Wet-process sprayed mortar and concrete for repair

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Wet-Process Sprayed Mortar and Concrete for Repair

By

Christopher Ian Goodier

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy of Loughborough University

30th June 2000

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ABSTRACT

The primary aim of this research was to improve the understanding of the influence of the process and the mix constituents on the fresh and hardened properties of wet-process sprayed mortars and concretes. The main objectives were: to improve the wet-mix spraying process; to specify, measure and optimise in-situ properties; and to disseminate the information obtained in appropriate form to practising engineers to accelerate the use of wet-process sprayed mortar and concrete for repair.

The research focused on three types of repair mortars/concretes: pre-blended proprietary mortars (<3 mm aggregate), designed laboratory/site batched mortars and fine concretes (<8 mm aggregate). Thirty mixes were pumped and sprayed using seven pumping/spraying systems. Nineteen types of test were conducted to measure the fresh and hardened properties using three types of specimen production (cast mould, sprayed mould and in-situ specimen). Ten repair scenarios generally encountered in the UK were identified and classified in terms of their characteristics and relevant mixes were identified to satisfy these differing requirements.

A rheological audit has been developed and a variety of tests were used to characterise the pumpability and sprayability of each mix, including: rotational viscometers (Tattersall two-point test and Viskomat), pressure-bleed, shear vane, slump, build, fresh density, output, stream velocity (using high-speed video), reinforcement encasement and core grading. A new approach that defines the build in terms of the maximum shear and tensile bending stresses generated at failure was also developed.

Hardened properties measured include: compressive and flexural strength, tensile bond strength, drying and restrained shrinkage, elastic modulus, air permeability, sorptivity and hardened density. The hardened performance was generally higher when sprayed with the wet process compared with hand application and lower when compared with the dry process (which was expected), although the values obtained were more than sufficient for normal repair work.
All the pre-blended mortars could be pumped and sprayed with a small worm pump. Twelve laboratory-designed mortars were pumped and sprayed in a dedicated spraying chamber constructed at Loughborough and the best of these performed as well as, and produced hardened properties that equalled or surpassed, the pre-blended materials. For worm pumping the grading of a mortar was found to be important and a suitable combined material grading zone has been determined.

Two pre-blended and a laboratory-designed mortar were sprayed with a piston pump as were the nine designed concrete mixes, the former producing similar in-situ properties to worm pumping. One pre-blended mix was sprayed successfully with five different wet-process pumps (four worm plus one piston) and three pre-blended mortars and one designed fine concrete were sprayed by the dry-process to benchmark performance, along with data from three repair contracts. The hardened property measurements obtained from spraying directly into steel moulds with a low-volume worm pump were consistent enough to have applications for quality control.

The research demonstrated that low-volume wet spraying is a healthier, cleaner and more controllable process (compared with the dry process) which can produce consistently high quality mortars and fine concretes suitable for a range of applications in the UK.

*Keywords:* Sprayed concrete, repair, wet process, mortar, rheology, pumpability, sprayability, shotcrete, gunite
Dedicated in loving memory
to my mother, Pam Goodier
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>iv</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>ix</td>
</tr>
<tr>
<td><strong>1 INTRODUCTION</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1 Wet process sprayed concrete for repair</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Aim and objectives</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Methodology</td>
<td>5</td>
</tr>
<tr>
<td>1.4 Guide to thesis structure</td>
<td>6</td>
</tr>
<tr>
<td><strong>2 LITERATURE REVIEW</strong></td>
<td>8</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>8</td>
</tr>
<tr>
<td>2.2 Concrete repair</td>
<td>9</td>
</tr>
<tr>
<td>2.2.1 Causes of defects in concrete</td>
<td>9</td>
</tr>
<tr>
<td>2.2.2 Concrete repair and methods</td>
<td>11</td>
</tr>
<tr>
<td>2.3 Sprayed concrete for repair</td>
<td>15</td>
</tr>
<tr>
<td>2.3.1 The dry process</td>
<td>17</td>
</tr>
<tr>
<td>2.3.2 The wet process</td>
<td>17</td>
</tr>
<tr>
<td>2.3.3 Comparison of the wet and dry processes</td>
<td>19</td>
</tr>
<tr>
<td>2.3.4 Preparation of repairs for sprayed concrete</td>
<td>21</td>
</tr>
<tr>
<td>2.3.5 Sprayed concrete repair procedure</td>
<td>24</td>
</tr>
<tr>
<td>2.3.6 Pre-blended proprietary materials</td>
<td>27</td>
</tr>
<tr>
<td>2.3.7 Binders</td>
<td>29</td>
</tr>
<tr>
<td>2.3.8 Aggregates</td>
<td>30</td>
</tr>
<tr>
<td>2.3.9 Admixtures and additions</td>
<td>34</td>
</tr>
<tr>
<td>2.3.10 Mix design</td>
<td>37</td>
</tr>
<tr>
<td>2.3.11 Standards and specification</td>
<td>39</td>
</tr>
<tr>
<td>2.4 Rheology of fresh mortars and concretes</td>
<td>41</td>
</tr>
<tr>
<td>2.4.1 Concept and definition</td>
<td>41</td>
</tr>
<tr>
<td>2.4.2 Newtonian flow</td>
<td>42</td>
</tr>
<tr>
<td>2.4.3 Other rheological behaviour</td>
<td>43</td>
</tr>
<tr>
<td>2.4.4 Rheology of cement pastes</td>
<td>44</td>
</tr>
<tr>
<td>2.4.5 Rheology of concretes</td>
<td>45</td>
</tr>
<tr>
<td>2.4.6 Rheology of mortars</td>
<td>47</td>
</tr>
<tr>
<td>2.4.7 Effects of mix composition on rheology</td>
<td>49</td>
</tr>
<tr>
<td>2.5 Pumping of mortars and concretes</td>
<td>52</td>
</tr>
<tr>
<td>2.5.1 Background</td>
<td>52</td>
</tr>
<tr>
<td>2.5.2 Concrete state in the pipeline</td>
<td>53</td>
</tr>
<tr>
<td>2.5.3 Pumpability</td>
<td>53</td>
</tr>
<tr>
<td>2.5.4 Design considerations for a pumpable mix</td>
<td>56</td>
</tr>
</tbody>
</table>

iv
### 2.6 Spraying of mortars and concretes
- 2.6.1 Sprayability
- 2.6.2 Build-up thickness
- 2.6.3 Rebound
- 2.6.4 Ageing effect
- 2.6.5 Compaction and fresh density
- 2.6.6 Reinforcement encasement

### 2.7 Performance of hardened mortars and concretes
- 2.7.1 Introduction
- 2.7.2 Compressive strength
- 2.7.3 Bond strength
- 2.7.4 Flexural strength
- 2.7.5 Shrinkage
- 2.7.6 Permeability
- 2.7.7 Sorptivity
- 2.7.8 Modulus of elasticity
- 2.7.9 Density

### 2.8 Conclusions

### 3 EXPERIMENTAL PROGRAMME AND METHODS

#### 3.1 Introduction

#### 3.2 Repair scenarios

#### 3.3 Equipment
- 3.3.1 Spraying chamber
- 3.3.2 Moulds
- 3.3.3 Spraying machines

#### 3.4 Materials and mixes
- 3.4.1 Materials
- 3.4.2 Pre-blended proprietary mixes
- 3.4.3 Laboratory designed mixes
- 3.4.4 Air voids measurement

#### 3.5 Mixing, pumping, spraying and casting procedures
- 3.5.1 Mixing
- 3.5.2 Pumping
- 3.5.3 Spraying
- 3.5.4 High Speed Photography
- 3.5.5 Field trials
- 3.5.6 Casting
- 3.5.7 Curing

#### 3.6 Test methods and specimen preparation: fresh properties
- 3.6.1 Rheological testing
3.6.2 Slump and vane shear strength 110
3.6.3 Two-point test 110
3.6.4 Viskomat 111
3.6.5 Pressure bleed test 112
3.6.6 Adhesion and build thickness 112
3.6.7 Reinforcement encasement 112
3.6.8 Water permeability 114
3.6.9 Fresh density 114
3.6.10 Air content 114

3.7 Test methods and specimen preparation: hardened properties 115
3.7.1 Sprayed concrete 115
3.7.2 Compressive strength 115
3.7.3 Bond strength 116
3.7.4 Flexural strength 116
3.7.5 Shrinkage 116
3.7.6 Air permeability 117
3.7.7 Sorptivity 118
3.7.8 Modulus of elasticity 118
3.7.9 Density 119

3.8 Summary 119

4 FRESH PROPERTIES 129
4.1 Introduction 129

4.2 Mortars 129
4.2.1 Rheological overview 129
4.2.2 Workability (slump and shear vane strength) 130
4.2.3 Flow resistance and torque viscosity – Two-point test 132
4.2.4 Flow resistance and torque viscosity – Viskomat 133
4.2.5 Comparison of Two-point and Viskomat results 135
4.2.6 Pressure bleed test 135
4.2.7 Adhesion and build thickness 137
4.2.8 Reinforcement encasement 140
4.2.9 Observations during the pumping and spraying process 142
4.2.10 Summary 147

4.3 Fine concretes 149
4.3.1 Rheological overview 149
4.3.2 Workability (slump and shear vane strength) 149
4.3.3 Flow resistance and torque viscosity – Two-point test 152
4.3.4 Adhesion and build thickness 152
4.3.5 Reinforcement encasement 154
4.3.6 Observations during the pumping and spraying process 156
4.3.7 Summary 159

4.4 Comparison between mortars and fine concretes 161
4.4.1 Introduction 161
4.4.2 Pumpability 161
4.4.3 Sprayability 164
4.4.4 Effect of particle grading, permeability and void content 170
4.4.5 Summary and conclusions 173

5 HARDENED PROPERTIES 199
5.1 Introduction 199

5.2 Mortars 199
  5.2.1 Compressive strength 199
  5.2.2 Bond strength 201
  5.2.3 Flexural strength 202
  5.2.4 Drying and restrained shrinkage 202
  5.2.5 Air permeability and Sorptivity 204
  5.2.6 Modulus of elasticity 205
  5.2.7 Hardened density 206
  5.2.8 Wet- and dry-process sprayed mortars compared 207
  5.2.9 Summary 208

5.3 Fine concretes 210
  5.3.1 Compressive strength 210
  5.3.2 Bond strength 211
  5.3.3 Flexural strength 211
  5.3.4 Drying and restrained shrinkage 212
  5.3.5 Sorptivity 213
  5.3.6 Modulus of elasticity 214
  5.3.7 Hardened density 215
  5.3.8 Wet- and dry-process sprayed concretes compared 215
  5.3.9 Summary 216

6 COMPARISONS AND IMPLICATIONS 230
6.1 Comparison between the mortars and fine concretes 230

6.2 Effect of constituents on the fresh and hardened properties 235

6.3 Implications for practice 242

7 CONCLUSIONS AND RECOMMENDATIONS 249
7.1 Introduction 249

7.2 Conclusions 249
  7.2.1 Fresh properties of mortars and fine concretes 249
  7.2.2 Hardened properties of mortars and fine concretes 251
  7.2.3 Effect of constituents on fresh and hardened properties 254
  7.2.4 Repair scenarios 256
7.3 Recommendations for further research
7.3.1 Materials and mixes
7.3.2 Pumping and spraying
7.3.3 Fresh property test methods
7.3.4 Hardened property test methods

8 REFERENCES

9 APPENDICIES
A.1 Conversion to fundamental units
A.2 Table of mixes
A.3 Repair scenarios
A.4 Aggregate gradings
A.5 Pre-blended aggregate gradings
A.6 Vane shear strength calculations
A.7 Test method Investigation
A.8 Published papers
A.9 Failure stress calculations
A.10 Hardened property results
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1 INTRODUCTION

1.1 WET PROCESS SPRAYED CONCRETE FOR REPAIR

Repairing with sprayed concrete is attractive because of the flexibility of the application process and the elimination of formwork, but nearly all sprayed concrete repair projects in the UK are carried out by the dry process. The wet process has become dominant for large scale tunnelling applications involving robot-controlled spraying (e.g. in Scandinavia and more recently in the UK with NATM), but is not a common solution for repair work.

The dry process is capable of producing high quality concrete but has several drawbacks including quality and consistency, high material losses and a dusty and dirty working environment. The wet process has the potential to produce more consistent concrete, with lower wastage, and in a healthier working environment, but the technology developed to date is inappropriate for repair work, because it is based on rock support, inappropriate mixes and high volume production (not controlled overlays).

The dry process is capable of producing high quality concrete but has three significant drawbacks:

1. quality and consistency are a function of water content, operating pressures and spraying techniques, all of which are highly dependent on the skill and care of the operatives;
2. high material losses (20 to 40% on vertical faces, 30 to 50% overhead), consisting largely of rebound aggregates, are not only wasteful but present a substantial removal problem; and
3. the spraying produces a dusty and dirty environment, which can be harmful to operatives and can cause problems on sensitive sites or in restricted spaces.

Whilst the wet process has the potential to produce more consistent and controllable concrete in a healthier working environment, the technology for repair applications is underdeveloped. Potential disadvantages include shorter transporting distances of the pumped concrete or mortar and a lack of stop-start flexibility (where there are
numerous breaks in placement, it is not suitable to process small quantities of wet-process sprayed concrete or mortar, as prolonged stoppages in spraying necessitate the removal of hardening material, and a thorough cleaning of the spraying unit). There is little data on the rheological properties of wet-process concrete that influence these factors. Nor is there much published information on mix design or hardened properties of mortars and concretes suitable for repair.

The wet process could replace a significant amount of current dry-mix work and also extend the use of sprayed concrete for repair, the latter involving expenditure of around £500 million p.a. in the UK. Low-to-medium volume wet process applications are increasing, especially for repair, because of its greater consistency and the improvements in materials and production technology, particularly its stop/start flexibility. Whilst the cost of materials in sprayed concrete account for only a fraction of the total expenditure on concrete repair, the potential savings are much greater if more durable repairs can be effected which increase the remaining life expectancy of the structure.

Until recently, sprayed concrete repair projects in the United Kingdom have almost exclusively been carried out using the dry process, a recent example being the Runcorn Bridge over the River Mersey (Hayward, 1995). Two of the main concerns regarding concrete repair are the durability and compatibility of the repair material with the substrate. These are compounded by a lack of appropriate tests methods, although several CEN committees are currently working on the development of standards for both hand, cast and sprayed applications.

In some countries there has been a big swing towards the wet process, partly because of better control over mix proportions (particularly the water/cement ratio). These include Norway and Sweden, where the majority of work is wet process, and the USA where the two techniques have a roughly equal share and are both used for repair (Austin, 1995a). Although the proportion of wet-process concrete is increasing in the UK, other countries (in particular Germany) are still predominately orientated towards the dry process. These differences partly reflect the functional emphasis of the two processes (i.e. wet process for high output applications such as tunnelling, and dry
process for low to medium output applications such as repair, or situations requiring greater transport distances and flexibility like mining).

Wet- and dry-process sprayed concrete and mortar has been described by several terms, including shotcrete and gunite. This document uses the terminology standardised by the European Federation of National Associations of Specialist Repair Contractors (EFNARC), namely sprayed concrete, with mixes containing aggregate with a maximum size of 3 mm being classed as sprayed mortars. The maximum aggregate size used in this work was 8 mm and these mixes are classed here as fine concretes. Sprayed concrete can be additionally defined as ‘mortar or concrete conveyed through a hose and pneumatically projected at high velocity from a nozzle into place.’

1.2 AIM AND OBJECTIVES

The aim of the research was to advance the understanding and technology of the wet process, with an emphasis on mortars and small aggregate concretes, to enable it to be specified and used with confidence for repair in the United Kingdom.

The objectives of the research were:

1. to build upon, and link research to previous work in the field;
2. to gain a fundamental understanding of the influence of the pumping/spraying process, mix constituents and proportions on the fresh and hardened properties of wet-process sprayed concrete; and
3. to disseminate information in appropriate form to practising engineers to promote and accelerate the use of wet-process sprayed concrete and mortar for repair in the UK.

The objectives can be divided further into twelve sub-objectives which are presented in Table 1.1, together with the methods employed to achieve these objectives.
<table>
<thead>
<tr>
<th>Objectives</th>
<th>Sub-Objectives</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. To build upon, and link research to previous work in the field</td>
<td>(a) Develop an understanding of sprayed mortars and concretes</td>
<td>Literature review, talking to industry, attending trade events and training courses. Build a literature database and library Qualitative and quantitative comparison of rheological and hardened properties</td>
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<tr>
<td></td>
<td>(b) Compare with research findings</td>
<td></td>
</tr>
<tr>
<td>2. To gain a fundamental understanding of the influence of the pumping/spraying process, mix constituents and proportions on the fresh and hardened properties of wet-process sprayed concrete</td>
<td>(a) Define relevant properties and test methods</td>
<td>Review of literature, industrial opinion, concept of rheological audit</td>
</tr>
<tr>
<td></td>
<td>(b) Devise mixes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(c) Measure rheological and hardened properties</td>
<td>Review published work, industrial information and current practice, available materials, constituent material properties</td>
</tr>
<tr>
<td></td>
<td>(d) Compare the properties of mortars and concretes</td>
<td>Spray mixes and produce specimens with a variety of pumps. Carry out tests to defined methods and standards and develop new tests where required</td>
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<td></td>
<td>(e) Investigate the interaction between the fresh and hardened properties</td>
<td>Analyse and compare data from rheological and hardened property tests. Statistical analysis of data and trends</td>
</tr>
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<td></td>
<td>(f) Suggest implications for practice</td>
<td>Investigate the affect of, and identify the links between, the rheological properties and the hardened properties and the consequences of a change in one property on another Suggest mixes from this work and provide advice on mix design to satisfy the repair scenarios</td>
</tr>
<tr>
<td>3. To disseminate information in appropriate form to practising engineers to promote and accelerate the use of wet-process sprayed concrete and mortar for repair in the UK</td>
<td>(a) Produce an industry guideline document</td>
<td>Guideline Document produced with the Concrete Society (in press)</td>
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<tr>
<td></td>
<td>(b) Publish refereed journal papers</td>
<td>One paper published (Magazine of Concrete Research), one in press (MCR) and two in writing</td>
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<td></td>
<td>(c) Present papers at relevant conferences</td>
<td>Papers presented at Creating with Concrete conference in Dundee and the Biannual Conference of the Concrete Institute of Australia</td>
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<tr>
<td></td>
<td>(d) Write magazine and journal articles to promote the work and results</td>
<td>Two articles published (in Concrete Engineering International and Concrete magazine)</td>
</tr>
</tbody>
</table>
1.3 METHODOLOGY

The aim and objectives of this work are outlined in Section 1.2 and the main methods employed to achieve these aims and objectives are listed in Table 1.1.

A sprayed concrete publications library and database was created and maintained and now contains more than 800 entries. Previous work (Seymour and Turner, 1995) had identified a set of 6-8 repair scenarios, and their performance requirements, to cover the range of repair situations commonly encountered in the UK. This was achieved by conducting a survey and interviews with local authorities, consultants, contractors and material suppliers. This was used when deciding on the sequence of testing and on the mix designs. This work contributed to achieving objective one.

Three types of repair mortar/concrete were identified as ripe for development and the sequence of work was consequently structured to reflect this. The three types were:

1. mortars (<3 mm aggregate), pre-blended and bagged by specialist material suppliers;
2. mortars (<3 mm aggregate), designed and laboratory/site batched; and
3. fine (<8 mm aggregate) concretes, designed and laboratory/site batched.

The first two categories can be applied by worm and piston pumps, whereas the fine concretes are restricted to piston pumping. Details of the mix designs tested in this work are provided in Section 3.4. This order was also logical from the point of view of research. The first type was available in the form of materials developed for hand-applied repair, from which experience and performance data were gained (and which also served as a benchmark). These mixes could then form the platform for the development of the designed mixes. The majority of the research (and all the initial work) was also conducted with a small worm pump, purchased by Putzmeister UK for the project, as it was likely that any mix working with such a pump would also be suitable for larger worm and piston pumps. The construction of a dedicated spraying facility at the University allowed spraying trials to be conducted locally, interspersed with appropriate laboratory work and on-site field trials. Details of the equipment used, including the spray shed, pumps and moulds are provided in Section 3.3.
The work encompassed both fundamental rheology tests such as the two-point test and slump, together with basic material hardened property tests such as compressive and bond strength to characterise performance. The latter can also be used for quality control and this aspect was given additional emphasis in the work. The testing also included more pragmatic tests that were appropriate to quantify important aspects of the sprayed installation (including build thickness and reinforcement encasement). Details of the test methods employed are given in Section 3.6 (fresh properties) and Section 3.7 (hardened properties) and a review of the hardened property test methods was conducted prior to the beginning of the testing. This work contributed to achieving objective two.

The dissemination of the information in an appropriate and useable form was an essential part of the work and the main findings have been included together with existing good practice in a Guideline Document to be published by the Concrete Society (Austin et al., 2000). Refereed journal papers (Austin et al., 1999a, and Austin et al., 1999b), conference proceedings (Austin et al., 1999c and Austin, 1999), and magazine articles (Austin et al., 1998) have all added to the dissemination process. This work contributed to achieving objective three.

1.4 GUIDE TO THESIS STRUCTURE

The contents of this thesis are organised as follows.

Chapter 2 provides a state-of-the-art review of wet-process sprayed concrete for repair. It reviews the present knowledge on sprayed concrete and mortar for repair, including details on the dry and wet processes, sprayed concrete repair procedure, constituent materials, mix design and standards relating to sprayed concrete. It explains the principles of concrete and mortar rheology and describes the concepts of pumpability and sprayability. Finally, it discusses the performance of hardened sprayed mortars and concretes.

Chapter 3 describes the experimental programme and research methods, including the repair scenarios, the equipment and spray shed used, the materials and mixes and the mixing, pumping, spraying and casting procedures. It also describes the test methods used to measure the fresh and hardened properties.
Chapter 4 presents the data obtained and the analysis of the fresh properties of the mortars and fine concretes. A comparison is made between the mortars and fine concretes and the effect of mix proportions and particle grading is discussed.

Chapter 5 presents the data obtained and the analysis of the hardened properties of the mortars and fine concretes.

Chapter 6 compares the mortars and fine concretes and the interaction of the fresh and hardened properties is discussed. The implications for practice are also presented.

Chapter 7 brings together and discusses the conclusions from Chapters 4, 5 and 6 and presents recommendations for further work.
2. LITERATURE REVIEW

2.1 INTRODUCTION

In the majority of cases, concrete completes what it is designed to do for the design life of the structure. However, the quality and the behaviour of the concrete is influenced by both the internal structure of the concrete and by external factors such as the weather and construction practice. The serviceability of a structure may also be reduced due to adverse influences such as weathering, cyclic loading, wear and abrasion.

The repair and maintenance of structures is a growing market, both in the UK and internationally and has risen over the last ten years from about 25% of construction activity to about 50% (Mailvaganam, 1991) with the annual UK market worth about £500m (Emberson and Mays, 1990). In the United States, £30bn per annum is to be spent for the next 6 years on highway construction and, in particular, repair (McLellan, 1999). Nearly 60% of major roads in the US need significant repair work and 31% of bridges are structurally deficient or functionally obsolete (McLellan, 1999). This market expansion has led to an increase in the development and marketing of new materials, equipment and techniques especially for the repair market. However, the expanded range of products, techniques and services has both complicated the selection process and increased the possibility of problems occurring due to insufficient knowledge and experience. The testing and evaluation of these products and processes, especially their long-term performance have not kept pace with the development of new products. Products are being used without detailed independent data on their long-term performance and on why they perform as they do (or as they are claimed to do). This is especially true of wet-process sprayed mortars and concretes for repair where new products and techniques are being continually introduced but little information is known on how the basic properties and constituents of a mix influence the mixes performance, including it’s pumppability, sprayability and hardened properties. A large and increasing number of proprietary products and systems exist for wet-process sprayed repairs yet very little data exists on
their performance, except that published by the manufacturers. This data is not independent and generally only presents hardened property data, frequently using differing and inconsistent test methods which produce the most impressive results for that particular product. For these reasons it is difficult to use this data to determine which constituents, and at what proportion, influence which characteristic, be it pumping, spraying or a hardened property.

