig. 7.4, and fig. 7.5 shows the flow diagrams for structural concretes, mass concretes, and floors and pavements respectively, of the "Concrete Compaction" module of ESCON.

7.5.1. STRUCTURAL CONCRETES

This category includes the compaction of columns, walls, beams, slabs, etc. Structural concrete can be compacted either by manual methods, or by mechanical methods, using internal vibrators, or form vibrators. The system first selects either internal vibration, or reinforcement vibration, or form vibration as shown in Fig. 7.6.
Fig. 7.3 - Flow diagram for structural concrete part of "CONCRETE COMPACTION" module of ESCON.
Fig. 7.4 - Flow diagram for mass concrete part of "CONCRETE COMPACTION" module of ESCON
Fig. 7.5 - Flow diagram for floors and pavements parts of "CONCRETE COMPACTION" module of ESCON.
Fig. 7.6 - Selection of internal, reinforcement, and form vibration method.
7.5.1.1. INTERNAL VIBRATION

As a general rule, internal vibrators are selected for all sections that are large enough for insertion [159]. Otherwise, either form vibration or reinforcement vibration is selected. However, if the user selects the manual method, the system gives recommendations as explained in section 7.2.1.

If an internal vibrator is selected, then the system recommends that, the vibrator operators work as a team, rather than as individuals. The system asks for the consistency of the concrete in order to recommend the diameter, frequency, and the amplitude of the internal vibrator. The system also gives information about the radius of action, and compaction rates for the recommended vibrator. To give these recommendations, the system uses Table 7.1 and Table 7.3.

In the next stage, ESCON divides the compaction procedure of structural elements into:
   a) columns
   b) walls
   c) flat slabs
   d) sloped slabs
   e) concrete works around openings, ducts, etc.

a) Columns
In compaction of columns, the system recommends that the following points are noted:
   i) If possible, continuous placing and compaction is recommended. In many instances, holding the poker somewhere in the center of a small column is enough to compact the entire area of the concrete in the form. This depends on the radius of action of the vibrator. The vibrator should be pulled out slowly and continuously while the concrete is continuously rising in the form.
   ii) If concrete is to be placed in layers, the first layer will require the maximum attention since honeycombing frequently occur
near the bottom. The thickness of this layer should not exceed 300 mm (1 ft). The poker should be lowered into the bottom layer (if it is newly placed concrete) about 100-200 mm to avoid the formation of cold joints between the layers.

iii) The concrete being placed and compacted should be seen by the vibrator operator.

b) Walls
In compacting walls, ESCON recommends that:

i) the first layer requires special attention as explained above in (a) (ii). The thickness of the other layer can be up to 450 mm depending on the length of the head of the poker.

ii) the vibrator should be inserted systematically, in vertical and staggering pattern by overlapping the radii of action of the vibrator. Insertion should be at regular spaces equal to about 1.5 times the radius of action of the vibrator used.

iii) contact between the vibrator and the form is detrimental to the appearance of the concrete. This should be avoided when the appearance is important.

iv) contact between the vibrator and reinforcement may be detrimental if the reinforcement is embedded into already hardened concrete.

v) conical heaps should be avoided, but sometimes they are unavoidable. In this case, first "melting" will be exercised as explained in section 7.3.3. (v). Normal compaction will commence after flattening.

c) Flat Slabs
In compaction of flat slab concrete, the system recommends that, the poker is inserted vertical and systematically as explained in section 7.3.3. (a). ESCON also recommends that, the poker should not touch the form or reinforcement as explained above (iv) and (v).

d) Sloped Slabs
The system recommends that when the slope of the slab exceeds 10 deg. from the horizontal, then special precautions are necessary to
compact the concrete. In this case, the following points should be considered:

i) in placing the concrete, a weighed slip form screed should be used. But the slip form should not be vibrated.

ii) the concrete in front of the slip form should be vibrated by internal vibrators. After the full compaction the slip form should be pulled upward.

iii) the slump of the concrete shouldn’t exceed 1 in (25 mm) [151] to prevent the slumping of concrete after the slip form.

iv) the compaction procedure should be the same as explained in section (c) above.

e) Concrete Works Around Openings, Ducts, etc.

To compact concrete around openings, duct, etc., the system recommends that, first, concrete is placed to one side of the opening up to about 300 mm above the bottom of the opening [37]. The concrete should be compacted until the concrete fills the bottom of the opening completely, and starts to rise from the other side. Then, concrete should be placed and compacted from the other side. Otherwise, the formation of voids under the opening is likely.

The system gives detailed information about the rate of penetration, and withdraw of the vibrator, and the duration of vibration for each penetration as explained in section 7.3.3.2. and 7.3.3. (a). The system also reminds the user that, if the vibrator is operated by compressed air, on very cold days it is necessary to use an alcohol type antifreeze to avoid freezing the moisture in the air [126].

ESCON recommends revibrating of concrete when the amount of settlement cracks, and bleeding is considerable. Bleeding and settlement cracks may be excessive when the slump of concrete is more than 100 mm (4 in), the thickness of the lift is high, and there is lack of fine particles in the mixture.

The system reminds the user that, using intentionally entrained air will not reduce the normal vibration duration. Some amount of entrained air may be removed by vibration, but normally, this is
considered by the engineer who designs the concrete mix.

ESCON states that it is difficult to prevent the formation of bugholes completely on the formed surfaces. But they can be reduced by special precautions as was explained in section 7.4.2. These precautions are recommended for concreting works where its appearance is important. Finally, the system reminds the user that leakage through the joints of the form should be avoided since it may cause sand streaks and loss of grout. Leakage can be avoided by:

i) using 25X100 mm closed cell rubber or polyvinyl chloride foam strips

ii) extending the form sheathing about 3 mm beyond the frame of the of the form. Thin sections conform more easily and tightly to adjacent surfaces than wide faces of form framings.

7.5.1.2. REINFORCEMENT VIBRATION

ESCON recommends that the reinforcement vibration is only applied in the case of:

i) columns, walls, or beams construction with an opening of more than 750 mm and the reinforcement is so congested that, the internal vibrator can not get through.

ii) slab construction where it is so heavily reinforced that, the internal vibrator can not get through.

Reinforcement vibration is undertaken as explained in section 7.2.2.4. (b). In reinforcement vibration ESCON reminds the user that, the most important point is not to vibrate the reinforcement that is embedded into already stiffened concrete.

7.5.1.3. FORM VIBRATION

Form vibrators are selected to compact concrete in (i) columns, walls, or beams where their thickness is less than 75 mm, and the reinforcement is so congested that internal vibrators can not get
through, (ii) side walls or arch of tunnel construction, etc. type structures where the use of internal vibrators is impracticable, (iii) to vibrate the reinforcement as explained above in section 7.5.2.1.

Having selected the form vibrator, the system gives information about the frequency and amplitude of the form vibrator for a given consistency (see section 7.2.2.4.(b)(l)). The system recommends that, form vibrators are attached preferably to the steel shutterings. Timber shuttering isn’t good at distributing the vibration uniformly. But if the timber shutterings have to be vibrated, tongued and grooved wrought boarding should be used to prevent leakage of fines.

The system gives recommendations about the spacing of the vibrators, and the openings of the form that can be vibrated by form vibrators as explained in section 7.2.2.4. (b).

ESCON gives recommendations about revibration, compaction of entrained air concrete, procedures to reduce the bugholes on the surface of concrete, and precautions to stop the leakage through the joints of the form as explained in section 7.5.1.1.

7.5.2. MASS CONCRETE

ESCON states that internal vibrators are usually used to compact mass concrete, and gives the characteristics of the internal vibrators by using the Table 7.3. Two types internal vibrators are used to compact mass concrete.

i) manually operated vibrators: The vibrator operators should work as team,

ii) gang vibrators: In this case a group of internal vibrators are mounted on a bulldozer, and they work together as a gang. The tracks of the bulldozer may score the surface of the concrete. These marks should be closed by using an internal vibrator operated by a man on plywood “snow shoes”.
The thickness of the layers will be equal to the length of the vibrator head, minus 100-200 mm. If the bottom layer is so hard that, it can not be revibrated, then the thickness of the layer can be equal to the length of the vibrator head. But the thickness of the layer should not exceed about 0.5m to expedite the expelling of the entrapped air. In this case, the system recommends that, first, a richer concrete is placed on the bottom layer and is compacted fully, and then, the normal concreting starts. In this way, the void between the two layers is minimized.

ESCON gives recommendations about the rate of inserting, rate of pulling out, the duration of compaction at each insertion, use of compressed air vibrators, revibration, compacting of air entrained concrete, precautions to reduce bugholes on the formed concrete surfaces, and precautions about leakage through the joints of form. These recommendations are explained in section 7.5.1.1.

7.5.3. FLOORS

ESCON states that, floors can be compacted by internal and surface vibrators. Heavy duty industrial floors should be placed in two layers. The bottom layer can be compacted with internal or surface vibrators as in a normal slab. The top layer should have high resistance against wearing. So, this layer should be thin about 50-75 mm, [154] and placed by using less workable concrete. This layer can be compacted satisfactorily by rolling, tamping or surface vibration. In selection of surface or internal vibrator, the system considers the following:

a) surface vibrators can be used in compaction of slabs with (i) a thickness of less than 150 mm and with light reinforcement (light mesh); (ii) thickness of up to 200 mm but unreinforced

b) internal vibrators should be used for compacting slabs with (i) a thickness of more than 200 mm; (ii) a thickness of less than 200 mm, but normally reinforced. An extract from ESCON consultation about the selection of surface or internal vibrators is given below.
QUESTION COMPACT_SLAB_TYPE '£13£ What is the type of the slab?
£13£1- the thickness is less than 150 mm, and the slab is unreinforced or reinforced with only light mesh,
£13£2- the thickness is about 150-200 mm (6-8in), and it is unreinforced,
£13£3- the thickness is more than 200 mm (8in),
£13£4- the thickness is less than 200 mm but the slab is reinforced. £13£'

INTEGER 1 4

DISPLAY '£13£ Surface vibration is effective for the slabs with thicknesses of up to 150 mm (6 in). Therefore, when the thickness of a slab is less than 150 mm, and it is unreinforced, or contains only light mesh, the recommended vibration method is surface vibration. However, in some cases the use of this method may be difficult, such as, existing column starter bars. In this case, internal vibration can also be used. £13£'

STOP COMPACT_SLAB_TYPE
CLEAR COMPACT_SLAB_VIBRATION
INVESTIGATE COMPACT_SLAB_VIBRATION
ASSOONAS (COMPACT_SLAB_TYPE=1)

DISPLAY '£13£ When the slab is unreinforced, and the thickness is about 150-200mm, either internal or surface vibration can be used. In this case, the selection of vibration method depends on the availability, and other considerations.£13£'

STOP COMPACT_SLAB_TYPE
CLEAR PAVEFLOOR_IMPERFECTION COMPACT_SLAB_VIBRATION
INVESTIGATE PAVEFLOOR_IMPERFECTION
COMPACT_SLAB_VIBRATION
ASSOONAS (COMPACT_SLAB_TYPE=2)

DISPLAY '£13£ The effect of surface vibration is limited when the thickness of the slab exceeds 200 mm. Therefore, if the slabs thicknesses is more than 200 mm, or the thickness is less than 200 mm but, the slab is reinforced, the recommended vibration method is internal vibration. However, attention should be paid to insert the vibrator head into the concrete completely to avoid overheating the vibrator head. In this case the vibrator can be penetrated not vertical but at a slope. £13£'

STOP COMPACT_SLAB_TYPE
CLEAR PAVEFLOOR_IMPERFECTION COMPACT_SLAB_VIBRATION
INVESTIGATE PAVEFLOOR_IMPERFECTION
COMPACT_SLAB_VIBRATION
ASSOONAS (COMPACT_SLAB_TYPE>=3)
Whether internal or surface vibrators are selected, the system asks if any compaction imperfection is observed, and if so, gives its reason, and solution. The system covers the following floor compaction imperfections [154]:

1) **more than one-quarter of the entrained air is lost during the compaction**: The air content in the surface layer of the concrete can be checked by an air indicator after vibration. This should be compared with the air content of the concrete at the time of placement. This is caused by too much compaction. As a remedy, the duration of compaction should be reduced, or amount of the entrained air should be changed.

2) **after removing the side forms, honeycombing is noticed on the edge of the floor or pavement**: This is caused by insufficient compaction at that point. So, if internal vibrators are used, it is necessary to insert close to the form, or to increase the frequency or amplitude of the vibrator. If a surface vibrator is used, the speed of the screed should be reduced.

3) **having a mortar layer thicker than 6 mm at the top surface of the concrete**: This is caused by too much compaction. It can be solved by the precautions explained above in (1).

4) **excessive voids in the concrete**: This can be noticed on the surface of cores drilled from the concrete. It is caused by under vibration or insertion of poker at an incorrect angle (see section 7.3.3).

5) **insertion of subbase materials into the concrete**: This may be caused by lowering the internal vibrator too much, or inserting at an incorrect angle. (see section 7.3.3).

6) **lines of weakness that may become longitudinal cracks later**: This is caused by nonuniformity in the compaction mainly by gang vibrators (if used). (see section 7.3.3).

If an internal vibrator is selected to compact the floor concrete, then, the system gives all the recommendations explained in section 7.5.1.1. When a surface vibrator is selected, then, the system gives advice about the use of surface vibrators as was explained in section 7.3.1.(ii).
7.5.4. PAVEMENTS

The system states that, pavement concrete can be compacted by surface or internal vibration. The system explains the possible "pavement compaction imperfections" and their causes and solutions as explained in section 7.5.3.

If the depth of the concrete layer is more than 200 mm (8 in), then, the system recommends that the concrete should be compacted by internal vibrators. "L" shaped internal vibrators may be used to compact thin layers of concrete, or concrete over reinforcement mesh. Individual or gang vibrators can be used to compact pavement concrete. The system gives recommendations about the characteristics of the vibrators selected (using Table 7.1 and Table 7.3); the rate of insertion and pulling out of the vibrator; the duration of vibration; precautions about air operated vibrators; revibration; compaction of air entrained concrete; reducing the air voids on the formed surfaces; and stopping leaks through the joints of the form. All these recommendations are explained in section 7.5.1.1.

If the depth of the concrete layer is less than 200 mm (8 in), then, surface vibrators are recommended. Internal vibrators are preferred for the compaction of the floors with a thickness of 150 mm (6 in) for high production rates. When a surface vibration method is selected, the system gives recommendations on appropriate procedures as explained in section 7.3.1. (ii).
CHAPTER EIGHT: FINISHING OF UNFORMED CONCRETE SURFACES

8.1 Introduction
8.2 General Considerations
8.3 Finishing Tools
8.4 Finishing Techniques
8.5 Finishing Imperfections
8.6 "Finishing of Unformed Concrete Surfaces" Module of ESCON
8.1. INTRODUCTION

Finishing unformed concrete surfaces includes finishing concrete floors and slabs. Finishing is one of the most important factors that affects the quality and serviceability of a floor or slab. Without special precautions, the top surface of a concrete floor or slab can suffer from reduced quality. The imperfections which lower the quality of the top surface of a floor or slab are scaling, crazing, dusting, reduced wearing and abrasion resistance and reduce strength. These problems can be solved by experienced workers and adequate supervision.

This chapter describes the tools used in finishings, finishing techniques, and imperfections of finishings. In the second part of the chapter, the "finishing of unformed concrete surfaces" module of ESCON is explained.

8.2. GENERAL CONSIDERATIONS

The most important aspect of finishing an unformed concrete surface is, avoiding working back the bleeding water into the concrete. If the bleeding water is worked into the surface of a floor, the water/cement ratio of the concrete at the top is increased. This may result in imperfections such as scaling, crazing, dusting, and reduced strength. Therefore, proper finishing of floors or slabs requires more time and effort than for most other concrete. Proper finishing requires using a floor gang that knows the details of the work and the importance of good workmanship. Concrete design is outside the scope of this research. However, air entraining admixtures are good in reducing bleeding and improving the durability of concrete against freezing and thawing; the maximum aggregate size should not be more than three-quarters of the minimum clear spacing of reinforcement, or one-third the thickness of unreinforced slabs; the maximum slump should not be more than
100 mm (4in) [166]. See Table 8.1.

In this chapter, the finishing procedures discussed in detail are:
1) finishing tools
2) finishing techniques
3) finishing imperfections.

8.3. FINISHING TOOLS

The tools that are used in finishing concrete slab or floor can be grouped as follows:

a) Tools for Spreading
A short-handled square-ended shovel or come-along may be used in spreading concrete deposited in the form. In some cases, where the consistency of the concrete is stiff, special concrete rakes can also be used [167]. Proper leverage is lost with long-handled shovels, so they are not recommended. Round-ended shovels are not good for levelling the concrete. Rakes promote segregation of the concrete when the consistency is plastic or flowing, and should therefore be avoided.

b) Tools for Screeding
Concrete can be screeded by using specially made straight edges, roller screeds or vibrating screeds. For small jobs, 2X4 timber which is specially selected as a straightedge can be used, but normally magnesium straightedges are preferred. Vibrating screeds are made of steel angles or channels. Vibrating screeds should be moved forward rapidly to achieve proper consolidation. Moving too slowly creates a weak mortar layer on the top surface of the concrete.
<table>
<thead>
<tr>
<th>Class</th>
<th>Usual traffic</th>
<th>Use</th>
<th>Finishing techniques</th>
<th>Slump mm (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Light foot</td>
<td>Residential or tile covered</td>
<td>Medium steel trowel</td>
<td>100 (4)</td>
</tr>
<tr>
<td>2</td>
<td>Foot</td>
<td>Offices, churches, schools, hospitals, Ornamental residence</td>
<td>Steel trowel: special finish for nonslip</td>
<td>100 (4)</td>
</tr>
<tr>
<td>3</td>
<td>Light foot, pneumatic wheels</td>
<td>Drives, garage floors and sidewalks for residences</td>
<td>Float, trowel and broom</td>
<td>100 (4)</td>
</tr>
<tr>
<td>4</td>
<td>Foot and pneumatic wheels</td>
<td>Light industrial commercial</td>
<td>Hard steel trowel and brush for nonslip</td>
<td>75 (3)</td>
</tr>
<tr>
<td>5</td>
<td>Foot and wheels-abrasive wear*</td>
<td>Single-course industrial integral topping</td>
<td>Special hard aggregate, float and trowel</td>
<td>75 (3)</td>
</tr>
<tr>
<td>6</td>
<td>Foot and steel-tyre vehicles-severe abrasion</td>
<td>Bonded two-course heavy duty industrial</td>
<td>BASE COURSE: Surface levelled by screeding</td>
<td>100 (4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TOP COURSE Special power float with repeated steel trowelling</td>
<td>25 (1)</td>
</tr>
<tr>
<td>7</td>
<td>Classes 3,4,5,6</td>
<td>Unbonded toppings</td>
<td>As explained above</td>
<td></td>
</tr>
</tbody>
</table>

* Under abrasive conditions on floor surface, the exposure will be much more severe and a higher quality surface will be required for Class 4 and 5 floors. Under these conditions a Class 6 Two-course floor or a mineral or metallic aggregate monolithic surface treatment is recommended.
c) **Tools for Bullfloating**

Bullfloats (skip floats) are used to remove high or low spots on the surface after screeding. They are made of either wood or magnesium. Wood bullfloats are generally more efficient in straightening the surface, but they tend to tear the surface. Magnesium bullfloats are easier to operate, but tend to seal the surface of the concrete. During the bullfloating stage, sealing the surface is undesirable as it causes an accumulation of bleeding water under the surface. Normally, wood bullfloats are preferred for normal weight concretes to minimize this sealing effect [168]. Magnesium bullfloats may be used with light weight concretes, or air entrained concretes where the adverse effects of sealing is less important since, the bleeding is reasonably reduced [167]. In this way tearing the surface is also reduced. Long handled bullfloats facilitate floating the surfaces further from the form.

d) **Tools for Darbying**

Darbies are used to smooth the surface with close screeding by removing high or low spots. They are moved across the concrete surface in a sawing arc motion. They should be kept as flat as possible to prevent sealing the surface. Short-handled wood darbies are preferred for normal weight concretes. High-handled darbies do not have proper leverage. Metal darbies are unsatisfactory for producing surfaces with close tolerances [166]. Since they are short handled, darbies are mainly used near the side of the form, or in congested areas where long handled bullfloats are impractical.

e) **Tools for Edging**

Edgers are used to make neat round edges next to the forms. They are usually made of stainless steel and should be thin lipped. Round edges help to resist chipping of the corners under traffic. The width of the edges should be at least 150 mm (6 in) [167]. Wider edges help to distribute the applied force during edging. Low pressure is good to avoid sealing the surface. A narrow edger tends to rotate and dig into the surface. Shorter edgers are used for curving floor edging.
The radius of the edger should be 3 mm (1/8 in) for floors, and 13 mm (1/2 in) for sidewalks, driveways, etc.

f) **Tools for Jointing**
Jointers, also called groovers, are used to make narrow grooves in slabs up to a thickness of 125 mm (5 in). The depth of the groove will be at least one-fifth of the thickness of the slab, or 19 mm (3/4 in) whichever is larger, to form a plane of weakness. The slab cracks along this weakness when it contracts. The jointer should have a 3 mm (1/8 in) radius for floors, and a 6 to 13 mm (1/4 to 1/2 in) radius for sidewalks, and driveways [166]. A power saw with a masonry cutting blade can also be used for jointing the floors.

g) **Tools for Floating**
Floats can be grouped as hand floats or power floats. Hand floats are made of wood or metal. Wood floats tend to stick on the surface and tear it [169]. Therefore, they are not recommended especially for air entrained concretes. Metal floats produce a smoother surface texture with less work. Any water attachment for wetting the concrete during finishing should be prohibited.

h) **Tools for Trowelling**
Trowels can be grouped as hand trowels and power trowels. Hand trowels are usually made of spring steel or hard stainless steel. First trowelling is preferred by trowels having a minimum dimension of 450X120 mm (18X4.75 in) [166]. Second and third trowellings can be done by smaller trowels. Most machines can be used for both trowelling and floating. The trowel blades are tilted more for second, third or other additional passes.
8.4. FINISHING TECHNIQUES

Each type of floor requires a special finishing technique. In selecting a type of finish, the expected wear resistance, impact resistance, slipperyness, chemical resistance, and decoration of the surface should be considered. ACI committee 302 [166] classified concrete floors or slabs and their proposed finishing techniques as shown in Table 8.1.

8.4.1. FINISHING OF CLASS 1 FLOORS

This finishing technique is recommended for residential or tile covered floors or slabs. Its procedure comprises the following:

i) Spreading and compacting: Spreading should be performed without segregation by using proper equipment as explained in section 8.3.(a). Concrete must not be spread by vibration. Concrete compacting equipment is described in detail in chapter 7.

ii) Screeding: Screeding is the process of striking off the surface of concrete to a predetermined grade immediately after placement. Screeding should be done with one of the tools described in section 8.3.(b). Screeding must be completed before any excess moisture or bleeding water accumulates on the surface of the concrete.

iii) Darbying: Darbying should be done immediately after screeding and must be completed before any excess moisture or bleeding water is present on the surface of the concrete [170]. ACI Committee 302 states that, "any finishing operation performed while there is excess moisture or bleeding water on the surface will cause dusting and scaling". Darbying is done with one of the tools described in section 8.3.(c). The purposes of darbying are to eliminate the ridges and fill in the voids produced by screeding, and slightly embed the course aggregate to prepare the surface for subsequent operations.

iv) Bullfloating: The principles and objectives of bullfloating is exactly the same of darbying. Depending on the area to be floated, either a darby or bullfloat is used. But both of them should not be performed
on the same surface. Bullfloating should be done at right angles to the
direction of travel of the straight edge (parallel to the straight edge).
They are operated by slowly pushing forward and pulling back.

v) Waiting: After darbying or bullfloating, there should not be any
subsequent operation until all the moisture or bleeding water
disappears and the concrete sustains a foot pressure with only about
6mm (1/4 in) indentation [166,168,170].

vi) Edging: In many jobs edging is not required, but if is required, it
is performed with one of the tools described in section 8.3.(e).
Edging should be done after the excess moisture and water have
evaporated.

vii) Jointing: Hand jointing is performed either after or at the same
time of edging. The slab or floor is grooved with the tool described in
section 8.3.(f). It is good practice to use a straight board as a guide. If
a power saw is used, it is advisable to cut as soon as possible after
hardening. The timing of the cutting is important, because any delay
may cause the development of shrinkage cracks. If it is done too
early, the saw may tear the concrete. Sometimes joints can be
created by inserting suitable crack inducing strips into the concrete
while it is still plastic [171]. Joints are spaced for unreinforced slabs
at intervals equal to the width of the slab, but not more than 6 m (20
ft) apart [166,172]. For reinforced slabs, the space between crack
joints may be up to 10 m apart (33 ft).

viii) Floating: After edging and hand jointing, the floor or slab should
be floated with one of the tools described in section 8.3.(g). The aims
of floating are, to embed the large aggregates just under the surface;
to produce a level surface by removing any voids or ridge of
bullfloating; and to compact the mortar at the surface for the next
finishing operations. Floating should be done when the water sheen
on the surface of concrete disappears and the footprint of a man on
the concrete is barely perceptible. See fig. 8.1.
Fig. 8.1 - Floating is done when the footprint of a man is barely perceptible.
ix) **Trowelling:** Trowelling is done just after the completion of floating. Darbying or bullfloating does not make the concrete ready for trowelling. Floating is required. Trowelling can be done by hand or machine as explained in section 8.3.(h). For timing power trowelling a simple "hand test" can be used. If the mortar adheres to the palm when touched on the surface of the concrete, the surface is still not ready for power trowelling. Power trowelling should be started when concrete loses its stickyness, and nothing adheres to the hand. During the first trowelling the trowel should be kept as flat as possible to prevent undesirable washboards. It is better to use an old trowel first and one which is not less than 120 mm (4.75 in) wide [170]. With hand trowelling, any surplus mortar on the surface of the concrete will be removed by exerting a considerable physical pressure on the trowel. Trowelling normally produces a slippery surface. The surface can be roughened by using a soft-bristled broom just after the completion of trowelling.

x) **Additional Trowelling:** Additional trowelling helps to increase the compaction of fine particles on the surface. Secondary trowelling increases the density and wearing resistance of the concrete. There must be an elapsed time between successive trowellings depending on the relative humidity, temperature of the air, and the wind velocity.

8.4.2. **FINISHING OF CLASS 2 AND CLASS 3 FLOORS**

This finishing technique is recommended for floors or slabs for offices, churches, schools, hospitals, garages, and driveways either ornamental or plain.

a) **General procedure for plain concrete surfaces:** The general procedures explained in section 8.4.1 should be followed for plain concrete floors. The procedures of colored, nonslip, monolithic surfaces, and exposed aggregate surfaces are explained in sections 8.4.2.(b),(c),(d).
b) **Monolithic surface treatment for colored surfaces:** This type of finishing is sometimes called "dry shakes". After the concrete is bullfloated or darbied, and the excessive moisture or bleeding water has evaporated from the surface, a preliminary floating is done to bring moisture to the surface and to level the ridges of the previous operation. Then, about two-thirds of the premixed dry-shake color material is shaken evenly by hand over the surface. In a few minutes, the dry material absorbs the moisture from the concrete surface. The concrete should then be thoroughly floated preferably by using power floats. Immediately following this, the remainder of the specified amount of the dry-shake color material is shaken evenly over the surface, and thoroughly floated. In this operation care should be taken to produce a uniform color. Edging and jointing if required, should be done both before and after the dry shake. If a trowelled surface is required, flat trowelling is done immediately after floating. For exterior surfaces, a third trowelling may be necessary. This final trowelling is done by hand, and should eliminate all the washboards or trowel marks.

c) **Nonslip monolithic surface treatment:** Slip-resistant material is mixed with neat dry portland cement at a proportion ranging from 1:1 to 1:2 [166]. Then, the procedure explained in section (b) above is followed.

d) **Exposed aggregates:** Flat particles or particles smaller than 19 mm (3/4 in) may not bond well and easily become dislodged during the operation of exposing the aggregate. After darbying or bullfloating, the selected aggregates should be scattered by hand. The surface should be completely covered by an even distribution of aggregates. The initial embedding of the aggregates is done by patting with a darby or a board (50X100 mm). Immediately following this, the surface is hand floated by using preferably a magnesium float or darby. The whole of the aggregates are embedded in this way, and completely covered by mortar leaving no hole on the surface. In large jobs, a retarder may be applied to control the exposing operation.
But, in small jobs, the retarder is not necessary. The exposing operation is started as soon as brushing and hosing will not overexpose or dislodge the aggregate. If a smooth surface is required, no retarder is applied and the surface is ground after the surface has hardened. Since aggregates completely cover the surface, in exposed surfaces joints are made by saw cutting.

8.4.3. **FINISHING OF CLASS 4 FLOORS**

These floors or slabs are used for light duty industrial or commercial purposes. The procedure for this finishing is similar to the one explained in section 8.4.1. When increased wear resistance is required, a third trowelling is also applicable.

8.4.4. **FINISHING OF CLASS 5 FLOORS**

The finishing procedure for this class of floors or slabs is similar to the procedure explained in section 8.4.1. except for the cases where a special treatment is required to increase the wearing resistance. The procedure of monolithic surface treatment for wear resistance is the same as explained in section 8.4.2.(b). The only difference is that, in this case the special wearing resistance material is prepared on the site. To improve its wearing resistance the trowelling is repeated many times.

8.4.5. **FINISHING OF CLASS 6 FLOORS**

This class of finishing is applied for floors under the traffic of steel tyred vehicles where severe abrasion is expected. The floor comprises two courses. The top course must be at least 20 mm (3/4 in) thick, and with a maximum slump of 25 mm (1 in) [166]. The bottom course may have a slump of up to 100mm (4in) and should be
levelled by screeding. The two courses may be integral or bonded.

**a) Integral two-course Floors**
The top course of the floor is placed when the moisture and the bleeding water on the surface of the bottom course disappear, and the concrete is so hard that the footprints of the workmen are barely perceptible. The general procedure for finishing the top course is the same as explained in section 8.4.1. It is recommended that, both floating and trowelling should be done by power floats and power trowels respectively. Additional trowelling is necessary to improve the wearing resistance of the surface. However, the final trowelling should preferably be done by hand trowel to clear the marks of the power trowells.

**b) Bonded two-course Floors**
In these types of floors it is important to locate the joints on the same line to control the cracks properly. After the bottom course is partially set, the surface should be brushed with a coarse wire broom to remove the laitance and scores on the surface. The base course should be wet cured, and after removing the free water of curing, a grout layer should be scrubbed in. The grout is a 1:1 mixture of portland cement and sand passing a no:8 (2.36 mm) sieve. The grout should be at a cream consistency. While the grout is still damp, the top course should be spread and screeded. The finishing of this course will be as explained in section (a) above. If a time has passed between the end of curing of the bottom layer and the placing of the top layer, and the bottom layer has become dirty, the surface of the bottom layer must be cleaned by using detergent and commercial hydraulic acid.
8.4.6. **FINISHING OF CLASS 7 FLOORS**

This is the finishing of two course unbonded floors of classes of 3, 4, 5, and 6, explained above. The thickness of the topping should be a minimum of 64 mm (2.5 in). The top course can be placed at any time after the bottom course has hardened. The bottom course is covered by plastic sheets. Sufficient wire fabric (30 lb/ sq ft) [166] should be placed into the top course to prevent shrinkage cracks. The general procedure for finishing the top course should be as explained in section 8.4.1. However, in this finishing, power floats and power trowels are preferred. The final troweling is performed by hand trowels to clear the marks of the power trowel.

8.5. **FINISHING IMPERFECTIONS**

The major imperfections on the surface of floors or slabs caused by improper finishing procedures are as follows:

1) limited abrasion resistance
2) scaling
3) dusting
4) crazing.

8.5.1. **LIMITED ABRASION RESISTANCE**

The abrasion resistance of concrete is defined as the ability of a surface to resist being worn away by rubbing and friction [21]. On concrete floors, the causes of abrasion are foot traffic, light or heavy trucks, and scraping or sliding of objects. The factors that affect the abrasion resistance are the compressive strength of the concrete, properties of the aggregates, finishing techniques, and the curing of the surface. However, here, only the effects of the finishing techniques will be discussed.
The abrasion resistance of a surface can be improved by proper finishing procedures and timing of floating and trowelling. It is crucial that, after darbying or bullfloating no operations occur until the moisture and bleeding water completely disappear from the surface. If excess water on the surface is remixed with the concrete at the top, the water/cement ratio at this part will eventually increase. This will reduce the compressive strength of concrete which in turn will reduce the abrasion resistance of the surface. Research [166] has shown that, float finished surfaces have less wearing resistance than trowel finished surfaces. (See fig. 8.2.)
Additional trowelling increases the hardness of the surface, and reduces the wearing of the concrete. When the hardness of the surface is measured by a Schmidt hammer, it has been shown that additional trowellings increase the mean rebound index of hammer as shown below [173].

<table>
<thead>
<tr>
<th>Number of trowellings</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>1 delayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean rebound index</td>
<td>33</td>
<td>37</td>
<td>43</td>
<td>39</td>
</tr>
</tbody>
</table>

This research also proves that a delayed single trowelling may be better than two trowellings. Applying a dry shake coat of cement and hard fine aggregate, or of cement and iron aggregate will also make the surface layer more abrasion resistant.

8.5.2. SCALING

Scaling is normally the result of freezing and thawing. In scaling, the finished surface flakes or peels off up to a depth of about 5 mm (3/16 in) [174]. This can be avoided by introducing air entraining admixtures. Another cause of scaling, is faulty workmanship [175]. Any of the finishing operation, screeding, darbying, bullfloating, floating, or trowelling, performed while there is excess water or bleeding will cause scaling. Mixing this excess water into the surface will cause the segregation of surface fine particles (sand or cement) and promote scaling.
8.5.3. **DUSTING**

Chalking or powdering at the surface of concrete floor is called dusting. Such surfaces powder under any kind of traffic and can easily be scratched with a nail or even by sweeping.

The faulty finishing operations that cause dusting are:

i) premature floating or trowelling. (explained in section 8.5.2.)

ii) floating and/or trowelling of condensation moisture from warm humid air on cold concrete. In cold weather concrete sets slowly. If the humidity is relatively high, water will condense on the freshly placed concrete [175]. If this water is floated or trowelled into the surface, dusting will be promoted. This can be avoided by decreasing the difference between the ambient temperature and concrete temperature. If this is not possible, as an emergency, a dry mixture of one part of portland cement and one part of well-graded concrete sand should be well mixed, and evenly distributed over the condensed surface. Floating and trowelling should immediately follow this dry-shake. A second trowelling should not be done, since additional condensation may take place after the first trowelling. Neat cement or a mixture of sand and cement to absorb the bleeding water should not be used.

8.5.4. **CRAZING**

Crazing is the development of a network of fine hair cracks in the surface of newly hardened concrete due to shrinkage. Generally, craze cracks occur in the early age of the surface. However, they appear the day after placement, or by the end of the first week [175]. They may not be readily visible until the surface has been wetted, and it begins to dry. The faulty finishing operation that causes crazing is premature floating or trowelling [174]. This operation will bring an excess of fines and moisture to the surface. A rapid loss of this moisture will cause shrinkage at the surface and may result in
crazing. To avoid this, floating and trowelling should not be started until the concrete has started to set initial. To avoid excess moisture on the surface, slump may be reduced and air entrainment can be used. Crazing may also be caused by excessive floating which has a tendency to draw water and fines to the surfaces resulting in a weak concrete subject to high shrinkage stresses [176]. Applying dry cement, or a mixture of dry cement and sand to the surface to absorb the bleeding water should be prohibited. Trowelling of dry cement into the surface may also cause crazing cracks [177].

8.6. "FINISHING OF UNFORMED CONCRETE SURFACES"
MODULE OF ESCON

The major imperfections in finishing of unformed concrete surfaces are given in section 8.5. These imperfections can be alleviated by a proper workmanship in the finishing procedures. A specification which provides the necessary information on the finishing procedures also helps to reduce the imperfections.

Fig. 8.3 shows the flow diagram for the Finishing of Unformed concrete Surfaces module of ESCON. ESCON divides the floor types into eight as:

a) residential or tile covered floors with light foot traffic
b) floors for offices, churches, schools, hospitals with foot traffic.
c) ornamental residential floors with foot traffic (exposed aggregate, colored, nonslippery, and geometric patterned surfaces)
d) driveways, garage floors, and sidewalks for residence with light foot traffic or pneumatic wheel traffic
e) light duty industrial or commercial floors with foot and pneumatic wheel traffic
f) single course industrial integral topping floors with abrasive wear wheeled traffic
g) bonded two course heavy duty industrial floors with steel tire
vehicles traffic that causes severe abrasion

h) unbonded two course floors for floor types of d, e, f, g above.

The system gives the entire procedures of finishing for each type of the floors given above. ESCON recommends that, the finishing procedures for type (a), type (b), type (c), type (d), type (e), type (f), type (g), type (h) should follow the methods as explained in section 8.4.1., 8.4.2.(a), 8.4.2.(b), 8.4.1., 8.4.3., 8.4.4., 8.4.5., and 8.4.6. respectively.

Finally, the system recommends that, a new floor should be protected for about 2 days from foot traffic, and 7 days from wheel traffic [171]. It is a good practice to cover the slab or floor with a plastic sheet for curing for as long as possible. If the early use of a new floor is essential, ESCON recommends that, concentrated traffic routes are covered by hardboard sheets.
Fig. 8.3 - Flow diagram for the "Finishing of Uniformed Concrete Surfaces" module of ESCON.
CHAPTER NINE: CURING OF CONCRETE

9.1 Introduction
9.2 Objectives of Curing
9.3 Normal Curing
9.4 Achievements of Curing
9.5 "Concrete Curing" Module of ESCON
9.6 Conclusions for Concreting Operations and ESCON
9.1. INTRODUCTION

When cement is mixed with water, a chemical reaction, called hydration, takes place. This reaction causes the concrete to harden and develop strength. This strength development is maximized if the concrete is maintained in an environment of moist and favorable temperature especially during the first few days. This is called curing.

Properly cured concrete has a better quality. A well cured concrete is more durable to chemical attacks, wearing effects, and weathering actions. When the appearance of the concrete is important, curing should be provided to prevent discolouration.

The first part of this chapter examines the moisture and temperature effects on the concrete, the precautions to be considered in hot and cold weather, and the achievements and methods of curing. In the second part of the chapter, the "Concrete Curing" module of ESCON is described in detail.

9.2. OBJECTIVES OF CURING

When portland cement is mixed with water, a chemical reaction called hydration starts. The strength, durability and the density of concrete are determined depending on the extent to which this reaction is completed. Most of the fresh concrete contains more than enough water to complete the hydration of cement in the mixture. However, a considerable amount of water leaves the concrete by evaporation. The rate of evaporation is affected by the temperature of the air, relative humidity, the temperature of concrete, and the velocity of the wind. Fig. 9.1 shows a chart to determine the expected rate of evaporation of water from the surface of concrete. Any loss of water by evaporation will prevent or delay the completion of hydration. Hydration is relatively rapid in the first few
Fig. 9.1 - Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of surface moisture loss from concrete.
(Based on : ACI 305.R-77)
days of placement, and therefore, it is important to retain water inside the concrete for this duration. After this duration the rate of hydration, and in turn, the rate of strength gain decreases. In many instances, this duration is expressed in terms of the percentage of the strength to be gained.

The rate of hydration is usually very slow in low temperatures. At or below the freezing temperature, there is little or no strength development due to the slow rate of hydration.

Therefore the two objectives of curing are:

1) to prevent or replenish the loss of moisture from the concrete,
2) to control the temperature of concrete for a definite duration.

9.3. NORMAL CURING

Concrete can be cured either by using an accelerated method, which is accomplished by steam, electricity, etc., or by using normal curing methods. Accelerated curing is normally preferred in concrete product plant to increase the rate of production. On construction sites, normal curing methods are less complex and therefore, accelerated curing methods are left outside the scope of this research.

In normal curing, attention should be paid to the following:

1) maintaining a satisfactory moisture content
2) maintaining a favorable temperature
3) the duration of curing
4) the curing methods and procedures.
9.3.1. SATISFACTORY MOISTURE CONTENT

The chemical reaction between portland cement and water starts when the two substances are combined. However, the point at which it ceases depends on the curing procedure adopted. Powers [178] discovered that, the hydration proceeds at an appreciable rate when the vapor pressure (relative humidity) in the capillaries in the concrete is more than 80 percent. This means if the vapor pressure of concrete drops below 80 percent at an early age, then, the useful hydration will stop. Eventually, the strength, durability, and permeability of concrete will be impaired [179]. The vapor pressure in the capillaries is reduced either by evaporation or by loss internally. Water is lost internally by "self-desiccation" [180]. When water reacts with cement, little water remains to saturate the surfaces of solids. This results in a decrease in the relative humidity. Self-desiccation is thus important in sealed concrete when the water/cement ratio is less than about 0.5 [24]. In this case, the internal relative humidity in the capillaries decreases below the minimum value (80 %) necessary for curing. Therefore, one of the objectives of curing is to keep the concrete saturated, or nearly saturated until the originally water-filled space in the fresh cement paste has been occupied up to the desired level by the hydrated cement. However, in practice, the active curing nearly always stops long before the maximum possible hydration has taken place.

9.3.2. FAVOURABLE TEMPERATURE

The rate of cement hydration varies with the temperature of the concrete. The hydration proceeds slowly at cooler temperatures down to 14 F (-10 C), and more rapidly at warmer temperatures up to somewhat below 212 F (100 C). But concrete temperatures below 50 F (10 C) are unfavorable for the development of early strength.
Below 40 F (5 C) the development of early strength is greatly retarded, and at 32 F (0 C) little strength develops [181].

Normally, the temperature of curing concrete should not exceed about 160 F (71 C) [180]. Higher temperatures may cause rapid evaporation of the mixing water. Curing at temperatures above 325 F (163 C) with hot steam (autoclaving) greatly accelerates the hydration, and may produce strength in a few hours equal to those obtained in 28 days of curing at 70 F (21 C). But autoclaving is a special case, and is not usually applied on construction sites. Although the main criterion is to maintain the concrete temperature in the range of 40 to 160 F (5 to 71 C), the optimum curing temperature is usually considered to be about 90 F (32 C) [182]. The Transportation Research Board [183] states that for pavements, in winter and in hot conditions the temperature of concrete will be in the range of 55 to 70 F (13 to 21 C) and 60 to 90 F (16 to 32 C) respectively.

The curing problems associated with temperature can be classified as:

1) hot weather problems
2) cold weather problems
3) large mass concrete problems.

9.3.2.1. **HOT WEATHER PROBLEMS**

Hot weather is defined by ACI committee 305 [113] as "any combination of high air temperature, low humidity, and wind velocity tending to impair the quality of fresh or hardened concrete or otherwise resulting in abnormal properties". When the rate of evaporation (calculated from fig. 9.1) approaches or exceeds about 1 kg/sq m/ hr, hot weather conditions are assumed. In hot weather, the strength of concrete improves very quickly initially. But, the strength at 28 days is lower than if it had been cured at lower temperatures [135,181,182,184]. The reason for this is that, with a
high initial temperature, there is often not sufficient time available for the hydration products to diffuse away from the cement grains to form a uniform precipitation. As a result, a concentration of hydration products is built up in the vicinity of the cement grains. This process further retards hydration and thus the development of long-term strength [24]. Therefore it is important to reduce the temperature of fresh concrete in hot weather. ACI Committee 305 [113] recommends that, the best assurance of good results when concreting in hot weather is to limit the temperature of the concrete to something preferably between 75 F (24 C) and 100 F (38 C). The temperature of freshly mixed concrete can easily be calculated from that of its ingredients by using the given formulas [24]:

a) Concrete temperature in C or F without using ice as some part of the mixing water:

\[
\frac{0.22 (Ta*Wa + Tc*Wc) + Tw*Ww + Ta*Wwa}{0.22 (Wa + Wc) + Ww + Wwa} \quad \text{(Eq. (1))}
\]

Where,

- \(Wa\): mass of dry aggregate (kg/m\(^3\) or lb/yd\(^3\))
- \(Wc\): mass of cement (kg/m\(^3\) or lb/yd\(^3\))
- \(Ww\): mass of added water (kg/m\(^3\) or lb/yd\(^3\))
- \(Wwa\): mass of water absorbed by the aggregate (kg/m\(^3\) or lb/yd\(^3\))
- \(Ta\): temperature of dry aggregate (C or F)
- \(Tc\): temperature of cement (C or F)
- \(Tw\): temperature of added water (C or F)
b) Concrete temperature in C or F when ice is used as some part of the mixing water:

\[
\text{Concrete temperature} = \frac{0.22 (Ta*Wa + Tc*Wc) + Tw*Ww + Ta*Wwa - L*Wi}{0.22 (Wa + Wc) + Ww + Wwa + Wi} \quad \text{(Eq. 9.2)}
\]

Where, the terms are as in Eq. 9.1 except that mass of added water \((Ww)\) is the mass of fluid water at \(T_w\)
- \(Wi\): mass of ice
- \(L\): is the ratio of latent heat of fusion of ice to the specific heat of water, and is equivalent to 80 C (144 F).

To avoid the adverse effects of hot weather on the quality of concrete, it is necessary to observe the following points [113, 138]:

i) place concrete at the lowest practiceable temperature. The temperature of concrete produced can be reduced by cooling the aggregates, water and the cement. The cooling of aggregate, water, and cement has an influence on the temperature of fresh concrete by 60 %, 30 %, and 10 % respectively [185]

ii) if the concrete is a slab on the grade, dampen the subgrade before placing

iii) dampen the form before placing

iv) erect wind breaks and sun shades

v) reduce the time between the placing and the start of curing

vi) minimize the evaporation particularly in the first few hours after placing by using fog spraying

vii) a water curing method which is applied continuously throughout the duration of curing specified should be used. However, water for curing which is much colder than the concrete should not be used

viii) if curing compounds are used, prompt application of white pigmented curing compounds should be considered.
The problems of cold weather concreting are the slow development of the strength of concrete, and the damage of frost action on the fresh concrete [186]. The importance of the first problem is evident when removing the formwork. In this respect, the recommended minimum times to remove the formwork are given in Table 9.1.