This chapter reviews the existing published knowledge available on wet-process sprayed concrete for repair. Concrete repair in general, including causes and methods, is reviewed in Section 2.2 and sprayed concrete for repair is reviewed in Section 2.3. Published information on the rheology of fresh mortars and concretes is reviewed in Section 2.4 and the literature available on the pumping and spraying processes is reviewed in Sections 2.5 and 2.6 respectively. Finally, the published literature available on the performance of hardened sprayed mortars and concretes is reviewed in Section 2.7.

2.2 CONCRETE REPAIR

Repair refers to the modification of a structure, damaged in its appearance or serviceability, to restore, partly or wholly, the pre-existing characteristics of serviceability, load-bearing capacity and if necessary, improve its durability (FIP, 1991). This is separate from strengthening, which is a modification of a structure, not necessarily a damaged one, with the purpose of increasing its load-carrying capacity or stability. Structural repair restores lost sectional or monolithic properties to damaged concrete members while serviceability repairs restore concrete surfaces to a satisfactory operational standard (Mailvaganam, 1991).

2.2.1 Causes of defects in concrete

Concrete damage usually results either from reinforcement corrosion, the effects of fire or from an impact, and the success of a repair depends upon the source or sources of the initial damage being removed. Detailed investigations are often needed to identify the source or sources of the damage and previous research has indicated that
over 90% of concrete deterioration is probably due to either design or construction errors, misconceptions in specifications, or bad workmanship (Shaw, 1993).

It is essential to carry out an initial survey of the condition of the concrete before any repair contract is undertaken in order to identify the problem, quantify the extent of the damage and to prepare appropriate remedial action (Es, 1995). To be successful, a proper survey must visually assess the effects of the concrete deterioration, identify the cause of deterioration by any necessary testing (carbonation and chloride levels must at least be checked) and identify the likely extent of latent damage, i.e. those areas in which deterioration has started but which, as yet, show no visual signs of distress.

The yearly costs of an efficient inspection programme are said to be approximately 0.1% of the initial construction costs and those of a proper maintenance programme are a further 1.0 to 1.5% (FIP, 1991).

Deterioration of concrete is usually in the form of cracking, caused by the corrosion, and therefore expansion, of the steel reinforcement. This reinforcement is normally protected by the alkalinity of the concrete cover but this can fail for two main reasons: carbonation, and chloride ion penetration. Carbonation is caused by the neutralisation of the alkaline protective layer by acids from external sources, mainly carbon dioxide. Carbonation is inevitable due to the presence of carbon dioxide in the atmosphere, but it is the rate of carbonation which is important when considering the corrosion of the reinforcement. This increased rate of carbonation can result from inadequate concrete cover, cracking or a permeable concrete cover caused from either too high a water/cement ratio, insufficient cement content or inadequate curing. Chloride ion contamination can result from de-icing salts, sea water or from the concrete mix itself, usually in the form of inadequately washed sea dredged aggregates or from the use of calcium chloride accelerating admixtures. Other types of chemical attack can arise in the form of (Perkins, 1986):

(i) aggressive compounds in solution in the sub-soil and/or ground water;
(ii) aggressive chemicals in the air surrounding the structure;
(iii) aggressive chemicals or liquid stored in, or in contact with, the structure; and
(iv) chemical reaction between the concrete constituents, such as alkali-aggregate reaction.

Physical attacks on concrete structures can result from:

(i) freeze/thaw action;
(ii) thermal shock caused by a sudden and severe drop in the temperature of the concrete, such as spillage of liquefied gases;
(iii) abrasion, e.g. on the surface of industrial ground floor slabs;
(iv) high velocity water in the form of cavitation, abrasion from water containing grit and impact from a high velocity jet; and
(v) abrasion in marine structures caused by the action of sand and shingle.

Other defects in the concrete can develop due to moisture movements whilst the concrete is in the plastic state (Kay, 1992). Possible early-age defects include:

(i) plastic shrinkage cracks, caused by the evaporation and consequent loss of the mix water;
(ii) plastic settlement cracks caused by the downward movement of the solid constituents within the concrete mix; and
(iii) cracks formed by early thermal movement due to the temperature rise within the concrete as the cement hydrates.

2.2.2 Concrete repair and methods

After identifying the source of the deterioration, the next step in designing a successful concrete repair is to consider the objective of the repair which will generally be to restore or enhance one or more of the following: durability, structural strength, function or appearance (Allen et al., 1993). Of these, the restoration of durability is usually the main requirement of a repair (Allen, 1986). Once this objective is decided appropriate repair materials and removal and repair methods should be chosen, bearing in mind (Mailvaganam, 1991):

- modifications required to remedy the cause of the damage
- advantages and disadvantages of permanent vs. temporary repairs
• the availability of repair materials and methods
• the economic viability of each material and method
• restrictions to the access of the structure
• restrictions to noise, dust, vibration, and exhaust fumes
• method of disposal of watery waste

Kay (1992) also suggested taking into account the future life requirement of the structure, the overall quantity of repairs and size of individual repairs, the requirement for the continued use of the structure during the repair and the time available for repair. For example, sprayed concrete is often chosen to repair fire-damaged structures because it can be applied quickly and economically to the large areas involved and new reinforcement can be incorporated relatively easily. Carbonation and the resulting corrosion damage on a building facade usually requires relatively small isolated repairs using cement-based or polymer-modified mortars and so lends itself to hand-applied patch repairs. Repairs frequently have to be completed during brief shut-down periods during which the building cannot be used and so sprayed concrete is often the only viable choice to place the required volume of repairs in the available time.

The selection of a concrete repair material must be based upon knowledge of its physical and chemical properties in conjunction with those of the environment into which it will be placed, together with a clear understanding of its purpose. Several hundred concrete repair systems are commercially available and Emberson and Mays (1990) categorised these into three groups: cementitious mortars, polymer-modified cementitious mortars and resinous mortars. These can be further subdivided into nine generic types, as shown in Table 2.1. Of these, two of the most widely used are the SBR-modified cementitious and cement/sand mortar types. Commercial considerations prevent the publication of the formulations of these pre-blended mortars, but they typically contain all or most of the following constituents, depending on the type (Austin et al., 1999a):

(i) A combination of fine aggregates from 75 µm to 2 mm in diameter;
(ii) lightweight fillers, 75 µm to 300 µm in diameter;
(iii) Portland cement in approximately the ratio of 1.3 - 3.4 : 1;
(iv) silica fume (approximately 5% of the cement);
(v) admixtures such as SBR;
(vi) polypropylene fibres up to 6 mm in length; and
(vii) chemical shrinkage compensators.

Table 2.1 Generic systems for concrete patch repair (Emerson and Mays, 1990)

<table>
<thead>
<tr>
<th>Cementitious Materials</th>
<th>Polymer-modified cementitious Mortars</th>
<th>Resinous Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement/sand mortar</td>
<td>SBR modified</td>
<td>Epoxy</td>
</tr>
<tr>
<td>High alumina cement mortar</td>
<td>Vinyl acetate modified</td>
<td>Polyester</td>
</tr>
<tr>
<td>Flowing concrete</td>
<td>Magnesium phosphate modified</td>
<td>Acrylic</td>
</tr>
</tbody>
</table>

In general, resin based mortars are more suited to concrete subjected to chemical attack, where thick sections have to be applied or a rapid strength gain is required (Little, 1986). However, cementitious mortars are lower in cost than resin mortars and they possess thermal expansion and movement characteristics more compatible with the substrate concrete. Important requirements for a repair mortar include:

- good bond to substrate
- movement characteristics similar to the substrate
- low permeability
- structural strength
- freeze/thaw durability
- weathering resistance
- easy application
- alkaline passivation of reinforcement
- the inherent ability to resist carbonation and chloride ingress

Table 2.2 shows some of the important properties to consider in the selection of a repair material and the desirable relationship between the property of the repair material (R) and the substrate concrete (C).
Table 2.2 General requirements of patch repair materials for compatibility
(Emberson and Mays, 1990)

<table>
<thead>
<tr>
<th>Property</th>
<th>Relationship of repair material (R) to concrete substrate (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrinkage strain</td>
<td>R&lt;C</td>
</tr>
<tr>
<td>Creep coefficient (for repairs in compression)</td>
<td>R&lt;C</td>
</tr>
<tr>
<td>Creep coefficient (for repairs in tension)</td>
<td>R&gt;C</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>R=C</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>R=C</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>R=C</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>R&gt;C</td>
</tr>
<tr>
<td>Adhesion</td>
<td>R&gt;C</td>
</tr>
<tr>
<td>Porosity and resistivity</td>
<td>R=C</td>
</tr>
<tr>
<td>Chemical reactivity</td>
<td>R&lt;C</td>
</tr>
</tbody>
</table>

Curing of a repair is vital and inadequate curing can result in high permeability, low strength, surface cracking, poor bond and a short life span. Effective curing maintains the moisture inside the repair material for the effective hydration of the cement to take place. The surface layer is therefore the most vulnerable to poor curing which can lead to surface problems of deterioration and poor durability (Schrader, 1992).

Cusson and Mailvaganam (1996) observed three major modes of failure for concrete patch repairs:

(i) tensile cracking through the thickness of the patch which can cause moisture and salt ingress;

(ii) shearing of the substrate concrete below the surface which can cause delamination of the repair together with a layer of the substrate concrete; and

(iii) bond failure.
2.3 SPRAYED CONCRETE FOR REPAIR

Sprayed concrete repairs have been successfully completed in many fields including: bridge soffits, beams, parapets and abutments; steel and reinforced concrete framed buildings; cathodic protection; cooling towers; industrial chimneys; tunnels; water-retaining structures; jetties, sea walls and other marine structures (Taylor, 1995). Interest in sprayed concrete as a repair method has increased greatly in the last few years (Walter, 1998). A recent use includes the repair of the Canadian port of Montreal with fibre-reinforced, air-entrained, wet-process silica fume sprayed concrete. 272 m$^3$ of non-fibre reinforced sprayed concrete was applied to fill deep voids within the structure followed by an overlay of 30 m$^3$ of steel-fibre reinforced sprayed concrete. 140 m$^3$ of polypropylene fibre reinforced sprayed concrete was also used in the repair (Morgan et al., 1998). A £500,000 contract for repairs to the Runcon-Widnes bridge over the river Mersey was completed in 1995. A pre-blended repair mortar was sprayed to build up deck beams that had been damaged by chloride attack and then further material was sprayed to provide a protective overlay to a cathodic protection system (Hayward, 1995).

A recent successful example which illustrates the flexibility of wet-process sprayed concrete was the £4.3m contract to strengthen and repair the Lancaster Place Vaults at the North end of Waterloo bridge in London (Bridge, 1999). Wet-process sprayed concrete proved the cheapest alternative for strengthening the brick archways compared with conventionally cast concrete due to their irregular shapes eliminating the possibility of re-usable shutters. 500 m$^3$ of concrete was used with 10 mm aggregate and 340 kg/m$^3$ of sulphate-resisting cement together with a plasticiser, a stabiliser and an accelerator (added at the nozzle).

Sprayed concrete, both wet and dry, can offer several advantages when compared with cast in-situ and hand-applied repairs (King, 1995):

- reduction or elimination of formwork (hence cost savings)
- the construction of free form profiles
- efficient construction (due to rapid placement of thin layers)
- reduced access problems (by remote location of equipment)
• thicker layer build
• reduced thermal stresses (by placing several thinner layers)
• good bond to substrate and between layers

However, against these must be balanced potential disadvantages (King, 1995):

• the specialist experience needed to produce suitable design solutions and good quality construction
• variability of concrete quality (owing to high dependence on operator skill and lack of control of the water/cement ratio with the dry process)
• high materials costs (arising from specialist mixes, high cement content and wastage of material from rebound, overspray and cutback)
• incomplete encasement behind heavy concentrations of reinforcement
• more labour-intensive finishing
• greater effort in quality control to ensure a satisfactory finished product

Garshol (1999) recently reported on the international practices and trends in sprayed concrete, and although he was referring to sprayed concrete for tunnelling, it is the authors view that the trends will soon be apparent in sprayed concrete for repair. He concluded that: the wet process is dominating over dry, with a clear trend for further increase; reinforcing mesh is generally used, but with an increasing volume of steel fibres; there is a drive towards mechanisation, automation and higher capacity; and there is an increasing focus on stricter regulations for safety, working environment and external environment.

Beaupré et al. (1999) have also recently conducted research into wet-process sprayed concrete for repair and have investigated the use of steel and polypropylene fibres and temporary high air contents. He measured properties such as air content, compressive and flexural strengths and drying shrinkage, which are discussed in Sections 2.6.5, 2.7.2, 2.7.4 and 2.7.5 respectively.

Sprayed concrete or mortar can be defined as a concrete or a mortar conveyed through a hose and pneumatically projected at high velocity from a nozzle into place. Sprayed concrete can be applied in two ways: the dry process and the wet process and although both methods are capable of producing high quality concrete they both possess
fundamental differences that influence the choice of process for different applications (Maidl and Sommavilla, 1995).

2.3.1 The dry process

In the dry process the dry (or slightly damp) constituents (cement, aggregate and any powdered admixtures or fibres) are batched together before being conveyed by compressed air down the delivery hose to the nozzle, where pressurised water is introduced (with or without liquid admixtures) and the mix projected into place. This process is illustrated in Figure 2.1.

The two most common types of dry-process spraying machines are the rotating barrel gun (Figure 2.2) and the rotating feed bowl gun (Figure 2.3). These machines produce outputs of between 0.5 and 10 m³ per hour (Austin, 1995a and ACI 506R, 1990) and they are relatively simple to operate and small in size. They are driven by diesel, electric or compressed air motors. The rate of water addition is controlled by a valve at the nozzle by the nozzleman who will continually adjust the flow of water to produce a consistent in-situ material. Pre-blended materials are used or mixes are batched on site either manually or automatically. The dry materials are sometimes pre-dampened or pre-moisturised before they are fed into the gun in order to reduce dust formation and rebound. The conventional nozzle for the dry process consists of a conical plastic tube preceded by a water ring through which the water is injected to the flow of dry material (Maidl and Sommavilla, 1995). This water flow is normally regulated by the nozzle operator who thus has a significant influence on the quality of the in-situ mix, as well as dust development and rebound.

2.3.2 The wet process

In the wet process the constituents (cement, aggregate, admixtures and fibres (if present) and water) are batched and mixed together before being fed into the delivery equipment or pump. The mix is then conveyed under pressure to the nozzle, where compressed air is injected to project the mix into place. Liquid accelerators can be injected at the nozzle if required. The wet process is shown in Figure 2.4.
The two most common types of wet-mix concrete pumps are:

1. the double-piston pump for medium to high outputs (5-20 m³/hr) (Figure 2.5); and
2. the worm or screw pump for low outputs (<5 m³/hr) (Figure 2.6).

Due to the nature of worm pumps, they can only pump aggregate up to approximately 4 mm in size and are unable to pump steel fibres. The speed and capacity of the pump and its ability to handle different size aggregates and consistencies are all affected by the size and type of worm, the type of rubber of the sleeve and the size and clearance of the worm in the sleeve (Gordon, 1993). Their main disadvantage is high wear, especially when coarser aggregates are used (Muller, 1984).

Several nozzle designs are available, their main difference being the way in which the compressed air is injected to project the concrete: either transversely into the concrete stream or around the circumference of the nozzle through a ring of jets (Maidl and Sommavilla, 1995). The type and design of the nozzle together with its size can have a significant effect on the compaction and finish of the repair (Gordon, 1991). The hose size used depends upon the output of the pump and the size of the fibres used (if present), 25, 50 and 100 mm diameters being typical sizes.

The choice of equipment should be left to the contractor. Pumps should be capable of delivering a continuous, even flow of material to the nozzle and an uninterrupted supply of compressed air should be available (King, 1995).

All in one mobile units are sometimes used, with all the necessary equipment (spraying machine, water pump, hoses etc.) and energy sources (compressed air, electrical power) on board (Maidl and Sommavilla, 1995). Wet-process machines have also been developed such as the M-tec Duo-mix and the Putzmeister Betojet 250EHM which have integral forced-action mixers and automatic water meters that precisely administer water to the mix to achieve a defined water/cement ratio. Machines are also available that are capable of spraying either dry or wet with the conversion being performed within a few minutes.
For low output applications (up to 3-5 m³/hr), materials are usually batched on site either in a conventional drum mixer or in a mixer that is part of the pump (Austin, 1995a). For medium and large output applications (above 5 m³/hr) a batching plant will be used and the mix will then be transported to site to be used in the pump. For very large pumping operations a purpose built batching plant is sometimes constructed on site.

2.3.3 Comparison of the wet and dry processes

Both methods offer several advantages for a range of applications and a knowledge of the job is needed before a pump is selected. For example, the dry process is advantageous in contracts that require an intermittent supply, whilst the wet process produces less rebound and dust and gives more control over the mix proportions. The principle aspects to be considered when comparing the two methods are operational, concrete technology, occupational health and economic aspects with both methods offering advantages for specific applications (Maidl and Sommavilla, 1995).

Large amounts of published data exists on large scale wet-process sprayed concrete. Malmberg (1995) showed that the most consistent quality of sprayed concrete is achieved with site-batched wet-process sprayed concrete when compared with wet process ready mix and the dry process.

An advantage of the wet process is that there is much better control of the mix proportions and hence strength and other properties. Also, if anything is wrong with the mix then it is immediately obvious at the nozzle (Parker, 1998). The wet process is also said to be more energy efficient (Muller, 1984). With the dry process the proportions and therefore quality and strength of the mix can vary considerably due to the water being metered by the nozzleman (Muller, 1984 and Gordon, 1993). The dry and wet processes are summarised and compared in Table 2.3.
<table>
<thead>
<tr>
<th></th>
<th>Dry Process</th>
<th>Wet Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>Mixing water added at nozzle, consistency controlled by &quot;nozzle man&quot; therefore mix is operator sensitive</td>
<td>Mortar premixed to correct consistency before introduction into pump, not operator sensitive</td>
</tr>
<tr>
<td>Rebound</td>
<td>Rebound can be between 25-75% dependent on location and orientation</td>
<td>Minimum rebound</td>
</tr>
<tr>
<td>Rebar</td>
<td>Maximum two layers of rebar can be sprayed by experienced operative</td>
<td>Maximum two layer of rebar can be sprayed by experienced operative</td>
</tr>
<tr>
<td>Pressure</td>
<td>High pressure can lead to incorporation of rebound and shadowing behind the bars</td>
<td>Lower pressure and soft texture allows material to flow behind rebar</td>
</tr>
<tr>
<td>Dust</td>
<td>Dust level can be high even with pre-dampened material</td>
<td>Minimum dust level</td>
</tr>
<tr>
<td>Distance</td>
<td>Can be transported over long distances, 500m horizontally and 100m vertically can be achieved</td>
<td>Pump to nozzle distance is unlikely to be greater than 40m horizontally or 10m vertically</td>
</tr>
<tr>
<td>Compressor</td>
<td>Requires a 350 cfm (10 M³/m) compressor</td>
<td>Can be sprayed with 20 cfm (0.5 M³/m) to 125 cfm (3 M³/m) compressor dependent on consistency</td>
</tr>
<tr>
<td>Stop/start flexibility</td>
<td>Spraying can be stopped and started at will, minimum cleaning required</td>
<td>Only short stop periods allowed, pump and hose lines must be cleaned out after a 10-15 min stop</td>
</tr>
<tr>
<td>w/c ratio</td>
<td>Low w/c ratio can be obtained with normal sand cement mixes</td>
<td>Use of specially formulated mixes required to obtain low w/c ratios</td>
</tr>
<tr>
<td>Density</td>
<td>Greater density from enhanced compaction reduces permeability</td>
<td>Greater density from enhanced compaction reduces permeability but can be counter acted by increased w/c ratio to allow pumping</td>
</tr>
<tr>
<td>Early Strength</td>
<td>High early strength and protection against scour</td>
<td>Lower early strength can be modified with admixture</td>
</tr>
<tr>
<td>Finishing</td>
<td>Must be finished immediately</td>
<td>Longer open time for finishing</td>
</tr>
<tr>
<td>Substrate Primer</td>
<td>No substrate bonding primer required, priming with water only</td>
<td>No substrate bonding primer required, priming with water only</td>
</tr>
<tr>
<td>Output</td>
<td>Large volumes can be placed rapidly</td>
<td>Large volumes can be placed rapidly</td>
</tr>
<tr>
<td>Build</td>
<td>High build vertically and on soffits</td>
<td>Greater build vertically and on soffits (less than the dry process)</td>
</tr>
<tr>
<td>Equipment</td>
<td>The gun is small and easily manoeuvrable and powered by air</td>
<td>The pump can be large and is powered by 3 phase electric, petrol or diesel or air</td>
</tr>
<tr>
<td>Material</td>
<td>Most grades of material can be sprayed</td>
<td>Requires careful grading to ensure trouble free pumping</td>
</tr>
<tr>
<td>Skill</td>
<td>Requires skilled and experienced operatives</td>
<td>Requires semi-skilled operatives</td>
</tr>
</tbody>
</table>
2.3.4 Preparation of repairs for sprayed concrete

Many aspects of sprayed concrete preparation and production, including substrate preparation, formwork construction, construction joints, finishing and curing are similar to cast concrete construction. In order for an effective and durable repair to be completed established good practice needs to be followed by skilled and trained operatives in conjunction with a knowledgeable and experienced engineer.

Before the start of any concrete repair work all the damaged or deteriorated concrete must be removed whilst ensuring that no damage is done to the substrate concrete, particularly with high impact tools. The preparation of the substrate directly influences the bond strength of a concrete repair which is only as good as the effort spent in preparing the substrate surface (Pan, 1995). The surface should be structurally sound and free from dirt, dust, oil and grease. The desired condition depends upon the type of repair being undertaken and the removal technique also depends upon the nature and condition of the concrete. Concrete removal techniques can be classed as blasting, cutting, impacting, pre-splitting, and spalling (Pan, 1995):

- **blasting** involves the use of explosives placed in boreholes to induce controlled fracture
- **cutting methods** include diamond saw cutting, thermal lances, electric arc equipment and high-pressure water jetting
- **impacting methods** include jackhammers, both hand-held and machine operated
- **pre-splitting** include hydraulic splitters, water pulse devices, and expansive agents which are placed in bore holes to induce splitting
- **spalling methods** employ mechanical devices to generate tensile stresses large enough to remove small pieces of concrete

Methods of surface preparation include chemical, mechanical, blast, flame cleaning, and acid etching. Chemical cleaning, such as using detergents or a proprietary concrete cleaner is used to remove oil and grease etc., and should be thoroughly rinsed afterwards to remove all residues. Mechanical cleaning generally involves rotary equipment such as discs and grinders which are used mainly for low strength
concretes, and impact tools such as bush hammers, scabblers and needle guns which can be successfully used on low or high strength concretes. However, mechanical aggravation is known to decrease the maximum bond strength due to the substrate surface containing micro-fractures (Shrader, 1992).

Blast cleaning includes wet and dry sandblasting, shot blasting, and water jetting. Sandblasting uses compressed air to eject a high-speed stream of sand particles from a nozzle to abrade the concrete, but with this method dust and residual sand on the substrate are problems. Shot blasting incorporates a rotating wheel, which propels some metallic shot onto the concrete surface which then rebounds into a recovery unit. Flame cleaning is generally used to remove coatings on concrete and further wire brushing or similar abrasion is needed to remove any melted residue. Acid etching can remove laitence and dust but thorough washing of the concrete surface is then required.

Water blasting consists of directing a high velocity water jet onto the concrete surface and is regarded as one of the most effective surface preparation techniques due to the minimisation of noise and dust, the absence of potentially damaging mechanical vibration (which could possibly cause structural damage) and mechanical abrasion (which could damage the reinforcement) and the fact that the water removes inferior concrete whilst leaving sound concrete intact.

Bonding agents and cement slurries are sometimes applied to improve the bond between the repair and the substrate, but this takes both extra time and expense. Care has to be taken to ensure that the grout does not dry before the repair is applied and that the grout is not applied too thickly, both of which can reduce the bond. It is also argued (Mailvaganam, 1991) that they can lose their effectiveness since they can be driven off the substrate during the initial pass of sprayed concrete. Also, the effect of rebound, especially in the dry process, produces a cement rich layer between the repair and the substrate which fulfils a similar purpose. When spraying onto a vertical surface, an epoxy or grout bonding agent can also act as a lubricant and cause the new material to slough or slide.
It is general practice to wet the substrate before the application of the repair, with saturated surface dry (SSD) being assumed to be the ideal condition. However, care needs to be taken to ensure the surface is not over-wetted, as this can cause the cement paste to become diluted at the bond line and thus have a higher water/cement ratio with resulting higher shrinkage and lower strength (Schrader, 1992). Adequately mixed sprayed concrete that is properly placed will have a similar bond strength to the tensile strength of the repair material unless the receiving surface is damaged, contaminated, badly carbonated, or improperly treated (Schrader, 1992). Gebler (1995) emphasises that special care needs to be taken in substrate preparation when spraying onto masonry (due to it's highly absorptive nature) or onto rock (due to it's often loose and fragmented surface). AFNOR (1997) also mention that any cause of vibration (road or rail traffic, vibrating machines etc.) must be removed prior to spraying which might be detrimental to the bonding of the sprayed concrete.

It is recommended that sprayed concrete be reinforced when the thickness exceeds 50 mm and that the minimum reinforcement diameter should be 3 mm (AFNOR, 1997). The arrangement of reinforcing bars should enable the sprayed concrete to fill behind and fully encase the steel. Layers of bars and mesh should also be staggered for similar reasons and should not be spliced or laid together. The Sprayed Concrete Association (1990) recommend a maximum bar size of 25 mm which should be spaced at least 50 mm apart (or four times the bar diameter, whichever is the greater) and at least three times the maximum bar diameter (or 40 mm, whichever is the greater) away from the substrate. If a repair contains two layers of reinforcement then a better result may be obtained if the second reinforcing layer is not placed until the first has been sprayed. Wire mesh is often used to limit the development and depth of cracks resulting from shrinkage and temperature stresses. Consideration should also be given to the cover to the reinforcement which should be appropriate to the exposure condition and class of the sprayed concrete. Expanding rock bolts or deep grout anchors are sometimes necessary to secure mesh or other reinforcement, especially in the repair of tunnels or sea walls. It is also essential to provide reinforcement stirrups between the existing and new concrete when doing in-depth repairs and strengthening work, provided in the form of drilling, overlapping or welding bars.
One of the main advantages of sprayed concrete is the reduction or elimination of formwork. Where required it is generally similar to that for conventionally cast concrete, although the hydraulic pressures against the formwork will be less due to the ability of the sprayed concrete to support itself (Gebler, 1995). Forms and temporary screed boards are used to help to spray corners and edges, and construction and expansion joints. These are secured a certain distance from the substrate to allow the rebound and compressed air to escape beneath and are then removed prior to spraying the adjacent face. It is important to fix the formwork rigidly, as the force of the sprayed concrete can vibrate the form and disturb the build up of material. Guide strips and ground (piano) wires help when cutting back the material to produce surface profiles. Plastic or metal depth gauges can also be effective, although care has to be taken not to affect the integrity of the material. Concrete patch repairs are often small in area and the finished line and level can be easily taken from the surrounding concrete.

2.3.5 Sprayed Concrete Repair Procedure

Many guides have been published on repair procedure and spraying techniques, including those by Ryan (1973), ACI Committee 506R (1990), the Sprayed Concrete Association (1990), the ASCE (1995) and Austin and Robins (1995).

With the wet process, it is essential to lubricate the hoses before spraying with a creamy mix of cement and water (Gordon, 1993). Approximately 7-10 litres is usually sufficient. Lubrication with water only or water and the repair material will frequently lead to blockages.

The reinforcement, sprayed concrete thickness and the required finish are all predetermined by the designer but they all influence the spraying programme, choice of equipment and the screed layout (Ryan, 1973). Spraying should generally be done at right angles to the target face at a distance of 0.5-2.0 m, although a distance of approximately one metre is usually used in order to obtain adequate compaction and minimum overspray (Austin, 1995a). Distances of 0.2-0.45 m have also been
suggested for low-output wet-spray application (Gordon, 1993). The thickness of each layer will be determined by the amount that can be applied without it sloughing off, (Taylor, 1995) which in turn is influenced by the position of reinforcement, plane of application, mix design and the constituents (SCA, 1990). Overhead spraying can also be done closer as gravity reduces the impact velocity and increases rebound. Overhead work is generally applied in 25-50 mm layers as thicker layers may sag or cause dropouts (Gebler, 1995). Horizontal work is usually sprayed in single layers and extra caution must be exercised in the removal of rebound. The nozzle must in general be 90° from the surface and never more than 45° with the further the angle from 90° the greater the rebound and the less the compaction (Ryan, 1973).

Accepted good practice is to gyrate the nozzle and to rotate the stream in a series of small oval or circular patterns across the surface. This method of application has been proven to reduce rebound and dust generation and increase material uniformity (Maidl, 1991). In general, the material is built up from the bottom with care being taken to fully encase the reinforcement so as to avoid the inclusion of rebound, sandy material and air pockets. When applying thick single layers the top edge is benched to enable the rebound to fall clear and a second operative is often used to remove the rebound with a blowpipe. Internal corners should be sprayed first to prevent the build up of rebound and overspray. When spraying a second layer, the preceding layer should be allowed to stiffen and then all loose or excess material should be scraped or brushed away before the second layer is added. The nozzle should be held closer than normal and at a slight upward angle when spraying through and encasing reinforcement to minimise the accumulation of rebound. Wherever possible, sections should be sprayed to their complete design thickness in one layer, thereby reducing the possibility of cold joints and laminations within the concrete. Mailvaganam (1991) also recommends maintaining the thickness as constant as possible as abrupt changes can decrease the bonding capacity of the sprayed material and increases the possibility of voids being formed. If any irregularity in the feed occurs then the stream must be directed away from the placed material until the feed again becomes consistent (Ryan, 1973).
The quality of a sprayed concrete or mortar repair is very operator dependent and bad quality repairs are very often the result of poor spraying. Because of this, training and certification schemes have been set up in the UK by the Construction Industry Training Board (CITB) in conjunction with the Sprayed Concrete Association. Similar schemes also exist in the United States.

Losses are any material that is not part of the final in-situ material and can be classed as (Austin, 1995a):

1. **overspray** - material that misses the surface (which should be small);
2. **cutback** - material which is shot but subsequently removed before setting (also small if a skilled nozzleman and guiding wires/boards are used); and
3. **rebound** - material which strikes the surface but does not adhere. This is in the region of 5-10% for vertical surfaces for the wet process compared with 20-30% for the dry process (Opsahl, 1985). Opsahl reported that the highest wet-process rebound levels (9-14%) were obtained with either large diameter aggregates (12 mm), high steel fibre contents, low dosages of accelerator or thin layers (30-50 mm). Little further data is available due to the relatively small volume of the losses for the wet process, although much work has been conducted into rebound in the dry process (Ryan, 1975 and Austin, 1997).

Rebound, overspray and dust can result in damage to adjacent structures, prepared substrates, equipment and personnel, especially on windy days. Consideration therefore has to be given to the effects of the spraying and covers such as plywood or polythene may have to be used.

The preferable finish is a natural or gunned finish as the material has not been disturbed by finishing and will possess it's best possible characteristics in terms of bond, strength and durability (Austin, 1995a). A textured finish can also be obtained if required by the use of a trowel, float or brush. It is recommended to brush the as-shot surface with a soft brush approximately one hour after spraying to reduce the occurrence of shrinkage cracks in the cement-rich outer layer (Kay, 1992). Flash coats are also common to either cover reinforcing fibres within the sprayed concrete,
produce a smoother, more workable finish, or to apply a different colour finish. Flash coats are usually applied in a thin layer at a higher water content than the main layer.

The adequate curing of sprayed concrete is essential as its relatively high cement content, low water/cement ratio and often thin section make it particularly susceptible to poor curing. The ACI (1994) recommends five methods for curing: ponding or continuous sprinkling, covering with an absorptive mat or sand that is kept continuously wet, covering with an impervious sheet material, curing compounds and natural curing (only if the ambient relative humidity is maintained above 95%). Damp hessian and spray or brush applied chemical curing membranes can provide adequate curing if properly applied. Ideally the concrete should be kept wet for 7 days in a temperature above 5°C (40°F) (ACI 506R-90). It should not be placed onto a frozen substrate or when the air temperature falls below 3°C (SCA, 1990).

Due to the serious hazard to exposed skin and eyes, personal protective equipment and clothing must be worn by all those within the vicinity of the spraying work. Long sleeved overalls, gloves, head protector and eye protection (goggles or visor) should always be worn. Special care and precautions should be taken in enclosed areas and dust masks or respirators should be provided if needed.

Good guidance for general site safety for sprayed concrete operations is given by Miller (1995). He details the safety precautions to be taken with both plant and equipment and materials as well as protective clothing. All plant must be well maintained, kept clean, well positioned (on safe level ground with sufficient operating space) with all necessary protective guards in place. Care must be taken when handling materials, especially pre-blended mortars (which are very fine and can cause breathing problems or eye damage) and additives (which can be toxic).

2.3.6 Pre-blended proprietary materials

Pre-blended proprietary materials are becoming increasingly popular due to increasing demands for quality and consistency (Walter, 1998). They usually have properties (such as compressive strength, tensile strength, flexural strength and elastic modulus)
comparable with similar strength concrete (Gordon, 1995) so as to have similar (or better) durability as well as compatibility with the substrate.

Simple sand/cement mortars may be inappropriate for many repairs where there is a need for high performance during installation or in service. The increasing use of both steel and polypropylene fibres has also increased the use of pre-blended mixes as the level of mixing required to adequately disperse the fibres and eliminate and bundles of fibres is not generally available on site (Gordon, 1995). Some pre-blended materials may have up to seven different aggregates and fillers blended together to give handling and performance properties superior to site batched materials (Gordon, 1995).

Modern repair materials have both low water/cement ratios and are thixotropic, and so can be applied at much greater thicknesses than when applied by hand, with an increase of 2 or 3 times depending on the orientation (Table 2.4).

<table>
<thead>
<tr>
<th>Property</th>
<th>Hand application</th>
<th>Wet-spray application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh wet density</td>
<td>1975 kg/m$^3$</td>
<td>2084 kg/m$^3$</td>
</tr>
<tr>
<td>Immersed density</td>
<td>1950 kg/m$^3$</td>
<td>2060 kg/m$^3$</td>
</tr>
<tr>
<td>Compressive strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 day 19 N/mm$^2$</td>
<td>1 day 36 N/mm$^2$</td>
<td></td>
</tr>
<tr>
<td>7 days 29 N/mm$^2$</td>
<td>7 days 47 N/mm$^2$</td>
<td></td>
</tr>
<tr>
<td>28 days 40 N/mm$^2$</td>
<td>28 days 59 N/mm$^2$</td>
<td></td>
</tr>
<tr>
<td>ISAT</td>
<td>10 min 0.002 ml/m$^2$/sec</td>
<td>10 min 0.002 ml/m$^2$/sec</td>
</tr>
<tr>
<td></td>
<td>60 min 0.001 ml/m$^2$/sec</td>
<td>60 min 0.0 ml/m$^2$/sec</td>
</tr>
<tr>
<td>Build</td>
<td>Vertically 38-50 mm</td>
<td>Vertically 100-150 mm</td>
</tr>
<tr>
<td></td>
<td>Soffit 19-25 mm</td>
<td>Soffit 25-38 mm</td>
</tr>
<tr>
<td>Bond strength</td>
<td>1.5 N/mm$^2$</td>
<td>2.3 N/mm$^2$</td>
</tr>
</tbody>
</table>

Factory batched products also make it easier to incorporate fillers such as silica fume, polymers, rheology modifiers, and pigments for various ranges of colour, at controlled and consistent rates of addition. The major disadvantage of pre-blended materials is their increased cost compared with site batched materials, especially for high volume construction.
2.3.7 Binders

Portland cement (PC) was used in most of the sprayed concrete produced before 1980 (Robins, 1995). More recently, rapid setting and/or high-early strength gain cements have become popular although Portland cement is likely to remain the most common type of cement. It is, however, being increasingly used in combination with supplementary cementing materials such as silica fume and fly ash.

In the design of normal concrete mixes, the cement content is kept to the minimum required for economical reasons. This is also the case for pumped or sprayed concrete, although a higher cement content is necessary to facilitate adhesion and build up thickness and to reduce bleeding and form a lubricating layer around the inside of the pipe. Increased cement content is also known to reduce rebound (Nordstrom, 1996). Various recommended cement contents for pumped or wet-mix sprayed concrete are given in Table 2.5.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Cement content (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCPA, 1979</td>
<td>300</td>
</tr>
<tr>
<td>EFNARC, 1996</td>
<td>300 minimum</td>
</tr>
<tr>
<td>Warner, 1995a</td>
<td>390</td>
</tr>
<tr>
<td>Isaak and Zynda, 1992</td>
<td>390</td>
</tr>
<tr>
<td>Morgan, 1995</td>
<td>400-500</td>
</tr>
<tr>
<td>Beaupre, 1994</td>
<td>400-450</td>
</tr>
<tr>
<td>RMC and ARC (readymix for spraying)</td>
<td>450</td>
</tr>
</tbody>
</table>

AFNOR (1997) recommended different cement contents depending upon the repair application, as shown in Table 2.6.

<table>
<thead>
<tr>
<th>Application</th>
<th>Cement Content (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repair of masonry</td>
<td>500</td>
</tr>
<tr>
<td>Surface repair</td>
<td>350</td>
</tr>
<tr>
<td>Repair of reinforced concrete structures</td>
<td>450</td>
</tr>
</tbody>
</table>

Neville (1995), reports that the volumetric cement content must be at least equal to the void content of the aggregate. The effect of the relation between cement content and
void content on pumpability is shown in Figure 2.7. However, this does not take into account the influence of the aggregate particle shape on void content.

Silica fume is a highly pozzolanic mineral additive which can be used as a cement replacement or as an additive to improve the rheological and hardened properties of a concrete mix. Silica fume is approximately 100 times finer than cement and has a significantly higher reactive silica content (SiO₂) which ensures that it combines with and distributes the products of hydration more effectively, thus improving the density and homogeneity of the concrete (Neville, 1995). Silica fume produces a cohesive mix with reduced rebound and better bond strength (Nordstrom, 1996). It is generally used as a cement replacement in wet-process sprayed concrete and Table 2.7 shows various recommended addition rates. In the wet process it is often used in conjunction with a water reducer or superplasticiser to maintain workability. It can be added in condensed or un-densified powdered form or as an aqueous slurry. The slurry, a 50/50 aqueous suspension of silica fume powder is widely used in the wet process and was developed to overcome the problems of handling and transporting silica fume in its powdered form.

<table>
<thead>
<tr>
<th>% Cement replacement (by weight)</th>
<th>Suggested addition rates of silica fume to shotcrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norwegian Concrete Association, 1992</td>
<td>3-15%</td>
</tr>
<tr>
<td>Morgan, 1995</td>
<td>5-15%</td>
</tr>
<tr>
<td>EFNARC, 1996</td>
<td>15% max.</td>
</tr>
<tr>
<td>Neville, 1995</td>
<td>7-11%</td>
</tr>
<tr>
<td>Robins, 1995</td>
<td>2-15%</td>
</tr>
</tbody>
</table>

In terms of hardened concrete, silica fume reduces permeability and improves the bond between the cement and the aggregate particles. The use of silica fume results in reduced bleeding and segregation, thus improving pumpability, and with better cohesion and adhesion, thicker layers can be sprayed with minimal rebound loss.

2.3.8 Aggregate

The distinction between sprayed concrete and sprayed mortar, is the same as for conventional concrete, where mortars contain no coarse aggregate. For this work mortars are defined as having a maximum aggregate size of 3 mm and fine concretes a
maximum aggregate size of 8 mm. Most of the characteristics of aggregate influence the workability of fresh mortar or concrete, with factors such as grading having a large effect on pumpability.

The International Tunnelling Association, or ITA (1993) has reviewed recommendations and specifications from 15 different countries (Table 2.8).

<table>
<thead>
<tr>
<th>Coarse aggregate Specification</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum aggregate size 8 mm</td>
<td>Japan Tunnelling Association 1991</td>
</tr>
<tr>
<td>16 mm</td>
<td>Sprayed Concrete Association 1990</td>
</tr>
<tr>
<td>No fraction &gt;30% of total agg.</td>
<td>Norwegian Concrete Assoc. 1992</td>
</tr>
<tr>
<td>Specific gravity &gt;2.5 kg/dm³</td>
<td>Japan Tunnelling Association 1991</td>
</tr>
<tr>
<td>Water absorption &lt;3.0%</td>
<td>Japan Tunnelling Association 1992</td>
</tr>
<tr>
<td>Loss by washing &lt;1.0%</td>
<td>Japan Tunnelling Association 1993</td>
</tr>
<tr>
<td>Clay content &lt;0.25%</td>
<td>Japan Tunnelling Association 1994</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sand Specification</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fineness modulus 2.3-3.2</td>
<td>Japan Tunnelling Association 1994</td>
</tr>
<tr>
<td>Surface water</td>
<td>Japan Tunnelling Association 1994</td>
</tr>
<tr>
<td>2-4%</td>
<td>AFTES 1992</td>
</tr>
<tr>
<td>&lt;7%</td>
<td>AFTES 1992</td>
</tr>
<tr>
<td>Specific gravity &gt;2.5 kg/dm³</td>
<td>Japan Tunnelling Association 1994</td>
</tr>
<tr>
<td>Water absorption &lt;3.0%</td>
<td>Japan Tunnelling Association 1994</td>
</tr>
<tr>
<td>Loss by washing &lt;5.0%</td>
<td>Japan Tunnelling Association 1994</td>
</tr>
</tbody>
</table>

Sand gradings are critical to the rheological properties of fresh mortars and concretes and the structure of the hardened product. The grading of aggregate and the distribution of sizes of particles of aggregate all determine the basic surface area of all the aggregate in the mix. It also determines the amount of cement paste which will be necessary to coat all the particles with a layer of cement paste sufficiently thick and workable to improve the potential for movement and re-arrangement of the particles, and achieve the required workability of the fresh concrete mix. A maximum aggregate size of 8-10 mm is preferable, due to limitations on pumping equipment, and also to minimise loss through rebound (Warner, 1995a; ITA, 1993 and Hills, 1982). An increase in the proportion of coarse aggregate has been shown to increase the pumping pressure needed and reduce the mix workability (Norris, 1999).
Melbye et al. (1995) explain that the lower part of the grading is particularly important. Too little fine material leads to segregation and increases the risk of bleeding and hence blockages. This can be compensated for by the addition of fillers, extra cement or silica fume. Too much fine material causes high stiffness and increases the frictional resistance (which can also lead to blockage). This may be rectified by increasing the workability of the mix, e.g. by the addition of water-reducing admixtures. Clearly a balance is required and they suggest that fine material (<125 µm) should be between 4-9%. Particles below 75 µm are classed as silt which tends to have a high water demand, and if included in high proportions can lead to internal disruption and volume changes. Table 2.9 gives recommendations for fines contents from various sources.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Recommended Fines Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooke, 1990</td>
<td>350-400 kg/m³ &lt;0.25mm, with 10-20% passing 0.3mm</td>
</tr>
<tr>
<td>Neville, 1995</td>
<td>For pipes &lt;125mm, 15-30% &lt;0.3mm, and 5-10% &lt;0.15mm</td>
</tr>
<tr>
<td>BCPA, 1979</td>
<td>15% &lt;0.3mm</td>
</tr>
<tr>
<td>AFNOR, 1997</td>
<td>6-8% &lt;0.08mm</td>
</tr>
</tbody>
</table>

In the UK, Aggregates should conform to BS 882 (1983), falling at the coarse end of medium grading (Robins, 1995). Melbye et al. (1995) suggest that for wet-mix spraying the grain distribution should fall within the limits shown in Figure 2.8. The quantity of aggregate >8 mm should not exceed 10%, and no particles should be >16 mm. This same grading is also suggested by EFNARC (1996) and the ITA (1993), whilst AFNOR (1997) recommend a narrower grading zone for aggregates of 8 mm and below.

Aggregates that are used in concrete mixes for pumping should have a continuous grading (BCPA, 1990), and thus a combination of coarse and fine aggregates that will produce as low a void content as possible. The ideal grading is that in which the voids in the largest particle size are filled with particles of the next size fraction down, and so on. For pumpable mortars, Kempster (1967) recommended a grading for sand, as given in Figure 2.9. There is little other published information on suitable gradings for mortars and fine concretes.
The packing of sand influences its void content (Lee, 1975), and the dry compacted bulk density may be considered as a true indication of the voids present. A poorly graded sand (i.e. having a low dry compacted density) requires a high proportion of material to fill the voids. If this material is cement or water, then bleeding and high drying shrinkage will result. An apparatus for measuring the voids content of dry materials with continuous voids was developed by Browne and Bamforth (1977).

The shape of the aggregate particles also influences the optimum mix proportions for good pumpability. Both rounded and irregular aggregates can be used, although angular particles tend to require a higher volume of mortar to coat the particles effectively. In general, a sand with angular particles will offer a greater resistance to the flow of paste through it than a sand with rounded particles. The particle shape also has some effect on pumping characteristics (Kempster, 1967). A rounded soft sand will often have a lower segregation pressure than one with angular particles. On the other hand, the angular sand can result in slightly higher frictional resistance and, therefore, increased pumping pressure.

Hills (1982) found that in practice, although crushed rock fine aggregate was incorporated into sprayed concrete mixes, crushed rock coarse aggregate was never used. Neville (1995), points out however, that care must be taken when using crushed fines, as they tend to be deficient in the 500-600 µm size fraction, but have excess material <150 µm. Neville also recommends that when crushed fines are used, the fine aggregate content should be increased by 2%. In normal concrete mixes with crushed coarse aggregate, higher cement and fines contents (and often admixtures) are required. Natural gravels and sands are usually better for pumping than crushed rock because of their rounded particle shape, and because the grading is more continuous which therefore minimises the void content. Coarse aggregate of marine or river origin is also common.

Flakiness and elongation are not usually specified for sands, although they can be determined by visual inspection under a low-power microscope. Flakiness in fine aggregate increases water demand, causing bleeding and segregation, leading to
reduced strength and durability. Aggregate surface texture is reported to influence the bond between the aggregate particles and the hardened cement paste.

Several methods are available for combining aggregates which can be done by hand, some of which have been written as computer programs to enable quick comparisons of several types of aggregate. Lydon (1972) described two methods of combining different grades of aggregate to obtain a desired grading. In the arithmetical method no more than two gradings may be combined successfully, whereas a limitless number may be combined in the graphical method. Neville (1995) also describes by example both an arithmetical (in which he combines three aggregates) and a graphical method. Another technique of predicting the optimum combination of aggregates to obtain the maximum packing density is the graphical Fuller-Rotfuchs method described by Ball (1998) where separate single-sized aggregates are blended to a theoretical ideal distribution.

These methods assume that all the aggregates have the same specific gravity, but the physical composition of concrete is based upon volumetric proportions and so if the specific gravity of the aggregates differ appreciably then the proportions should be adjusted accordingly (Neville, 1995). This is especially important with lightweight aggregates.

2.3.9 Admixtures and additions

Many admixtures and additives are available but this review will concentrate on those that have been used in this research, namely superplasticisers, air entrainment, fibres (both steel and polypropylene) and styrene-butadiene rubber (SBR). Other admixtures and additives include fly ash, ground, granulated blast furnace slag (GGBS), water reducers, retarders, accelerators, stabilisers and activators, none of which were used in this research. Nuruddin et al. (1999) recently researched the effect of partially replacing the cement with GGBS in wet-process sprayed concrete and concluded that a replacement level of 40% gave the best performance in terms of compressive and bond strength and permeability.
It is essential that all admixtures to be used are tested for compatibility in the combinations and quantities to be used (Norris, 1999). An admixture than performs in a particular way can react differently at a different cement content or workability or when used in conjunction with other admixtures.