### Table 9.1 - Recommended minimum times to remove the formwork to normal structural concrete when they will be carrying its own weight only [187].

<table>
<thead>
<tr>
<th>Cement type</th>
<th>Weather conditions</th>
<th>Beam sides of walls, columns (days)</th>
<th>Slabs: props left under (days)</th>
<th>Beam soffits props left under (days)</th>
<th>Removal of props to slabs (days)</th>
<th>Removal of props to beams (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary portland cement concrete</td>
<td>Cold weather (air temp about 3°C)</td>
<td>3</td>
<td>7</td>
<td>14</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Normal weather (air temp about 16°C)</td>
<td>0.5</td>
<td>4</td>
<td>8</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>Rapid hardening portland cement</td>
<td>Cold weather (air temp about 3°C)</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Normal weather (air temp about 16°C)</td>
<td>0.5</td>
<td>3</td>
<td>6</td>
<td>8</td>
<td>11</td>
</tr>
</tbody>
</table>
However, the main problem of cold weather is the latter, i.e. the freezing of fresh concrete. Concrete can be damaged when the temperature of concrete drops below 32 F (0 C), and the concrete is still at an early stage of curing, and contains a large quantity of free water in the capillaries. Such a temperatures damage concrete so that, its compressive strength can be reduced by about half, and durability by more than half [182]. In cold weather the recommended minimum concrete temperatures are given in Table 9.2. Meanwhile, Table 9.3 and Table 9.4 give the recommended times to protect concrete against cold weather.

The severity of the weather determines the precautions to be taken. As far as curing protection is concerned, cold weather can be divided into three categories:
   a) when the temperature of air falls below 40 F (5 C), but does not fall below freezing point
   b) slight frost only at nights
   c) severe frost.

a) **Air Temperature is 32-40 F (0-5 C)**
The recommended general precautions are:
   i) keep the formwork in position for durations as shown in Table 9.1, or use rapid hardening cement or both.
   ii) make sure the concrete is delivered to the point of placing at a temperature defined in Table 9.2.
Table 9.2 - Recommended concrete temperatures for cold weather concreting [24].

<table>
<thead>
<tr>
<th>Air temperature</th>
<th>Minimum dimension of section</th>
<th>Minimum concrete temperature as placed and maintained</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Below 300 mm (12-36 in)</td>
<td>300-900 mm (36-72 in)</td>
</tr>
<tr>
<td>Below 5 C (40 F)</td>
<td>13 C (55 F)</td>
<td>10 C (50 F)</td>
</tr>
<tr>
<td>Above -1 C (30 F)</td>
<td>16 C (60 F)</td>
<td>13 C (55 F)</td>
</tr>
<tr>
<td>-18 to -1 C (0 to 30 F)</td>
<td>18 C (65 F)</td>
<td>16 C (60 F)</td>
</tr>
<tr>
<td>Below -18 C (0 F)</td>
<td>21 C (70 F)</td>
<td>18 C (65 F)</td>
</tr>
<tr>
<td>Maximum concrete temperature drop permitted in first 24 hour after end of protection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 C (50 F)</td>
<td>22 C (40 F)</td>
<td>17 C (30 F)</td>
</tr>
</tbody>
</table>
Table 9.3 - Recommended protection times for cold weather concreting (using air-entrained concrete) [24].

<table>
<thead>
<tr>
<th>Cement type, admixture, cement content</th>
<th>Protection time (days) for preventing frost damage for service category</th>
<th>Protection time (days) for safe level of strength for service category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1  2  3  4</td>
<td>1  2  3  4</td>
</tr>
<tr>
<td>Ordinary Portland (Type I) cement</td>
<td>2  3  3  3</td>
<td>2  3  6</td>
</tr>
<tr>
<td>Modified Type (II) cement</td>
<td></td>
<td>see table 9.4</td>
</tr>
<tr>
<td>Rapid-hardening portland (Type III) cement, or accelerator, or 20% extra cement</td>
<td>1  2  2  2</td>
<td>1  2  4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>see table 9.4</td>
</tr>
</tbody>
</table>

Service categories: 1: no load, no exposure
2: no load, exposure
3: partial load, exposure
4: full load, exposure.
Table 9.4 - Recommended protection times for fully loaded concrete exposed to cold weather [24].

<table>
<thead>
<tr>
<th>Type of cement</th>
<th>Duration of protection (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percentage of 28 days strength</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Ordinary portland (Type I) cement</td>
<td>For concrete temperature of 10°C (50°F)</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Modified (Type II) cement</td>
<td>9</td>
</tr>
<tr>
<td>Rapid hardening portland (Type III) cement</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>For concrete temperature of 21°C (70°F)</td>
</tr>
<tr>
<td>Ordinary portland (Type I) cement</td>
<td>4</td>
</tr>
<tr>
<td>Modified (Type II) cement</td>
<td>6</td>
</tr>
<tr>
<td>Rapid hardening portland (Type III) cement</td>
<td>3</td>
</tr>
</tbody>
</table>

b) **Slight Frost only at Nights**

In this case, the following precautions should be taken in addition to the precautions explained in (a):

i) make sure the aggregate is not frozen

ii) cover the top of the concrete with insulating materials

iii) make sure the concrete is not placed against frozen subgrade, or a reinforcement or form covered with snow

iv) place concrete quickly

v) insulate steel formwork.
c) **When There is Severe Frost Day and Night**

In this case, take the precautions below in addition to all of the above precautions:

1. insulate all the formwork
2. heat the water and if necessary the aggregate
3. if concrete is delivered to the point of placing at a temperature as low as 50°F (10°C), then place quickly, and provide continuous heating either to the concrete or to the building if it is indoor [187].

When the mixing water is heated, the expected temperature of concrete, \( T \), can be calculated by using the following formula [24]:

\[
T = \frac{0.22(T_a W_a + T_c W_c) + T_w W_w + W_{wa}(0.5T_a - L)}{0.22(W_a + W_c) + W_w + W_{wa}}
\]  

(Eq. 9.3)

Where, the terms are as in Eq. 9.2.

Heating the water to more than 180°F (80°C) is inadvisable since it may cause a flash set of the cement. If more heat is required, aggregate may be heated indirectly by the use of steam.

### 9.3.2.3. **LARGE MASS CONCRETE PROBLEMS**

Mass concreting most frequently occurs in piers, abutments, dams, heavy footings, and similar massive constructions where large volumes of concrete are required. In these situations, the heat generated by the hydration of the cement, and the expected volume changes should be considered. The excessive heat generated and the volume changes promote the formation of thermal cracks. The reason for thermal cracking is, the restrain to contraction on cooling from a temperature generated by hydration. A high difference between the ambient temperature and concrete temperature should be avoided. ACI Committee 308 [181] states that, during the
hydration, the internal temperature should not rise more than 20-25 F (11 to 14 C) above the mean annual ambient temperature. To achieve this, the recommended steps are:

1) If possible revise the mix proportion, and aggregate size
   i) use the maximum practicable aggregate size to reduce
      the cement content
   ii) use entrained air (6-7 % of entrained air may help to
      reduce the temperature of concrete by 30 %) [188]
   iii) use the lowest practicable workability to reduce the
      water content and in turn to reduce the cement content

2) revise the cement selection
   i) use low heat portland cement
   ii) use pozzolan to replace the cement by as much as 35 %
       [188]

3) precool the concrete by cooling its ingredients

4) Postcool the concrete
   i) by circulating the cold water through pipes embedded
      into the concrete at spaces of about 1.5 to 2 m. (Take
      necessary precautions to avoid blocking the pipes.
      Otherwise, there is no way to control overheating.)
   ii) in postcooling keep the thickness of the lifts to 5 ft
       (1.5 m) [188].

9.3.3. DURATION OF CURING

When the daily mean ambient temperature is above 40 F (5 C), and normal portland cement (Type I) is used, curing should be continuous for a minimum 7 days, or for the necessary duration to attain 70 percent of the specified compressive or flexural strength, whichever is shorter. If rapid hardening cement (Type III) is used, the curing duration may be as short as 3 days. For unreinforced massive sections, the minimum continuous curing duration should be 14 days, providing pozzolan is not used. When pozzolan is used as some part of the cementitious materials, the minimum continuous
curing time should 21 days. For heavily reinforced massive sections curing should be continuous for a minimum of 7 days [181].

9.3.4. METHODS OF CURING

In every curing method the objective is similar, i.e. to maintain a satisfactory moisture level and a favourable temperature for the concrete to maintain the process of hydration. In this respect, Çelik, Thorpe, and McCaffer [189] collected all the curing methods under two topics:

1) continuous supply of water (water curing)
2) evaporation prevention methods.

Selecting an appropriate curing method and material largely depends on economical and managerial considerations, and availability. No matter which method is selected, it should be applied to the formed surfaces within a maximum of 0.5 hr after removing the formwork.

9.3.4.1. CONTINUOUS SUPPLY OF WATER

This method is theoretically the best method available. But the crucial point is that, the surface of the concrete must be kept continuously damp for the required curing period. Otherwise it may be harmful to the concrete [190,191]. Intermittent wetting in the first 2 or 3 days of placing is likely to result in surface cracks, and reduces durability. However, if in the first 2 or 3 days the curing is satisfactory, then afterward intermittent wetting will not stop the strength gaining. However in this case, the strength gain will not be as rapid as in continuous curing. Where the appearance of the concrete is important, the water must be free of harmful substances that may stain or discolor the concrete.
Curing water cooler than the concrete temperature by about 20 F (11 C) [182] should not be used.
The methods of water curing are:
   a) ponding
   b) fog spraying or sprinkling
   c) burlap, cotton mats, or rugs
   d) earth, sand, sawdust, straw, or hay

a) Ponding
Ponding is applicable for horizontal slabs, floors, or pavements. A small dike is set up around the perimeter of newly placed concrete area, and the water is pumped into the pond. This method is very efficient, and is recommended for cases where the formation of shrinkage cracks is expected. However this method is rather messy. Ponding should be started as soon as the concrete will not be damaged from flooding.

b) Fog Spraying or Sprinkling
In this method water is forced out through a nozzle. This method is applicable to horizontal or vertical surfaces. It is very efficient, but it is costly. In this method, care should be taken to avoid erosion especially on vertical surfaces. On hot or windy days, spraying or sprinkling should be started 3-2 hr after finishing the concrete. In this method, continuity is paramount, so that, the surface of the concrete never dries out. When the temperature is more than 15 C (59 F), it is recommended to sprinkle water at every 3 hr during the day times, and once or more during the night especially during the first 3 days. The sprinkling should be a minimum of 3 times in 24 hr [192].

c) Burlap, Cotton Mats, or Rugs
In this method the entire surface of concrete (vertical or horizontal) is covered by burlap, or cotton mats, or rugs, and then wetted by spraying water. It must be kept wet throughout the curing period. Double thicknesses may be an advantages to extend the elapsed time
between the sprayings. At the edges of the strips, overlapping should be provided and protected against the wind. With these materials, a true contact between the concrete surface and the curing material should be provided.

d) Earth, Sand, Sawdust, Straw, or Hay

This method is used for horizontal surfaces where the appearance of concrete is not important. Normally, this method causes discoloration and stains on the surface of concrete. If earth is used, it should be free of particles larger than 25 mm (1 in). The thickness of the earth, or sand, or sawdust should be about 50 mm (2 in). The thickness of straw or hay will be about 150 mm (6 in) [100]. Sawdust, straw, or hay should be protected against the wind. These materials are wetted by spraying water at intervals of approximately 1.5 times of the duration that these materials retain the moisture [192].

9.3.4.2. PREVENTING EVAPORATION OF WATER

In this method, sealing materials are used to seal the moisture in the concrete. It is not as efficient as the first method, but it is still sufficient for all normal concreting works [191]. These methods are less costly and easier to handle on the site. This method comprises the use of the following materials:

a) plastic sheet
b) bituminous paper
c) liquid membrane curing compounds
d) leaving the formwork in place

When the water/cement ratio is less than about 0.5 by weight, self-desiccation in the concrete becomes an important point to consider. See section 9.3.1. The vapor pressure in the capillary pores may drop under the required minimum value of 80 percent when the water/cement ratio is less than 0.5 [23,180]. Therefore, if the water/cement ratio is less than 0.5, the use of curing compounds is
not advisable. In the use of other sealing materials (plastic sheet, paper etc), self-desiccation can be avoided by flooding the concrete surface under these sealing materials.

a) plastic Sheets
Plastic sheets are an effective moisture barrier when the surface is covered carefully. ASTM C 171 [193] specifies the minimum thickness of the sheet as 0.1 mm to be used for concrete curing purposes. Plastic sheets are available in black, clear or white colors. Normally, black sheet is preferred in winter time, and white in hot weather. Clear sheet is not recommended in the summer time since it is not a good shading material. Care is required to provide several inches of overlap at the edges of the strips. All the edges of a strip should be protected against the wind. When the appearance of the concrete is important, the use of plastic sheets is not recommended. Moisture condensing on the underside of the smooth plastic creates an uneven distribution of the water in the concrete, and results in a mottled appearance. Wrinkling of the sheet should also be avoided to prevent discoloration. Plastic sheets should be placed as soon as possible without marring the surface. On very hot days, the surface of the concrete under the plastic sheet should be flooded occasionally. This also helps to reduce the adverse effect of the plastic sheet on the appearance of the concrete.

b) Bituminous Paper
Bituminous paper is composed of two sheets of paper cemented together with a bituminous adhesive and reinforced with fiber. They provide a moisture barrier and do not require a periodical addition of water. They also offer some protection against the frost. The edges of the paper should overlap for several inches and be secured against to the wind.
c) **Liquid Membrane Curing Compounds**

Liquid membrane curing compounds comprise three general categories [185]: those having a synthetic resin (plastic) base; those with a wax base; and those with a combination of wax-and-resin base. Resin based compounds are more expensive, but they do not leave any residue on the surface of concrete after about 28 days, or if there is any residue, it can be removed easily. Wax based compounds are difficult to remove, and since they are gummy, they tend to hold dirt and other job litter.

Curing compounds can be clear, white, gray, or even black. **Clear compounds** are recommended for architectural surfaces. Since the residue can be removed easily, any type of painting is applicable. A clear compound does not provide good shading against the sun, therefore, the temperature of the concrete rises in hot weather. The Transportation Research Board [183] states that clear compounds should not be used when the ambient temperature exceeds 80 F (27 C).

**White or gray compounds** are recommended in hot weather since they reflect most of the heating rays and help to reduce the temperature of the concrete. White pigmented compounds act as a shading material and may cause the temperature of concrete to reduce by up to 40 F [28].

**Black compounds** absorb the heat and increase the temperature of the concrete, so they should be avoided in hot weather. They can be used in places where the surface of concrete will be covered by tiles or linoleum.

Compounds should be applied as soon as the bleeding stops and the water sheen on the surface of concrete disappears. If the surface has lost water and become dry before the application of the curing compound, the compound will be absorbed by the concrete and will not form a surface film. In this case, the concrete surface should be
wetted and the compound applied. However, if the application is too early, the standing water will prevent the formation of a continuous film free of pinholes or voids. When the evaporation rate exceeds 1 kg/sq m/hr, it may be difficult to estimate whether the bleeding has stopped or not. If the rate of bleeding is lower than the rate of evaporation from the surface of the concrete, the concrete may be dry, but the bleeding may still be continuing. In this case, one of the following may occur:

i) evaporation may be stopped effectively, but continuing bleeding results in a layer of water forming below the compound film which promotes scaling.

ii) evaporation may be stopped temporarily, but continuing bleeding may results in map cracking of the membrane.

Therefore, to avoid these faults, the evaporation should be minimized by shading or by use of other methods.

On formed surfaces, the compound should be applied either immediately, or within 0.5 hr of removing the form [191]. Curing compounds can be applied either by hand or by power sprayer at about 75 to 100 psi (0.5 to 0.7 MPa) pressure [181]. In very small jobs, the compound can also be applied with a wide soft brush or paint roller. The usual coverage range of one coat is about 150 to 200 ft²/gal. (0.2 to 0.25 litre/m²) ([28,181,185,191]. However, research [194] has shown that, the moisture of the concrete sealed with a coverage rate of 200 ft²/gal. differs little than of the concrete sealed with a coverage rate of 50 ft²/gal. So the thickness of the compound film applied on the surface has little effect on the moisture content of the concrete. If a clear compound is used, it is recommended that, two coats are applied. Each coat should have a rate of coverage equal to the half of the standard rate of the coverage, and the second coat should be applied perpendicular to the first coat.
d) **Leaving the Formwork in Place**

Impervious forms provide satisfactory protection against loss of moisture. The forms should be left on the concrete as long as practical. However, if they are to be removed before the end of the specified duration of curing, another curing method should be started without delay. Wood forms left in place should be kept moist by sprinkling, especially during hot, and dry weather. If this has not been done, they should be removed as soon as practical and another curing method should be applied immediately.

### 9.4. **ACHIEVEMENTS OF CURING**

Proper curing affects the following characteristics of the concrete:

- **a)** strength
- **b)** abrasion resistance
- **c)** appearance
- **d)** shrinkage
- **e)** thermal cracks
- **f)** impermeability

#### a) **Strength**

It is stated in reference 185 that, the compressive strength of properly cured concrete is increased by about 80 to 100 percent over that which has not been cured at all. Birt [38] reports that, laboratory specimen exposed to dry air from the time it is made, is only about 42 percent as strong as the specimen continuously moist cured at six months age. Results of the experiments undertaken at CITB (see chapter 10) shows that, the 28th day strength of moist cured concrete is about 33 percent more than the 28th day strength of concrete left to indoor air dry.
b) **Abrasion Resistance**

Abrasion resistance of concrete is defined in chapter 8. ACI Committee 201 [21] states that, curing is one of the important factors for improving the abrasion resistance of concrete. A surface cured for 7 days is nearly twice as wear resistant as one cured for only 3 days, and additional curing results in further improvement.

c) **Appearance**

Proper curing reduces the evaporation of water from the concrete surface. Thus the amount of calcium hydroxide liberated at the end of the evaporation is limited. This reduces the efflorescence and improves the appearance of the concrete.

d) **Shrinkage**

Proper curing controls the evaporation of excess water from concrete. This reduces the drying shrinkage. If the excess water in concrete is allowed to evaporate too quickly, then excessive shrinkage and resultant cracking is inevitable [185].

e) **Thermal Cracks**

Thermal cracks mostly occur in massive concrete works as explained in section 9.3.2.3.

f) **Impermeability**

The greater the hydration of the cement the more gel is produced in the capillary pores. This gel blocks and disconnects the capillary pores and therefore, improves the watertightness of the concrete. Table 9.5 gives the appropriate curing periods of hydration required to segment the capillary pores.

Impermeability of concrete improves its resistance to freezing and thawing, and chemical attacks.
Table 9.5 - Approximate duration of curing to produce enough hydration at which capillaries become segmented [24].

<table>
<thead>
<tr>
<th>Water/cement</th>
<th>Degree of hydration (%)</th>
<th>Required duration of curing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>50</td>
<td>3 days</td>
</tr>
<tr>
<td>0.45</td>
<td>60</td>
<td>7 days</td>
</tr>
<tr>
<td>0.50</td>
<td>70</td>
<td>14 days</td>
</tr>
<tr>
<td>0.60</td>
<td>92</td>
<td>6 months</td>
</tr>
<tr>
<td>0.70</td>
<td>100</td>
<td>1 year</td>
</tr>
<tr>
<td>over 0.70</td>
<td>100</td>
<td>impossible</td>
</tr>
</tbody>
</table>

9.5. "CONCRETE CURING" MODULE OF ESCON

An adequate curing is achieveable by a competent supervision, and experienced workmen. The supervisory staff should be aware of all the curing methods and how to apply them properly. A well prepared specification which includes sufficient information on curing methods and procedures can improve the quality of the supervision on the site.

The "Concrete Curing" module of ESCON is therefore aimed to transfer knowledge to the novice users on the methods and procedures of curing. This part of ESCON can also produce a detailed specification including the necessary information on the workmanship requirements about the curing of concrete.

Since proper curing depends upon the weather, the system first tries to fix the prevailing weather conditions Fig. 9.2 shows the flow diagram for defining the weather conditions. The system recognises three types of weather condition, hot weather, normal weather, and cold weather. If the user is capable of defining the weather condition
Fig. 9.2 - Flow diagram to define the weather conditions
on the concreting day, then the system directly starts to give recommendations about that weather condition. However, if the user is unable to define the weather, then, the system tries to determine it by asking the user a series of questions. The system determines the weather condition in two ways:

a) by calculating the rate of evaporation of water from the surface of the concrete
b) by finding the temperature of the concrete.

a) Calculating the Rate of Evaporation
ESCON states that, the determination of weather condition by calculating the rate of evaporation of water from the surface of concrete is the most reliable method. The calculation of the rate of evaporation is based on the chart given in fig. 9.1. Each curve on the chart was formulised by using curve fitting theory [195]. The formulas of the curves were obtained by using Curve and Surface Fitting, FORTRAN Library Manual [196]. These formulas are given in Appendix B. The system asks for the ambient temperature, ambient relative humidity, concrete temperature, and the wind velocity. Knowing these parameters, the system calculate the expected rate of evaporation of water from the surface of concrete. When the rate of evaporation is equal to or greater than 1 kg/sq m/hr (0.2 lb/sq ft/hr), then the system defines the weather as hot [113,181]. However, if the rate of evaporation is less than 1 kg/sq m/hr, then, the weather may be normal or cold. When the daily mean temperature falls below 40 F (5 C), then the weather is defined as cold [187].

b) Considering Concrete Temperature
Although the best method to determine hot weather, normal or cold weather is the calculation of the rate of evaporation, when the necessary parameters to calculate it is not known, then, the weather condition may be fixed by considering the temperature of concrete. The system can obtain the temperature of concrete in two ways:
i) **reliable field record**: When a reliable field record exists about the concrete temperature for the similar conditions, then, the system accepts that record.

ii) **Calculation of the temperature of concrete**: In this case, the system asks the temperatures and weights of the ingredients, and by using the Eq. 9.1 calculates the expected concrete temperature.