Superplasticisers are high performance water-reducers which disperse the 'fines' more effectively within a mix and therefore improve the workability and cohesiveness. Two of the commonest types of superplasticisers are (Neville, 1995):

1. sulphonated melamine formaldehyde condensates (which form a lubricating film on the particle surfaces); and
2. sulphonated napthalene formaldehyde condensates (which electrically charge the cement particles so that they repel each other).

Superplasticisers can be used to either reduce the water/cement ratio for a given workability (thereby increasing the compressive strength and durability) or to increase the workability for a given water/cement ratio (thereby increasing the pumpability of a mix). The workability can return to normal approximately 20 minutes after the addition of the superplasticiser and so they should be added immediately before placing (Neville, 1995). They are not known to affect the setting or the final hardened properties of the concrete. The use and dosage of superplasticisers depends on the mix specification, the water/cement ratio, required workability, and cement and aggregate types. Morgan (1995) suggests that superplasticisers are required in the range of 0.5-1.0 litre/100 kg of cement in wet-process silica fume sprayed concrete.

Air entraining agents are added to wet-sprayed concretes to create a hardened concrete with small, well distributed air pores which act as expansion tanks for water pressurised away by freezing (Nordstrom, 1996). It enhances the freeze-thaw durability and de-icing chemical scaling resistance. ACI Standard 506.2 (1994) specifies that wet-mix shotcrete exposed to severe freeze-thaw conditions must be air-entrained. However, as much as one half of the air content can be lost on impact with the receiving surface (Nordstrom, 1996), and it can be difficult to obtain an in-situ air content greater than 4% although there is some evidence to suggest that sprayed
concretes may require a lower air content (2-3%) for freeze-thaw resistance than conventionally placed concrete (Robins, 1995).

Air entraining agents can be neutralised vinsol resins, salts of sulphonated hydrocarbons, or salts of fatty acids. They act by stabilising small air bubbles created during mixing or by forming physiochemical links between the bubbles and the cement. Air-entrainment can also greatly improve the flow properties of mortar, to some extent replacing the water as a lubricant between the sand particles. Air-entraining agents are usually in the form of a liquid although powdered forms are also available for use in dry-process sprayed concrete (Beaupré et al., 1999).

However, difficulties in pumping can sometimes occur as the bubbles are compressed or destroyed. The flow properties of the mix then revert back to those of the same mix in its un-air-entrained state, which can lead to segregation and blocking of the pump. This is more likely to occur in piston pumps than worm pumps due to the high fluctuating pressures found in piston pumps (Kempster, 1967).

Fibre reinforcement can improve the ductility, energy absorption, impact resistance, and crack resistance of sprayed concrete (Gordon, 1995). They enable the sprayed concrete to continue to carry stresses after cracking, which helps maintain structural integrity and serviceability of structures under load. The use of fibres in sprayed concrete is becoming increasingly common and is seen as one of the biggest changes in the industry (Walter, 1998). Steel, polypropylene and glass fibres have all been used, with steel by far the most common. Steel fibres have typical lengths of 25-40 mm and aspect ratios (i.e. length/diameter) between 50-100 (Jones, 1998). The higher the fibre aspect ratio and volume concentration, the higher the hardened performance of the sprayed concrete but the lower the pumpability of the mix as it becomes more difficult to mix, pump and spray. Morgan (1995) recommends an addition rate for steel fibres of 50-80 kg/m³ depending on the required toughness. The length of the steel fibres should not exceed 0.7 of the internal diameter of the pipe or hose (EFNARC, 1996).
By the mid 1980s monofilament and collated fibrillated polypropylene fibres were being used in low doses (approximately 1 kg/m$^3$) in wet-mix sprayed concrete (Robins, 1995). At these low rates the benefits are mainly to the fresh properties such as cohesiveness and plastic shrinkage cracking but more recently high dosages (4-7 kg/m$^3$) have been used to provide toughness behaviour similar to steel fibre reinforced sprayed concrete.

Latex solutions such as SBR (styrene-butadiene rubber) are sometimes used in wet-process sprayed concrete to improve the permeability, abrasion and chemical resistance of the hardened concrete (Warner, 1995a). It can also improve the adhesion and freeze/thaw resistance (Schrader and Kaden, 1987). The latex should be proportioned at about 10-15% of latex solids by weight of cement (Warner, 1995a).

Yeon and Han (1997) found that SBR mortars had a higher strength, a higher rate of strength development, better chemical resistance and a slightly higher thermal expansion coefficient than similar cement mortar. Fowler (1997) reported that SBR concretes may have strengths slightly higher or slightly lower than normal concrete and a lower modulus of elasticity. Other research has shown that SBR concretes have slightly higher compressive strengths, up to 40% higher tensile strengths, smaller water absorption rates and values of drying shrinkage almost 50% less (Folic and Radonjanin, 1998). The elastic modulus was not significantly affected. Latex solutions are also sometimes used as bonding agents (see Section 2.3.4). In the early 1980s repair mortars were blended on site from sand, cement, latex and water but poor quality control often led to unsatisfactory mortars (Allen et al. 1993). To overcome this problem 'bag and bottle' mixes of latex and pre-blended sand and cement became commercially available as did powdered polymers which could be incorporated into pre-blended mortars.

2.3.10 Mix design

Pumped or sprayed concrete is essentially no different to conventionally placed concrete of similar proportions, and can be designed for strength, workability and durability in a similar way with only minor variations (Norris, 1999). ACI 506R-90
(1990) recommends that the mix design procedure is carried out in accordance with ACI 211.1 (1985), with only an aggregate content correction for pumped concrete. The British Concrete Pumping Association (1979) outline a procedure for adjusting normal concrete mixes for pumping and Austin (1995b) provides guidance on materials selection, specification and mix design. The mix designer must bear in mind the mechanics of concrete pumping, as the concrete must not only meet specification for strength, but must also meet pumpability and shootability requirements (Cooke, 1990).

Sprayed concrete can be specified using either the designed mix or prescribed mix approach. The designed mix approach is preferable as the contractor is free to select constituents to produce the best pumping performance for a mix (King, 1995) i.e. the specification should be performance, rather than method, based. This performance-based mix design is a major advantage of the wet process compared with the dry with respect to consistency and Quality Control.

An effective material for wet-process pumping and spraying needs to be the stiffest mix that will pump through the nozzles, will remain at a workable consistency when left in the hose during breaks in pumping, will not stiffen under the increased temperatures which exist in pumped material (the pump can generate considerable increases in temperature in a long spraying operation), and will atomise easily with the available air supply.

Most reference sources recommend a slump of between 50-150 mm, with a loss of 10-25 mm caused by compaction by the pumping process. A target slump of 75 mm ± 25 mm is common which is used by ready-mix companies who produce concrete for pumping (BCPA, 1990). A slump of 50-80 mm is seen as a good compromise between pumpability and shootability (Beaupré, 1994). Kempster (1967) recommends a slump of 150-200 mm for pumpable mortars, although a mix of this slump would probably slough when sprayed.

The water content of a concrete mix for pumping is critical, as it is the water that transmits pressure to the other mix constituents. If it is too low, coarse aggregate
particles will not move longitudinally in a coherent mass in suspension, but will exert pressure on the walls of the pipe. At the correct or critical water content, friction develops only at the surface of the pipe, and in a thin 1-2.5 mm layer of lubricating layer which allows 'plug' flow to occur. Excess water will lead to segregation of the mix. Neville (1995) recommends a water/cement ratio of 0.40-0.55 for wet-process sprayed concrete, with EFNARC (1996) also stating a maximum of 0.55. A water/cement ratio below 0.35 produces high performance sprayed concrete, which requires superplasticisers (Beaupré, 1994).

If the sand to cement ratio is 1:1 or 2:1, the mix is very unlikely to segregate unless it is also extremely wet (Kempster, 1967). Such cement-rich mixes are rare, and the more normal mixes in the range of 3:1 up to 6:1 are more likely to have segregation problems. The fines content (<80 µm) including cement must be greater than 17% of the dry mix (by weight) (AFNOR, 1997).

A mix may be unpumpable for several reasons, including it not being mixed properly (it takes only 0.05 m³ of unmixed material to cause a blockage (BCPA, 1990)). However, the two main problems are bleeding and excessive friction. Bleeding may occur when the cement content is too low, or if poor or badly graded aggregate has been used. This may be remedied by improving the grading of the aggregate, and by increasing the fines and cement content. Excessive friction may be caused by having long pipes, high cement contents and low values of slump. The solution to this problem is to increase the fines content and the slump, and to introduce a wetting agent.

2.3.11 Standards and specification

The most recent European specification is the EFNARC Specification for Sprayed Concrete published in 1996. Both the EFNARC document and DIN 18 551 have recently been put before the CEN (Comité Européan de Normalisation) committee TC/104/SC8/WG10 which is producing an EN standard for sprayed concrete, with the latest draft being in September 1999. The British Standards Institution has not produced any national standards relating to sprayed concrete, but has supported moves
towards developing a European Standard. The main specification used in the United
States is the ACI's *Standard Specification for Materials, Proportioning and
Application of Shotcrete (ACI 506, 1990)*, which was followed several years later by a
revision (ACI 506.2). These specifications are also complemented by several ASTM
national standards relating to sprayed concrete:

- **C1141-89** - Standard specification for admixtures for shotcrete
- **C1140-89** - Standard practice for preparing and testing specimens from shotcrete
  concrete panels
- **C1117-89** - Standard test method for time of setting of shotcrete mixtures by
  penetration resistance

The French standard AFNOR NF P95-102 introduced in 1992 (with an English
translation in 1997) relates only to repair and strengthening, but gives detailed,
pragmatic advice for sprayed concrete applications in general. Germany introduced
their DIN 18 551 in 1979 which concentrates mainly on production and quality
control. AFTES, the French Association for Underground Works, has also published a
useful document has been produced by the International Tunnelling Association,
This document summarises the specification and guidance documents in the fifteen
ITA member countries and includes substantial references to the ACI, AFTES,
ASTM, DIN, EFNARC and others.

Several guides and Codes of Practice have also been published on the spraying of
concretes and mortars, including:

- ACI Committee 506R Guide to Shotcrete (1990)
- Sprayed Concrete Association Code of Good Practice (1990)
2.4 RHEOLOGY OF FRESH MORTARS AND CONCRETES

2.4.1 Concept and definition

Rheology can be defined as 'the science of deformation and flow of matter', and is concerned with the relationships between stress, strain and time. In terms of fresh concrete, the field of rheology is related to the flow properties of concrete or with its mobility before setting takes place. Rheological characteristics of a concrete mixture constitute the most important factor in workability, and perhaps the only aspect that can be evaluated quantitatively (Powers, 1968).

Rheological parameters enable us to predict the amount of deformation or flow which will occur when a given stress is applied, or vice versa, the stress caused by a certain amount of deformation (Bartos, 1992). It is also important to be aware of the limitations of both theoretical and practical rheology when applied to a material as complex as concrete. Bartos states that the rheological equations which determine basic rheological characteristics and parameters are based on several assumptions that the material is:

1. a continuum, i.e. a material with no discontinuity between two points;
2. a homogeneous mix, i.e. a material with uniform composition throughout; and
3. an isotropic material, i.e. a material with the same properties in all directions.

Fresh concrete however, is a 'highly heterogeneous material, with extreme internal mechanical discontinuities, and assuming medium continuity is unacceptable' (Legrand, 1993). It would be too complex to take the heterogeneity of a fresh mix into account in order to study its rheological behaviour, as there are numerous phases involved: solid; free liquid; absorbed liquid and gases and the nature, dimensions and shape of cement and aggregate particles vary considerably. It is therefore necessary to elaborate a simpler model (Legrand, 1993).
2.4.2 Newtonian flow

Load applied to an ideal solid will produce deformation. Such a solid body will follow Hooke’s law, where the deformation is proportional to the load, or, stated more generally, the strain is proportional to the stress. In the case of shear stresses, this is represented in Figure 2.10. Hooke’s law states that $\tau$ (the shear stress, or $\text{F}/\text{A}$) is proportional to $\gamma$ (the angle of deformation), or:

$$\tau = \eta \cdot \gamma \quad \text{(equ. 2.1)}$$

where $\eta$ is the constant of proportionality and is termed the shear modulus. If $\tau$ is plotted as a function of $\gamma$, the result is a straight line whose slope is $\eta$ as shown in Figure 2.11. When a shear stress is applied to a liquid, the liquid deforms and keeps deforming until the stress is relieved. The continuous increase in $\gamma$ would occur no matter how small the stress $\tau$, but the rate at which it occurred, measured by the time differential of $\gamma$, would depend on $\tau$ and, in the case of a simple liquid, would be simply proportional to it. Thus, the equation for a simple liquid is:

$$\tau = \eta \frac{dy}{dt} \quad \text{(equ. 2.2)}$$

The stress-strain relationship in the Hookean equation has now been replaced by the shear-strain rate. If a liquid is confined between two parallel plates, one fixed and the other mobile, a laminar motion of the liquid is caused. Newton’s law of viscous flow states that a shear stress is proportional to the velocity $v$, and inversely proportional to the distance $y$ between the plates. This may be expressed mathematically as:

$$\tau = \eta \frac{dv}{dy} \quad \text{(equ. 2.3)}$$

$dv/dy$ is called the velocity gradient, which is the same as $dy/dt$, so Newton’s law of viscous flow may be written as:

$$\tau = \eta \dot{\gamma} \quad \text{(equ. 2.4)}$$

This relationship is only valid for laminar flow where velocity varies only in the $y$ direction. Fluids that obey this law are termed Newtonian. Providing laminar flow is observed, the single constant $\eta$ (termed the coefficient of viscosity) is sufficient to characterise the flow properties of a Newtonian liquid (at constant temperature). This
constant according to equation 2.4 can be determined simply by a single measurement of one pair of values of stress and shear rate.

2.4.3 Other rheological behaviour

Newtonian behaviour is the simplest behaviour for a fluid, but many materials show more complex behaviour where the observed rate of shear is not linearly proportional to the applied stress, and is dependent on the shear rate, and the length of time that the shear stress is applied. Such behaviour is shown by flow curves that are not straight lines passing through the origin, and thus can not be characterised by a single constant (Figure 2.12).

Curves (a) and (b) are termed pseudoplastic, or power law fluids, conforming to the relationship;

\[ \tau = A \gamma^n \]  

(equ. 2.5)

where \( n < 1 \) = shear thinning, and \( n > 1 \) = shear thickening. ‘A’ is a constant dependant upon the type of fluid. In shear thickening, viscosity increases when shear rate is high, thus the liquid flows less as the flow rate is increased. Shear thickening is sometimes accompanied by dilatancy, a repacking of particles resulting in an increase in volume. In shear thinning, the viscosity decreases as shear rate increases, resulting in a higher degree of flow at higher shear rates. This is the sort of curve one might expect from a material whose structure is capable of being broken down or altered by shearing.

Liquids (b) and (c) also have a yield value, a minimum stress below which flow will not occur. Flow curve (c) represents the Bingham behaviour, where once the yield value has been overcome, there is a linear relationship between the applied shear stress and the shear rate. This behaviour can be expressed by the following equation;

\[ \tau \gamma = \tau_0 + \mu \]  

(equ. 2.6)

where \( \tau_0 \) = yield stress (Pa), and \( \mu \) is a constant which has the dimensions of viscosity and is termed plastic viscosity (Pa.s).

While a measurement at a single shear rate is sufficient to characterise a Newtonian liquid, measurements at more than one shear rate or shear stress are needed for a non-
Newtonian liquid. Two in principle are adequate, although more are preferred in order to reduce experimental errors. Bingham materials may also show time-dependent behaviour in the form of a reduction in shear stress at a constant shear rate, which is more severe at higher shear rates. If the thinning is permanent, irreversible structural break down is said to have occurred, a phenomena called rheomalaxis or rheodestruction (Tattersall and Banfill, 1983). If the structure reforms after shearing has stopped, the material is said to be thixotropic. In either case, the reduction takes place as a result of the work of shearing applied during the course of the test, and the flow curve of shear rate against shear stress exhibits hysteresis, as shown in Figure 2.13.

2.4.4 Rheology of cement pastes

Plain fresh concrete or mortar can be described as a composite material consisting of a suspension of aggregates in a matrix of cement paste. It would seem reasonable then, that to obtain a full understanding of the behaviour of fresh mortars or concretes, first the rheological behaviour of the matrix must be fully stated. Tattersall and Banfill (1983) however, suggested that as the rheological behaviour of cement paste is so complicated, progress along these lines would be so slow as to as to have no impact on practical problems for a long time to come. Early work has also revealed that the flow properties of concrete could be represented by the Bingham model, and appeared to be much simpler than cement paste.

There still remains a lack of qualitative agreement between the results of different workers on the subject, due to the widely varying techniques of measurement used. There is no doubt however, that cement pastes exhibit an irreversible structural breakdown under shear, and that Bingham behaviour is observed at low shear rates. It is probably due to the latter fact that concrete itself conforms loosely to the Bingham model (Tattersall and Banfill, 1983). When reporting rheology results it is therefore important to give an indication of the previous shear history of the mortar. The mortar should preferably be completely broken down in order to provide unambiguous results. Apparatus used for testing the rheology of mortars can also be used for testing cement pastes and several of these are described in Section 2.4.6.
2.4.5 Rheology of concretes

Workability of concrete

Workability is defined by ASTM C125 as "that property determining the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity." On the other hand, the ACI Committee 309 (1987) defined workability as "that property that determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished."

Legrand (1993) stated that it is important not to seek to obtain intrinsic rheological characteristics from the results of standard workability tests. The results will depend not only on the material studied but also on the equipment geometry and the test conditions. The results from these empirical tests should be quoted quantitatively but with reference to the test. When designing a workability test it should be noted that the concrete needs to be measured in conditions resembling as closely as possible to the actual placing conditions.

Tattersall (1991) grouped the different terms for workability into three classes, qualitative, quantitative empirical and quantitative fundamental. He recommended that qualitative terms such as flowability, pumpability and compactability should only be used in a general descriptive way without any attempts at quantification. The quantitative empirical terms such as slump, compacting factor and Vebe time should be used as a simple quantitative statement of behaviour in a particular set of circumstances. The quantitative fundamental terms such as viscosity and yield value should be used as defined in BS5168: 1975 Glossary of rheological terms. He suggested that the actual term workability should be retained for the most general use without quantification.

Tattersall reported that Wierig (1984) reviewed the different types of workability tests and he reported that over one hundred methods have been proposed for the measurement of workability. He classified them as: flow tests, remoulding tests, deforming tests, compacting tests, penetration tests, pull out tests, drop out tests and mixer tests.
De Larrard *et al.* (1993) discussed how the concrete production process (mixing of the constituents) leads to the incorporation of a volume of air in the mixture. After mixing, a fairly stiff concrete could easily exhibit a swelling of up to 10% by volume. This change in size will be restored to within 1-3% of the original volume after placing and compaction. The final material therefore differs slightly from the original.

He also mentioned the importance of keeping the sample sufficiently homogeneous in order for it to be representative.

Tattersall (1976) related and compared the results from different workability tests and concluded that the slump test is a measure of the yield value (or g) of fresh concrete. He reports that slump and g for a 20 mm aggregate fresh concrete have an approximate inverse square root relationship (Figure 2.14). However, Morinaga (1973) reported a simple linear relationship between slump and g.

**Two-point workability test**

Tattersall (1983) developed an apparatus in which the element on which the torque is measured is continuously presented with a new volume of concrete by the mixing process, and he initially achieved this by using a Hobart food mixer. The electrical power required to drive a stirrer at three different speeds about the bowl axis was measured using a dynamometer wattmeter when the bowl contained a standard quantity of concrete, and also when it was empty. The difference between these two powers, P, was divided by the speed, N, to give the value of torque, T, in arbitrary units. When torque was plotted against speed, it was found that the relationship was linear, or very nearly so (Figure 2.15). The linear curve is represented by the equation:

\[ T = g + hN \]  

where T is the torque required to drive the impeller (Nm), g is the intercept on the torque axis (Nm), h is the reciprocal of the slope of the line (Nm.s), and N is the impeller angular speed (rev/s). Beaupré (1994) refers to g as the flow resistance, and h as the torque viscosity. This equation is of the same form as that of the Bingham model, \( \tau = \tau_0 + \mu \gamma \), and thus it can be said that g is a measure of yield value, and h is a measure of plastic viscosity. Later versions of the apparatus consist of an impeller
immersed in a sampling bowl, rotated at the required speeds by the use of an electric motor driving through a hydraulic transmission. A simple pressure gauge is connected to the hydraulic line, and the torque calculated by dividing the difference in pressure by speed. The formulas for converting constants $g$ and $h$ to fundamental units of $\tau_0$ and $\mu$ are included in Appendix 1.

The Mk II version used in this investigation is known to be satisfactory for medium- to high-workability concretes. However, it has been suggested that the apparatus might not be sensitive enough for mortars or low workability concretes if the torque’s exerted on the impeller are too low to give a significant increase in pressure (Tattersall, 1991). However, sufficient change was observed in this work.

2.4.6 Rheology of mortars

Mortar shows irreversible structural breakdown as a result of mixing both before and during testing. The latter results in flow curves where the down-curve falls to lower torque’s than the up-curve. When structural breakdown is complete, either as a result of prolonged shearing or after completion of the up-curve, the down-curve conforms to the Bingham model (Banfill, 1987, 1990). The yield values and plastic viscosity’s obtained are intermediate between those reported in the literature of cement paste and concrete (Banfill, 1990). This seems likely in view of the likely contribution of the aggregate in the material: as aggregate size increases, a greater proportion of the externally applied stresses can be borne by the aggregate and so the material becomes stiffer. It also confirms ordinary objective assessment of the fresh materials. Although the two-point test apparatus works well for concrete, Banfill (1987) reported that “attempts at using it to measure rheological parameters of mortars have been unsuccessful, as the torque’s exerted on the rotating impeller are too low to give a significant increase in pressure readings above the idling pressures.” However, sufficient increases in pressure readings were observed in this work and the two-point test was therefore used to measure the workability of mortars (Section 3.6.3).

The coaxial cylinder viscometer has been widely used for the rheological testing of mortars (Banfill, 1987) but the large sample needed for testing made the apparatus
cumbersome and inconvenient (Banfill, 1994). The Viskomat and its predecessor, the ViscoCorder, were thus developed which could test small mortar samples (approximately 1 kg) using the two-point principle developed by Tattersall (Section 2.4.4 and 2.4.5). Details of the Viskomat apparatus are included in Section 3.6.4. Several types of Rheometer have also been developed to measure the workability of mortars (Banfill et al., 1991, Jian-Zhong, 1993 and Larrard et al., 1997) but none have been as universally adopted as the ViscoCorder and Viskomat. Banfill (1994) conducted fundamental tests into the effects of altering the mix constituents of mortars and the trends are the same as those presented in Table 2.10. An increase in the proportion of sand fines within a mix produced an increase in both g and h and an increase in the proportion of silica fume (or micro silica) produced an increase in g and a decrease in h (Figure 2.16).

Hornung (1991) used a ViscoCorder to measure the value of g with mortars made with different cements at different water/cement ratios. He then compared these values to the slump of the resultant concrete made with the mortar as shown in Figure 2.17. A relationship between the value of h for mortar and the slump value of the resultant concrete was not found.

Tattersall (1991) presented and discussed results obtained by Dimond (1980) who compared values for g and h obtained for 2 cement pastes made with different cements (A and B) with the g and h values obtained from the concrete made with the cement paste (Figure 2.18). The cement pastes he used had water/cement ratios between 0.36 and 0.53 and the paste made with cement B consistently gave values of g and h double that of cement A. However, Figure 2.18 shows that when the cements were tested in concretes of 4:1 and 8:1 aggregate: cement ratios at various w/c ratios, there was no difference between the g and h values. When he repeated the experiment on the 4:1 mix using a different nominally identical aggregate, g increased by about 35%. Thus the unplanned change in aggregate properties had a greater effect than the change from one cement to another of widely different rheological properties.