Considering the temperature of concrete, the system defines the weather condition according to the following criteria:

<table>
<thead>
<tr>
<th>Weather condition</th>
<th>Concrete temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>more than 75 F (24 C) [113]</td>
</tr>
<tr>
<td>Normal</td>
<td>50-75 F (10-24 C)</td>
</tr>
<tr>
<td>Cold</td>
<td>less than 50 F (10 C).</td>
</tr>
</tbody>
</table>

**9.5.1. HOT WEATHER**

Fig. 9.3 shows the diagram of concrete curing during hot or normal weather. Curing of concrete requires special precautions in hot weather. The system defines these precautions as explained in section 9.3.2.1. ESCON also gives the minimum duration of curing for different cement types as explained in section 9.3.3. ESCON divides the concrete surfaces into formed or unformed.
FIG. 9.3 - Flow diagram for Hot Or Normal Weather Curing part of "Concrete Curing" module of ESCON.
i) Formed Surfaces: When curing formed surfaces, ESCON recommends a water curing method when there is an ample supply of water on the site, and good supervision is available. Good supervision is essential to maintain a continuous wetting of the surfaces. The possible water curing methods are wet burlap, cotton mats, rugs, or water spraying. The system defines these methods, and gives advice about how they can be applied, as explained in section 9.3.4.1. However, if the supervision is poor, or there is not an adequate supply of water on the site, but the water/cement ratio is equal to or greater than 0.5, then, an evaporation prevention method is recommended. See fig. 9.4. Evaporation prevention methods include using plastic sheets, bituminous papers, liquid membrane curing compounds, or leaving the formwork in place. These methods are explained in section 9.3.4.2. To select a specific type of curing method, the system investigates the air temperature, the importance of the appearance of the surface, and the application of any surface treatment. See fig. 9.5. The system gives the necessary information to apply each selected curing material as explained in section 9.3.4. If timber is used as the formwork material, the system recommends that, the timber is kept wet.

ii) Unformed Surfaces: Unformed concrete surfaces are divided into horizontal or sloped surfaces.

Horizontal Surfaces: Where the water/cement ratio is equal to or greater than 0.5 and there is ample water for water curing, and there is good supervision to provide continuity of moist curing, then the system recommends water curing. The possible water curing methods are ponding, fogging or spraying, wet burlap or cotton mat or rug, or earth, sand, straw, sawdust, or hays. ESCON explains the applications of these materials as in section 9.3.4.1.

Sloped surfaces: The curing of sloped surfaces is similar to the curing of horizontal surfaces, except to ponding. Obviously ponding can not be applied on sloped surfaces.
A WATER CURING METHOD WHICH REQUIRES LESS WATER (THICK BURLAP, OR PLASTIC SHEETS WHERE CONCRETE SURFACE UNDER THE SHEETS IS FLOODED) SHOULD BE USED.

Fig. 9.4 - Selection of curing method in hot or normal weather
Fig. 9.5 - Selection of curing materials in hot weather when "Evaporation Preventing" method is used.
If there is not an adequate supply of water for continuous water curing, or the supervision is poor, then, the system recommends that, one of the following curing methods can be used: (i) **Wet burlap**: A double thickness or a very thick burlap layer is preferred to increase moisture retention; (ii) **Straw, sand, earth, sawdust, or hay**: These are applicable when the appearance of the surface is not important; (iii) **Plastic sheets**: This is applicable when the appearance of the concrete is not important. However, if the surface of concrete can be flooded under the sheet, then, plastic sheets can also be used for the concretes where their appearance is important. The features of these methods are explained in section 9.3.4.1 and 9.3.4.2.

If there is not an adequate supply of water, the supervision is poor, and the water/cement ratio is more than 0.5, than the system recommends the use of clear resin based liquid compound, bituminous paper, plastic sheet, or wax based white or gray compound. The selection procedures of these methods is shown in fig. 9.5.

### 9.5.2. COLD WEATHER

Fig. 9.6 shows the flow diagram of concrete curing in cold weather. ESCON recommends that, in cold weather the newly finished concrete should be protected for durations as shown in Table 9.2. The system divides cold weather curing conditions into three:

1) air temperature is below 5 C, but no frost
2) slight frost only at night times but not severe
3) severe frost day and night

For each case, the system gives advice as explained in section 9.3.2.2. (a), (b).
Fig. 9.6 - Flow diagram for cold weather curing part of "Concrete Curing" module of ESCON.
9.5.3. **NORMAL WEATHER**

ESCON defines the minimum duration of curing for normal weather conditions as explained in section 9.3.5. The system gives advice about formed or unformed horizontal or sloped surfaces as explained for hot weather conditions in section 9.5.1. The only difference is that, there is no limitation on the use of "clear resin based curing compounds" in normal weather. See fig. 9.7. In hot weather, the use of clear resin based compound is not recommended for the cases where the temperature of air exceeds 80 F (27 C).

Consequently, the system asks if the concrete is a mass concrete construction, such as, piers, abutments, dams, heavy footings, etc. In these cases, the system recommends that, the thermal temperature of concrete should be controlled. When the difference between the ambient temperature and internal temperature exceeds 20-25 F, then, ESCON recommends that, one or more of the precautions explained in section 9.3.2.3 is used.
Fig. 9.7 - Selection of curing materials in normal weather when "Evaporation Preventing" method is used.
Po.0 workmanship of concreting operations including batching, mixing, transporting and placing, compacting, finishing of unformed concrete surfaces, and curing, adversely affect the quality of the finished concrete structure. These mistakes and deficiencies can be minimized and the workmanship can be improved by a knowledgeable and experienced concreting staff. The provision of a well prepared specification including the necessary information on the workmanship requirements of the concreting operations can help to improve the effectiveness and the efficiency of the supervision on the sites. This also helps to reduce the mistakes.

The "Concrete Batching" module of ESCON aims to transfer knowledge on the factors given in chapter 4 to improve the accuracy of the batching. In this module, the batching methods are divided into two: on-site batching and off-site batching. After selecting a batching method, this module gives advice on how to apply the method. The "Concrete Batching" module includes 54 questions, 21 variables, 60 actions, and 4 groups. The size of this module is about 58100 bytes over 1430 lines.

The "Concrete Mixing" module of ESCON gives advice and recommendations on the factors that affect the uniformity of the mixing as defined in chapter 5. This module includes 30 questions, 89 actions, and 2 groups. The size of the module is about 69500 bytes over 1670 lines.

The "Transporting and Placing Concrete" module of ESCON gives advice on the transporting and placing factors that promotes segregation, slump loss, ingredient loss, and formation of cold joints. This module first gives recommendations on 13 different types of transporting and placing equipment. The module then gives information on concrete placing techniques for columns, walls, slabs, and mass concretes. The module includes 55 questions, 2 variables,
156 actions, and 6 groups. The size of the module is about 90000 bytes over 2140 lines.

The "Concrete Compaction" module of ESCON includes information on the compaction imperfections including honeycombing, excessive entrapped air voids, sand streaking, and pour lines. This module selects a concrete compaction method from manual compaction, internal vibration, surface vibration, form vibration, and reinforcement vibration. After selection the method, the module gives information on the appropriate use the equipment in that method. This module includes 34 questions, 2 variables, 107 actions, and 1 group. The size of the module is about 72200 bytes over 1600 lines.

The "Finishing of Unformed Concrete Surfaces" module of ESCON divides the floors or slabs into 7 different groups and produces advice on the procedures of finishing for each type. This module includes 12 questions, 2 variables, and 35 actions. The size of the module is about 70900 bytes over 1350 lines.

The "Concrete Curing" module of ESCON transfers information to the novice users on concrete curing methods and procedures. This module divides the weather conditions into hot, normal, and cold, and gives advice on the applicable curing methods in each conditions. When it is necessary, the module is capable of calculating the expected rate of evaporation from the surface of the concrete, and the expected concrete temperature. This module includes 56 questions, 88 variables, 129 actions, and 9 groups. The size of the module is about 141000 bytes and 3400 lines.

A detailed specification on each concreting operation can also be produced at the end of each run of ESCON.
CHAPTER TEN : EVALUATION OF ESCON

10.1 Introduction to Evaluation
10.2 Difficulties in Evaluating an Expert System
10.3 Characteristics of Expert Systems to be Evaluated
10.4 Expert Systems Evaluation Techniques
10.1. INTRODUCTION TO EVALUATION

Expert systems are normally tested while they are being developed to improve their design and the performance (see section 3.7.(d)). This testing involves evaluating the performance and utility of the prototype program, and is called informal evaluation [197]. During this informal evaluation, the system builder improves the system by including feedback from the domain experts to produce a better version of the system. In testing, rules in the knowledge base are changed, added, or deleted, or the knowledge representation is refined, or the user facilities are improved. So, development of an expert system involves an inherent evaluation loop.

This chapter addresses the formal evaluation of the system. During evaluation the adequacy of the knowledge representation, the correctness of reasonings, the consistency of the embedded knowledge with the experts, and the ease of interaction of the system with the user are checked. At the end of the evaluation, the ability of the system to perform the required task is analysed. If the system performs the task satisfactorily, it is accepted as useful. So, evaluation can be defined as measuring the degree of success of an expert system in performing a required task. However, measuring the degree of success of an expert system objectively presents some difficulties. There may be no formal way to prove whether a decision is correct or the best possible available choice. When a decision relies on subjective judgements, the correctness of the decision may be disputed. The validity of an answer may depend on the ability of the system to persuade the user about the reliability of the argument given to support the answer [48].

Gaschnig, et al. [197] stated that, the existing technology for evaluation of an expert system is primitive, and it is not a science. Whilst no one knows how to evaluate a human expert, the evaluation of an expert system must also include some subjective judgements.
However, criteria, like correctness, efficiency, or ease of use applies in evaluating an expert system, like all other computer programs.

In the first part of this chapter, the difficulties in evaluating the expert systems, and the characteristics of expert systems to be tested are discussed. In the second part of the chapter, ESCON was evaluated by using the following techniques: (1) comparison with an objective standard; (2) sensitivity analysis; (3) expert's experience; (4) novice users; (5) case study.

10.2. DIFFICULTIES IN EVALUATING AN EXPERT SYSTEM

In evaluating an expert system, the major difficulties are as follows:

i) **Identifying who is making the evaluation**: The evaluation of an expert system varies depending on who is making it. Normally, there are three parties involved in evaluating an expert system. The first party is the knowledge engineer. He is interested in identifying the problem areas and weak sections of the knowledge base in order to improve, modify, and extend it. Feedback from the user and expert helps the knowledge engineer in evaluation. The second party is the expert(s). Experts perform a comparison between the knowledge base and their own, looking for consistency and completeness. They also compare the reasoning and conclusion of the system on a specific case with their own. They may also make suggestions to improve the system. The third party is the user. Users also evaluates the system by considering the facilities to assist them in using the system, methods of input and output of the system, and speed of operation.

ii) **Constraints of expert systems**: An expert system is limited to a small portion of the human expert's domain of competence. So, the results of evaluation studies may be unfairly biased, if the performance of a limited expert system is compared with its human counterpart. An expert system can not deal with the full range of
knowledge on all fields of a human expert. Therefore, the selection of the task for evaluation is crucial. This task must be within the range of activities of the expert system. Additionally, a program is written with a computer language that may include restrictions in communication compared to any natural language.

iii) **The quality of expert knowledge:** The quality of knowledge of a human expert used to evaluate a system is important. The knowledge of the human expert is not infallible. So the reliability of knowledge compared by an expert system should be taken into account. The evaluator must be capable of analysing a poor outcome at the end of the evaluation. A poor result may come from the judgement of the expert which is in conflict with the views of the other experts. Or a poor result may be from any inadequacy in the structure of the system that provides incorrect or incomplete knowledge. This is particularly important when the domain contains different school of thoughts. For example, UK concrete practice differs from the USA concrete practice. The knowledge of ESCON was initially acquired from technical literature published mostly in the USA, since they have abundance of publications in concrete technology. Thus some of the British experts weren't familiar with several aspects of the knowledge of ESCON based on the USA concrete practice. For example, the maximum number of revolution of a truck mixer is limited to 300 revolution for both mixing and agitating concrete. British experts do not all recognise such a limitation.

iv) **Time limitation of experts:** Human experts are scarce. Finding an expert to evaluate an expert system may not be an easy task. If the program is complex, a human expert may not have enough time to discuss and evaluate the whole system.

v) **Domain related problems:** The problems inherent in the domain are the following:

- There may not be a straightforward or a standard solution for a given problem. In this case, the evaluation depends on subjective judgements.
- The data may be subjective which creates a lack of standard
measurement. This causes an improper assessment of the problem at hand.

Large and complex domains are not as good as restricted domains for improving the performance of an expert system. For example, if any expert requires days or weeks rather than hours to solve the problem, the domain is large and complex for the knowledge engineer [48]. The evaluation of such a system is difficult.

10.3. CHARACTERISTICS OF EXPERT SYSTEMS TO BE EVALUATED

Gashnig et al [197] suggested the following aspects of an expert system should be included into the evaluation process:

i) The quality of decision and advice: It is a fact that, no expert system will be accepted by the user if the system does not provide reliable decisions or advice.

ii) The correctness of the reasoning: An expert system reaches a decision in a human like way. If the user knows this reasoning, the reliability of the system increases.

iii) The quality of human-computer interaction: The interface (see section 3.7.(vi)) should perform its function.

iv) Efficiency of the system: A system that requires an excessive time to run may fail to be accepted by the user.

v) Its cost-effectiveness: An expert system can find acceptance in market if it reduces the cost of advice provided in the specified task.

The last two aspects, efficiency of the system, and its cost-efficiency are important for expert systems that are intended as commercial market product. As far as ESCON is concerned, it wasn't intended to produce a commercial package. The aim of developing ESCON was to show the feasibility of improving the quality of concreting knowledge with an expert system approach. Therefore, in evaluation of ESCON, only the first three aspects (i),(ii),(iii) above will be considered.
10.4. EXPERT SYSTEMS EVALUATION TECHNIQUES

Unlike many conventional programs, expert systems do not involve solving problems which can be assessed by clear answers like "right" or "wrong". Therefore, evaluation is not straightforward. The evaluation methods described aim to demonstrate that, solutions of the problems are reached in an optimal way. Five evaluation techniques were used which included:

1) comparison with an objective standard
2) sensitivity analysis
3) comparison with the experience of expert(s)
4) novice users
5) case study.

10.4.1. ESCON EVALUATION 1 - COMPARISON WITH AN OBJECTIVE STANDARD

Evaluation of an expert system by using a comparison technique requires the formation of a "gold standard". This standard should contain generally accepted correct answers with which the results of the new system can be compared. The evaluation of ESCON by using this technique relies on the experiments undertaken at CITB (Construction Industry Training Board) Bircham Newton, Norfolk. At CITB two series of experiments were undertaken. The aim of these experiments was to obtain a set of reliable data to compare with the statements of ESCON about the expected loss in the strength of concrete when some of its recommendations are ignored. ESCON contains a file to calculate the expected strength of concrete by multiplying 100 with factors defined for each goal. The factor for an obeyed goal is 1.00, whereas the factor for an ignored goal is less than 1.00. For example, if the curing is performed for a duration of 7 days (as recommended by ESCON), the factor is 1.00. If the curing is performed for a duration of 3 days instead of 7 days, the expected
strength of the concrete will reduce by 17 %. In this case, the factor will be \( \frac{100-17}{100} = 0.83 \). ESCON states the expected strength as the percent of the target design strength of the concrete. In the experiments undertaken at CITB the strength of concrete was calculated by ignoring a number of recommendations of ESCON.

a) **First Series of Experiments**

i) **Materials used:** The following type of materials were used:

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate</td>
<td>The maximum size 20 mm flint aggregate</td>
</tr>
<tr>
<td>Cement</td>
<td>Ordinary portland cement</td>
</tr>
<tr>
<td>Sand</td>
<td>Natural (uncrushed) sand</td>
</tr>
<tr>
<td>Admixture</td>
<td>None</td>
</tr>
<tr>
<td>Water</td>
<td>Normal drinkable water</td>
</tr>
</tbody>
</table>

ii) **Proportions:** The measured free moisture content of coarse aggregate and sand were 1.7 % and 8 % respectively. The necessary adjustment for the weights of aggregates and water was performed. The adjusted weights of materials were as follows:

<table>
<thead>
<tr>
<th>Material</th>
<th>Adjusted Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate</td>
<td>1400 kg/ cu m</td>
</tr>
<tr>
<td>Sand</td>
<td>520 kg/ cu m</td>
</tr>
<tr>
<td>Cement</td>
<td>380 kg/ cu m</td>
</tr>
<tr>
<td>Water</td>
<td>118 kg/ cu m</td>
</tr>
</tbody>
</table>

The water/cement ratio and the slump were aimed to be about 0.5 and 50 mm respectively.

iii) **Batching and mixing:** Coarse aggregate sand and cement were measured in weight. The mixing water was measured volumetrically, through a vertical tank. The mixer was a nontilting drum mixer with a rated capacity of 0.4 cu m. The materials were mixed until the mixer operator was satisfied that a uniform mixing was attained. The duration of mixing was about 2 min.

iv) **Transporting and placing:** Concrete was transported by a hydraulically tipped dumper for a distance of about 200 m. At the
point of placing the slump of concrete was measured as 42 mm. While concrete was being placed into the form of a wall structure, (DELTA project), see Fig. 10.1, a sample was obtained to prepare 8 concrete cubes of 150X150X150 mm.

v) Compaction and curing: Concrete in the wall (DELTA project) was compacted by internal vibrators with a head diameter of about 1.5 in. The form was stripped off the next day and no curing was applied after that. The structure was indoors and away from drying wind or other adverse weather conditions.

vi) Preparing the cubes: A total of 4 pairs of cubes (8 cubes) were prepared. Each pair was called as a set, and the result of each set was obtained from the average of the two cube results. All of the cubes were tested on the 28-th days of casting. The features and the results of each set are given in Table 10.1. Preparing and curing of the cubes were performed according to BS 1881 [198].

vii) Cores: Three weeks after of casting, one core from the top 400mm, and one core from the bottom 300 mm were drilled out from the DELTA wall structure. The cores were capped by using high alumina cement and stored for one week as described in BS 1881.

The cores were tested on the 28-th days of casting. The results of the tests were explained in terms of estimated potential strength. Estimated potential strength is stated in the Concrete Society Technical Report 11 [199] as "an estimate of Potential Strength from a limited number of standard cubes or cores". (Potential Strength is the nominal strength of concrete considered as the average Standard Cube Strength at 28 days for a single batch of concrete molded wholly as standard cubes). The results were as follows:

Top core strength : 29.5 N/sq mm
Bottom core strength : 39.8 N/sq mm.
Fig. 10.1 - DELTA project
Table 10.1 - Features and results of the first series experiments

<table>
<thead>
<tr>
<th>Set no</th>
<th>Compaction</th>
<th>Curing</th>
<th>Compressive strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Normal compaction</td>
<td>28 days standard moist curing</td>
<td>55.6</td>
</tr>
<tr>
<td>2</td>
<td>Normal compaction</td>
<td>7 days wet hessian and plastic sheet wrapping</td>
<td>54.0</td>
</tr>
<tr>
<td>3</td>
<td>Normal compaction</td>
<td>No curing at all</td>
<td>42.1</td>
</tr>
<tr>
<td>4</td>
<td>Under compaction</td>
<td>7 days wet hessian and plastic sheet wrapping</td>
<td>50.1</td>
</tr>
</tbody>
</table>

Normal compaction: Vibration with a 22 mm internal vibrator for 20 sec.
Under compaction: Vibration with a 22 mm internal vibrator for 10 sec.

b) Second Series of Experiments:

i) Materials: The materials used for the first series of experiments were also used for the second series of experiments.

ii) Proportioning: The proportioning was also the same of the first series of experiments as explained in section (a) above. But in the second series of experiments the moisture of aggregate was not adjusted. The proportions for this experiment were as follows:

- Coarse aggregate: 1375 kg/ cu m
- Sand: 485 kg/ cu m
- Cement: 380 kg/ cu m
- Water: 180 kg/ cu m.

iii) Batching and mixing: Batching and mixing were the same as explained in section (a) above. The only difference was that, the mixing time was reduced to 50 sec which was almost the half of the mixing time for the first experiment series.
iv) **Transporting and placing:** Concrete was transported within a wheelbarrow for about 200 m. But at the destination point, the concrete was remixed to eliminate segregation. At the time of placing, the slump of concrete was 160 mm.

v) **Preparing the cubes:** Again 4 pairs of cubes were prepared as explained in BS 1881. Each pair was called as a set, and the result of each set was obtained by averaging the results of two cubes tested on the 28 days of casting. The feature and the results of each set are given in Table 10.2.

<table>
<thead>
<tr>
<th>Set no</th>
<th>Compaction</th>
<th>Curing</th>
<th>Compressive strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Normal compaction</td>
<td>28 days standard moist curing</td>
<td>41.2</td>
</tr>
<tr>
<td>2</td>
<td>Under compaction</td>
<td>No curing at all</td>
<td>23.8</td>
</tr>
<tr>
<td>3</td>
<td>Under compaction</td>
<td>3 days wet hessian and plastic sheet wrapping</td>
<td>35.6</td>
</tr>
<tr>
<td>4</td>
<td>Under compaction</td>
<td>7 days wet hessian and plastic sheet wrapping</td>
<td>38.9</td>
</tr>
</tbody>
</table>

Normal compaction: Vibration by 22 mm internal vibrator for 13 sec
Under compaction: Vibration by 22 mm internal vibrator for 6 sec.
c) Discussion of the Results

The results of this study showed that, the 28 day strength of concrete cured for 28 days was only 3% more than the strength of 7 day cured concrete. 28 days cured concrete samples were tested straight from the curing tank i.e. undried. However, the 7 days cured concrete samples were left to air dry after the 7-th days of casting, and they were completely dry on the day of testing. This could reduce the gap expected between 28 days and 7 days cured samples.

The omission of complete curing caused a reduction in the strength of the 7 days cured concrete by about 22%. Reducing the normal compaction duration by half, caused a reduction in the strength of concrete by about 7%.

The combined effects of reducing the mixing time by half, and omitting the adjustment for aggregate moisture (1.7% for coarse aggregate, and 8% for sand) caused a reduction in the strength of concrete by about 26%. The combined effect of reducing the mixing time and compaction duration of concrete by about half, omitting completely the adjustment for aggregate moisture, (1.7 for coarse aggregate, and 8% for sand), and instead of 7 days curing only 3 days with wet hessian wrapped by plastic sheet, reduced the strength of concrete by about 36%. Additional to these, if no curing was performed, then the strength of the concrete was reduced by about 57%.

d) Comparison of the Experiment Results with the Recommendations of ESCON

During one running of ESCON normally more than 30 recommendations are produced. Ignoring any one of these goals will adversely affect the strength of concrete. So, in one run of the system, the strength of concrete may be affected by 30 factors which produce $30^{30} = 2.059 \times 10^{44}$ combinations. It was impossible to make so many experiments. Therefore, only eight of these
combinations were selected, and to find out their effects on the strength of concrete, the relevant experiments were undertaken at CITB. In selecting these combinations, the dominant factor was the ease with which their results can be expressed in terms of compressive strength of the concrete. The selected eight combinations, the results of the experiments, and the comparison of ESCON with the experimental results are summarized in Table 10.3.

The effects of ignoring these recommendations on the strength of concrete is shown in Fig. 10.2 and Fig. 10.3. Both Fig. 10.2 and Fig. 10.3 show how the strength of concrete was effected by ignoring any four of the recommendations. The combinations of these four recommendations were selected randomly. Fig. 10.2 was developed for the cases where the curing was omitted completely. Fig. 10.3 was based on a curing duration of 3 days. The ignored recommendations and the combinations are given below:

**Ignored recommendations:**

1) **Compaction:** The duration of compaction was reduced by half of the duration of normal compaction. Therefore, the concrete was undercompacted.