Tattersall (1991) also reported the investigation carried out by Yeoh (1982) of the relationship between the value of g for a cement paste and the value for g of the
resultant concrete (Figure 2.19). Each mix was made with a different cement and he tested the pastes with a coaxial-cylinders viscometer and the concretes with the two-point test apparatus. The concretes had an aggregate: cement ratio of 3:1, with 40% fines and a water/cement ratio of 0.40. The correlation’s for the plastic viscosity (h) of the cement pastes and resultant concretes were similar (Figure 2.20).

2.4.7 Effects of mix composition on rheology

All the constituents within a concrete or mortar (i.e. cement, aggregate and water, plus, if present, additives and additions such as silica fume, plasticiser and fibres) have an effect on the rheology of the combined mix. A change in the proportion, or type of each constituent will produce a corresponding change in the rheology of the mortar. The effects of these constituents are summarised below. The effect of time is also considered as this also obviously affects the rheology of a material. The information in this section is taken mainly from both Tattersall (1991) and Tattersall and Banfill (1983) unless otherwise stated. The effects are summarised in Table 2.10.

**Time**

During the initial mixing period rapid hydration takes place and during the initial setting period (up to approximately 2-3 hours, depending on the mix) the flow resistance increases, although the plastic viscosity is not usually affected. The setting time may be modified by: changing the temperature, water/cement ratio or cement content, or by the use of superplasticisers, stabilisers, accelerators or rapid hardening cements.

**Water-cement ratio**

An increase in the water/cement ratio produces a decrease in plastic viscosity and a decrease in flow resistance. The type of cement, and the type and quantity of other cementitious materials, will all affect the rheology.

**Admixtures**

It is difficult to predict specific effect of any mix without testing due to interactions between the cement, the mineral admixtures and any other admixtures present within
the mix. The effect of different types of admixture is summarised in Figure 2.21 (Gjørv, 1992).

Superplasticisers and water-reducers

Water-reducers and superplasticisers have a similar affect on the rheology of a mix, namely a decrease in both flow resistance and plastic viscosity. They can be used to provide either a higher workability with strength unchanged, or a higher strength with unchanged workability; or a lower cement requirement for the same strength and workability. Care should be taken in their use as superplasticisers lose their effectiveness over time and can lead to false set.

Air-entraining agents

Increasing the air content decreases both the flow resistance and the plastic viscosity and has been shown to have some potential as a means of increasing the pumpability of a fresh concrete mix (Beaupré, 1994 and Beaupré, 1996). It enables a lower water/cement ratio to be used to obtain the same workability in a similar way to the use of a superplasticiser. Air entrainment would also produce a decrease in the fresh and hardened density.

Silica fume

Adding silica fume to a mix increases the cohesiveness and reduces bleeding and even a small amount (2-3% by weight of cement) can increase the pumpability of a mix (Tattersall, 1991). Care should be taken when conducting slump tests with silica fume concrete and mortar as the material can stick to the cone, making an accurate result difficult to obtain. Silica fume mixes are often used together with a superplasticiser to adequately disperse the silica fume and to counter-act the reduction in workability. Different sources of silica fume can also produce different effects on both the flow resistance and torque viscosity (Tattersall, 1991).

Pulverised fuel ash (PFA) and ground granulated blast furnace slag (GGBS)

In general, cement replacement with PFA or GGBS produces a decrease in both flow resistance and torque viscosity but by different amounts, depending on the type and proportion of aggregate and the grading. GGBS has a smaller effect on workability
than PFA and hydrates more slowly than Portland cement and so produces a longer setting time.

**Fibres**

Fresh fibre reinforced concrete conforms to the Bingham model and as the fibre content increases, flow resistance and torque viscosity both increase (Tattersall, 1991). The addition of fibres increases the water needed to maintain the same workability and so are often used together with superplasticisers or water-reducers. Similar results produced by Llwellyn (1990) (as reported by Tattersall (1991)) showed that an increase in the quantity of polypropylene fibres also produced an increase in flow resistance, which was greater than the increase observed for the torque viscosity.

<table>
<thead>
<tr>
<th>Change</th>
<th>Effect on:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yield value</td>
</tr>
<tr>
<td>Increase water content</td>
<td>Decrease</td>
</tr>
<tr>
<td>Increase sand content</td>
<td>Increase</td>
</tr>
<tr>
<td>Increase sand content</td>
<td>Increase</td>
</tr>
<tr>
<td>Increase fineness of sand</td>
<td>Increase</td>
</tr>
<tr>
<td>Add plasticiser</td>
<td>Decrease</td>
</tr>
<tr>
<td>Add air entrainer</td>
<td>No change</td>
</tr>
<tr>
<td>Replace part of cement with:</td>
<td></td>
</tr>
<tr>
<td>Fly ash</td>
<td>Decrease</td>
</tr>
<tr>
<td>Micro silica</td>
<td>Increase</td>
</tr>
</tbody>
</table>
2.5 PUMPING OF MORTARS AND CONCRETES

2.5.1 Background

Wet-process sprayed concrete is divided into two parameters, pumping and spraying, and in order that a mix can be sprayed, it must first be capable of being pumped. Thus, a clear understanding of what happens to concrete when it is pumped through a pipeline is fundamental to any study of wet-process sprayed concrete.

Pumping has itself been used for placing concrete for over fifty years. Research into the behaviour of concrete in the pipeline goes back to as early as 1949 when Dawson conducted tests under site conditions. Since then Ede (1957); Weber (1968); Morinaga (1973); Loadwick, Browne and Bamforth (1973); and Browne and Bamforth (1977), have developed theories and basic tests in the mechanics of concrete pumping. Cooke (1990) has published a very good book on the pumping of concrete and the Concrete Society have recently published a Good Concrete Guide on concrete pumping (1998), whose main points were summarised by Lewis (1998).

Work conducted by Beaupré (1994), has attempted to study the relationship between pumpability and shootability of high performance shotcrete, and its rheological properties in terms of yield value (g) and plastic viscosity (h). This work contributed to the development of models to predict pumpability and shootability. The fundamental laws, basic tests and subsequent models resulting from this previous work have been developed mainly for piston pumps, and large diameter steel pipes for large-scale pumping operations.

Work has been done by Loadwick, Browne and Bamforth (1973), Ellis (1967) and others on the effect of pumping on concrete strength. Ellis concluded that there was no change in concrete quality or compressive strength after pumping. Loadwick published results showing that pumping did not effect either the cube strength development with age or the hardened cube density. However, a slight increase (1.6%) was detected in the fresh wet density.
Wet-process sprayed concretes have been applied at slumps of 20-150 mm, but usually the slump is in the range of 40-80 mm (Gordon, 1995). Mixes with slumps greater than 80 mm would normally only be used for predominately downward shooting e.g. construction of canal linings.

2.5.2 Concrete state in the pipeline

It has been established that fresh concrete conforms to the Bingham model. In pipes, material of this nature flows in the form of a solid plug separated from the pipe by a cement paste lubricating layer consisting of cement, water and fine sand particles (Figure 2.22). The plug consists of aggregate, sand and cement particles, all separated by a continuous water layer which is hydraulically linked to the water in the lubricating layer (Loadwick, 1970). This behaviour is known as 'plug flow', and is schematically shown in Figure 2.23. According to hydraulic theory, the distribution of velocity is constant across the width of the plug, with no relative velocity between the aggregate particles. The velocity drops across the lubricating layer, to zero at the pipe wall. The British Concrete Pumping Association, or BCPA, stated that under realistic conditions, the central plug is barely smaller than the pipe diameter. For concrete flowing at 30 m$^3$/hr in a 100 mm diameter pipe, a lubricating shearing layer of about 3 mm in thickness would be typical.

Tobin (1972) conducted some field observations of on-site concrete pumping and he recorded velocities of between 1 - 4 m/sec. The lower velocity is observed with pipe diameters of 120 to 180 mm and the higher velocity with small diameters of 50 to 75 mm. However, with piston type concrete pumps, the velocity of flow is not constant at all times and the concrete actually has zero velocity for a short instant between pump strokes.

2.5.3 Pumpability

Pumpability can be described as the "mobility and stability of concrete in an enclosed pipe under pressure", where mobility is defined as the ability of fresh concrete to flow, and stability is defined as the capacity of concrete to maintain its initial homogeneity during transport, handling and placing. Previous workers have often tried to estimate
pumpability by the actual pump pressure required to effectively pump a certain mix, and attempts have been made to estimate pumpability graphically by considering pump pressure, slump, pumping distance and line diameter.

To pump any mix the force exerted by the pump must first overcome the friction between the pipeline and the concrete, the inertia of the concrete in the pipe, the resistance of the internal components of the concrete to readjustments at tapers and bends, the energy used in changing direction and the pressure due to the head of concrete when placing higher than the level of the pump. The pressure must be transmitted by the concrete and since only water is naturally pumpable, it is the water in the mix that transmits the pressure.

Any saturated combination of solids and liquid has a segregation pressure. This is the pressure required to separate liquid and solids, thus transferring pressure from the liquid phase to the solids. When this occurs, as shown by Ede (1957), the combination becomes an unpumpable material. The mix therefore needs to have a segregation pressure higher than the pressure required to pass it through the pump and pipeline.

Gary (1962), developed a “go or no go test”, to determine the influence of aggregate grading and shape on pumpability, and found that for the same slump a concrete may or may not be pumpable. He concluded that, “if a concrete is pumpable, it would have adequate workability, while on the other hand, it may be workable but not pumpable.” This effectively means that because of the stability requirement, an attempt to predict pumpability from mobility test measurements is not always successful.

Browne and Bamforth (1977) showed that in relation to tests carried out by Ede (1957), it is possible to change from a saturated to an unsaturated state by excessive loss of mix water due to pressure, thus increasing frictional stress, and even blockage, as shown in Figure 2.24.

Browne and Bamforth stated that it is essential that a concrete has a low permeability to flow of its own mixing water. The pressure bleed test apparatus (Figure 2.25) was thus developed to measure the fresh water permeability of a concrete mix, and thus its
stability under pressure. A sample of concrete is compressed in a section of pipeline, and the mix water allowed to drain out under pressure. A concrete that dewaters quickly under pressure will be prone to blocking in a pipeline. Beaupré (1994) built a modified version of the test apparatus, using compressed air and an air bag to maintain the load on the piston, instead of a hydraulic piston. He also stated that ways of decreasing pressure bleeding and increasing stability include: a continuous grading of aggregates, air entrainment, increasing the proportion of fines, optimising the w/c ratio and paste content and using thickening admixtures.

If the void content of the solid particle system can be minimised, the proneness of a mix to dewatering will also be reduced. The importance of the void content is explained in Section 2.5.4. The void content can be measured according to BS812: Part2: 1975. The mass of a sample of aggregates filling a specified container is determined. Voids are then expressed as a percentage of the volume of the test cylinder, determined from the difference between the volume of the test cylinder, and calculated volume of aggregate. This is a little more complicated in terms of a sample of mixed aggregate, or a sample of dry-batched concrete mix (including cement and cement replacements), as the relative density of the overall sample may be difficult to obtain.

Browne and Bamforth (1977) therefore developed a new air voids test as illustrated in Figure 2.26. This is a simple test, involving one direct measurement once the scale has been calibrated. The method is based on measuring the head of water that can be supported by a partial vacuum created within the aggregate. By combining the aggregates in such a way as to produce a minimum voids content, it follows that to fill these voids, a minimum cement content will be required to produce a concrete which is sufficiently impermeable for pumping. The voids meter has been found to be a useful tool in the assessment of aggregates for pump mixes, and can also be used to measure the effectiveness of alternative void filling materials such as fine sand or cement substitutes such as silica fume, pfa or ggbs.

Larrard (1999) suggested that the dominant parameter controlling pumpability was the plastic viscosity, which he measured as being proportional to the resistance to
pumping (recorded as bar/minute). A research program is currently being carried out to verify this finding and to develop a scientific method of predicting pumpability.

2.5.4 Design considerations for a pumpable mix

A mix must be able to both bind all the constituents together under pressure from the pump (therefore avoiding bleeding and segregation) and also allow the radial movement of sufficient grout to maintain the lubricating layer along the inside of the pipe wall. The mix should also have the ability to deform whilst flowing, without causing segregation. To achieve this, the proportion of fine material, i.e. cement and fine aggregate below approximately 0.25 mm in size is extremely important. There are two main reasons why blockages (excluding any mechanical problems) occur (Cooke, 1990):

1. water is forced out of the mix and a blockage is caused by the dry material jamming in the pipe (i.e. bleeding occurs); and
2. the frictional resistance of the mix constituents on the pipe wall is too great.

Both of these blockages can occur due to poor grading of the constituents. The first instance is caused by too few fines in the mix which gives the constituents a high voids content thus allowing the cement paste to bleed out of the aggregate. The second instance is caused be a high proportion of very fine material which increases the overall flow resistance. This is shown graphically in Figure 2.7.

A concrete that is to be pumped is usually firstly designed for compressive strength in the usual way (BCPA, 1990 and Cooke, 1990). Gradings of aggregates must then be chosen that are close and continuous enough to prevent water and/or the finer constituents from being forced through the coarser elements. A void meter, as described in Section 2.5.3 can be used for this. The BCPA recommends a slump of approximately 75 mm. The optimum sand content is then determined for this slump. An extra 3 to 4 % of sand is usually added as a degree of protection against undersanding due to mix variations. The grading is then re-examined and the air voids measured to ensure a well graded mix. The cement content is then calculated to ensure that all the voids in the aggregate are adequately filled. This procedure is mainly applicable for the design of concretes with large aggregates but the principles are the
same for fine mortars with aggregates of 2 mm in diameter and smaller. It is generally agreed that 10-20% of the fine aggregate should pass through a 0.3 mm sieve. The Concrete Society (1984) recommend that the minimum ‘filler’ content (i.e. cement, additions, and the sand fraction passing through a 0.3 mm sieve) should be 450 kg/m³ for a maximum aggregate size of 10 mm. AFNOR (1997) suggest a cement content of "about 30%" for the wet process and they include a grading envelope of aggregate (up to 8 mm) and cement mixes for use in both the dry and wet processes (Figure 2.27). Little information is available on the mix design of pumpable mortars and grouts.
2.6 SPRAYING OF MORTARS AND CONCRETES

2.6.1 Sprayability

In order that wet-process concrete can be sprayed, it must first be pumped, and it is often said that if a concrete can be pumped, it can be sprayed. Sprayability has no precise definition, and can only be considered qualitatively as the ability of the material to be sprayed. It is a property that incorporates parameters such as adhesion (ability of plastic mix to adhere to the surface), cohesion (the ability of plastic mix to stick to itself and be built-up in thick sections), and rebound (Beaupré, 1994).

Experience has showed that to apply thick coats of sprayed material efficiently, the mix needs to be stiff, and can be enhanced even further with the addition of an accelerator. Prior to Beaupré (1994), however, there had been no previous attempt to explain this in terms of rheological parameters. He theoretically proposed that the existence of a yield value provided a good explanation as to why sprayed concrete is shootable. It makes sense that the higher the yield stress, the better the shootability (i.e. the greater the thickness that can be built-up without sloughing) and that a material with no yield value (such as water), could not remain in place after shooting. Similarly, a flowing concrete with a low yield value would not be suitable for spraying as it would slough off the receiving surface unless special agents (such as accelerators) were added at the nozzle. Conversely, mixes with a high yield value (low workability) could be unsuitable for spraying, because of pumping difficulties.

Work has been done on studying the stream produced by sprayed concretes. Some work in this area has been done by Armelin et al. (1996) but this was on the dry process using particles shot one at a time. Opsahl (1985) measured the velocity of wet-process sprayed concrete by spraying onto the perimeter of a wheel, causing it to rotate at the same speed as the stream of concrete. From measuring the rotation rate (rev/min) and the radius of the wheel he could then calculate the velocity of the concrete stream. He recorded velocities of 30 to 36 m/s. Armelin and Banthia (1998a and 1998b) also measured particle velocities with an EKTAPRO 1000 high speed camera to verify a mathematical model they had developed to predict the amount of
rebound. However, they used a single particle accelerator powered by compressed air to shoot 14 and 25.4 mm diameter glass spheres (which had a similar density to aggregate) into a fresh concrete substrate. They reported velocities of approximately 4.5 to 23 m/s.

2.6.2 Build-up thickness

It is accepted that substantial increases in build can be obtained, both vertical and to soffits, with the use of wet spraying when compared with hand application (Gordon, 1991). Beaupré (1994), considered sprayability in terms of the efficiency with which a mix sticks to the receiving surface, by measuring build-up thickness and relating it to the rheological properties of the mix. He found that there was a clear linear relationship between the build-up thickness and the yield value of the mix after spraying, and after theoretical analysis concluded that sprayability increases when the flow resistance is increased, and thus is in conflict with pumpability which has the opposite relationship. Figure 2.28 shows that when the in-place flow resistance of sprayed concrete is high, the build-up thickness is high and vice-versa (Beaupré, 1996). Higher builds can be obtained with silica fume modified wet-process sprayed concretes than conventional sprayed concretes, both vertically and overhead.

Jolin et al. (1999) developed further the work done by Beaupré. He measured the build thickness by dry spraying into an overhead 600 mm square panel, which contained reinforcing bars and mesh in order to anchor the fine concrete. They also measured the consistency of the sprayed concrete with a penetration test but found poor correlation between this and the build thickness due to the difficulty of evenly filling the large (600 mm) panels and of assessing the thickness of the sprayed concrete with the required precision. For these reasons, cohesiveness rather than build thickness was measured and plotted against the penetration stress, as in Figure 2.29. The cohesiveness was defined as the average tensile strength over the ruptured area of the sprayed mortar and was calculated as the weight of the mortar in the panel (mounted on load cells) divided by the area of the ruptured surface of the sprayed mortar after fallout. He then assumed the cohesiveness to be related to the maximum build thickness.
2.6.3 Rebound

Rebound losses are usually between 5 to 15 % for the wet process which is low when compared with the dry process where rebound of up to 50 % has been reported (Armelin, 1996). Because of this, little research has been done on the rebound of wet-process sprayed concrete although several investigations have been completed on the rebound of the dry process (Cabrera and Whoolley, 1996, Austin et al., 1997). Armelin and Banthia (1998a and 1998b) have also modified the classical rebound theory to apply to aggregate rebound in dry-process sprayed concrete. They also developed a model which can predict both the composition and the overall rate of rebound in the dry-process. However, this is beyond the scope of this research.

Besides the effect that rebound has on the cost per cubic metre of sprayed concrete, its consequences are actually much greater. The rebound tends to cause the in-situ material to have a higher cement content than the design mix due to the rebound being largely composed of aggregates. This cement rich mix is then more prone to both thermal and shrinkage cracking. Armelin et al. (1996) reported that for a dry mix a relationship can be found between particle size and the amount of rebound with the larger aggregates travelling slower and rebounding more than the smaller aggregates. Armelin and Banthia (1998c) also found that for a dry mix the use of shorter steel fibres led to significantly lower rebound and for a given fibre length, the greater the fibre diameter the less the rebound.

The amount of rebound and its composition is influenced by the rheological properties and thickness of the previously applied sprayed material. Beaupré (1994), measured rebound at different build-up thicknesses, and found a relationship existed between the cumulative rebound and thickness. When impacting a hard surface, the rebound is at a maximum and decreases to a constant rate after a certain thickness has been applied. Beaupré established however, that there was no relationship between rebound and rheological properties.
2.6.4 Ageing effect

Ageing is referred to as a reduction in mobility or stiffening, and can be observed by measuring the loss in slump at different times. It is caused by the slow hydration of the cement during the dormant period, and by a progressive reduction in the efficiency of superplasticisers (if present). Because the rheological properties of the fresh concrete change at different rates in different mixtures, it is important to measure them with respect to time. Work has shown that it is mainly the yield (the flow resistance) that changes with time rather than the viscosity. Beaupré (1994) evaluated ageing by defining the fresh concrete ageing rate (FCAR), which is the rate of change of flow resistance (Nm). However, this was not measured in this work.

2.6.5 Compaction and fresh density

Compaction is simply the expulsion of entrapped air or entrained air. For cast concrete, the energy required is generally obtained through vibration. For sprayed concrete, the speed of the particles, which depends on the amount of compressed air added at the nozzle, and their impact on the receiving surface produce the compaction effect. Compaction may also be caused by the pumping process (pumping compaction). The combined compaction (or total compaction), is the loss of air due to both pumping and spraying. Tests have shown that wet spraying produces a slight increase in the fresh wet density compared with hand application (Gordon, 1991). A small amount of work has been done by Cabrera and Whoolley (1996) on the effect of air pressure on the compressive strength of sprayed concrete and reported that increasing the air pressure increases the compressive strength of the sprayed concrete.

Increasing the air-content produces a reduction in flow resistance and so compaction should therefore produce the opposite effect, i.e. an increase in flow resistance. To verify the effect of compaction caused by the shooting process, it is not enough to measure the rheological properties before pumping and after spraying, due to the effects of ageing and compaction caused by the pumping process. Thus, in order to isolate the effect of compaction caused by spraying, the air content and rheological properties must be measured after casting, after pumping, and after spraying. Beaupré (1994), found that each compaction causes some stiffening, as shown in Figure 2.30.
Beaupré has also investigated the use of temporary high air contents as an aid to pumpability for wet-process sprayed concretes. He introduced the idea when discussing the compromise needed to be reached with the wet-process between pumpability and sprayability (Beaupré, 1994) and he later applied it in practice to wet-process sprayed repairs (Beaupré et al., 1999). A high air content (15-20%) was used to increase the fluidity (and hence pumpability) of concretes with a low water/cement ratio which resulted in in-situ air contents of 5-6.8%. These results, together with the mix designs used are shown in Table 2.11.

Table 2.11 Mix design and fresh properties (Beaupré et al., 1999)

<table>
<thead>
<tr>
<th></th>
<th>w/c = 0.3</th>
<th></th>
<th>w/c = 0.35</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Cement HSF (kg/m³)</td>
<td>447</td>
<td>440</td>
<td>460</td>
<td>453</td>
</tr>
<tr>
<td>Sand (kg/m³)</td>
<td>1126</td>
<td>1140</td>
<td>1155</td>
<td>1110</td>
</tr>
<tr>
<td>10mm coarse agg. (kg/m³)</td>
<td>440</td>
<td>430</td>
<td>415</td>
<td>455</td>
</tr>
<tr>
<td>Water (kg/m³)</td>
<td>134</td>
<td>132</td>
<td>138</td>
<td>155</td>
</tr>
<tr>
<td>Fibres (kg/m³)</td>
<td>nil</td>
<td>45 steel</td>
<td>9 poly.</td>
<td>nil</td>
</tr>
<tr>
<td>Silica fume (kg/m³)</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>10</td>
</tr>
<tr>
<td>Water reducer (l/m³)</td>
<td>nil</td>
<td>nil</td>
<td>nil</td>
<td>1.5</td>
</tr>
<tr>
<td>Superplasticiser (l/m³)</td>
<td>5.3</td>
<td>11</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>Air entrainment (l/m³)</td>
<td>7</td>
<td>5</td>
<td>3.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Slump (mm) before</td>
<td>180</td>
<td>150</td>
<td>200</td>
<td>220</td>
</tr>
<tr>
<td>Air content (%) before</td>
<td>16</td>
<td>13</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Air content (hardened concrete)</td>
<td>6.5</td>
<td>5.9</td>
<td>5.0</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Table 2.12 shows the fresh wet densities for the mortars described in Table 2.13. They show an increase when wet sprayed, compared with hand application, of 15% for mortar A, 16% for B, 3% for C and 5% for mortar D. These mortars are examined further in Section 2.7.