2) **Moisture adjusting and Mixing:** Aggregate free moisture content (1.7% for coarse aggregate, and 8% for sand) was not adjusted and the mixing time was also reduced by about half of the normal mixing time.

3) **Curing:** Curing was omitted completely.

4) **Slump reduction:** No reduction in the slump of concrete was considered as the concrete was raised in the form of wall.
(a) - Randomly selected four combinations for four recommendations ignored.

(b) - The average obtainable strength of the concrete for four combinations shown in (a) above

Fig. 10.2 - The effects of ignoring any four of the recommendations on the strength when the curing was omitted completely.
(a) - Randomly selected four combinations for four recommendations ignored.

(b) - The average obtainable strength of the concrete for four combinations shown in (a) above.

Fig. 10.3 - The effects of ignoring any four of the recommendations when the curing was performed for only 3 days.
### TABLE 10.3 - Comparison of the recommendations of ESCON with the results of experiments.

<table>
<thead>
<tr>
<th>No</th>
<th>Combinations for deficiencies in concreting operations</th>
<th>Reduction in strength %</th>
<th>Differ.</th>
<th>Aver. diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Omitting the adjustment of aggr. moisture content (1.7% for coarse aggr; 8% for sand); and reducing the normal mixing time by half</td>
<td>26</td>
<td>40</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>Omitting the adjustment of aggr. moisture content (1.7% for coarse aggr; 8% for sand), and reducing the normal mixing time by half; and reducing ther normal compaction duration by half</td>
<td>28</td>
<td>44</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>Omitting the adjustment of aggr. moisture content (1.7% for coarse aggr; 8% for sand), and reducing the normal mixing time by half; and reducing ther normal compaction duration by half; and curing only 3 days</td>
<td>36</td>
<td>55</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>Omitting the adjustment of aggr. moisture content (1.7% for coarse aggr; 8% for sand), and reducing the normal mixing time by half; and reducing ther normal compaction duration by half; and no curing at all</td>
<td>57</td>
<td>69</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>Only 3 days of curing vs. 7 days of curing</td>
<td>9</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>No curing at all vs. 7 days curing</td>
<td>39</td>
<td>44</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>No slump reduction while concrete is rising in form of wall or column (Strength=50MPa)</td>
<td>26</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>No slump reduction while concrete is rising in form of wall or column (Strength=50MPa) and no curing at all</td>
<td>45</td>
<td>55</td>
<td>10</td>
</tr>
</tbody>
</table>
**Combinations:**

**Combination A:** Compaction + moisture adjusting and mixing + curing + slump reduction.

**Combination B:** moisture adjusting and mixing + compaction + curing + slump reduction.

**Combination C:** Curing + moisture adjusting and mixing + compaction + slump reduction.

**Combination D:** Slump reduction + curing + moisture adjusting and mixing + compaction.

According to the Fig. 10.2, when curing was completely omitted, ignoring any one, two, three, or four recommendations reduced the strength of concrete by 15 %, 45 %, 57 %, and 65 % respectively. Fig. 10.3 shows that, when instead of 7 days, 3 days of curing was performed, ignoring any one, two, three, or four of the recommendations reduced the strength of concrete by 10 %, 31 %, 43 %, and 52 % respectively.

**Conclusions**

As it is seen in Table 10.3, the strength losses predicted by ESCON are generally higher than the experimental results. This may be because of the method ESCON uses to calculate the expected strength of the concrete. ESCON defines a factor for each deficiency by using the formula \(((100 - \% of strength loss caused by the deficiency)/100)\). When there is more than one deficiency, ESCON calculates the expected strength of the concrete by multiplying the design (target) strength with the factors of these deficiencies. In this way the effects of the deficiencies on the strength of the concrete is combined cumulatively. However, the experiments undertaken at CITB show that the expected strength loss calculated in this way can be greater than the experimental results. This indicates that the overall strength loss of the concrete is some function of the individual strength losses which may not be purely cumulative. For this reason the figures given by ESCON can be regarded as maximum
potential strength losses.

However, according to the Table 10.3, the recommendations of ESCON differed from the results of the experiments on average by about 11%. So, considering the experiments undertaken at CITB as an objective standard, the statements of ESCON about the expected strength loss when some of the recommendations are ignored have a correctness of about 89%. This indicates that in this respect, the knowledge of ESCON is reliable as much as 89%.

10.4.2. **ESCON EVALUATION 2 - SENSITIVITY ANALYSIS**

This evaluation technique comprises the analysis of sensitivity of an expert system to slight changes in either the knowledge represented, or input data. To evaluate ESCON, the following sensitivity test procedures were developed.

- The model was run for an imaginary case including batching (on-site), mixing, transporting, placing, compacting, finishing, and curing of concrete.

- During the running of the model, eight sensitivity variables were selected. The selection of these variables was based on their expressibility in terms of strength when they were changed. The selected variables and their effects on the strength of concrete are summarized in Table 10.4.

- Changes were then introduced to these variables. Eight variables produce $8^8 = 16,777,216$ combinations. Each combination may produce concrete with a different strength. In this case, it was impossible to run the model for each combination. So, the model was run for 57 combinations as explained in the following section. First, only one of the variables was changed, and this procedure was repeated for eight variables. Then, any two variables were randomly selected and changed. This procedure was repeated for eight times.
Then, any three, four, five, six, and seven of them were randomly selected and changed. For each case the procedure was repeated 8 times. Finally, eight of the variables were changed. For each combination the strength of the concrete was calculated.

The strength of each combination was plotted and the sensitivity curve was drawn as shown in Fig. 10.4.

As can be seen in Fig. 10.4, changing any one of the variables reduced the strength of concrete by 13% on average. The changing any two of the variables reduced the strength of concrete by 24%. When eight of the variables were changed, the strength of the concrete was reduced by 67%. Thus, ESCON is highly sensitive to any changes in its variables. This shows that, the variables or the rules of ESCON were correctly selected, and are effective indicators for the quality of the concrete.
<table>
<thead>
<tr>
<th>No</th>
<th>Sensitivity variables</th>
<th>Recommendations of ESCON</th>
<th>Variations made</th>
<th>Caused % reduction in strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Batching method</td>
<td>Weight batching (w/c=0.5) and the rate of changing by about 15%</td>
<td>Volume batching was used. Aggr. was measured in shallow containers with a large sectional area; levelled roughly; no allowance for bulking of sand; Cement was measured in weight</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>Cement storage</td>
<td>Proper storage and first come first used</td>
<td>Cement was stored in normal conditions, but waited for 4-6 weeks [200].</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>Agg. moisture adjustment</td>
<td>Do adjustment for aggregate moisture</td>
<td>No aggregate adjustment made. Aggr. overall moisture content was 2.0 %</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Mixing time</td>
<td>Mix concrete for a min. duration defined in chapter 5.</td>
<td>The normal mixing time was reduced by about half</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>Reduction of slump as conc rises in forms of walls, colm.</td>
<td>Reduce the slump as concrete is rising in forms of walls or columns (see ch. 6)</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Vibration duration</td>
<td>Vibrate concrete for a normal duration defined in chapter 7</td>
<td>The normal vibration duration of concrete was reduced by about half</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>Revibration</td>
<td>Revibration was recommended as explained in ch. 7</td>
<td>Revibration was not performed</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>Curing duration</td>
<td>Minimum curing duration is 7 days</td>
<td>Curing was performed only for 3 days</td>
<td>17</td>
</tr>
</tbody>
</table>
10.4.3. ESCON EVALUATION 3 - EXPERT'S EXPERIENCE

ESCON was developed in collaboration with six experts in concrete technology. While developing the system, it was demonstrated to and discussed with these experts. The system was improved by including their views after discussion. Finally, the system was demonstrated for critical appraisal to the last expert. The views of the expert and the discussion of these views are given below.

The expert was invited to the Civil Engineering Department, and a demonstration took place on a personal computer. Before commencing the demonstration the expert was informed that, his detailed criticism was expected. Therefore, the expert examined the model carefully. The demonstration started with an imaginary case study. The expert answered the questions of ESCON and read the recommendations executed by the system. He then compared the recommendations of ESCON with his own experience. A discussion took place about the reasons of asking the antecedent questions, and how the decision was made. This procedure was repeated for every set of rules of ESCON throughout the session. In some cases, the expert wanted to see the other recommendations by changing his answer for a question. In these cases, that part of the model was repeated. Meanwhile, the expert indicated some of the weak points and the gaps in the system. This demonstration and discussion lasted for 5 hours as two sessions, 1.5 hr in the morning, and 3.5 hr in the afternoon. Later, the expert sent a letter mentioning his views about ESCON. In this letter, the expert mentioned his opinions by stating the following:

"The work is thorough and comprehensive. It is to a high technical standard and well researched. The system is user friendly and should present no problem at site level. The system effectively leads the user through an option routine which converges towards the solution without the need to search redundant data."
The expert commented that, to improve ESCON as a "commercial guide", the following refinements are necessary:

1) To produce an "ideal" site tool, ESCON should be edited by an expert having 10-15 years experience in practical aspect of concrete works.

2) "Footnotes" should be provided for the limitations or exceptions of the decisions in some key area. This is particularly important when ESCON produces a decision that includes some rules, for example, "x must not exceed y".

**Discussions of Expert's Evaluations**

The expert examined ESCON thoroughly as explained in section 10.4.3. He compared the recommendations of ESCON with his own experience and knowledge. Then, a discussion took place about the reasoning of the recommendations of ESCON. He wanted to see the other recommendations of ESCON by changing his replies for some critical questions. At the end of this demonstration, he generally was satisfied with the knowledge base of ESCON. However, he was not familiar with several recommendations of ESCON since these recommendations were based on the USA practice. Finally, he mentioned his views about the applicability of ESCON on the concreting sites.

ESCON is a prototype expert system to give advice only for workmanship of concreting operations. As mentioned previously, the aim of ESCON is to show the feasibility of improving the quality of concrete by transferring the required knowledge to the site as an application of an expert system on concreting operations. Therefore, at this stage ESCON is not a commercial package. At this stage, the evaluation of ESCON includes testing the correctness of its decisions and reasonings, and the success of transferring information to the user. It was indicated by the expert that, the knowledge of ESCON is comprehensive and user friendly. It was concluded that, ESCON is a reliable tool and should present few problems at site level.
10.4.4. **ESCON EVALUATION 4 - OPINION OF NOVICE USERS**

ESCON was tested by 4 post-graduate civil engineer students who were unfamiliar with the system and inexperienced in concreting technology. These volunteers sat in front of the computer and ran the program for an imaginary case. They were asked to comment on the flowing of knowledge from the system, the understandability of the recommendations, and the ease with which the system can be used.

These users readily understood the presented knowledge, and found the recommendations of ESCON "understandable". They found the explanation facility (amplify) within the system helpful and that it also prompted them with information of which they were previously unaware. Thus it helped to instruct or teach them on correct concreting procedures. Their major comments were as follows:

1) In some cases, explanations or descriptions can be more effectively made by figures. Producing a figure on the screen saves time and is more understandable.

2) References should be provided for some descriptions or explanations when the user requires more information about them.

3) When a user improves his knowledge and experience, he may desire to change some of the rules in the knowledge base. Unfortunately, the user can not access in the knowledge base while running the program.

However, these comments can be included if ESCON is restructured, and another shell is used which facilitates direct access to the knowledge base while running the program, and an easy access to an external program with graphic facilities. Unfortunately, SAVOIR is not capable of doing these.
ESCON was also evaluated by comparing it to a real life case study. The job was a concrete bridge construction. The required properties of concrete were as follows:

- Compressive strength : 40 N/mm$^2$
- Slump : 100 +/- 25 mm
- W/C : 0.5
- Maximum aggregate size : 20 mm
- Cement content : 375 kg/m$^3$.

The weather was cloudy, dry, and the ambient temperature was about 14°C. A complete session of ESCON for this case is shown in Appendix C. The comparison of actual site applications and the recommendations of ESCON are summarized in Table 10.5. The following observations were made in relation to Table 10.5. In this case, ESCON provided 31 major recommendations. 21 of these recommendations were applied on the site exactly. The remaining 10 recommendations were not practiced on the site. These 10 recommendations will be discussed in below:

1) **Supervision**: Supervision was not permanent, and sufficient. The insufficiency of the supervision appears in the following discussions.

2) **Truck Mixer Loading Method**: During discharging the concrete, some cement balls were observed. Cement balls are discussed in section 10.4.5.(5).

3) **Rotation Speed of the drum**: ESCON recommends that, for uniform mixing, the mixing speed of the drum should be about 18 rpm. But in practice the drum speed was about 10-12 rpm. This reduces the uniformity of the concrete.
4) **Mixing Prior to Discharging:** ESCON recommends that, the drum of the mixer should be rotated for about 30 revolutions before discharging the concrete. This procedure is useful in reblending any unmixed water near to the discharge end of the mixer, and to minimize the difference in the consistency of concrete between the first and last portion of the batch. This procedure was not exercised on the site. As a result, the first portion of the concrete was more workable than the last portion.

5) **Cement Balls:** In every batch, several cement balls were observed. The diameter of the balls was up to 150 mm. Cement balls contained mainly cement, sand, and sometimes a little amount of coarse aggregate. These balls were usually smashed by a worker on the grid of the pump hopper. But the constituents of these balls were never mixed uniformly with the concrete. This creates weaknesses in the structure. To avoid the formation of cement balls, ESCON gives recommendations as explained in section 5.4.1.(c).

6) **Compaction Equipment:** Having compacted the concrete completely by internal vibrators, a vibrating screed was used for the purpose of screeding. ESCON does not recommend the use of surface vibrators after compaction of the concrete by internal vibrators. The reason is that, compaction of concrete by internal vibrators increases the amount of mortar at the top portion of the concrete. After internal vibrators, any surface vibration (for example, vibrating screed) pulls more mortar towards the top of the concrete. Eventually, the concrete segregates and a weak mortar portion is produced at the top of the concrete.

7) **Team Compaction:** In this job, three internal vibrators were used at the same time. ESCON recommends that, the vibrator operators should work as a team rather than individual (see section 7.3.3.(a)). However, this did not occur on this job.
8) **Systematic Penetration of Internal Vibrators:** ESCON recommends that, the internal vibrators should be penetrated systematically. (see section 7.3.3.(a)). But, on this site, the vibrators were penetrated at haphazard angles and the spacing of penetration was randomly. Sometimes, vibrators were penetrated about 3 ft (0.9 m) apart. This is too large a spacing. Unsystematic penetration of the vibrators promotes incomplete compaction.

9) **Pulling out of Vibrator:** ESCON recommends that, internal vibrators should be withdrawn slowly (about 3 in/sec). On this site, the vibrators were pulled out very quickly. In this case, the holes in the concrete left by the vibrators may not be closed by the concrete without entrapping air.

10) **Curing of Formed Surfaces:** ESCON recommends that, the selected curing method should be applied on the formed surfaces within 1/2 hour of removing the formwork. On the site, the side formwork was removed the next day, but no curing was applied on these surfaces. Although the top surface of the bridge deck was cured well by liquid compound, the concrete could still lose some of its moisture through the uncured side surfaces before complete hydration had occurred.

The reasons for these 10 deficiencies were discussed with the supervisor of the job, and the following conclusions were reached:

a) The supervisor admitted that they have some problems with the formation of cement balls in the truck mixer. He said that, cement balls occur commonly, and it is a ready mixed concrete producer's problem. He believed that these balls should not affect the quality of concrete since they were smashed during dumping;

b) The supervisor said that, the concrete arrived at the job site as mixed, so the rotation speed of the drum or the necessity of mixing the concrete for about 30 revolutions prior to
discharge was not a matter to be considered; It seemed that, the supervisor did not want to be involved with batching, mixing, and transporting the concrete to the site, considering this to be the responsibility of the ready mix supplier.

c) When the sales and technical managers of the ready mixed concrete producer which supplied the concrete to this site were visited, they accepted that, cement balls usually occur in the truck mixers. It was implied that, the cement balls will occur in the truck mixers until the contractors appreciate their adverse effect on the quality of the concrete, and ask the concrete suppliers to avoid them.

d) The supervisor said that, the vibrating screed was used just for striking-off, and didn't recognise any harmful effect on the quality of the concrete when it was used after compacting concrete completely by internal vibrators;

e) He said that, some of their vibrator operators were inexperienced and didn't know how to use the vibrators. He admitted the advantages of "team compaction", "systematic penetration", and "pulling out rate" of internal vibrators, but maintained that in practice perfect compaction is difficult;

f) He was not aware of the necessity of application of curing on the formed surfaces immediately after removing the side forms.

g) If the specification included sufficient information on the workmanship requirements, the supervisor could avoid some of these mistakes. For this case, a sample specification prepared by ESCON is given in Appendix D.

As a result, in this case some deficiencies and mistakes were observed. Although these mistakes could not be quantified or expressed in terms of strength lost, as they are discussed in the previous chapters, the above 10 features affected the expected strength of concrete adversely. If ESCON had been applied carefully, the strength of concrete should not be affected by these failures.
Therefore, it can be concluded that;

- many of the rules and recommendations of ESCON matched with the procedures exercised in a large concreting project,
- in this project some of the rules of ESCON were not applied, and eventually the quality of concrete suffered. It is believed that, if ESCON was applied on this project strictly, the appreciation of both supervisory staff and workmen on the site would be improved, and these 10 failures could be avoided. Thus, this case study demonstrated that, ESCON is capable of specifying the appropriate procedures to follow in a concreting operation.
TABLE 10.5 - Comparison of the recommendations of ESCON with the actual site applications in the case study.

<table>
<thead>
<tr>
<th>No</th>
<th>Recommendations of ESCON</th>
<th>Actual site applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Off-site batching method may be used</td>
<td>Off-site batching was used</td>
</tr>
<tr>
<td>2</td>
<td>While ordering, specify the properties of aggregates, slump and strength of concrete.</td>
<td>As ESCON recommended</td>
</tr>
<tr>
<td>3</td>
<td>Provide a good supervision</td>
<td>Insufficient and partly supervision</td>
</tr>
<tr>
<td>4</td>
<td>Since cement balls were observed, &quot;slurry mixing&quot; should be considered to load the truck mixers.</td>
<td>Truck mixers were loaded by &quot;Ribbon loading&quot; method</td>
</tr>
<tr>
<td>5</td>
<td>Total minimum number of rotation of the drum of the mixer should be 70 revolutions.</td>
<td>120-150 revolutions. (As ESCON recommended)</td>
</tr>
<tr>
<td>6</td>
<td>Speed of rotation of the drum while mixing should be about 18 rpm.</td>
<td>10-12 rpm.</td>
</tr>
<tr>
<td>7</td>
<td>Prior to discharge, rotate the drum of the mixer at the mixing speed for about 30 revolutions</td>
<td>Prior to discharge, the drum of the mixer was rotated sometimes and only 1-4 revolutions</td>
</tr>
<tr>
<td>8</td>
<td>Avoid formation of cement balls by considering the precautions explained in chapter 5.</td>
<td>Insufficient effort to avoid the formation of cement balls</td>
</tr>
<tr>
<td>9</td>
<td>Remixing is not recommended</td>
<td>As ESCON recommended</td>
</tr>
<tr>
<td>10</td>
<td>No overmixing</td>
<td>As ESCON recommended</td>
</tr>
<tr>
<td>11</td>
<td>Ready mixed concrete supplier was tested before, no need to perform the mixer performance tests</td>
<td>(As ESCON recommends)</td>
</tr>
<tr>
<td>12</td>
<td>Retempering should not be performed</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>13</td>
<td>The slump of concrete should be 2-5 in for good pumping.</td>
<td>Slump of concrete was 4 in. (As ESCON recommended)</td>
</tr>
<tr>
<td>14</td>
<td>No downhill pumping so no extra precautions to avoid segregations</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>15</td>
<td>The maximum aggregate size of less than 2.5 in is good for concrete pumping</td>
<td>The maximum aggregate size was 3/4 in (20 mm). (As ESCON recommended)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>16</td>
<td>Flexible hoses are recommended for short distances to reduce the required pump pressure</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>17</td>
<td>If pump pressure is insufficient, take the precautions explained in ch. 6.</td>
<td>Pump pressure was sufficient, so no precautions were required</td>
</tr>
<tr>
<td>18</td>
<td>Pipes should be lubricated properly</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>19</td>
<td>While placing, the thickness of concrete should be about 12-20 in.</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>20</td>
<td>Internal vibrators are recommended for compaction</td>
<td>Internal and surface vibrators were used at the same time.</td>
</tr>
<tr>
<td>21</td>
<td>Vibrator operators should work as a team rather than individuals</td>
<td>Vibrator operators worked as individuals.</td>
</tr>
<tr>
<td>22</td>
<td>Internal vibrators should be inserted systematically as explained in ch. 7</td>
<td>Internal vibrators were not penetrated systematically</td>
</tr>
<tr>
<td>23</td>
<td>Internal vibrators should be penetrated quickly</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>24</td>
<td>Internal vibrators should be pulled out slowly</td>
<td>Internal vibrators sometimes were pulled out very quickly</td>
</tr>
<tr>
<td>25</td>
<td>Vibration should continue until the signs of full compaction are observed (see chapter 7)</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>26</td>
<td>A spare vibrator should be provided on the site</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>27</td>
<td>Revibration is not required</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>28</td>
<td>Normal weather curing conditions should be applied</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>29</td>
<td>Minimum curing duration should be 7 days</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>30</td>
<td>One of the liquid curing compound could be used for both formed and unformed surfaces</td>
<td>(As ESCON recommended)</td>
</tr>
<tr>
<td>31</td>
<td>After removing the formwork, apply liquid curing compound on the formed surfaces within 1/2 hours.</td>
<td>After removing the formwork, no curing was applied on the formed surfaces.</td>
</tr>
</tbody>
</table>
CHAPTER ELEVEN: CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions
11.2 Benefits of ESCON
11.3 Envisaged Application of ESCON
11.4 Further Works
11.1. CONCLUSIONS

The quality of the concrete in a finished structure is affected by both the quality of the freshly mixed concrete and the standard of the workmanship applied during its handling, compaction, finishing, and curing. The quality of the freshly mixed concrete is affected by the quality of its ingredients, and the procedures of production. Therefore, whether during the production, or construction phases, workmanship is important in achieving the required quality in the finished structure.

In this research the entire concrete production, handling, placing, compacting, and curing methods were explored through literature, and by visiting concreting sites in Cyprus and Turkey. A total of 120 major different points were examined throughout the concreting operations which have a great influence on the quality of the finished concrete structure. During the 84 site visits in Cyprus a total of 19 major mistakes were observed. The essential 6 causes of these mistakes were also noticed. Specifications were examined on 84 sites in Cyprus, and 1 site in the UK. In this survey it was concluded that, the specifications contained insufficient information on the workmanship requirements of the concreting operations.