Table 2.12 Wet densities of pre-blended mortars (Gordon, 1995)

<table>
<thead>
<tr>
<th>Application method</th>
<th>Fresh wet density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mortar A</td>
</tr>
<tr>
<td>Hand</td>
<td>1830</td>
</tr>
<tr>
<td>Dry Spray</td>
<td>2100</td>
</tr>
<tr>
<td>Wet Spray</td>
<td>2120</td>
</tr>
</tbody>
</table>
Table 2.13 Description of four typical pre-blended repair mortars (Gordon, 1995)

<table>
<thead>
<tr>
<th>Mortar</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Designed for hand-application with graded aggregates, lightweight fillers, Portland cement, shrinkage compensators and permeability controlling admixtures.</td>
</tr>
<tr>
<td>B</td>
<td>Designed for hand-application with graded aggregates, silica fume, lightweight fillers (higher proportion than 'A'), Portland cement, shrinkage compensators, spray dried polymers, polypropylene fibres and rheology modifying admixtures.</td>
</tr>
<tr>
<td>C</td>
<td>Designed for hand-application with graded aggregates, Portland cement, shrinkage compensators, spray dried polymers and rheology modifying admixtures.</td>
</tr>
<tr>
<td>D</td>
<td>Designed for wet or dry spray application with graded aggregates, silica fume, lightweight fillers, Portland cement, shrinkage compensators, spray dried polymers, polypropylene fibres and rheology modifying admixtures.</td>
</tr>
</tbody>
</table>

2.6.6 Reinforcement encasement

Large amounts of information and guidance exists on the type, size and arrangement of reinforcement needed for sprayed concrete (Taylor, 1995; Robins, 1995; Austin, 1995a; SCA, 1990; ACI Committee 506, 1990; ASCE, 1995). However, no test exists to quantify how well the concrete or mortar has encased the reinforcement. Reinforcement encasement tests have been developed for use with flowable and superplasticised concrete (Özkul et al., 1999) but none exist for sprayed concrete. Cores have traditionally been taken from both the in-situ material and from test panels and a visual inspection made. A method of visually grading the encasement on a scale of 1 to 5 was originally proposed by Crom (1985) and was further reported by Gebler (1995). However, no method for grading the encasement quantitatively is known to exist.
2.7 PERFORMANCE OF HARDENED MORTARS AND CONCRETES

2.7.1 Introduction

Large amounts of information exists on high output, large volume wet-process sprayed concrete, but there is little available on low output wet-process sprayed concrete, especially for repair. Manufacturers publish hardened property data for their pre-blended mortars but little information is usually provided on the test methods. Comparative data between different commercially available products is rare, as is comparative data between hand applied and sprayed mortars.

Although there is little published data on mix designs for low volume wet-sprayed mortars for repair, work has been conducted on the long term performance (Mangat and O'Flaherty, 1996) and the structural effectiveness (Mays and Barnes, 1996) of sprayed concrete repairs.

Tests were conducted by Hills (1982) on both wet- and dry-process sprayed concrete and he compared these results with those obtained from cast concrete. He concluded that the performance of the sprayed concretes did not appear significantly different from those of properly compacted cast mixes of similar composition and he argued that it was the modified mix design needed for sprayed concretes that altered the hardened properties, not the method of placement. However, more recently, Banthia et al. (1999) have argued that cast and sprayed concrete are of a different nature, with the spraying process affecting the internal arrangement of constituents and hence the strength and durability. Rebound, although low with the wet process (<10%), produces an increase in the in-situ cement content of the mortar which also influences strength and durability.

A BRITE/EURAM funded research project investigating the practical and design related issues of wet-process sprayed concrete has recently been completed and the data accumulated is just beginning to be published (Norris, 1999).
This section reviews the limited published data on relevant hardened properties of wet-sprayed mortars and fine concretes, including compressive, bond and flexural strength, drying shrinkage, permeability, sorptivity, elastic modulus and density.

2.7.2 Compressive strength

Wet-process sprayed concretes have traditionally been considered inferior to dry-process sprayed concretes for their strength potential mainly because of the wet mixes higher water demand for a given cement content (Gordon, 1995). With the use of superplasticisers and silica fume however, it is possible to design wet-process sprayed concretes with strengths equal to dry-process sprayed concretes, although extremely high strengths should be avoided as they can lead to incompatibility problems (Emberson and Mays, 1990).

The compressive strength of sprayed concrete is usually measured by the compression testing of cores (to BS 1881: Part 120, 1983; ASTM C42, 1990 or similar) taken either in-situ or from sprayed test panels. Cubes can also be sawn from sprayed panels and the wet process offers the opportunity of casting cubes both before, and after, pumping.

Compressive strengths for conventional wet-process sprayed concretes are generally 20-45 MPa for water/cement ratios of 0.7-0.45, with the use of silica fume and a water reducer or superplasticiser bringing this to 60 MPa (Robins, 1995).

Work conducted by Deykin et al. (1996) on wet-sprayed pre-blended repair mortars concluded that the wet process achieves greater compaction than hand application and that the materials tested achieved compressive strengths approximately 30% higher when wet sprayed than when hand applied. They also showed very little difference in compressive strength (approximately 2-3 MPa) when a mortar was sprayed with the wet process compared with the dry.

Gordon (1995) investigated the effect on the hardened properties of mortars (mainly pre-blended) of both wet and dry spraying. He compared the compressive strengths of
four different pre-blended mortars (Table 2.13) which had been hand applied and sprayed with the wet and dry processes. These compressive strengths are shown in Table 2.14. He compared hand applied samples with cores or prisms cut from sprayed material.

<table>
<thead>
<tr>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Application method</strong></td>
</tr>
<tr>
<td>Hand</td>
</tr>
<tr>
<td>Dry Spray</td>
</tr>
<tr>
<td>Wet Spray</td>
</tr>
</tbody>
</table>

The results from Table 2.14 show increases in compressive strengths when wet sprayed compared with hand application of 86% for mortar A, 13% for B, 54% for C and 40% for mortar D. The results for the dry process are generally even higher (with the exception of mortar D), reflecting the different water/cement ratios achieved. These changes are mainly due to the increase in density and the reduction in entrapped air, although the increases in the wet density are smaller than for the strengths (Table 2.12). Effort was made to reduce the water/cement ratio when mortar D was formulated as it was designed to be sprayed with both the wet and dry processes. This is reflected in the similar values for strength and density (Table 2.12) when sprayed with the wet and dry processes.

Small improvements in compressive strength can result from the addition of steel fibres, but the increase is usually only several MPa and is therefore not usually the sole reason for their inclusion (Gordon, 1995 and Robins, 1995). Polypropylene fibre addition however, results in a reduction in compressive (and flexural) strength, as shown in Table 2.15 (Morgan, 1989).

<table>
<thead>
<tr>
<th>Fibre dosage (kg/m$^3$)</th>
<th>0</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 day compressive strength (MPa)</td>
<td>47.4</td>
<td>41.9</td>
<td>39.6</td>
</tr>
<tr>
<td>28 day flexural strength (MPa)</td>
<td>5.4</td>
<td>4.7</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 2.15 Properties of polypropylene fibre reinforced wet-process sprayed concretes (Morgan, 1989)
Compressive strengths of 80 MPa or more are possible with the use of silica fume together with a superplasticiser (Gordon, 1995). Typical values of compressive strength for wet-process sprayed concrete (with and without silica fume at 13.4% by weight of cement) are shown in Table 2.16.

<table>
<thead>
<tr>
<th>Table 2.16 Compressive strength for wet-process sprayed concrete (Gordon, 1995)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (MPa)</td>
</tr>
<tr>
<td>Plain</td>
</tr>
<tr>
<td>At 24 hours</td>
</tr>
<tr>
<td>7 days</td>
</tr>
<tr>
<td>28 days</td>
</tr>
</tbody>
</table>

The compressive strengths of the 10 mm aggregate concretes wet sprayed by Beaupré (1999) (Table 2.11) are shown in Table 2.17. The tests were conducted at 7 and 35 days on 75 mm diameter, 150 mm long cores that had been stored at 23°C and 100% RH. These high strengths are due to the low water/cement ratios of the mixes, which were possible due to the use of superplasticisers, water reducers and temporary high air contents.

<table>
<thead>
<tr>
<th>Table 2.17 Tests on hardened wet-process sprayed concrete (Beaupré, 1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Mix designs: Table 2.11)</td>
</tr>
<tr>
<td>Comp. Strength (N/mm²)</td>
</tr>
<tr>
<td>7d</td>
</tr>
<tr>
<td>Flex. Strength (N/mm²)</td>
</tr>
<tr>
<td>28d</td>
</tr>
<tr>
<td>Air content (%)</td>
</tr>
<tr>
<td>Shrinkage (µm/m) -120d</td>
</tr>
</tbody>
</table>

*104 day results instead of 120 days

2.7.3 Bond strength

CIRIA have published guidance on standard pull-off tests for repair materials (McLeish, 1993) and they describe three different failure modes: failure in the substrate; failure at the bonding surface; and failure in the sprayed concrete layer. Combinations of these failure modes are also possible.
Gordon (1991) showed that the bond strength of several types of mortar increased when wet sprayed compared with hand application. Bond strengths will also usually be greater than the tensile strength of the concrete being repaired (Gordon, 1995).

Opsahl (1982) quoted bond strengths for mesh and fibre reinforced wet-process sprayed concrete of 0-1.0 MPa and 0.8-2.5 MPa respectively, measured from 60 mm diameter core pull-off tests. The presence of mesh obstructs the stream of material being shot at the substrate and also allows sand pockets to form behind the bars, thus decreasing the bond strength (Robins, 1995). Opsahl (1985) also reported wet-process sprayed concrete bond strengths of 0.4-2.2 MPa. Deykin et al. (1996) reported bond strengths measured with a Limpet pull-off tester of 2.3 MPa for a wet-sprayed pre-blended mortar and 2.4 MPa for a pre-blended mortar sprayed with the dry process.

Tests by Mirasa et al.(1995) have shown that beams repaired with sprayed concrete possess similar load carrying capacities and crack distributions as undamaged beams and that de-bonding of the interface layer does not occur until about 70% of the failure load of the beam. Other work has shown that sprayed concrete repairs up to 35 mm in depth to reinforced concrete beams remain bonded and act compositely throughout loading to failure (Abdel-Halim and Schorn, 1989).

### 2.7.4 Flexural strength

The flexural strength of sprayed concrete is usually measured (to ASTM C78, 1984; BS1881: Part118, 1983; or EFNARC, 1996) from beams that have been sawn from a sprayed test panel. When comparing results it is important to remember that the specimen size, span and loading geometry all effect the values for flexural strength (Robins, 1995).

Tests conducted by Abdel-Halim and Schorn (1989) have shown that the flexural strength of a 150 mm deep reinforced beam reduces by 8% when the beam is repaired with wet-process sprayed concrete to a depth of 20 mm and 12.5% when repaired to a depth of 35 mm. The cracking patterns and failure modes were similar to unrepaired beams.
Gordon (1995) reported typical values of flexural strength for wet-process sprayed concrete at 28 days of 5.3 MPa (without silica fume) and 6.7 MPa (with silica fume at 13.4% by weight of cement). Other results show ranges of 3-5 MPa at 28 days for plain sprayed concrete and 6-8 MPa at 28 days for silica fume concretes sprayed with the wet and dry processes (Robins, 1995). Adding steel fibres to a plain sprayed concrete mix at rates of 40-80 kg/m³ has been shown to increase flexural strength by around 13-24% for the dry process and 6-24% for the wet process (Banthia et al., 1994a). The flexural strength increases with increasing aspect ratio and volume concentration of the steel fibres (Robins, 1995). However, high addition of polypropylene fibres results in a reduction in the flexural strength (Table 2.15 (Morgan, 1989)). Opsahl and Buhre (1985) quote flexural strengths of up to 10 MPa for wet-process sprayed steel fibre concrete with fibre contents of 4.5-6% by weight. Opsahl (1985) also presented quality control results from twenty five different wet-process sprayed concrete tunnelling projects in Norway, with 28 day flexural strengths in the range of 5.5-11.0 MPa.

The flexural strengths of the 10 mm aggregate concretes wet sprayed by Beaupré (Table 2.11) are shown in Table 2.17. All the mixes show a high flexural strength from 7.5 to 9.5 MPa.

2.7.5 Shrinkage

Shrinkage figures quoted in specifications without definition and reference to accepted test methods are meaningless. It is important to distinguish between plastic shrinkage (that occurs for a short time after placing) and drying shrinkage (which can take place for several months or even years). Most shrinkage occurs in the plastic state. Shrinkage is very complex and is affected by, amongst others, w/c ratio, cement content, aggregate content, curing regime and length of cure, size and shape of test specimen, surface area/volume ratio of test specimen, relative humidity and size of aggregate. Shrinkage is also directly proportional to the water/cement ratio and inversely proportional to the aggregate/cement ratio (Robins, 1995). The shrinkage at the surface of the sprayed concrete may be expected to be greater than that deeper
within the concrete which is protected from drying out. This can cause differential shrinkage which can in turn induce stresses and therefore cracking.

Many pre-blended concrete repair mortars are described by their manufacturers as low shrinkage, expansive, non-shrinking or shrinkage-compensating. However, Emmons et al. (1994) found that only 15% of the 46 surface repair mortars tested could be labelled as low shrinkage.

Wet-process sprayed concrete displays higher shrinkage than dry-process sprayed concrete due to the higher water demand for a given cement content in the wet process (Gordon, 1995). Results have also shown silica fume modified wet-process sprayed concretes displaying lower drying shrinkage than conventional cement sprayed concretes. Hills (1982) concluded that shrinkage values for sprayed concretes were similar in range to cast concretes. For his site-batched sprayed concrete the drying shrinkage at six months was 400-1000x10^{-6}, with the wet process mixes generally showing the greatest shrinkage. Schrader and Kaden (1987) quote typical shrinkage values for wet-process sprayed concrete of 600x10^{-6} (w/c=0.42, cement content 415 kg/m^3) and shrinkage values for the dry process of 900x10^{-6} (w/c=0.37, cement content 505 kg/m^3). These shrinkage differences are more likely to be due to the differences in in-situ mix proportions rather than a difference in shrinkage values due to the spraying process (Robins, 1995).

Ramakrishnan (1985) reported that by including 1.0% by volume (about 80 kg/m^3) of 30 mm long hooked-end wire wires in dry-process sprayed concrete the shrinkage was reduced by approximately 30%. Steel fibres can also restrict the crack widths and distribute the cracking in a restrained shrinkage situation (Robins, 1995). However, Opsahl (1985) concluded that steel fibres did not significantly influence the shrinkage of wet-process sprayed concrete.

Deykin et al. (1996) measured shrinkage by sawing 70x70x270 mm prisms after 24 hours from 100x100x500 mm beams which had been formed by directly spraying into beam moulds. Locating discs (with a gauge length of 200 mm) were then glued to each face and a de-mountable strain gauge was used to measure the drying shrinkage.
The prisms were stored at 20°C and 65% RH and their initial results show very similar shrinkage curves for both wet- and dry-sprayed prisms and for cast prisms.

The drying shrinkage of the 10 mm aggregate concretes wet sprayed by Beaupré (Table 2.11) are shown in Table 2.17. The tests were conducted on 400x100x75 mm prisms according to ASTM C157 which were sawn from test panels sprayed on site. The prisms were then stored in water for 7 days, at which point the first shrinkage measurement was taken. The values of shrinkage were 616-647 microstrain at 120 days which compares favourably with similar mixes sprayed by Beaupré et al. (1999) with the dry process (862-767 microstrain at 88 days).

Although a standard method for measuring the restrained shrinkage does not exist, several tests are available such as the ring test, the doubly restrained plate specimens and uniaxial tests (Banthia et al., 1993; Rizzo and Sobelman, 1989). However, spraying a representative sample for these tests is not usually practical. There is also no universally accepted technique for quantifying the effectiveness of fibres under the conditions of restrained shrinkage (Banthia et al., 1993) despite one of the main reasons for using fibres (particularly polypropylene) being the reduction or elimination of cracking under restrained shrinkage conditions.

2.7.6 Permeability

Although a low permeability mix is desirable, it should be noted that a higher permeability mix that has not cracked is more water-tight than a low permeability mix that has developed substantial micro-cracks due to drying shrinkage (Robins, 1995).

Ramakrishnan (1985) reported that the permeability of steel fibre sprayed concrete increased with decreasing compressive strength and also increased with increasing water/cement ratio. Permeability of pre-blended mortars will normally be exceptionally low compared with normal cast concrete (Gordon, 1995).

Opsahl and Buhre (1985) quoted values for wet-process silica fume steel fibre sprayed concrete in the range 0.2 to 1x10⁻¹³ m/s for a 45 MPa compressive strength mix and
<10^{-15} for a 75 MPa mix. Schrader and Kaden (1987) quoted permeability for dry-process sprayed concrete in the range 3000 to 3 \times 10^{-13} m/s for moderately low to very high strength concrete.

ISAT results for both wet- and dry-process sprayed concretes have been found by Hills (1982) to be similar to cast concretes, namely 0.14-0.35 ml/m² per second for dry and 0.35-0.41 ml/m² per second for the wet process after 30 minutes. Results presented by Deykin et al. (1996) give values of 0.001 ml/m² per second for a pre-blended mortar sprayed with the wet process after 30 minutes and 0.002 ml/m² per second for a pre-blended mortar sprayed with the dry process. The lower rate for the wet-sprayed mortar was said to arise from the wetter material producing a more closed surface when trowelled. ISAT results published by Gordon (1991) showed that wet-spraying a mortar could reduce the permeability by approximately 50% when compared with hand application, although highly polymer-modified mortars showed little difference. Table 2.18 shows some data published by Gordon (1995) which compares the permeability of the four mortars described in Table 2.13. It shows the wet-sprayed mortars have generally a lower permeability than the hand applied mortars with the dry-process sprayed mortars being even lower. These values compare with the Concrete Society (1987) classification for low permeability of less than 0.1 ml/m² per second after 60 minutes.

<table>
<thead>
<tr>
<th>Application method</th>
<th>Initial surface absorption after 60 min. (ml/m² per second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand applied</td>
<td>A: 0.068  B: 0.047  C: 0.024  D: -</td>
</tr>
<tr>
<td>Dry sprayed</td>
<td>A: 0.008  B: 0.010  C: 0.012  D: 0</td>
</tr>
<tr>
<td>Wet sprayed</td>
<td>A: 0.024  B: 0.019  C: 0.024  D: 0</td>
</tr>
</tbody>
</table>

2.7.7 Sorptivity

Very little data has been published on the sorptivity of wet-process sprayed concretes and mortars, although data can be found on the water absorption of wet-process sprayed concretes. Neville (1995) describes the method for measuring sorptivity of concretes and mortars and reports typical sorptivity values of 0.09 mm/min^{0.5} for
concrete with a water/cement ratio of 0.4, and 0.17 mm/min$^{0.5}$ for a water/cement ratio of 0.6.

Hills (1982) reported 20 minute water absorptions (to BS1881: Part 122, 1983) in the range 2.3-3.6% for the dry process, 3.5-4.7% for the wet process and 2.6-4.0% for equivalent cast concretes. Banthia et al. (1994a) compared five different steel fibre types (at a constant rate of 60 kg/m3) and plain control mixes in dry-process silica fume sprayed concrete. He found that the values for absorption and boiled absorption were very consistent for all the mixes (with and without the fibres). However, Robins (1995) reported that the inclusion of steel fibres in a mix produces small increases in absorption values.

### 2.7.8 Modulus of elasticity

It is generally accepted that the elastic modulus of the repair material should be the same as the substrate concrete so that uniform load transfer can be achieved across the section. Rizzo and Sobelman (1989) mention that a low modulus would be advantageous in keeping internal stresses low and ensuring good long-term adhesion and lack of cracking. They also mention that a new repair may experience some shrinkage relative to the parent structure that will negate the influence of the elastic modulus.

Deykin et al. (1996) sprayed a pre-blended repair mortar using the dry and wet processes and compared their elastic modulus with typical cast concrete (Table 2.19). These results show a lower elastic modulus compared with the compressive strength for the sprayed mortars than for the typical cast concrete.

<table>
<thead>
<tr>
<th>Comp. strength (MPa)</th>
<th>Wet process</th>
<th>Dry process</th>
<th>Typical concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>59.5</td>
<td>57.5</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>26.1</td>
<td>22.7</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 2.19 Comparison of elastic modulus (Deykin et al., 1996)
2.7.9 Density

It is generally accepted that spraying (either wet or dry) increases both the fresh and hardened densities of a mortar compared with hand application due to the greater compaction obtained with the spraying process, providing no voids are present.

The hardened density of normal weight concrete lies within the range 2200 to 2600 kg/m³ (Neville, 1995). Deykin et al. (1996) reported a cast immersed density of 1950 kg/m³ for a pre-blended mortar developed for use with the wet and dry processes, compared with 2060 kg/m³ for the same mortar when sprayed with the wet process and 2080 kg/m³ for the same mortar when sprayed.
2.8 CONCLUSIONS

The continual improvements in materials and spraying technology will ensure that sprayed mortar and concrete will be used increasingly in the future for concrete repair, and the wet process, with its advantages over the dry process of consistency, lower wastage and a safer working environment, will begin to dominate as the preferred method of application. However, from the above review it is apparent that there is little published information on low-volume wet-process sprayed mortars and fine concretes for repair, with the majority of published data being on either dry-process mortars and concretes for repair or high-volume wet-process concretes for tunnelling.

Concrete repair in general and the durability of concrete has been (and still is) well researched but little of this has dealt with low-volume wet-process sprayed mortars and fine concretes. Important properties of sprayed repairs such as in-situ restrained shrinkage and reinforcement encasement are especially under-researched. A steady amount of research has also been completed on the rheology of cement pastes, mortars and concretes (especially by Banfill and Tattersall), but little of this is related to pumping and spraying. Pumping has also been investigated by several researchers, but this has been mainly concerned with high-volume and large-aggregate mixes. Only a limited amount of research exists (mainly by Beaupré) that investigates both the pumping process, the spraying process and their influence on the hardened performance of the in-situ repair material. This study aims to address this.
Fig. 2.1 The dry spraying process (Maidl and Sommavilla, 1995)

Figure 2.2 Rotating barrel dry-process gun (Aliva)
Figure 2.3 Rotating feed bowl dry-process gun (Reed Manufacturing)

Figure 2.4 The wet process spraying process (Maidl and Sommavilla, 1995)
Figure 2.5 The double-piston pump (Vandewalle, 1990)

Figure 2.6 The worm or screw pump (Vandewalle, 1990)
Figure 2.7 Relationship of cement content to the void content of aggregate with respect to pumpability (Neville, 1995)
Figure 2.8 Recommended aggregate grading for wet-process sprayed concrete up to 8 mm max. (Melbye et al., 1995; ITA, 1993; EFNARC, 1996; AFNOR, 1997)

Figure 2.9 Recommended sand grading limits for pumpable mortars (Kempster, 1967)
Figure 2.10 Hooke's law for a material in shear: $F/A = \eta \gamma$

Figure 2.11 Hookean solid in shear
Figure 2.12 Non-Newtonian flow curves

Figure 2.13 Hysteresis loop for material suffering structural breakdown
Figure 2.14 Relationship between slump and g (Tattersall, 1976)
\[ T = g + hN \]
Where;
\( g \) = intercept on \( T \) axis
\( h \) = slope of line

Figure 2.15 Bingham flow curve for concrete

Figure 2.16 Effect of sand fineness and silica fume replacement on \( g \) and \( h \) (Banfill, 1994)
Figure 2.17 Effect of $g$ (for mortar) on slump (for concrete) (Hornung, 1991)
Figure 2.18 Effect on $g$ and $h$ of two cements and two samples of aggregate

(Tattersall, 1991)

Figure 2.19 Plot of concrete yield value vs yield value of cement paste

(Tattersall, 1991)
Figure 2.20 Plot of concrete plastic viscosity vs plastic viscosity of cement paste

*(Tattersall, 1991)*

Figure 2.21 Effect of additives *(Gjørv, 1992)*
Figure 2.22 Model for concrete flow state in a pipe (Loadwick, 1970)

Figure 2.23 Velocity profile for plug flow (BCPA, 1979)
Figure 2.24 Dewatering of concrete in a pipe (Browne and Bamforth, 1977)

Figure 2.25 Pressure bleed test apparatus (Browne and Bamforth, 1977)
Figure 2.26 Voids meter (Browne and Bamforth, 1977)
Figure 2.27 Combined grading envelope for dry- and wet-process mixes (AFNOR, 1997)

Figure 2.28 Relationship between the build-up thickness and the in-place flow resistance of sprayed concrete (Beaupre, 1996)
Figure 2.29 Cohesiveness as a function of the penetration stress (or consistency) (Jolin et al., 1999)

Figure 2.30 Effect of compaction on flow resistance (Beaupre, 1996)
3. EXPERIMENTAL PROGRAMME

3.1 INTRODUCTION

The timing of the research programme was a direct result of the test methodology, in particular the phasing of the work to cover the three sprayed concrete types (Section 3.4).

The scope of the experimental work is shown in Appendix A2 which shows the permutations of variables investigated. This covers 30 mixes within three sprayed material categories, seven pumping/spraying systems, 19 types of test (carried out during the stages of pumping, spraying and hardened testing) and three types of specimen production.

The fine mortars (<3 mm) were pumped and sprayed first as this could be done using a worm pump which was small and portable enough to operate and store at Loughborough. This group was divided into pre-blended proprietary mortars and laboratory mixes, which were designed and batched at Loughborough. Spraying began with the pre-blended proprietary mortars as these are often sprayed by the concrete repair industry and they also provided a benchmark for when testing of the laboratory mixes began. Several manufacturers were also willing to supply samples of their pre-blended mortars in return for the test data obtained.

After pumping and spraying the mortars with the worm pump a selected representative group of pre-blended mortars and laboratory-designed mortars were pumped and sprayed with a piston pump. This enabled a comparison of the affects of pumping and spraying the mortars through different types of pump. The same piston pump was used to pump and spray the laboratory-designed fine concretes (<8 mm aggregate). A pre-blended mortar and a fine concrete mix were also sprayed with the dry process. Field trials were conducted when possible with different types of pump (Section 3.5.5)
3.2 REPAIR SCENARIOS

A survey of local authorities, consultants, contractors and material suppliers was carried out at Loughborough University by Seymour and Turner (1995) in order to identify a set of generic repair scenarios and their performance requirements. Eleven organisations participated in the survey, each providing information either through interviews or by completion of a standard questionnaire form. These scenarios covered a broad range of repair situations encountered in the UK, mainly: bridge soffits; bridge abutments and marine structures; buildings, water retaining structures and chimneys; fire damaged structures; tunnels; and sewers, masonry tunnels and arch bridges. They are grouped in terms of characteristics common to various repair applications, including; purpose; orientation; geometry; reinforcement; substrate; surface finish; construction method and environment. The scenarios are tabulated and presented in Appendix A.3.

From the survey it was found that most patch repairs are hand applied or cast (with flowable materials) using pre-blended proprietary materials. Factory-blended materials are chosen because they are perceived by both the client and the contractor to be of higher quality than site-batched materials or ready-mixed concrete. Contractors and local authorities carry out few, if any, quality control tests on these pre-blended materials, considering it unnecessary and too costly. As most repairs are carried out with these materials it was decided to begin testing these before moving on to the designed mixes.

3.3 EQUIPMENT

3.3.1 Spraying chamber

The majority of the pumping and spraying work was conducted in an outside storage area next to the laboratory which was converted into a spraying chamber (Figure 3.1). This enabled spraying trials to be conducted at our discretion with the same equipment in the same conditions. Two spraying trials were conducted inside the laboratory when the external temperature fell below 5°C. Supports were fitted to the walls of the
spraying chamber to enable test panels to be temporarily secured both vertically and overhead.

3.3.2 Moulds

The majority of the test panels were 500x500x100 mm and were reusable. Some of the test panels were 600x600x100 mm but were not re-usable. Steel moulds to BS1881 were also sprayed directly into (100 mm cubes and 100 mm beams) and to cast specimens (as previous, plus 75x75x229 mm prisms).

3.3.3 Spraying machines

Several possible pumps for the mortar trials were considered in discussions with Putzmeister, a concrete pump manufacturer and one of the industrial collaborators on the research project.

The work was initially conducted with a Putzmeister WSA56 worm pump but this required a 250 cfm (0.118 m³/s) compressor which was both costly and inconvenient to hire. This was therefore exchanged for a Putzmeister TS3EVR worm pump with which most of the research work was completed (Figure 3.2(a) and (b)). No performance data for the WSA56 is therefore included. A 25 mm diameter hose was used with the TS3EVR together with a rendering spray gun equipped with a brass nozzle. Compressed air was supplied from a portable 10 cfm (0.00472 m³/s) compressor via an airline to the nozzle which projected the pumped mortar from the nozzle. The manufacturers performance data for each of the pumps used in the research is presented in Table 3.1.

<table>
<thead>
<tr>
<th>Manufacturers</th>
<th>Putzmeister TS3EVR</th>
<th>Putzmeister WSA56</th>
<th>Putzknecht S30 UE45/7</th>
<th>Reed B-10</th>
<th>Reed SOVA</th>
<th>M-Tec Duo-mix</th>
<th>M-Tec P-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive</td>
<td>Electric</td>
<td>Air/electric</td>
<td>Electric</td>
<td>Diesel</td>
<td>Air or electric</td>
<td>Dry</td>
<td>Electric</td>
</tr>
<tr>
<td>Pump Output (l/min)</td>
<td>12</td>
<td>12-15</td>
<td>50</td>
<td>80</td>
<td>13-115</td>
<td>22</td>
<td>3-15</td>
</tr>
<tr>
<td>Hose diameter (mm)</td>
<td>25 or 35</td>
<td>35</td>
<td>32</td>
<td>25 or 35</td>
<td>19-38</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Max. aggregate size (mm)</td>
<td>3-4</td>
<td>3-4</td>
<td>4</td>
<td>10</td>
<td>10</td>
<td>3-4</td>
<td>3-4</td>
</tr>
</tbody>
</table>

Table 3.1. Manufacturers data for mortar and concrete pumps
Five other types of pump were also investigated. The fine concretes and three of the mortars (P2p, P1p and D1p) were pumped and sprayed with a Reed B-10 piston pump (Figure 3.3), together with a 25 mm diameter rubber hose, a 365 cfm (0.172 m³/s) compressor at an output of approximately 80 l/min. CP1p was pumped with a 35 mm diameter hose due to the large proportion of fibres in the mix which made it difficult to pump through a 25 mm diameter line. Mixes P1d and C2d were pumped and sprayed with a Reed SOVA dry-process gun (Figure 2.3) using a 25 mm diameter rubber hose, a 365 cfm (0.172 m³/s) compressor at an output of approximately 50 l/min. Mix P2W was pumped with a Uelzener Putzknecht S30 UE45/7 large-diameter worm pump using a 32 mm diameter rubber hose, a 125 cfm (0.059 m³/s) compressor at an output of approximately 50 l/min. Mix P2 was also sprayed with a M-Tec Dumiix (designated mix P2w2) and a M-Tec P-20 (mix P2w3) with a 25 mm hose, a 10 cfm (0.00472 m³/s) compressor at measured outputs of 7.6 and 5.1 l/min respectively.

Four types of nozzle were tested with the TS3EVR:

1. a brass texturing spray gun designed for plasters and sealants with an aperture diameter of 9 mm. The air is controlled at the nozzle and is fed into the mortar radially around the circumference of the nozzle;
2. a plastic 'collar' nozzle with an aperture diameter of 16 mm designed for site mortars (Figure 3.4(a)). The air is fed centrally into the mortar;
3. a plastic 'collar' nozzle with an aperture diameter of 12 mm designed for fine plaster. This is the same as (ii) but with a different plastic 'collar'; and
4. a stainless-steel nozzle designed and supplied by Fosroc International Ltd with an aperture diameter of 9 mm (Figure 3.4(b)). The air is fed into the mortar at a slight angle around the circumference of the nozzle to create a spiralling effect.

A trial was conducted to compare the nozzles with mix P1w at a slump of 60 mm. Each nozzle was securely supported and the stream was filmed with an Ektapro High Speed camera (Section 3.5.4). The velocity and dispersion angle of each mortar stream was then measured from the recorded video.
3.4 MATERIALS AND MIXES

As a result of my initial studies, and the advice of the industrial collaborators, three types of repair mortar/concrete were identified as suitable for research and the programme was consequently structured to reflect this. The three types were:

1. mortars (<3 mm aggregate), pre-blended and bagged by specialist material suppliers (designated P1 to P8);
2. mortars (<3 mm aggregate), designed and laboratory or site batched (D1 to D12); and
3. fine (<8 mm aggregate) concretes, designed and site batched (C1 to C5).

The order of mixes was logical from the point of view of research. Type (i) was available in the form of pre-blended materials developed for hand-applied repair, from which experience was gained and performance data obtained which could also be used as a benchmark and as the basis for the development of the designed mixes. The majority of the research (and all the initial work) was conducted with the TS3EVR worm pump, as it was likely that any mix working with this pump would also be suitable for larger worm and piston pumps, and for the dry-process pumps.

The pre-blended mortars were designated P1 to P8 and the method by which they were pumped and sprayed was designated either w (for a small diameter worm pump), W (for the large diameter worm pump), d (for the dry process) and p (for the piston pump). P2w was therefore pre-blended mix P2 which was pumped and sprayed through a small diameter worm pump (the TS3EVR). Mortar P2 was also pumped through two additional worm pumps and is therefore designated P2w2 (for the M-Tec Duo-mix) and P2w3 (for the M-Tec P-20). The laboratory designed mixes were all pumped and sprayed with the TS3EVR worm pump and so are designated D1w to D12w, with the exception of mix D1 which was also piston pumped with the B-10 (designated D1p). The fine concretes are designated C1 to C5, together with the suffix S for steel fibres, A for air entrainment and P for polypropylene fibres (at two doses, CP1p and CP2p), in addition to the suffix for piston pumped (p) and the dry process (d).
3.4.1 Materials

Cement

The cement was Class 42.5N Portland cement conforming to BS12: 1996 and supplied by Castle Cement Ltd. Its main chemical and physical properties are given in Table 3.2.

<table>
<thead>
<tr>
<th>Class (BS12)</th>
<th>Fineness</th>
<th>Soundness</th>
<th>Compressive strength (40x40x160 mm mortar prisms)</th>
<th>Chloride content</th>
<th>Alkali content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specific surface (m²/kg)</td>
<td>Initial set (min.)</td>
<td>2 days (MPa)</td>
<td>7 days (MPa)</td>
<td>28 days (MPa)</td>
</tr>
<tr>
<td>42.5 N</td>
<td>400</td>
<td>100</td>
<td>25.0</td>
<td>40.0</td>
<td>56.5</td>
</tr>
</tbody>
</table>

Aggregate

The designed mortars D1 to D8 contained combinations of a crushed Portland stone sieved to a maximum size of 3 mm and a building sand supplied by the David Ball Group and graded between 75 µm and 2.36 mm. The fine concretes C1 to C5 contained 6 mm maximum sized uncrushed river gravel supplied by Porterway Limited from a source in Derby. Mortars D9 to D12 were combinations of up to three different fine aggregates supplied by Fosroc International Ltd, a red soft building sand supplied by Mix-It and purchased at a local builders merchants and a coarse building sand supplied by the David Ball Group. The red soft building sand was also sieved through a 300 µm sieve and these fines were incorporated in mix D10w. The fine concretes C4p and C5p also contained a coarse (2-8 mm) smooth aggregate supplied by Fosroc International Ltd. A lightweight filler called Fillite and supplied by Trelleborg Fillite Ltd was one of the constituents in mix D12w. Three additional sands (designated sands 1, 2 and 5) supplied by Fosroc International Ltd were used in mix D9w. The gradings of these aggregates are given in Appendix A.4.

Additives and additions

All the designed mortars (with the exception of D5w) included a single part-modified styrene-butadiene rubber (or SBR) liquid additive called Ronafix supplied by Ronacrete Limited. This was added in a 3:1 water:SBR solution.
The steel fibres in mix C1Sp were Dramix® ZP 30/.50 (30 mm long and 0.5 mm diameter), a collated hook-ended fibre supplied by Bekaert. The main physical properties are given in Table 3.3. The polypropylene fibres were Fibermesh Harbourite 320. These were 19 mm long, fine fibrillated fibres and some of the main physical properties are given in Table 3.4.

<table>
<thead>
<tr>
<th>Table 3.3 Properties of the steel fibres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type (Dramix®)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>ZP 30/.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3.4 Properties of the polypropylene fibres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type (Fibermesh)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Harbourite 320</td>
</tr>
</tbody>
</table>

The superplasticiser in most of the fine concrete mixes (with the exception of C2d, C3p and C3Ap) was Sikament FF supplied by Sika Limited, a melamine-formaldehyde. Key chemical and physical properties are given in Table 3.5.

<table>
<thead>
<tr>
<th>Table 3.5 Properties of the superplasticiser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Sikament FF</td>
</tr>
</tbody>
</table>

The condensed silica fume was an undensified powder, added to the designed mixes (D1 to D12) and a water-based slurry used in the fine concrete mixes (C1 to C5). The silica fume powder was Ronafix HBA supplied by Ronacrete Ltd. The slurry was EMAC 500S supplied by Elkem Materials with a 50% silica fume content by weight. Its chemical composition and main physical properties are given in Table 3.6.
Table 3.6 Properties of the silica fume slurry

<table>
<thead>
<tr>
<th>Type</th>
<th>Specific surface (m²/kg)</th>
<th>Average particle size (μm)</th>
<th>Coarse particles &gt;45 μm (%)</th>
<th>Dry solids by weight (%)</th>
<th>pH value</th>
<th>SiO₂ (%)</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMSAC 500S</td>
<td>20000</td>
<td>0.15</td>
<td>max. 2.0</td>
<td>50 (± 2)</td>
<td>5.0 - 7.0</td>
<td>&gt; 86</td>
<td>Grey</td>
</tr>
</tbody>
</table>

An air entrainment admixture called AER 5 supplied by Sika Ltd was used in mixes C1Ap, C3Ap and D8Aw.

**Substrate Concrete**

Grit-blasted concrete substrates for core pull-off testing and build tests were cast in advance of spraying to ensure that they had reached sufficient strength. The mix design was based upon work done by Pan (1995) and consisted of a mix proportion by dry weight of cement : fine aggregate : coarse broken aggregate of 1 : 2.3 : 2.3 with a water/cement ratio of 0.48. Two 250x500x50 mm slabs were cast at a time in a test panel and were grit-blasted after 28 days on one side to produce a surface roughness index (or SRI, (CEN, 1999)) of approximately 220 mm. They were used for pull-off testing at ages of six to eighteen months.

Concrete substrates were also needed for the restrained shrinkage test. Old 3’x2’ (593x897x50 mm) paving slabs were bought second hand and grit blasted on one side. Old slabs were needed as shrinkage readings would be inaccurate if a recently cast substrate was used as the substrate could still be experiencing drying shrinkage.

### 3.4.2 Pre-blended proprietary mixes

Commercial considerations prevent the publication of the formulations of the pre-blended mortars, but they typically contain all or most of the following constituents, depending on the type:

i.) a combination of fine aggregates from 75 μm to 2 mm in diameter;

ii.) lightweight fillers, 75 μm to 300 μm in diameter;

iii.) Portland cement in a ratio of 1 : 1.3 - 3.4 with the aggregate;

iv.) silica fume (approximately 5 % of the cement);

v.) admixtures such as an SBR;
vi.) polypropylene fibres up to 6 mm in length; and
vii.) chemical shrinkage compensators.

The gradings (of the combined aggregate and cementitious components) of the mixes obtained by wet sieving are shown in Figure 3.5, and the constituents of the mortars in Table 3.7. The w/c ratio in Table 3.7 is the water/total cementitious value and the Agg/c value is the aggregate (including filler)/total cementitious value. In order to obtain the aggregate/cementitious ratio the particles collected on each sieve were examined under a x40 magnification microscope. The approximate proportion of aggregate, filler or cementitious material on each sieve (to the nearest 10 %) was determined and the weight of each calculated accordingly. The gradings of some of the pre-blended aggregates, with and without the filler component, are included in Appendix A.5. Additional tests were conducted on some of the pre-blended mortars and these mix designations are included in Table 3.8.

Table 3.7 Constituents of the pre-blended proprietary mortars

<table>
<thead>
<tr>
<th>Mix</th>
<th>Pump</th>
<th>W/c Ratio</th>
<th>Agg/c Ratio</th>
<th>Polymer Modified</th>
<th>Poly. Fibres</th>
<th>Shrinkage Comp.</th>
<th>Filler</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1w</td>
<td>Worm</td>
<td>0.59</td>
<td>2.3</td>
<td>N</td>
<td>N</td>
<td>Some</td>
<td>N</td>
<td>Basic repair</td>
</tr>
<tr>
<td>P1d</td>
<td>Dry Spray</td>
<td>-</td>
<td>2.3</td>
<td>N</td>
<td>N</td>
<td>Some</td>
<td>N</td>
<td>mortar</td>
</tr>
<tr>
<td>P1p</td>
<td>Piston</td>
<td>-</td>
<td>2.3</td>
<td>N</td>
<td>N</td>
<td>Some</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>P2w</td>
<td>Worm</td>
<td>0.41</td>
<td>1.45</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>High build</td>
</tr>
<tr>
<td>P2p</td>
<td>Piston</td>
<td>-</td>
<td>1.45</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Repair mortar</td>
</tr>
<tr>
<td>P2W</td>
<td>L.Worm</td>
<td>-</td>
<td>1.45</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>P3w</td>
<td>Worm</td>
<td>-</td>
<td>1.58</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>2-part re-profiling</td>
</tr>
<tr>
<td>P4w</td>
<td>Worm</td>
<td>0.47</td>
<td>2.31</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Basic repair mortar</td>
</tr>
<tr>
<td>P5w</td>
<td>Worm</td>
<td>0.39</td>
<td>1.33</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Repair mortar</td>
</tr>
<tr>
<td>P5d</td>
<td>Dry Spray</td>
<td>-</td>
<td>1.33</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>P6w</td>
<td>Worm</td>
<td>0.45</td>
<td>1.62</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Repair mortar</td>
</tr>
<tr>
<td>P7w</td>
<td>Worm</td>
<td>0.90</td>
<td>3.42</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Lightweight mortar</td>
</tr>
<tr>
<td>P8d</td>
<td>Dry Spray</td>
<td>-</td>
<td>-</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>-</td>
<td>Dry Spray</td>
</tr>
</tbody>
</table>

Table 3.8 Additional pre-blended proprietary mortars

<table>
<thead>
<tr>
<th>Mix</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2w2</td>
<td>Same mix as P2w but from a different batch</td>
</tr>
<tr>
<td>P2w1</td>
<td>Too stiff to pump, therefore additional water added to make mix P2w1-1</td>
</tr>
<tr>
<td>P2w1-1</td>
<td>Mix P2w1 with additional water added</td>
</tr>
<tr>
<td>P2-1</td>
<td>Slump and 2-point test only, not sprayed</td>
</tr>
<tr>
<td>P2-2</td>
<td>Slump and 2-point test only, not sprayed</td>
</tr>
<tr>
<td>P2-3</td>
<td>Slump and 2-point test only, not sprayed</td>
</tr>
<tr>
<td>P2-4</td>
<td>2-point test only, not sprayed</td>
</tr>
<tr>
<td>P4w2</td>
<td>Same as mix P4w but from a different batch</td>
</tr>
<tr>
<td>P4w1</td>
<td>Same as P4w, sprayed only, no rheological tests conducted</td>
</tr>
</tbody>
</table>
3.4.3 Laboratory mixes

**Designed mortars**

The laboratory designed mortars D1 to D8 were combinations of crushed Portland stone and a local building sand sieved to a maximum size of 3 mm in ratios of 6:0 to 0:3 by weight, together with Portland cement, silica fume (as an undensified powder at 5% by weight of cement) and an SBR in a 3:1 water suspension. The mix proportions are given in Table 3.9. The combined (aggregate and cementitious components) gradings of mixes D9 and D10 were designed to lie at the bottom and top limits respectively of the range of pre-blended proprietary mortar gradings, as shown in Figure 3.6. Mixes D11 and D12 were designed to have combined gradings just outside of this range, as shown in Figure 3.7. The proportions of mixes D9, D10, D11 and D12 are shown in Table 3.10. The l/c number is the liquid (water and SBR)/cementitious (PC and silica fume) ratio. Some of the mix designs were tested more than once and these mix designations are given in Table 3.11.

### Table 3.9 Proportions of designed mortars D1-D8 (by weight)

<table>
<thead>
<tr>
<th>Mix</th>
<th>Pumped</th>
<th>Crushed stone</th>
<th>Building sand</th>
<th>Portland cement</th>
<th>Silica fume</th>
<th>SBR: Water</th>
<th>Liquid/cementitious ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1w</td>
<td>Y</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0.05</td>
<td>1:3</td>
<td>0.65</td>
</tr>
<tr>
<td>D1p</td>
<td>Y</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0.05</td>
<td>1:3</td>
<td>--</td>
</tr>
<tr>
<td>D2w</td>
<td>Y</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0.05</td>
<td>1:3</td>
<td>0.55</td>
</tr>
<tr>
<td>D3w</td>
<td>Y</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.05</td>
<td>1:3</td>
<td>0.48</td>
</tr>
<tr>
<td>D4w</td>
<td>N</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>0.05</td>
<td>1:3</td>
<td>0.44</td>
</tr>
<tr>
<td>D5w</td>
<td>Y</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0.05</td>
<td>0:3</td>
<td>--</td>
</tr>
<tr>
<td>D6w</td>
<td>Y</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>0.05</td>
<td>0:3</td>
<td>--</td>
</tr>
<tr>
<td>D7w</td>
<td>Y</td>
<td>6</td>
<td>0</td>
<td>1</td>
<td>0.05</td>
<td>1:3</td>
<td>0.93</td>
</tr>
<tr>
<td>D8Aw*</td>
<td>N</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0.05</td>
<td>1:3</td>
<td>0.60</td>
</tr>
</tbody>
</table>

*contained an air content of 15% before pumping

### Table 3.10 Proportions of designed mortars D9-12 (by weight)

<table>
<thead>
<tr>
<th>Mix</th>
<th>Pumped</th>
<th>Soft building sand</th>
<th>Coarse building sand</th>
<th>Sand 1</th>
<th>Sand 2</th>
<th>Sand 5</th>
<th>Portland cement</th>
<th>Silica fume</th>
<th>SBR: Water</th>
<th>l/c ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>D9w</td>
<td>Y</td>
<td>0.49</td>
<td>0.65</td>
<td>0.94</td>
<td>-</td>
<td>0.52</td>
<td>1</td>
<td>0.05</td>
<td>1:3</td>
<td>0.45</td>
</tr>
<tr>
<td>D11w</td>
<td>N</td>
<td>-</td>
<td>0.80</td>
<td>0.63</td>
<td>0.41</td>
<td>0.85</td>
<td>1</td>
<td>0.05</td>
<td>1:3</td>
<td>0.38</td>
</tr>
</tbody>
</table>

### Table 3.11 Proportions of designed mortars D10-D12 (by weight)

<table>
<thead>
<tr>
<th>Mix</th>
<th>Pumped</th>
<th>Portland stone</th>
<th>Fillite</th>
<th>Soft building sand (300µm)</th>
<th>Soft building sand (&lt;300µm)</th>
<th>Portland cement</th>
<th>Silica fume</th>
<th>SBR: Water</th>
<th>l/c ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>D10w</td>
<td>Y</td>
<td>0.25</td>
<td>-</td>
<td>1.36</td>
<td>0.1</td>
<td>1</td>
<td>0.05</td>
<td>1:3</td>
<td>0.51</td>
</tr>
<tr>
<td>D12w</td>
<td>Y</td>
<td>0.33</td>
<td>0.76</td>
<td>-</td>
<td>1</td>
<td>0.05</td>
<td>1:3</td>
<td>0.43</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.11 Additional designed mortars

<table>
<thead>
<tr>
<th>Mix</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1w-2</td>
<td>Very stiff mix (5 mm slump)</td>
</tr>
<tr>
<td>D1w-3</td>
<td>Very workable mix (95 mm slump)</td>
</tr>
<tr>
<td>D2w-2</td>
<td>Same as mix D2w but from a different batch</td>
</tr>
<tr>
<td>D8Aw-1</td>
<td>Air entrained, would not pump</td>
</tr>
<tr>
<td>D8Aw</td>
<td>Air entrained- mix D8Aw-1 with water added</td>
</tr>
</tbody>
</table>

A total of 12 laboratory designed mortars were designed for the pumping and spraying trials, of which 9 were successfully pumped and sprayed. Three of the other mixes (D4w, D11w and D12w) were designed to be un-pumpable, to test our ability to predict what mixtures would and would not pump.