The causes of the deficiencies were discussed with the workmen and the supervisors on the site. The main reasons for the deficiencies were the lack of appropriate specifications, the lack of knowledgeable supervision, and the lack of the appreciation of the site staff on the effect of bad workmanship on the quality of the concrete. The lack of knowledge is one of the important aspects in concrete construction that greatly influence the quality. As Neville [201] stated, the man who knows nothing, has no difficulty in mixing "gone off" cement, and bucketsful of water.
In the literature there are few publications on the workmanship of concreting operations, and they do not appear to satisfactorily transfer the knowledge to concreting sites. This research therefore, has produced a tool to: (1) transfer the necessary knowledge about the concreting operations to the supervisory staff and workmen; (2) prepare detailed specifications including the necessary information on the workmanship requirements of the concreting operations; (3) indicate the effects of bad workmanship on the strength of the concrete by calculating the expected strength of the concrete practiced; (4) train inexperienced supervisors and engineers in concreting practice.

In this research, concreting operations were divided into six modules: batching; mixing; transporting and placing; compacting; finishing of unformed concrete surfaces; and curing. For each operation, the main factors that affect the quality of concrete were defined. Using this knowledge a prototype expert system model was developed. This model was introduced to and discussed with six experts in the domain. The necessary corrections and refinements were made to include the comments of the experts. Two series of experiments were undertaken at the CITB to obtain a set of objective data to compare with the results of the system. Finally, the model was evaluated by five different methods including: (1) comparison of the model results with a set of objective data; (2) sensitivity analysis; (3) experience of expert; (4) novice users; (5) a real case study.

The model (called ESCON) is capable of:

1) defining, predicting and diagnosing the possible problems in concreting operations, and recommending expertise solutions for the problems;

2) helping to improve the knowledge of novice users by explaining the reasons behind the recommendations;

3) preparing comprehensive specifications on the workmanship of the concreting operations by using the knowledge base of ESCON.
4) calculating the expected loss in the strength of the concrete produced if recommendations are ignored;

From the work undertaken the following key findings were obtained:

1) **Batching of concrete:** The most important aspect of batching concrete is to maintain the accuracy in measuring for both individual and successive batches. The accuracy in batching is affected by: (1) method of batching; (2) adjusting the aggregate moisture content; (3) selected batching control system; (4) inspection of batching devices, and supervision of the batching procedures. The effects of these factors on the quality of the concrete are discussed in detail in chapter 4.

The "Concrete Batching" module of ESCON includes knowledge and experience on these factors. The module divides the batching methods into on-site batching, and off-site batching. The system is capable of adjusting the weights of the mixing water and aggregates due to the variations in the moisture content of the aggregates, providing the proportions and aggregates moisture contents are fed into the system. The module limits the use of manual batching control systems for a rate of production of less than 30 cu m per hr. Finally, the system highlights the necessity of proper maintenance for batching devices, and their supervision. This module also produces detailed specifications as explained in chapter 4. The "Concrete Batching" module of ESCON includes 54 questions, 21 variables 60 actions, and 4 groups. The size of the module is about 58100 bytes over 1430 lines.

2) **Mixing concrete:** Having placed the correct amount of concrete ingredients into the mixer, a thorough mixing is essential to produce uniform concrete. As explained in detail in chapter 5, the uniformity of the concrete is affected by the following mixing aspects: (1) sequence of loading the mixer;
(2) mixing time; (3) discharging the mixer; (4) capacity of the mixer; (5) formation of cement balls in the mixer; (6) formation of head packs in the hub of the truck mixers; (7) the design and the mechanical conditions of the mixers; (8) retempering.

Depending on the batching method used, the "Concrete Mixing" module of ESCON divides the mixing into three as: (a) mixing for off-site batching; (b) mixing for on-site volume batching; and (c) mixing for on-site weight batching. Having selected a mixing method, the module transfers information and gives advice to insufficiently experienced staff on the site about the above mentioned factors. This module also produces specifications as explained in chapter 5. This module includes 30 questions, 89 actions, and 2 groups. The size of the module is about 69500 bytes over 1670 lines.

3) Transporting and placing of concrete: During handling, the workability and the uniformity of the concrete may be impaired. As explained in chapter 6, the factors of transporting and placing of concrete that affect the quality are: (1) excessive slump loss; (2) the loss of ingredients; (3) segregation; (4) formation of cold joints in the structure.

The "Transporting and Placing Concrete" module of ESCON includes information and recommendations on these subjects. As explained in chapter 6, this module first gives advice on 13 different types of concrete transporting and placing equipment. Then the module gives recommendations on concrete placing techniques such as concreting of columns, walls, slabs, and mass concretes. Finally, the module can produce specifications as explained in chapter 6. This module includes 55 questions, 2 variables, 156 actions, and 6 groups. The size of the module is about 90000 bytes over 2140 lines.
4) **Compaction of concrete:** Fresh concrete placed into a form contains an amount of entrapped air. Each percent of entrapped air in the concrete reduces the strength of the concrete by about 5 to 6 percent. Therefore, this entrapped air should be eliminated as far as possible. As explained in chapter 7, this can be achieved by: (1) selecting proper compaction methods and equipment; (2) vibrating the concrete for an appropriate duration; (3) improving the vibration technique by penetrating the internal vibrator systematically and quickly, and pulling out slowly; (4) if applicable, revibrating the concrete.

The "Concrete Compaction" module of ESCON transfers knowledge and experience to the concreting staff about these points. This module provides information on the following compaction methods: (a) manual compaction; (b) internal vibration; (c) form vibration; (d) surface vibration; and (e) reinforcement vibration. This module also prepares specifications as explained in chapter 7. This module includes 34 questions, 2 variables 107 actions, and 1 group. The size of the module is about 72200 bytes over 1600 lines.

5) **Finishing of unformed concrete surfaces:** Proper finishing of unformed concrete surfaces improve the quality of the top surface of the concrete. As explained in detail in chapter 8, the main imperfections of these surfaces are, dusting, scaling, crazing, and weak abrasion resistance and strength. One of the major cause of these imperfections is enhancing the water/cement ratio at the top of the surface by working the bleeding water into the surface.

The "Finishing of Unformed Concrete Surfaces" module of ESCON produces information to avoid these imperfections. As explained in chapter 8, the module divides the types of slabs or floors into 8, and produces advice for each of them. Finally, the
module can produce a specification on the floor type selected. This module includes 12 questions, 2 variables, and 35 actions. The size of the module is about 70900 bytes over 1350 lines.

6) **Curing of concrete:** After compacting and finishing, the maximum hydration of the cement should be promoted by providing a suitable environment for the concrete.

The "Concrete Curing" module of ESCON provides information on the concrete curing methods and procedures. As explained in chapter 9, this module divides the weather conditions into three as hot, normal, and cold. The system gives advice on the applicable curing methods and procedures for each weather conditions. When asked, the module is capable of calculating the expected rate of evaporation from the surface of concrete and to predict the weather conditions. The system can also calculate the expected concrete temperature which is necessary to predict the weather conditions. Finally, this module can produce a detailed specification as explained in chapter 9. The module includes 56 questions, 88 variables, 129 actions, and 9 groups. The size of the module is about 141000 bytes over 3400 lines.

7) The concreting operations were observed on two sites in the UK, and it was concluded that, from a quality point of view there is poor communication between the ready mix concrete producer and the contractor. The contractor's side believes that, the ready mix concrete producer should be responsible for the quality of the concrete delivered, and thus they were not deeply involved with the batching, mixing, and transporting procedures. This created a gap in the whole quality control procedures of the concrete delivered. This gap can be covered by a knowledgeable supervisory staff, and a detailed specification.
8) The most difficult and laborious part of developing an expert system is acquiring the expert knowledge. For example, the time spent to acquire the knowledge of ESCON was more than 2 years. But, having established a powerful knowledge base, an expert system can be used on sites to give advice to novice users.

9) The outcomes of evaluation explained in chapter 10 included the following strong points of ESCON:
   a) The correctness of the predictions of ESCON on the strength loss when some of its recommendations are ignored is 89%. This is a good indication of the reliability of the system.
   b) ESCON was found to be highly sensitive to changes in its recommendations. This indicated that, the recommendations have a great influence on the quality of the concrete produced, and the rules of ESCON are correctly established.
   c) The opinion of the domain expert who examined ESCON confirmed that, the knowledge of ESCON is comprehensive and well researched.
   d) The reasoning of ESCON is effective and acceptable by the domain expert who examined ESCON.
   e) ESCON was found to be useful in transferring information and instructing novice users.
   f) The explanation facility of ESCON was found helpful by novice users.
   g) Most of the recommendations of ESCON are similar with the procedures followed in a large concrete project as are shown in Table 10.5.
   h) ESCON was found to be applicable on site and provided necessary recommendations for good concrete practice. If this information is strictly applied on the site, the mistakes in concreting operations are minimized. So, bad workmanship can be avoided.
i) The lack of sufficient information on the workmanship requirements in the specifications causes difficulties in supervising and controlling the work. A detailed specification prepared by ESCON (a sample is given in Appendix D) can prevent many of the workmanship problems.

j) A detailed specification prepared by ESCON can help to form a bridge between a ready mix concrete supplier and a contractor. Thus, poor procedures and workmanship in batching, mixing, and transporting, such as formation of cement balls, can be avoided.

10) The aspects of ESCON perceived as weakness include the following:

a) ESCON has some inherent weaknesses due to its shell, SAVOIR. These are difficulties in access to an external programs, and access to the knowledge base while running the program. The use of graphics in ESCON was excluded. In SAVOIR, if the user wants to access the knowledge base, he has to exit the running file into DOS, and open the knowledge file. This weakness of ESCON can be rectified by using a more sophisticated shell.

b) Transferring knowledge from experts to inexperienced staff requires a well developed expert system which may be too expensive especially for small contractors.

c) On small sites, calling a human expert and getting advice could be easier, quicker, and cheaper than providing an expert system. Human expert can be more affordable if they can provide advice in more than one domain.

The weaknesses given in (b), and (c) can be alleviated by more development in expert system technology.

d) Due to the conservative attitude of the construction industry, contractors may be reluctant to use expert systems. Expert systems may find more acceptance if
they are used in parallel with their human counterparts and the results are compared.

11) Having a preliminary knowledge from the literature about the interview techniques will help to improve the efficiency of knowledge elicitation from experts. It was experienced that, taking notes during interviewing mostly depends on immediate interpretation of the knowledge engineer. Therefore, an audio or video recording would be more effective and satisfactory.

12) Expected future of expert systems: Expert systems have only recently emerged but are increasingly being applied to engineering problems. Considering their improvements, the expected future for them can be stated as follows:

- As a by-product of expert systems, developers will construct large, and sophisticated knowledge bases. So, an independent, and new market may be developed for the codification of the knowledge.
- Computer technology may develop small and inexpensive computer hardware dedicated to particularly expert systems to be used by everybody and in every environment.
- Developing expert system technology may bring a solution to the conflicting expertise, and introduce a form of automated learning.

As a result, expert systems hold great promise for the future. Expert systems will find more users in environments where human experts are scarce. Since human experts are more scarce in developing countries, it is expected that, expert systems will become more widespread in these countries.
11.2. BENEFITS OF ESCON

Having proved that ESCON is a reliable and applicable tool on concreting operations, the following benefits accrue from it:

1) Its comprehensive expertise knowledge can be transferred to inexperienced supervisory staff on site. This is especially important when the expert in the domain is scarce as in the most developing countries. By improving the knowledge and experience of supervisory staff, the mistakes and deficiencies exercised in concreting operations can be reduced. This creates a medium to improve the quality of the concrete structures built.

2) The inexperienced workmen can be trained on the site cheaply, and easily, if the knowledge of ESCON is transferred to them by the supervisory staff.

3) Comprehensive and detailed specifications including all necessary information on the workmanship requirements of the concreting operations can be printed out at the end of a running of ESCON. Such specifications expedites the supervision and helps to reduce the mistakes on the sites. This also creates an environment to improve the quality of the concrete structures built.

4) The supervisory staff are reminded by ESCON of the results of bad workmanship on the quality of the concrete. This may motivate the supervisor to maintain a better supervision.

5) The knowledge of ESCON with reliable decisions, and correct reasonings can be used for training purposes.

6) In many cases, costs of consultation with human experts can be reduced.

7) In construction industry the decisions should normally be made promptly. The use of ESCON saves time.

8) Finally, the use of a computer on the site can provide many other additional benefits to contractors. For example, many other tedious, time consuming managerial, financial, or technical works can be done on this computer.
11.3. **ENVISAGED APPLICATION OF ESCON**

ESCON is a prototype expert system to give advice on concreting operations. The advice of ESCON creates an environment where the quality of the finished concrete structures can be improved. Thus, the envisaged application of ESCON can be stated as follows:

a) To transfer knowledge to inexperienced supervisory staff on the site to improve their knowledge and experience on the workmanship of concreting operations;

b) To train the inexperienced workmen on the site. The supervisory staff having obtained the knowledge through ESCON, they can transfer it to the workmen on the site. This can be an easy and cheap way of training the workmen on the site.

c) To prepare a comprehensive and detailed specification including the necessary information on the workmanship requirements of the concreting operations;

d) To predict the expected strength loss when some of its recommendations are ignored. This can be motivate the supervisory staff to do their job adequately.

e) Finally, for education purposes. The distilled knowledge of ESCON provides definitions, solutions and the reasons to the solutions of problems. This can be useful in teaching student users.
11.4. **FURTHER WORKS**

ESCON contains advice only about the workmanship of the concreting operations. If further programs are developed in the following areas, and combined with ESCON, greater benefit can be expected:

i) Selection of the equipment for the production and handling of concrete, considering construction methods, economy, contract duration, availability, and safety;

ii) Selection of the ingredients for the specified properties of the concrete, and combining this with programs for concrete mix design calculations;

iii) workmanship of the reinforcement bar bending and fixing;

iv) selection of the formwork material and formwork workmanship; and

v) determination of man power and equipment requirements and cost them for different construction methods.

ESCON calculates the expected strength loss for concrete when a number of its recommendations are ignored (see section 10.4.1 (d)). However experiments undertaken at CITB revealed lower strength losses than those predicted by the model. This may be explained by the manner in which the different strength losses are combined. Further investigations and experiments should be undertaken to ascertain the strength loss for individual deficiencies (insufficient vibration, insufficient curing, etc.) and combinations of these deficiencies. This will allow the model to predict strength loss with greater accuracy when its recommendations are ignored.
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APPENDICES

APPENDIX A: NATURE OF VIBRATION
APPENDIX B: FORMULAS OF THE CHARTS GIVEN IN FIG. 9.1
APPENDIX C: ESCON CONSULTATION
APPENDIX D: ESCON SPECIFICATION
APPENDIX A : NATURE OF VIBRATION

TERMINOLOGY

The energy required to consolidate fresh concrete is provided by vibrators. The vibrator transforms mechanical or electrical energy into oscillating energy. In the case of rotary vibrators, the oscillation are similar to simple harmonic motion. See Fig. A.1.

Considering Fig. A.1, the terminology of vibration can be summarised as follows:

Frequency is the number of oscillation or cycles per a given unit of time. \( n = 1/T, \text{ Hz} \).
Amplitude is the deviation from the X axis \( a = R \)
Angular velocity \( w = 2\pi n \).
Time is the elapsing time from the start of the motion, \( t \).
Movement is the position of \( M \) on YY axis and is given by

\[ a = OP = R \sin wt \]

Maximum amplitude is the maximum deviation of the position of \( M \) when \( wt = 90^0 \), or \( \sin wt = 1 \). Hence, the maximum amplitude is equal to

\[ A = a_{\text{max}} = R \]

Velocity at any time is given by

\[ V = \frac{da}{dt} = Aw \cos wt \]

Acceleration is given by

\[ \frac{dv}{dt} = -Aw^2 \sin wt \]
Fig. A.1 - Development of a simple sine curve (Redrawn from ref. 25)
Maximum acceleration is equal to $A_w^2$, when $\omega t = 90^0$, or $\sin \omega t = 1$

$$= A(2\pi n)^2 \text{ (mm/sec}^2\text{)}$$

Acceleration of gravity is 9810 mm/sec$^2$

Maximum acceleration in terms of gravity $= (A_n^2/248.86) \text{ g}$

(Therefore, the acceleration is proportional to the amplitude and the square of the frequency.)

Force is equal to $M \times$ acceleration, i.e.

$$P = MA_w^2 \sin \omega t$$

Maximum Force $= P_{\text{max}} = MA_w^2$

$= MRw^2$

$= MR(2\pi n)^2$
1. RELATIVE HUMIDITY CURVES

In curve fitting, the requirement is to approximate the set of data points as closely as possible with a specified function, \( f(x) \), whilst also satisfying the need for a smooth curve. However the requirements of smoothness and closeness conflict, and a balance has to be made between them. If the degree of polynomial is too high, the fit will be close to the data point, but not necessarily smooth. When the degree is low, the approximation to the data will be poor, but a curve with a better smoothness will be obtained. The necessary balance is achieved by the user comparing a selection of such fits each having a different degree of polynomial. When all curves are similarly good, the fit having the smallest number of coefficients, ie, degree of polynomials is chosen\([196]\).

In Fig. 9.1 there are ten curves for the relative humidities from 10 % to 100 %. By using the Curve and Surface Fitting subprogram of NAG FORTRAN Library Manual \([196]\), the equations of these ten curves were obtained. The curve fittings were evaluated by defining the coordinates of ten points on each curve. The polynomials were obtained for degrees of 3, 4, 5, and 6. Each set of the equations was used by ESCON to obtain a rate of evaporation from the concrete surface. The results of ESCON were compared by direct readings from the Fig. 9.1. The difference between them was at minimum for the polynomials with degrees of 5 and 6. These differences were about 3 %, and they were accepted as satisfactory. Therefore, the selected polynomial degree for the relative humidity curves is 5. The equations of the curves are as follow. (X and Y are horizontal and vertical axes respectively).
Relative Humidity Fitted Curves

10 % Y = 1.051 - 0.045X + 0.01263X^2 - 0.5677*10^{-3} X^3
   + 0.1109*10^{-4} X^4 - 0.7292 *10^{-7} X^5

20 % Y = 3.266 - 0.161X + 0.022X^2 - 0.7552 *10^{-3} X^3
   + 0.1422 *10^{-4} X^4 - 0.9792 *10^{-7} X^5

30 % Y = 3.659 + 0.007042X + 0.01227X^2 - 0.4458
   *10^{-3} X^3 + 0.1042 *10^{-4} X^4 - 0.8333 *10^{-7} X^5

40 % Y = 5.034 + 0.136X + 0.125 *10^{-3} X^2 + 0.4573
   *10^{-3} X^3 - 0.1047 *10^{-4} X^4 + 0.7708 *10^{-7} X^5

50 % Y = 6.053 - 0.2068X + 0.05833 X^2 - 0.02277 X^3 +
   0.4354 *10^{-4} X^4 - 0.2958 *10^{-6} X^5

60 % Y = 7.728 - 0.01733X + 0.03067 X^2 - 0.8417 *10^{-3} X^3
   + 0.1521 *10^{-4} X^4 - 0.1 *10^{-6} X^5

70 % Y = 8.617 + 0.2018X + 0.01796 X^2 - 0.3854 *10^{-3} X^3
   + 0.9479 *10^{-5} X^4 - 0.7917 *10^{-7} X^5

80 % Y = 10.13 + 0.1149X + 0.04294 X^2 - 0.001603 X^3
   + 0.3172 *10^{-4} X^4 - 0.2104 *10^{-6} X^5

90 % Y = 11.5 + 0.198X + 0.04142 X^2 - 0.001705 X^3 +
   0.3661 *10^{-4} X^4 - 0.2479 *10^{-6} X^5

100% Y = 13.01 + 0.1368X + 0.05808 X^2 - 0.002534 X^3
   + 0.5214 *10^{-4} X^4 - 0.3396 *10^{-6} X^5
2. **CONCRETE TEMPERATURE CURVES**

The seven equations of concrete temperature curves (from 40 F to 100 F) in Fig. 9.1 were found by using the simple algebra as follows:

<table>
<thead>
<tr>
<th>Concrete temperature</th>
<th>Fitted curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 F</td>
<td>Y = 11 - 1.0784X</td>
</tr>
<tr>
<td>50 F</td>
<td>Y = 16.5 - 1.0714X</td>
</tr>
<tr>
<td>60 F</td>
<td>Y = 24.85 - 1.12181X</td>
</tr>
<tr>
<td>70 F</td>
<td>Y = 36 - 1.1321X</td>
</tr>
<tr>
<td>80 F</td>
<td>Y = 51 - 1.1359X</td>
</tr>
<tr>
<td>90 F</td>
<td>Y = 69.5 - 1.1443X</td>
</tr>
<tr>
<td>100 F</td>
<td>Y = 94.9 - 1.125X</td>
</tr>
</tbody>
</table>

3. **WIND VELOCITY CURVES**

The seven equations of wind velocity curves in Fig. 9.1 were found from a simple algebra as follows:

<table>
<thead>
<tr>
<th>Wind velocity</th>
<th>Fitted curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 km/h</td>
<td>Y = 0.125X</td>
</tr>
<tr>
<td>3 km/h (2 mph)</td>
<td>Y = 0.225X</td>
</tr>
<tr>
<td>8 km/h (5 mph)</td>
<td>Y = 0.375X</td>
</tr>
<tr>
<td>16 km/h (10 mph)</td>
<td>Y = 0.585X</td>
</tr>
<tr>
<td>24 km/h (15 mph)</td>
<td>Y = 0.825X</td>
</tr>
<tr>
<td>32 km/h (20 mph)</td>
<td>Y = 1.0562X</td>
</tr>
<tr>
<td>40 km/h (25 mph)</td>
<td>Y = 1.3333X</td>
</tr>
</tbody>
</table>

In order to convert the values of "Y" into the rate of evaporation in terms of kg/m²/h, the obtained "Y" values were multiplied by 5/100.
APPENDIX C: ESCON Consultation

(Y...N or an option)
Y

WELCOME TO ESCON

ESCON is an EXPERT SYSTEM developed to improve the workmanship of concreting operations by transferring information to inexperienced staff on the site. This system includes 6 concreting operations as given below.

If you would like to have a session with concrete mixing, you are advised first to have a session with concrete batching, and then with concrete mixing. Otherwise, you can select any of the concreting operations to start with. This menu will be repeated at the end of each session.

1- Concrete Batching
2- Concrete Mixing
3- Transporting and placing of concrete,
4- Concrete Compaction
5- Finishings of unformed concrete surfaces,
6- Concrete Curing.
(1 to 6, ! if not known or an option)
1

Now you will have a session about CONCRETE BATCHING.

WELCOME to CONCRETE BATCHING.
(Type Y only or an option)
Y

Concrete batching methods may be divided as on-site, and off-site. In this session one of the batching methods will be selected, and advice will be given.

Is a ready mixed concrete producer available?
(Y...N or an option)
Y

Is there any available ready mix concrete producer that can deliver the concrete in a delivery time as shown in the tables given below?
**TABLE 1 - DELIVERY TIMES (HR) FOR ABOUT 5 % LOSS IN THE STRENGTH OF THE CONCRETE**

<table>
<thead>
<tr>
<th>Concrete temp. (F)</th>
<th>No delay before mixing</th>
<th>Cement last loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 (normal weather)</td>
<td>1.25</td>
<td>2.0</td>
</tr>
<tr>
<td>90 (Hot weather)</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

**TABLE 2 - DELIVERY TIME (HR) FOR ABOUT 10 % LOSS IN THE STRENGTH OF THE CONCRETE**

<table>
<thead>
<tr>
<th>Concrete Temp. (F)</th>
<th>No delay before mixing</th>
<th>Cement last loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 (normal weather)</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>90 (Hot weather)</td>
<td>1.25</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**TABLE 3 - DELIVERY TIME (HR) FOR ABOUT 15 % LOSS IN THE STRENGTH OF THE CONCRETE**

<table>
<thead>
<tr>
<th>Concrete Temp. (F)</th>
<th>No delay before mixing</th>
<th>Cement last loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 (normal weather)</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>90 (Hot weather)</td>
<td>1.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

(Y...N or an option)

(Y)

Are the concrete ingredients used by the ready mix concrete producer controlled regularly?
(Y...N or an option)

A

The source of aggregate may regularly be controlled by government, or local authorities. If there is no any independent authority to do this control, then the concrete purchaser can check the quality of the materials used.
(Y...N or an option)

Y
ESCON Consultation Continued

Is the maximum aggregate size less than 2.5 in (63 mm)?
(Y...N or an option)

Y

Can the ready mix concrete producer deliver the concrete at the required rate to avoid the formation of cold joints in the structure?
(Y...N or an option)

Y

Since the quality of the concrete ingredients are controlled, and/or there is a ready mixed concrete plant to deliver the concrete at the specified delivery time, and/or the maximum aggregate size does not exceed 2.5 in (63 mm), and/or the ready mixed concrete supplier can deliver the concrete at the required rate, then, you may select either ON-SITE or OFF-SITE batching method.

Have you selected off-site batching method?
(Y...N or an option)

Y

Now, you will have a session about off-site batching methods.

What is the concrete ordering method of the ready mix concrete purchaser?
1- The purchaser will be responsible for the selection of the proportions of the mixture,
2- Ready mix concrete producer will be responsible for the selection of the proportions,
3- Ready mix concrete producer will be responsible for the selection of the proportions with a minimum allowable cement content specified by the purchaser. This is applicable when the durability of concrete is important.
(1 to 3, ! if not known or an option)

2

It is recommended that, the purchaser should define the...
following when the ready mix concrete producer is responsible for the selection of the proportions for the required concrete.
1-size and shape of the aggregates,
2-slump or slumps desired at the point of delivery,
3-when air entrained concrete is specified, the air content at the point of discharge from truck mixer,
4-requirements for compressive strength as determined on samples taken from the transportation unit at the point of discharge,

Prior to the actual delivery, the purchaser should ask for a statement from the producer that includes the dry weights of the cement and saturated surface dry weights of the coarse and fine aggregates, type, and name of the admixture (if any) and the water content.

Is there a good supervision and careful quality control on the site?
(Y...N or an option)
N

The quality of the concrete produced is doubtful since there is no proper supervision on the site.

This is the end of the session about batching of concrete.

Do you want another session about other concreting operations (batching / mixing / transporting and placing / compacting / finishing of unformed concrete surfaces / curing )?
(Y...N or an option)
Y

The menu to select the other concreting operations will be repeated.

Please select the next concreting operation.
1- Concrete Batching
2- Concrete Mixing
3- Transporting and placing of concrete,
4- Concrete Compaction
5- Finishings of unformed concrete surfaces,
6- Concrete Curing.
(1 to 6, ! if not known or an option)
2
Now you will have a session about CONCRETE MIXING.

WELCOME to the CONCRETE MIXING module of ESCON.
(Type Y only or an option)
Y

The model will give you advice about the concrete mixing for the selected batching method.
(Type Y only or an option)
Y

Now, you will get some recommendations about mixing for off-site batched concrete.

Considering the permissible concrete delivery times given in the following tables, is it necessary to use the "cement last" loading method to load the mixers? [In this loading method the capacity of the truck mixer is reduced by about 25%].

<table>
<thead>
<tr>
<th>Concrete Delivery time (hr) for about 5% Tempera loss in the strength of concrete</th>
<th>(F) No delay before mix. Cement last loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>65 (normal weather)</td>
</tr>
<tr>
<td></td>
<td>90 (Hot weather)</td>
</tr>
</tbody>
</table>
| ***********************************************
<table>
<thead>
<tr>
<th>Concrete Delivery time (hr) for about 10% Tempera loss in the strength of concrete</th>
<th>(F) No delay before mix. Cement last loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>65 (normal weather)</td>
</tr>
<tr>
<td></td>
<td>90 (Hot weather)</td>
</tr>
</tbody>
</table>
| ***********************************************
Concrete Delivery time (hr) for about 15% Tempera loss in the strength of concrete

(F) No delay before mix. Cement last loading

<table>
<thead>
<tr>
<th>Temperature</th>
<th>2.5</th>
<th>4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 (normal)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90 (Hot)</td>
<td>1.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

When the cement last loading method is not necessary to be used, you can select either "slurry mixing" or "ribbon loading" or "sandwich loading" to load the truck mixers. The proper one will be recommended later.

Do you observe any cement balls while discharging the concrete from the mixer?

(Y...N or an option)

A

Cement balls are the accumulation of cement or sometimes cement and sand. The majority of cement balls are about 2-3 in. in diameter, but, occasionally they may be up to 6-8 in. in diameter.

Formation of cement balls is the result of a poor distribution of the cement when it comes in contact with water in the mixer. The major causes of formation of cement balls are as follow:
1- loading the mixer more than its rated capacity,
2- loading the water either too slow or too fast in ribbon loading,
3- loading cement too fast in ribbon loading,
4- having a small number of revolution of the truck mixer,
5- having worn or improperly designed blades in the mixer.
6- keeping the cement in contact with wet aggregate more than 2 hr without rotating the drum in the cement last loading.

The recommended solutions to avoid the formation of cement balls are as follow:

a) if "ribbon loading" method is used, charge the cement, water, and the aggregates simultaneously, uniformly and at the same time of duration.

b) undertake the mixer performance test known as "weight of coarse aggregate in a unit volume" to determine the effects of the design and wearing out of the mixer blades on the formation of cement balls. The weight of the coarse aggregate in a cubic foot of concrete from the first (discharging after 15%) and the last (discharging after 85%) portions of the batch should not vary more than 6% from the average of the two weights of the coarse aggregates. Excessive variation in the weight of coarse aggregate in a cubic foot of concrete indicates that, the mixer is improperly designed or the blades are excessively worn.

c) select "slurry mixing" method to load the truck mixers. Slurry mixing is a mixer loading method that, the whole mixing water is first loaded and then, the entire cement content is placed into the mixer, and they are mixed about 1min. before loading the other ingredients. This method avoids the formation of the cement balls and is the best method to improve the uniformity of the strength. Its disadvantage is that the loading time of the mixer is extended by about one minute.

It is recommended that, the minimum number of the revolution of the truck mixer is determined after undertaking the mixer performance test, known as "unit weight of air free mortar test".

Can you make this test to fix the minimum number of revolution of the mixer for a uniform mixing? (Y...!..N or an option)

N

The minimum number of revolution of the mixer should be fixed with the mixer performance test. But, since you can not do this, the minimum revolution number will be given arbitrarily as about 70 revolutions at a mixing speed of about 18 rpm.

The fine and the coarse aggregate of the concrete should be well distributed throughout
the discharge of concrete from the truck mixer. While discharging do you observe any excessive amount of coarse aggregate at the last portion of the batch? (Y...!..N or an option) N

It is good having a uniform concrete discharged from the mixer. Placing a down pipe to the end of the discharging chute to avoid the possible segregation of the concrete while dropping from the chute. The length of the pipe should be minimum 24 in. However, this procedure may not be applicable when there is not a 24 in height to drop the concrete.

Do you observe sand streaks in the concrete while it is flowing in the discharge chute specially in the 3/4th of the batch? (Y...!..N or an option) N

Do you observe any change in the color and in the slump of the concrete after discharging about the half of the batch? (Y...!..N or an option) N

No head packs formed at the head of the drum.

Has the concrete stiffened during agitating in the truck mixer? (Y...!..N or an option) A

Setting time of cement can be obtained either by using a Vicat apparatus or a Gillmore needle. Initial and final setting times change by temperature and type of the cement used. (Y...!..N or an option) N

Is the drum of the truck mixer rotated more than 300 times after introducing the cement and the mixing water or the aggregates? (Y...!..N or an option) N
Do you trust the quality of the concrete delivered by the truck mixer?
(Y...!...N or an option)
Y

Although an independent organisation or you observe and control the production procedures of ready mixed concrete, you are still advised to ask for the delivery tickets for the purposes of keeping records. But you may not require any test about the performance of the mixer.

This is the end of the session about off-site mixing of the concrete.

Do you want another session about other concreting operations (batching / mixing / transporting and placing / compacting / finishing of unformed concrete surfaces / curing)?
(Y...!...N or an option)
Y

The menu to select the other concreting operations will be repeated.

Please select the next concreting operation.
1- Concrete Batching
2- Concrete Mixing
3- Transporting and placing of concrete,
4- Concrete Compaction
5- Finishings of unformed concrete surfaces,
6- Concrete Curing.
(1 to 6, ! if not known or an option)
3

Now you will have a session about TRANSPORTING and PLACING of the CONCRETE.

WELCOME to CONCRETE TRANSPORTATION AND PLACING
(Type Y only or an option)
Y
ESCON Consultation Continued

Now, you will have a session about transporting of concrete.
All of the concrete transporting equipment used should be washed and cleaned at the end of the day.

What kind of equipment are you using for transporting and placing of the concrete?
1- Wheelbarrow
2- Buggy (Concrete cart)
3- Concrete Hopper
4- Bucket
5- Agitating Truck
6- Non-agitating Truck
7- Chute
8- Belt Conveyor
9- Dumper
10- Concrete Pumps
11- Drop Chute or Elephant Trunk
12- Rail-car
13- Hoist
(1 to 13, ! if not known or an option)

Now you will have a session about agitating trucks

What is the expected concrete delivery time?
1- up to 45 min.
2- More than 45 min.
(1 to 2, ! if not known or an option)

You can use either revolving drum type (truck-mixer) or agitational truck bodies, depending on the conditions, like economy, availability etc.

In some project, during the transporting of the concrete the permissible slump loss is defined. If it is not specified, it can be accepted 1 in (25 mm). In your case, is the expected or experienced slump loss more than that? (Y...!..N or an option)

N

There is no undesirable slump loss.
Have you got consultation for every of the equipment used to transport the concrete? (Y..!..N or an option)
N
Please select the next equipment for consultation.

What kind of equipment are you using for transporting and placing of the concrete?
1- Wheelbarrow
2- Buggy (Concrete cart)
3- Concrete Hopper
4- Bucket
5- Agitating Truck
6- Non-agitating Truck
7- Chute
8- Belt Conveyor
9- Dumper
10- Concrete Pumps
11- Drop Chute or Elephant Trunk
12- Rail-car
13- Hoist
(1 to 13, ! if not known or an option)

Now you will have a session about concrete pumps

What is the slump of the concrete?
1- less than 2.0 in.
2- 2.0 - 5 in.
3- more than 5 in.
(1 to 3, ! if not known or an option)

A slump of 2.0 to 5 in is the best range for pumping the concrete. But, a slump loss during the pumping should be considered. In every 100 ft of hose pipe, there is a slump loss equal to 3/4 in. In every 1000 ft of steel pipes there is about 1 in slump loss. However, the slump loss in the pipes can be reduced by using admixtures as retarders or water reducers.

Is it a downhill pump? (Y..!..N or an option)
N
What is the maximum aggregate size of the concrete?
1- up to 2.5 in
2- more than 2.5 in
(1 to 2, if not known or an option)

The maximum permissible aggregate size for a pumpable concrete is 2.5 in. However, for pumping the concrete the most suitable aggregate size is 3/4 in. Round and well graded (no gap in grading) aggregate is good for pumping. The grading of sand should be so that, (15-20)% passing no:50 screen and (3-6)% passing no:100 mesh. In any case the total void in the combined aggregate should not exceed 25% of the bulk volume.

What kind of pipes are used for pump lines?
1- steel pipes
2- flexible hoses
3- aluminium pipes
4- plastic pipes
(1 to 4, if not known or an option)

Flexible hoses are light and mostly used with squeeze pumps and hydraulic booms or at the end of the steel pipes. Any puncture or tear in the inner lining can cause blockage and calls for a higher pressure. Hoses are recommended to be reinforced by helical wire to prevent kinking. They are not recommended for long distances, because, they require more pressure than steel pipes, ie the pressure required to move the concrete in 1m of hose is equal to 2m of that steel pipe.

What is the relation of the cement content and the void content of the combined aggregates in volume?
1- void content is higher than cement content by more than 4%,
2- void content is less than cement content by more than 10%,
3- none of the above,
4- the relation is not known.
(1 to 4, if not known or an option)
VOID CONTENT of fine and coarse aggregates can be measured by using a void measuring apparatus. Void contents depend on the percentage and type of the aggregates. Round aggregates give a less void content than crushed or elongated aggregates. To reduce the void content, it is recommended to have fine aggregate percentage about 40% of the total aggregates. CEMENT CONTENT of the mixture should be minimum 280kg/cu m to fill the voids. But very high cement content will make the mixture very sticky and pumping will again be difficult. (1 to 4, ! if not known or an option)

Please answer the next question to get recommendations about arranging the cement content.

What is the required strength of the concrete?
1- high strength
2- medium strength
3- low strength
(1 to 3, ! if not known or an option)

A

HIGH STRENGTH concrete is the concrete with a compressive strength of more than 35MPA.
MEDIUM STRENGTH concrete is the concrete in between high and low strength concretes.
LOW STRENGTH concrete is the concrete with an aggregate/cement ratio of more than 6 or with a compressive strength of less than 15MPA.
(1 to 3, ! if not known or an option)

1

When the strength of the concrete is more than 35 MPa, a high friction between the concrete and the pipe may occur. High cement content with a relatively low water/cement ratio produces high surface area under the frictional force. The general remedy is to decrease the surface area of the particles as much as possible by increasing the proportion of materials in the range of 5mm to no:7 sieve (4.76mm-2.36mm). If possible the use of wetting agent is also a solution.

Have you lubricated the pipes before starting the pumping?
(Y..!..N or an option)
Y
Proper lubrication of the pipes reduces the possibility of blockage of the pipes. The effect of lubrication lasts about only a few minutes in hot weather and 15-20 min. in cold weather if the pumping stops. So, if necessary slow down the rate of the pumping, but do not interrupt the pumping.

Have you got consultation for every of the equipment used to transport the concrete? (Y...!...N or an option)  
Y

This the end of the consultations about concrete transporting equipment.

Is your work
1- columns or walls or deep beams concreting?  
2- slabs or general mass concreting.  
(1 to 2, ! if not known or an option)  
2

Now you will get some recommendations about placing of the concrete in the slab or general mass concrete.

What type of slab are you concreting?  
1- sloping surfaces  
2- monolithic placing of slab, columns, beams and walls (if any)  
3- flat slab.  
(1 to 3, ! if not known or an option)  
3

While concreting the flat slab or a mass concrete, the concrete should be placed in horizontal layers. The thickness of each layer should be up to 375-600 mm (15-24 in) for mass concrete and up to 300-500 mm (12-20 in) for the structural concrete. From a durability point of view, it is recommended to start the concreting from the corners. In this way, the accumulation of the fine particles at the corners is avoided. In order to prevent segregation of the concrete it is recommended to pay attention to these points;  
1- dump the concrete into the face of already placed concrete but not away from the concrete in place,  
2- if a rock pocket is formed, shovel the rocks from this
place onto softer sand area. But, do not try to shovel mortar on top of the rock pocket,
3- deposite concrete as near as possible to its final location. Do not let the concrete to be moved by shovel laterally more than 2-3 ft,
4- do not deposite a large stack that can not be vibrated properly or that needs to be moved horizontally more than 2-3 ft.

Is there other type of slabs you need to get recommendations? (Y..!..N or an option) N

This the end of the recommendations about slab placing .

Is the appearance of concrete important? (Y..!..N or an option) N

This the end of the consultation about transporting and placing of the concrete.

Do you want another session about other concreting operations (batching / mixing / transporting and placing / compacting / finishing of unformed concrete surfaces / curing ) ? (Y..!..N or an option) Y

The menu to select the other concreting operations will be repeated.

Please select the next concreting operation.
1- Concrete Batching
2- Concrete Mixing
3- Transporting and placing of concrete,
4- Concrete Compaction
5- Finishings of unformed concrete surfaces,
6- Concrete Curing.
(1 to 6, ! if not known or an option) 4
ESCON Consultation Continued

Now you will have a session about CONCRETE COMPACTION.

WELCOME to CONCRETE COMPACTION.
(Type Y only or an option)
Y

What is the type of your concreting work?
1- structural elements concreting
2- mass concreting
3- floors concreting
4- pavements concreting
(1 to 4, ! if not known or an option)
1

You will have a session about the compaction of the concrete for the structural elements. In such a concreting work, the recommended compaction methods are internal vibration, form vibration, or in some cases manual compaction. However, if the appearance of the concrete is important, it is recommended to use internal vibrators with a frequency of more than 8000 vibration per minute.

What kind of a structural elements are you concreting?
1- concreting works where the use of an internal vibrator is impracticable, like sidewalls or arch of the tunnel,
2- walls or beams concreting works, where the opening of the formwork is more than 750 mm, and the reinforcement is so congested that the internal vibrators can not get through the reinforcement
3- slab concreting works, where the reinforcement is so congested that the internal vibrators can not get through the reinforcement,
4- column, wall, or beam concreting works where the opening of the form is less than 750 mm, and the reinforcement is so congested that, the internal vibrator can not get through the reinforcement,
5- none of the above.
(1 to 5, ! if not known or an option)
5

If the use internal vibration method is applicable then always internal vibration will be preferred. Internal vibration can be made either by internal vibrators, or by manual rodding.
What is the selected internal compaction method?
1- vibrator
2- manual
(1 to 2, ! if not known or an option)

You will have a session about the use of internal vibrators. If more than one vibrators are used, then, one of them should be employed for "melting" down the concrete immediately after the placing. The other vibrator should be used to compact the concrete after flattening the concrete. In this case, it is recommended to work as a team, rather than individuals. Each vibrator operator should know what his allotted task is.

What is the consistency of the concrete?
1- stiff (0-25 mm slump)
2- stiff plastic (25-70 mm slump)
3- plastic (75-125 mm slump)
4- flowing (more than 125 mm slump)
(1 to 4, ! if not known or an option)

Stiff plastic concrete (25-75 mm slump) is usually used in general construction such as walls, columns, beams, heavy slabs etc. The recommended internal vibrator should have the following characteristics and performances;
1- diameter of head : 2-3.5in (50-90 mm)
2- recommended frequency : 6000-12000vibr/hr (130-200Hz)
3- suggested amplitude : 0.025-0.05in (0.6-1.3 mm)
4- approximate radius of action : 7-14in (180-360 mm)
5- approximate rate of compaction : 6-20cu yd/hr (4.6-15cu m/hr)

What kind of structural element are you compacting?
1- columns,
2- walls,
3- flat slabs,
4- sloped slabs,
5- concreting around openings, ducts etc.
(1 to 5, ! if not known or an option)
It is recommended to insert the vibrator at regular spaces which is equal to about 1.5 times the radius of action of the vibrator. When the thickness of the layer is less than the head length of the vibrator, then its full length should be inserted at a regular slope to penetrate the entire length of the head. Otherwise, the head will be overheated. It is also recommended not to touch the vibrator either to the form or the reinforcement. Especially when the appearance of the concrete is important, touching the vibrator on the form may cause blemishes. If the vibrator touches the reinforcement, it may cause the displacement of the reinforcement unless it is rigidly held. If the reinforcement is partly embedded and already stiffened, but is not yet one day old, then touching the reinforcement is detrimental.

Although the heaps should be avoided while placing, sometimes they are unavoidable. To flatten the heap, the poker should be inserted around its perimeter. The flattening should not be started from the top of the heap. Normal compaction will be started after flattening is completed.

Do you want a session about compaction of other structural elements also (column/wall/flat slab/sloped slab/ openings) ?
(Y...!..N or an option)
N

Do you penetrate vibrator in the concrete quickly?
(Y...!..N or an option)
Y

It is recommended to penetrate the vibrator in the concrete quickly. In that case the vibration will be started not from the top, but from the bottom. Therefore, the air bubbles at the bottom can be expelled without any difficulty.

After completion of the compaction, do you pull out the vibrator slowly?
(Y...!..N or an option)
N

If you pull out the vibrator from the concrete quickly, (a lot quicker than 3 in/sec) the hole left by the vibrator
ESCON Consultation Continued

head will not be closed up by the concrete and some air can be trapped in. This is dangerous and must not be permitted. The recommended pulling out rate is about 3in/sec or less.

Have you noticed one or more of the signs given below before halting the vibration?
- the appearance of cement paste near the forms or embedded parts,
- starting a glistening on the surface of the concrete
- the coarse aggregates blending into the surface, but not completely dissapeared,
- cessation of the rising of the air bubbles,
- changing the speed and sound of the vibrator, (operator can feel the changing of the speed and the sound that approach to a constant tone.).
(Y...!..N or an option)
N

Stopping the vibration before observing one of the points given above will cause undervibration. Undervibration is undesirable, since some of the air voids are left in the concrete. One percent of air voids left in the concrete will reduce the strength of the concrete about 5-6 percent. So the vibration should be maintained until observing one of those points given above.

Do you use compressed air vibrator?
(Y...!..N or an option)
N

Whether you use electrical or gasoline engine vibrators, depending on the capacity of the job, you are reminded to keep at least one spare vibrator in case of breaking down. Regular controlling of the frequency and amplitude of the vibrators is essential to have a good compaction.

Have you noticed any settlement cracks?
(Y...!..N or an option)
N

Have you observed an excessive bleeding which its internal effects may be detrimental?
(Y...!..N or an option)
N
When no settlement cracks are observed and the bleeding is not excessive, revibration of the concrete is not necessary. Revibration brings additional cost and has a detrimental risk if it is performed too late for the concrete to be converted into the plastic form again.

Have you used air entraining admixture?
(Y...N or an option)
N

Is the appearance of the concrete important?
(Y...N or an option)
N

Is there any leakage at the construction joints or at any other joints?
(Y...N or an option)
N

Do you want another session for the other types of concreting works (structural element/ mass concreting / floors concreting / pavements concreting)?
(Y...N or an option)
N

This the end of the consultation about the compaction of the concrete.

Do you want another session about other concreting operations (batching / mixing / transporting and placing / compacting / finishing of unformed concrete surfaces / curing )?
(Y...N or an option)
Y

The menu to select the other concreting operations will be repeated.

Please select the next concreting operation.
ESCON Consultation Continued

1- Concrete Batching
2- Concrete Mixing
3- Transporting and placing of concrete,
4- Concrete Compaction
5- Finishings of unformed concrete surfaces,
6- Concrete Curing.
(1 to 6, ! if not known or an option)

Now you will have a session about FINISHINGS of UNFORMED CONCRETE SURFACES.

WELCOME to the FINISHINGS of UNFORMED CONCRETE SURFACES.
(Type Y only or an option)

Y

What is the type of your floor, or slab?
1- residential or tile covered floors with light foot traffic,
2- floors for offices, churches, schools, hospitals with foot traffic,
3- ornamental residential floors with foot traffic,
4- drives, garage floors, and sidewalks for residence with light foot and pneumatic wheel traffic,
5- light duty industrial, commercial floors or slabs with foot and pneumatic wheels traffic,
6- single course, integral topping industrial floors or slabs with abrasive wear wheels traffic,
7- bonded two course heavy industrial floors or slabs with steel-tire vehicles traffic that causes severe abrasion.
8- unbonded two course floors for the types of 4,5,6,7.
(1 to 8, ! if not known or an option)

Now, the procedures for finishing of the industrial floors or slabs will be explained.

Does the floor require a special monolithic surface treatment to improve the wearing resistant?
(Y...N or an option)

A
In some cases, where floor is required to have a very high resistance to wearing, a highly wearing resistant material is applied on the surface of the floor as topping.

(Y...!...N or an option)

N

The recommended finishing procedure for industrial floors or slabs without monolithic surface treatment for wearing resistance is as follow;
- complete the screeding before any excess moisture or bleeding water appears on the surface,
- bullfloating or darbying should be performed just after the screeding but, must be completed before any excess of the moisture or bleeding water appears on the surface,
- waiting is essential for a slight stiffening of the concrete before further proceedings. No subsequent operation should be performed until the concrete will sustain the foot pressure with only about 3-6mm indentation. ANY FINISHING OPERATION UNDERTAKEN WHILE THERE IS EXCESS MOISTURE OR BLEEDING WATER ON THE SURFACE CAUSES DUSTING AND SCALING.
- edging (if necessary) should be done after all of the water dissapears,
- jointing should be undertaken either at the same time of the edging or just after the edging. If saw machine will be used, cutting should be done as soon as the surface of the concrete is firm enough to avoid the tearing or damaging by the blades of the machine. However, this procedure should be performed before the formation of random shrinkage cracks in the slab. This time is usually about 4-12hr after the placing,
- floating will be done after the edging and the hand jointing. But, the floating should not be started unless the water sheen on the surface of the concrete disappears and the concrete is hard enough carry a man. The floating will go on until the large aggregates are embedded beneath the surface and a thin layer of mortar is obtained on the surface. Excessive floating may produce a floor that will dust or craze,
- after the floating, trowelling should be performed by using a steel trowel. The trowelling must be started after the evaporation of the excess moisture brought to the surface by floating, and the concrete looses its stickyness. The practical method to determine the trowelling time is the use of the palm to see if the concrete is still sticky.
- Sprinkling of the cement or a mixture of the sand and the cement on the surface should be prohibited.
- if hand trowelling is used, any surplus mortar on the surface will be scraped by exerting a considerable physical pressure on the trowel.
The trowelling creates a very smooth and slippery surface. This slipperiness can be reduced by using a soft brush or a broom.

- Additional trowelling is recommended to increase the density of the concrete, and to have a higher resistance to wearing. If power trowelling is used, the blades can be tilted at a greater angle while the additional trowelling is performed. Second trowelling may be started as soon as the moisture on the surface of the concrete completely evaporated.

- For these floors, a minimum of three trowelling should be done.

Is it necessary to use the floor newly finished?
(Y..!..N or an option)
N

It is recommended that, a new floor should be protected for about 2 days from foot traffic and about 7 days from wheel traffic.

Do you want another session with another type of the floors?
(Y..!..N or an option)
N

This the end of consultation about finishings of the unformed concrete surfaces.

Do you want another session about other concreting operations (batching / mixing / transporting and placing / compacting / finishing of unformed concrete surfaces / curing )?
(Y..!..N or an option)
Y

The menu to select the other concreting operations will be repeated.

Please select the next concreting operation.
1- Concrete Batching
2- Concrete Mixing
3- Transporting and placing of concrete,
4- Concrete Compaction
5- Finishings of unformed concrete surfaces,
Now you will have a session about CONCRETE CURING.

WELCOME to CONCRETE CURING.
(Type Y only or an option)

Curing methods largely depend on the weather conditions. Which one of the following conditions fits your job?
1- hot weather
2- normal weather
3- cold weather
4- the weather condition can not be defined as above.
(Type 1 to 4, ! if not known or an option)

A HOT WEATHER conditions can be defined as, a high air temperature, low humidity, and high wind velocity that may impair the quality of the fresh concrete.
COLD WEATHER conditions can be defined as, a low air temperature that is difficult to keep the temperature of the concrete above 5 (40 F). NORMAL WEATHER condition is the one which is in between the hot and cold weather conditions.
(Type 1 to 4, ! if not known or an option)

2 The method of curing will be defined depending on your answer about the weather conditions.

Now, the proper curing methods will be defined in detail.
(Type Y only or an option)

Y

This is the session about curing of concrete in normal weather.
The minimum duration of the curing should be either the necessary time for the concrete to get a 70% of the
specified strength, or the times defined below, whichever is less:
7 days for ordinary portland cement concretes and concretes for reinforced massive sections,
3 days for rapid hardening cement concretes
14 days for unreinforced massive sections containing no pozzolans,
21 days for massive sections containing pozzolans.

If a high strength concrete is required (41 MPa or 6000 lb/sq.in.), the minimum curing period is recommended to be 28 days.

How is surface of the concrete?
1- formed surface,
2- unformed surface.
(1 to 2, ! if not known or an option)

This is the session about the curing of formed concrete surfaces. Normally the curing should be maintained for the duration specified above. But the ceiling surfaces or the indoor surfaces of the walls require no further curing if the forms are left in position for 4 days or more.

Is the water/cement ratio equal or greater than 0.50 by weight?
(Y..!..N or an option)

Have you got an abundance of water on the site to make continuous water curing?
(Y..!..N or an option)

Have you got a good supervision on the site to provide a continuous water curing?
(Y..!..N or an option)

Since there is no enough water for curing, or there is no a good supervision to provide a continuous water curing, it is recommended to use a curing method which depends on preventing the evaporation from the concrete surfaces. Evaporation preventing curing methods include liquid
membrane compound, plastic sheets, or bituminous papers. Curing of formed surfaces should be started within 1/2 hr of the removing the forms.

Is the appearance of the concrete important? (Y..!..N or an option)
N

Surface treatment;
1- is immediately after the removing of the formwork, or for unformed surfaces as soon as the surface hardens,
2- does not exist,
3- is several days after removing the formwork or for unformed surfaces several days after of casting.
(1 to 3, ! if not known or an option)
1

Since the appearance of the concrete is not important, and the surface treatment is not a problem, it is recommended to apply one of the following curing methods: clear resin based, or wax-based white or gray liquid membrane compound, bituminous paper, or white plastic sheets. The rate of the application of the wax-based compounds should be about 150 sq.ft/gal. The recommended coverage range of resin-based compound is 200 sq. ft per gal. But, curing compound is not recommended to the surfaces that require a positive bond, unless, it has been demonstrated that, the membrane can be satisfactorily removed before any subsequent application. If white plastic sheets or bituminous papers is applied, then it is recommended to overlap the edges about several inches and to secure all of the edges properly against the wind. On very hot days, flowing the water on the surface of the concrete under the cover gives very good results. It should be made sure that, there is no pinholes, or if there is few, double thicknesses are used.

Do you want another session for the other type of the surface (formed/unformed)? (Y..!..N or an option)
Y

The question to select the other type of the surface will be repeated.
How is surface of the concrete?
1- formed surface,
2- unformed surface.
(1 to 2, ! if not known or an option)

This is the session about curing of unformed concrete surfaces. Curing of unformed concrete surfaces should be started as soon as the surface is hard enough to support the curing material without marking the concrete. Any delay to start the curing causes the loss of the moisture and results in a weaker concrete.

Is the surface
1- horizontal?
2- sloped?
(1 to 2, ! if not known or an option)

Is the water/cement ratio equal or greater than 0.50 by weight?
(Y...!...N or an option)

Have you got an abundance of water on the site to make continuous water curing?
(Y...!...N or an option)

Have you got a good supervision on the site to provide the concrete surfaces continuously wet during the curing?
(Y...!...N or an option)

Is the appearance of the concrete important?
(Y...!...N or an option)
Surface treatment;
1- is immediately after the removing of the formwork, or for unformed surfaces as soon as the surface hardens,
2- does not exist,
3- is several days after removing the formwork or for unformed surfaces several days after of casting.
(1 to 3, ! if not known or an option)

Since the appearance of the concrete is not important, and the surface treatment is not a problem, it is recommended to apply one of the following curing methods: clear resin based, or wax-based white or gray liquid membrane compound, bituminous paper, or white plastic sheets. The rate of the application of the wax-based compounds should be about 150 sq.ft/gal. The recommended coverage range of resin-based compound is 200 sq. ft per gal. But, curing compound is not recommended to the surfaces that require a positive bond, unless, it has been demonstrated that, the membrane can be satisfactorily removed before any subsequent application. If white plastic sheets or bituminous papers is applied, then it is recommended to overlap the edges about several inches and to secure all of the edges properly against the wind. On very hot days, flowing the water on the surface of the concrete under the cover gives very good results. It should be made sure that, there is no pinholes, or if there is few, double thicknesses are used.

Do you want another session for other type of concrete surface (horizontal/sloped)?
(Y...!...N or an option)

N

Do you want another session for the other type of the surface (formed/unformed)?
(Y...!...N or an option)

N

This is the end of the session about the curing of the concrete in normal weather.
ESCON Consultation Continued

Is your job a mass concreting work such as piers, abutments, dams, heavy footings, or similar massive constructions? (Y..!..N or an option) N

Do you want another session about other concreting operations (batching / mixing / transporting and placing / compacting / finishing of unformed concrete surfaces / curing)? (Y..!..N or an option) N

Do you want to see how much the expected strength of the concrete can be reduced if some of the recommendations of the model are ignored? (Y..!..N or an option) N

This is the end of the sessions.

Do you want to get a printed specification on the workmanship of the concrete operations covered in this session?

PLEASE MAKE SURE THAT THE PRINTER IS CONNECTED TO THE COMPUTER AND IS READY TO OPERATE IF YOU ANSWER THIS QUESTION "YES" (Y..!..N or an option) Y

Do you want to have another session? (Y..!..N or an option) N

GOOD BYE !!!
APPENDIX D : ESCON Specification

<table>
<thead>
<tr>
<th>Name of the company</th>
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<tbody>
<tr>
<td>Name of the contract</td>
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<tr>
<td>Location of the contract</td>
<td>:</td>
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<tr>
<td>Starting date of the contract</td>
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SPECIFICATION ON THE WORKMANSHIP REQUIREMENTS OF CONCRETE BATCHING

ORDERING OF THE CONCRETE
The ready mixed concrete purchaser should specify the following when the ready mixed concrete producer is responsible for the selection of the proportions of the mixture:
1-size and shape of the aggregates,
2-slump or slumps desired at the point of delivery,
3-when air entrained concrete is specified, the air content at the point of discharge from truck mixer,
4-requirements for compressive strength as determined on samples taken from the transportation unit at the point of discharge,

Prior to the actual delivery, the purchaser should ask for a statement from the producer including the dry weights of cement and saturated surface dry weight of coarse and fine aggregates, type, and name of admixture (if any) and water content.

SPECIFICATION ON THE WORKMANSHIP REQUIREMENTS FOR CONCRETE MIXING

CEMENT BALLS
When cement balls are observed while discharging the concrete from the truck mixer, the following precautions should be considered:

a) if the truck mixers are loaded by "ribbon loading", the cement, water, and aggregates should be charged into the mixer simultaneously, uniformly and for the same duration.

b) the design and the degree of wearing of the blades in the mixer also affect the formation of the cement balls. Therefore, mixer performance test known as "weight of coarse aggregate in a unit volume" should be undertaken. The weight of the coarse aggregate in a cubic foot of concrete from the first (discharging after 15%) and the last (discharging after 85%) portions of the batch should not vary more than 5% from the average of the two weights of the coarse aggregates. Excessive variation in the weight of coarse aggregate in a cubic foot of concrete indicates that, the mixer is improperly designed or the blades are excessively worn, and should be avoided.

c) if the above precautions can not avoided the formation of cement balls, the mixers should be loaded by "slurry mixing". In this method, first, the whole mixing water should be loaded and then, the entire cement content is placed into the mixer. These materials should be mixed about 1min. before loading the other ingredients.

The number of revolution of the truck mixer should be a minimum of about 70 revolutions at the mixing speed of 18 rpm.
UNIFORMITY OF CONCRETE
While discharging the concrete from truck mixers, segregation should be avoided by a proper end control at the discharging end of the chute of the mixer. An acceptable end control is a down pipe with a minimum height of about 600 mm (24 in). However, this procedure may not be applicable when there is not a 600 mm (24 in) drop at the end of the chute.

SPECIFICATION ON THE WORKMANSHIP REQUIREMENTS OF TRANSPORTING AND PLACING CONCRETE

PUMPING CONCRETE
The slump range for pumping the concrete should be from 50 to 125 mm (2-5 in). But, slump loss during pumping should also be considered. In every 30 m (100 ft) of a hose pipe, a slump loss of about 19 mm (3/4 in), and in every 300 m (1000 ft) of steel pipes a slump loss of about 25 mm (1 in) should be considered. However, the slump loss in the pipes can be reduced by using admixtures as retarders or water reducers.

The maximum permissible aggregate size for pumpable concrete is 63 mm (2.5 in). However, for pumping the concrete the most suitable aggregate size is 19 mm (3/4 in).
Round and well graded (no gap in grading) aggregate is good for pumping. The grading of sand should be so that, (15-20)% passing no:50 screen and (3-6)% passing no:100 mesh. In any case the total void in the combined aggregate should not exceed 25% of the bulk volume.

Although aluminium pipes are very light, they should not be used for concrete pumplines, especially in hot weather and for long pipelines.

When the strength of the concrete is more than 35 MPa, high friction between the concrete and the pipe may occur. This high frictional force may block the pipeline. Therefore, the surface area of the particles should be decreased by increasing the proportions of materials in the range of 5mm to no:7 sieve (4.76mm-2.36mm). If possible the use of a wetting agent may be considered.

The pipelines should be lubricated before commencing the pumping. This lubrication should be made by grout or mortar. About 1 cu yd of grout or mortar should be pumped for each 300 M (1000 ft) of the pipeline and just after that, the concrete should be pumped. The effect of lubricating lasts about only a few minutes in hot weather and 15-20min. on cold weather. So, when necessary the rate of pumping can be reduced, but not interrupted.
PLACING CONCRETE
While concreting a flat slab or in a mass concreting work, the concrete should be placed in horizontal layers. The thickness of each layer should be up to 375-600 mm (15-24 in) for mass concrete and up to 300-500 mm (12-20 in) for structural concrete. From a durability point of view, it is necessary to start concreting at the corners and to finish at the center of the slab. In this way, the accumulation of the fine particles at the corners is avoided. In order to prevent the segregation, the following points should be considered:

1- Concrete should be dumped into the face of already placed concrete.
2- If a rock pocket is formed, the rocks should be shovelled from this place onto softer sand area. Shovelling the mortars on top of the rock pockets is not a solution.
3- Concrete should be deposited as near as possible to its final location. The concrete should not be moved by shovel or other means laterally more than 600-800 mm (2-3 ft).
4- A large stack of the concrete should not be deposited. It may not be vibrated properly or may need to be moved horizontally more than 600-900 mm (2-3 ft).

SPECIFICATION ON THE WORKMANSHIP REQUIREMENTS OF CONCRETE COMPACTION

INTERNAL VIBRATORS
If more than one vibrators are used, one of them should be employed for "melting" down the concrete immediately after the placing. The other vibrator should be used to compact the concrete after flattening of the concrete. In this case, it is recommended to work as a team, rather than individuals. Each vibrator operator should know what his allotted task is.

When the consistency of the concrete is stiff plastic (25-75 mm slump), the internal vibrators should have the following characteristics and performances:

1- Diameter of head: 50-90 mm (-3.5 in)
2- Recommended frequency: 8000-12000vibr/hr (130-200Hz)
3- Suggested amplitude: 0.6-1.3 mm (0.025-0.05 in)
4- Approximate radius of action: 180-360 mm (7-14 in)
5- Approximate rate of compaction: 4.6-15 cu m/hr (6-20 cu yd/hr).
COMPACTATION OF FLAT SLABS

The vibrator should be inserted at regular spaces which is equal to about 1.5 times the radius of action of the vibrator. When the thickness of the layer is less than the head length of the vibrator, then its full length should be inserted at a regular slope to penetrate the entire length of the head. Otherwise, the head will be overheated. While operating, the vibrator should not be touched on the form or the reinforcement. Especially when the appearance of the concrete is important, touching the vibrator on the form causes blemishes. If the vibrator touches the reinforcement, it may cause the displacement of the reinforcement unless it is rigidly held. If the reinforcement is partly embedded into the concrete and the concrete is not yet one day old, then touching the reinforcement is detrimental, and should be avoided.

Although the heaps should be avoided while placing, sometimes they are unavoidable. To flatten the heap, the poker should first be inserted around its perimeter. The flattening should not be started from the top of the heap. Normal compaction will be started after flattening is completed.

Internal vibrators should be penetrated into the concrete quickly. In that case the vibration will be started not from the top, but from the bottom. Therefore, the air bubles at the bottom can be expelled without difficulty.

The internal vibrators should be pulled out slowly, (about 75 mm/sec or less) to give the concrete enough time to close up the hole left by the vibrator.

The vibration of the concrete should be maintained until one of the following signs is observed:
- the appearance of cement paste near the forms or embedded parts,
- starting of a glistening on the surface,
- the coarse aggregates blending into the surface, but not dissapearing completely,
- cessation of the rise of the air bubbles,
- changing the speed and the sound of the vibrator, (operator can feel the changing of the speed and the sound that approach to a constant tone.).

LEAKAGE

Leakage causes imperfections such as, sand streak on the formed surfaces and removing of grout from the mixture. Therefore, leakage of the grout through any kind of joint should be avoided. To prevent the leakage, the following two precautions should be considered:
1- use 2.5X10cm closed cell rubber or polyvinyl chloride foam strips,
2- extend the form sheathing about 3mm beyond the form framing members since, thin edges of sheathing will conform more easily and tightly to adjacent surfaces than wide and unyielding faces of form framing members.
SPECIFICATION ON THE WORKMANSHIP REQUIREMENTS
UNFORMED CONCRETE SURFACES.

The finishing procedures for industrial floors without monolithic surface treatment for wearing resistance is as follow;
- the screeding should be completed before any excess moisture or bleeding water appears on the surface,
- bullfloating or darbying should be performed just after the screeding but, must be completed before any excess of moisture or bleeding water appears on the surface,
- waiting is essential for a slight stiffening of the concrete before further proceedings. No subsequent operation should be performed until the concrete will sustain the foot pressure with only about 3-6mm indentation. ANY FINISHING OPERATION UNDERTAKEN WHILE THERE IS EXCESS MOISTURE OR BLEEDING WATER ON THE SURFACE CAUSES DUSTING AND SCALING.
- edging (if necessary) should be done after all of the water dissapears,
- jointing (when necessary) should be undertaken either at the same time of the edging or just after the edging. If a saw machine is to be used, cutting should be done as soon as the surface of the concrete is firm enough to avoid the tearing or damaging by the blades of the machine. However, this procedure should be performed before the formation of random shrinkage cracks in the slab. This time is usually about 4-12hr after the placing,
- floating should be done after the edging and the hand jointing. But, the floating should not be started unless the water sheen on the surface of the concrete disappears and the concrete is hard enough carry a man. The floating will go on untill the large aggregates are embedded beneath the surface and a thin layer of mortar is obtained on the surface. Excessive floating may produce a floor that will dust or craze.
- after the floating, trowelling should be performed by using a steel trowel. The trowelling must be started after the evaporation of the excess moisture brought by floating, and when the concrete looses its stickyness. The practical method to determine the trowelling time is the use of the palm to see if the concrete is still sticky. Sprinkling of cement or a mixture of sand and cement on the surface should be prohibited. If hand trowelling is used, any surplus mortar on the surface will be scraped by exerting a considerable physical pressure on the trowel. The trowelling creates a very smooth and slippery surface. This slipperiness can be reduce by using a soft brush or a broom,
- additional trowelling is required to increase the density of the concrete, and to have a higher resistance to wearing. If power trowelling is used, the blades can be tilted to a greater angle while the additional trowelling is performed. Second trowelling may be started as soon as the moisture on the surface of the concrete has completely evaporated.
- for these floors, a minimum of three trowelling is required.

A new floor should be protected for 2 days from foot traffic and 7 days from wheel traffic. If a new floor is to have concentrated traffic, the route of the traffic should be covered by hardboard sheets.
SPECIFICATION ON THE WORKMANSHIP
REQUIREMENTS OF CONCRETE CURING

NORMAL WEATHER CONCRETE CURING

The minimum duration of curing should be either the necessary time for
the concrete to achieve 70% of the specified strength, or the times
defined below, whichever is less:
7 days for ordinary portland cement concretes and reinforced massive
sections,
3 days for rapid hardening cement concretes
14 days for unreinforced massive sections containing no pozzolans,
21 days for massive sections containing pozzolans.

If a high strength concrete is required (41 MPa or 6000lb/sq.in.), the
minimum curing period should be extended up to 28 days.

CURING OF FORMED CONCRETE SURFACES

When there is not enough water for curing, or there is inadequate
supervision on the site, one of the "evaporation preventing" curing
methods should be used. For formed surfaces the evaporation
preventing curing methods include liquid membrane compound, plastic
sheets, or bituminous papers. Curing of these surfaces should be
performed by using one of these materials within 1/2 hr of the removing
the forms. If a liquid membrane is to be used, it should not be used on
the surfaces that will receive paint, tile, or another layer of
concrete unless it has been demonstrated that the compound can be
removed or dissipates satisfactorily.

When the appearance of the concrete is not important, and the surface
treatment does not create any curing problem, it is required to apply
one of the curing methods: clear resin based or wax-based white or
grey liquid membrane compound, bituminous paper, or white plastic
sheets. The rate of the application of the wax-based compounds should
be 150 sq.ft/gal. The recommended coverage range of resin-based
compound is 200 sq.ft/gal.

If white plastic sheets or bituminous papers is applied, the edges
should be overlapped several inches and secured properly against to
the wind. It should be ensured that there is no pinholes, or if there
is few, double thicknesses are used.

CURING OF UNFORMED CONCRETE SURFACES

The curing should be started as soon as the surface is hard enough to
support the curing material without marking the concrete. Any delay to
start the curing causes the loss of the moisture and results in weaker
concrete.

The curing procedures for unformed concrete surfaces should be as
specified above for formed concrete surfaces.