**Fine concretes**

The laboratory designed fine concretes were combinations of a 6 mm maximum sized uncrushed river gravel, Portland cement, silica fume slurry (5% silica fume by weight of cement) and superplasticiser (1.5% weight of cementitious). This mix design was based upon previous work by Jones (1998) on sprayed concrete. The mix proportions are shown in Table 3.12. Mix C5p also contained crushed Portland stone, mixes C4p and C5p contained a coarse (2-8 mm) smooth aggregate, mix C1Sp contained steel fibres (30 mm hook ended at 80 kg/m³), mixes CP1p and CP2p contained polypropylene fibres (at 5 and 0.9 kg/m³ respectively) and mixes C1Ap and C3Ap contained an air entraining admixture.
Table 3.12 Mix design of fine concretes

<table>
<thead>
<tr>
<th>Mix</th>
<th>Sand</th>
<th>Portland stone</th>
<th>Shingle</th>
<th>Port. cement</th>
<th>Super-P % of PC</th>
<th>Agg./c ratio</th>
<th>Fibres kg/m³</th>
<th>Silica fume % of PC</th>
<th>w/c ratio</th>
<th>Air %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clp</td>
<td>2.7</td>
<td>--</td>
<td>--</td>
<td>1</td>
<td>1.5</td>
<td>2.6</td>
<td>--</td>
<td>5</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ClSp</td>
<td>2.7</td>
<td>--</td>
<td>--</td>
<td>1</td>
<td>1.5</td>
<td>2.6</td>
<td>Steel-80</td>
<td>5</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ClAp</td>
<td>2.7</td>
<td>--</td>
<td>--</td>
<td>1</td>
<td>1.5</td>
<td>2.6</td>
<td>--</td>
<td>5</td>
<td>0.39</td>
<td>18.0</td>
</tr>
<tr>
<td>C2d</td>
<td>2.9</td>
<td>--</td>
<td>--</td>
<td>1</td>
<td>--</td>
<td>2.8</td>
<td>--</td>
<td>5</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>C3p</td>
<td>3.1</td>
<td>--</td>
<td>--</td>
<td>1</td>
<td>--</td>
<td>3.0</td>
<td>--</td>
<td>5</td>
<td>0.63</td>
<td>--</td>
</tr>
<tr>
<td>C3Ap</td>
<td>3.1</td>
<td>--</td>
<td>--</td>
<td>1</td>
<td>--</td>
<td>3.0</td>
<td>--</td>
<td>5</td>
<td>0.53</td>
<td>12.5</td>
</tr>
<tr>
<td>CP1p</td>
<td>3.1</td>
<td>--</td>
<td>--</td>
<td>1</td>
<td>1.5</td>
<td>3.0</td>
<td>Poly-5.0</td>
<td>5</td>
<td>0.58</td>
<td>--</td>
</tr>
<tr>
<td>CP2p</td>
<td>3.1</td>
<td>--</td>
<td>--</td>
<td>1</td>
<td>1.5</td>
<td>3.0</td>
<td>Poly-0.9</td>
<td>5</td>
<td>0.45</td>
<td>--</td>
</tr>
<tr>
<td>C4p</td>
<td>2.0</td>
<td>--</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td>2.8</td>
<td>--</td>
<td>5</td>
<td>0.34</td>
<td>--</td>
</tr>
<tr>
<td>C5p</td>
<td>1.13</td>
<td>0.62</td>
<td>0.94</td>
<td>1</td>
<td>1.5</td>
<td>2.6</td>
<td>--</td>
<td>5</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

3.4.4 Air voids measurement

If the void content of the solid particle system can be minimised, then the susceptibility to dewatering under pressure can be reduced (Section 2.3.8 and 2.5.3). The void content of the dry mix constituents (aggregate, cement, silica fume etc.), both individually and combined together were measured using a voids meter produced by Jencon Scientific (Figure 2.26). The method is based on measuring the head of water which can be supported by a partial vacuum created within the aggregate. The material is placed in the sample jar in four equal layers, each is compacted by hand with a weight. The airtight lid is then screwed down and with the reservoir in the elevated position 1 (see Figure 2.26), the water level in the measuring tube is brought to a predetermined level by adjusting the water level in the reservoir. The reservoir is then lowered to position 2, creating a pressure head in the measuring tube. The head which can be sustained is inversely related to the volume of air in the sealed system, and the void content of the sample can be read directly from the calibrated scale. The results are shown in Table 3.13 and are the average of 2 samples.

Table 3.13 Void content of mixes and constituents

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Portland stone</th>
<th>Building sand</th>
<th>River sand</th>
<th>Portland cement</th>
<th>Silica fume</th>
<th>PFA</th>
<th>GGBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void content (%)</td>
<td>44.3</td>
<td>36.4</td>
<td>39.8</td>
<td>61.4</td>
<td>85.3</td>
<td>56.6</td>
<td>65.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mortar</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void content (%)</td>
<td>38.8</td>
<td>41.6</td>
<td>46.4</td>
<td>44.6</td>
<td>49.1</td>
<td>49.9</td>
<td>50.0</td>
</tr>
</tbody>
</table>
3.5 MIXING, PUMPING, SPRAYING AND CASTING PROCEDURES

3.5.1 Mixing

The pre-blended mortars were mixed in a 0.043 m³ capacity forced-action paddle mixer according to the manufacturers instructions. 3.3 to 4.0 litres of water were added per 25 kg bag and mixing carried out for between 2 to 5 minutes depending on the type of material. 3 to 4 bags were mixed together to produce 85 to 116 kg of mortar per batch. Water was added until the desired consistency for spraying was achieved i.e. workable enough to be pumped effectively yet stiff enough not to slough or sag once sprayed. Care was taken to ensure that the mortar was thoroughly mixed and that there was no dry powder around the inside of the mixing pan. The laboratory-designed mixtures were mixed in a similar way except that the dry constituents were mixed thoroughly before the addition of the liquid component.

All the mixes that were pumped and sprayed with the piston pump were batched in the integral mixer on the rear of the pump in a batch of approximately 260 kg. This could then be hydraulically lifted into the hopper ready for pumping. The dry constituents were added first and then the liquid components were added until the desired consistency was obtained.

The dry-sprayed mix C2d was mixed dry in the same paddle mixer as the wet-sprayed mortars in a dry batch of 100 kg. This dry material was then fed manually into the hopper of the dry-process machine.

3.5.2 Pumping

Trials were conducted with seven types of pump, the majority with a Putzmeister TS3/EVR variable-speed worm pump or a Reed B-10 piston pump (see Section 3.3.3).

The pumping procedures for the different types of wet-process pump were very similar. Before pumping the material, approximately 20 litres of cement slurry was
pumped through the machine and down the hose to lubricate the equipment. This also ensured that the equipment operated satisfactory and that no leaks were present in the pump or the line. The batched material was then added to the hopper and the rotostator (for the worm pumps), or the pistons (for the piston pump), fed the material through the pump, down the hose and to the nozzle. Compressed air was added at the nozzle to project the material into place. For the Reed SOVA dry-spray machine, the dry constituents (i.e. aggregate, cement and silica fume for mix C2d) were pumped down the hose by compressed air and were then projected into place by pressurised water at the nozzle.

3.5.3 Spraying

One operator controlled the pump and fed the mortar into the hopper. If a blockage occurred then the machine was stopped and the flow direction reversed to relieve the pressure in the line; this was essential before any of the line was disconnected. A second operative controlled the nozzle and sprayed the material. The author sprayed all the mixes using the low-volume worm pumps (TS3EVR, P-20 and Duo-mix) and an experienced nozzleman from Gunform International Ltd sprayed the mixes using the dry-process machine (Reed SOVA), the large-diameter worm pump (Putzknecht S30 UE45/7) and the piston pump (Reed B-10).

The test panels were sprayed in such a way as to minimise the number of voids and to produce the best quality panel possible. This was done by spraying directly into the corners of the panel first and then along the back edges of the panel. The panel was then steadily built up in horizontal strokes from the bottom upwards. The panels were sloped against the wall at approximately 30 degrees to the vertical. 593x897x50 mm grit-blasted paving slabs were also sprayed for several of the mixes to assess the restrained shrinkage and two 100 mm cubes and two 100x100x500 mm beam moulds were sprayed for testing at 28 days.

3.5.4 High Speed Photography

The mortar and concrete streams of mixes P1p, P1d, P2w, P2w, P3w, P7w, D1p, C1p, C1Ap, C1Sp and C2d were filmed with a Kodak HS (High Speed) digital camera
system capable of recording 40,000 frames per second (Figure 3.8). This equipment was loaned via the EPSRC from the Rutherford Appelton Laboratory. From these films it was possible to determine the velocity and angle of dispersion of the particles.

3.5.5 Field trials

Three sprayed-mortar repair contracts were visited and panels sprayed at each with the same equipment, materials and personnel as for the actual repair.

The first field trip was a bridge abutment repair on the A452 Chelmsley Wood collector road beneath the M6 motorway by Balvac Whitley Moran on the 31st of January, 1997. The concrete had suffered severe chloride attack from the corrosive action of road salts. Dry-process sprayed repairs were done in alternate 1m wide, 150 mm deep panels with a Markum ELP1 dry-spray machine with a 50 mm hose. Two 500x500x100 mm panels were sprayed and then cured with a spray-applied curing membrane. The panels were left overnight in the same conditions as the actual repair and were then transported back to Loughborough the following day to be sawn into prisms and stored in the curing tank. This mix was designated P8d.

The second field trial was the repair of 400 mm square reinforced concrete columns and beams at Fort Dunlop, Birmingham by Gunform International Ltd. The contractor sprayed two 500x500x100 mm panels with a Reed SOVA dry-process pump at a rate of 50 l/min with a 365 cfm (0.172 m³/s) compressor. The panels were cured and transported in the same way as the first field trial. This mix was designated P5d.

The third field trip was the wet spraying of a 150 mm layer of mortar onto the underside of a brick archway by Gunform International Ltd. This was at the Civil Engineering Department at Nottingham University and was part of a research project into the strengthening of brick archways with wet-process sprayed mortar (Peaston et al., 1996). Two 500x500x100 mm panels were sprayed, cured with damp hessian, and stored inside the laboratory overnight. A Uelzener Putzknecht S30 UE45/7 large-diameter worm pump was used at an output of approximately 50 l/min together with a
32 mm diameter rubber hose and a 125 cfm (0.059 m$^3$/s) compressor. This mix was designated P2W.

3.5.6 Casting

At each spraying trial moulds were cast and vibrated in two layers on a vibrating table. Specimens cast included: 100 mm cubes (for compressive strength testing), 100x100x500 mm beams (or flexural strength testing) and 75x75x229 mm prisms (for elastic modulus and shrinkage testing). Each reported result is the average of two specimens.

3.5.7 Curing

All cast specimens were cured for the first 24 hours with either polythene sheeting or with a concrete curing membrane (Sika Antisol 90) and then demoulded. Sprayed panels were cured with a curing membrane and then moved inside the laboratory before darkness on the day of spraying. All panels were sawn after 24 hours and the specimens placed under water in a curing tank at 20±2 °C, except for the shrinkage specimens which were stored in an environmental cabinet an 20 °C and 50 % RH. The restrained shrinkage panels were coated with a curing membrane immediately after spraying and were left outside exposed to the elements. The panels sprayed at the field trials were coated with a concrete curing membrane immediately after spraying, left on site overnight and then transported to the laboratory the day after spraying to be sawn into specimens and stored under water in the curing tank.
3.6 TEST METHODS AND SPECIMEN PREPARATION: FRESH PROPERTIES

3.6.1 Rheological testing

Eight rheological tests were conducted, two for workability (slump and shear vane), three for pumpability (two-point, Viskomat and pressure bleed) and three for sprayability (build, core grading and reinforcement encasement). The test methods are described briefly below and, taken in this order, they enable a rheological audit to be made of a mix as it progresses through the mixing, pumping and spraying process, as shown in Figure 3.9.

3.6.2 Slump and vane shear strength

Slump tests were conducted according to BS1881: Part102: 1983. Two tests were conducted and if these were within 15 mm of each other than an average of the two measurements was taken. If not, then a third slump test was conducted and an average of the three results taken.

A shear test was devised by modifying the shear vane test for soils (BS 1377: Part9: 1990). This was investigated as a simple, portable apparatus which could give an indication of the workability of a mortar or concrete at various points in the pumping and spraying process. It consisted of a torque measuring device at the head of the instrument together with a set of vanes to provide sufficient shear resistance to register on the torque scale. The maximum torque can then be used to calculate a shear strength for the material (in kPa). Two readings were taken for each mix and an average of these is reported here. The shear vane was calibrated with a torque wrench and these values were then used to calculate the shear strength according to BS 1377: Part 9: 1990. Details of these calculations are given in Appendix A.6.

3.6.3 Two-point test

The apparatus (Figure 3.10) was warmed up prior to testing for a period of 2 hours at a speed of 0.9 rev/s, until the change in recorded pressure at a constant speed with time was negligible. The idling pressures were then recorded between the speeds of
0.6 and 2.6 rev/s at increments of 0.2 rev/s. With the bowl rotating at 0.6 rev/s the bowl was gradually filled with approximately 25 kg of mortar to a level 75 mm below the top of the bowl. The speed was then increased in increments of 0.2 rev/s and the corresponding pressures recorded. Once 2.6 rev/s had been reached the speed was reduced incrementally in the same way and the corresponding pressures again recorded. The decreasing results that follow the structural breakdown (Figure 3.11) were used for calculating g and h. The values reported here are from one test only. Details of how to convert g and h into fundamental units are provided in Appendix A.1, although this was not done in this work.

Problems were sometimes encountered with the two-point test when used for mortars. The stiffness of the mortars required for spraying occasionally caused the rotating impeller to create a void in the mortar. Therefore, as the speed of rotation increased, no increased resistance was provided by the mortar and so the recorded torque values did not increase. This could be observed during the test and the results discounted.

3.6.4 Viskomat

Mortars for testing in the Viskomat rotational viscometer (Figure 3.12) were mixed in a variable-speed food mixer with a planetary motion at a speed of 110 rev/min for 60 seconds, then at 210 rev/min for a further 90 seconds. Only mortars with a maximum aggregate size of 2 mm could be tested in the Viskomat. Approximately 0.9 kg of mortar was then transferred into the temperature-controlled container on the Viskomat and the measuring paddle was lowered into it. The mortar temperature and the time after mixing at which the test was started were standardised at 20 ± 2 °C and 5 minutes respectively (these values being chosen after preliminary testing). The mortar was then subjected to a pre-programmed speed and temperature programme. The paddle torque, speed, temperature and time were continuously recorded by a computer as the test progressed and on completion the results were displayed and printed either graphically or numerically. Flow curves in the form of the Bingham model could be automatically produced. In principle, it is possible to convert g and h to fundamental units equivalent to $\tau_0$ and $\mu$ by calibration with standard fluids (Banfill, 1994) but
most investigations work with the direct parameters (which are equipment dependent) and these are reported here. One Viskomat test was conducted per mix.

3.6.5 Pressure bleed test

The pressure bleed apparatus (Section 2.5.3 and Figure 3.13) was filled with approximately 1700 cm³ of mortar and the top cap and piston secured in position. The apparatus was placed in a 100 kN Instron compression testing machine and the sample was subjected to a load of 12.2 kN, equivalent to 10 bar (1000 kPa), which was the highest pumping pressure recorded with the TS3EVR worm pump. The valve was opened after 10 seconds and the liquid (consisting of water, cement and, if present, silica fume particles and SBR) squeezed from the sample was collected in a container on a digital balance. Time and weight of the emitted liquid were digitally recorded for 30 minutes, from which a curve of liquid emitted against time elapsed could be produced. One pressure bleed test was conducted per mix.

3.6.6 Adhesion and build thickness

The build test consisted of two 250x500 mm substrates with grit blasted surfaces which were secured in vertical or overhead panels. The substrates were stored in water for 24 hours before use and periodically wetted to ensure the surface was saturated surface dry when sprayed. The sprayed material was built up from a 300x300 mm square base marked on the substrate and the length of the build continuously monitored until either a cohesive or an adhesive failure occurred. The mortar or concrete was then weighed and the build length, the total weight of material and the failure mode recorded. One build test was conducted per mix.

3.6.7 Reinforcement encasement

Inadequate reinforcement encasement can be a problem in both wet- and dry-process sprayed concrete, yet there is no test that will predict or quantify the degree of encasement. The degree of encasement is dependent on the density and orientation of the reinforcement, the mix design, the placement characteristics (e.g. nozzle design, stream velocity) and the skill of the nozzleman.
A test was devised consisting of a 500 mm square, 100 mm deep test panel fixed with reinforcing steel of various sizes (Figure 3.14(a)). Advice was taken on the positioning and sizing of the reinforcing bars (Dunlop, 1997; Roxbrugh, 1997; and Sprayed Concrete Association, 1990). The panel was sprayed to obtain as complete encasement of the steel as possible. One panel was sprayed per mix. At 28 days 55 mm diameter cores were taken at the intersections of the bars and examined visually for imperfections, i.e. laminations, shadowing and voids. A 5 mm disc was cut from the bottom (i.e. moulded face) and discarded (Figure 3.14(b)); a 20 mm thick disc was then sawn from the same end and a sorptivity test conducted on both the disc and the remainder of the core (where possible, as occasionally the voidage behind the reinforcement caused the core to fragment during sawing). The sorptivity was then related to the density of the reinforcement at the bar intersection. Four different methods for quantifying the density of reinforcement were investigated: summing the bar diameters, summing the bar cross-sectional areas, calculating the total projected bar area within the core and calculating the area of bar overlap. The area of bar overlap was chosen as this gave the broadest spread of results. The tops of the cores produced a wider sorptivity range than the corresponding bottom slice of the core, probably due to the voids produced in the mortar being concentrated directly beneath the bars and so these are the values presented. One panel was sprayed per mix.

The cores taken for the sorptivity test were also visually graded on a scale of 1 to 5 in accordance with the recommendations of Gebler (1995), based on a grading system originally proposed by Crom (1985). Each of the core grades relates to the quantity and size of imperfections visible on the surface of the core. A grade 1 core has a good paste content throughout, without laminations, sand areas or large hollows. Small air bubbles to a maximum dimension of 1.3 mm are acceptable. There are no sand pockets, hollows or shadows behind any of the reinforcing bars. At the other end of the scale, a grade 5 core can have flaws greater than 25 mm thick and 38 mm in length. Gebler (1995) states that a core grade of 1 or 2 is generally used for acceptance of a nozzleman on projects demanding high quality workmanship. Although the visual grading is subjective, the grading criteria are explicit and good correlation between independent gradings can be achieved by experienced engineers.
3.6.8 Water permeability

The water permeability of the aggregate for mixes D1, D2 and D3 was measured using the falling head permeability apparatus to BS1377: Part 5: 1990. The aggregate in mix D4 was too permeable to be accurately measured in the falling test apparatus and so the constant head permeability apparatus was used. In the constant head permeameter, water flows through the sample whilst a constant head of water is maintained above the sample (Figure 3.15(a)). The rate of water flow through the sample (q) and the head drop across the sample (h) are both measured and Darcy’s law is used to calculate the coefficient of permeability (or k, in m/s). In the falling head permeameter, a hydraulic head of water (h₀ - h₁) is set up above the sample and is then allowed to flow through the sample (Figure 3.15(b)). The rate at which the height of the water column changes can be measured and Darcy’s law can be used to calculate k. For both tests, an average of four readings were taken for each sample.

The permeability of mixes D1, D2, D3 and D4 were also measured in their fresh (i.e. mixed) state at a workability that would typically be sprayed in the worm pump. The falling head apparatus was used for all the mixes as the flow rate was too small for the constant head apparatus.

3.6.9 Fresh density

The fresh wet density was measured after spraying by weighing a 5.5 litre measuring cylinder, spraying directly into it, vibrating it on a vibrating table to remove excess air and then weighing it again. The mass of material could then be divided by the volume of the cylinder to obtain the fresh wet density. This test was conducted once per mix.

3.6.10 Air content

The pressure test (BS 1881: Part106: 1983) was used to measure the air content of the fresh concrete or mortar. Approximately 300 ml of material is placed in the device and vibrated to remove the excess entrapped air. The top is secured and water is added to provide an airtight seal. The device is then pressurised and zeroed, a button is pressed and the air content reading (in %) is read from the dial. The data reported is the average of two readings.
3.7 TEST METHODS AND SPECIMEN PREPARATION: HARDENED PROPERTIES

3.7.1 Sprayed concrete

For each hardened property the European, ASTM and BSI Standards (which existed in June 1996) were evaluated and the standard most applicable to sprayed concrete was chosen (and modified where necessary). Appendix A.6 records the study of each test method, whilst the test methods used in the research are outlined below. The standards for concrete rather than mortar were selected so that the results obtained for the mortars and concretes would be comparable. In some instances, new test methods were developed specifically for the research and these are also described below.

At the beginning of this research there was clearly a lack of suitable standards for testing sprayed concretes and mortars and this work contributed to the CEN Task Group which is developing test methods for sprayed concrete (CEN/TC104/WG10).

3.7.2 Compressive strength

Three types of 100 mm cube were tested for compressive strength:

1. cast into moulds (to BS1881: Part116: 1983) in two layers on a vibrating table;
2. sawn from test panels (and capped with plaster and steel plates on their loading faces to cope with the imperfect orientation and texture of the sides. The cubes then produced failures typical of cast cube specimens); and
3. sprayed into moulds.

Two of each type were tested at 28 days. Cast and sawn samples were sometimes also tested at 7 days.

Compressive strength was also determined from 55 mm and 100 mm diameter cores taken from the sprayed panels. They were sawn to the required length, capped in a positioning jig with a sulphur compound and tested to BS1881: Part120: 1983. The equivalent cube strength was then calculated using the overall (capped) length and it is the average of this value which is quoted.
3.7.3 Bond strength

This was measured at 7 and 28 days according to EN 1542-1995 (similar to BS1881: Part207: 1992) with a ‘Limpet’ pull off tester (McLeish, 1993). After the substrates were sprayed a curing membrane was applied and the specimens stored in air inside the laboratory. Two days before testing five 55 mm diameter partial cores were cut through the repair material and into the substrate to a depth of approximately 10 mm. A 50 mm diameter steel dolly was then glued to the top of the core the day before testing. An axial tensile load was applied on the day of testing at a rate of 2 kN/min to failure and the failure load and stress recorded along with the failure mode (substrate, interface or repair or a combination). The data presented here is an average of five pull of tests per material.

3.7.4 Flexural strength

As for compressive strength, three types of 100x100x500 mm long beam samples were prepared:

1. cast in moulds according to BS1881: Part118: 1983, in two layers on a vibrating table;
2. sawn from panels (and the loading points packed with plywood to allow for the imperfect texture of the sawn surface); and
3. sprayed into moulds.

Two specimens of each type were tested at 28 days and the average value reported. The beams were tested under four-point loading in a Dennison testing machine.

3.7.5 Shrinkage

Due to the placement technique of sprayed concrete it is not ideal to compare the shrinkage of a cast sample with that of an in-situ repair. Several standards and published papers were examined to develop a representative test method. 75x75x229 mm shrinkage specimens were cast to BS1881: Part5: 1970 and similar sized specimens were sawn from the sprayed panels. A pair of measuring studs with a gauge length of 200 mm were fixed to three of the faces of each prism the day after spraying and strain readings were taken at 1, 2, 3, 4, 7, 14, 21 and 28 days. Further readings were taken at monthly intervals for a period of one year. The samples were stored in a
climatic cabinet at 20 °C and 50% relative humidity. The shrinkage value quoted for each mix is an average of strains measured across a total of six longitudinal faces of two prism specimens.

25x25x285 mm shrinkage specimens to ASTM C157-86 were also cast for mixes D1 and P3, to compare the rates of drying shrinkage of different sized specimens. However, the 25x25x285 mm specimens were not used for all the mixes in this work as their small size made them difficult to cast with the fine concretes, especially the steel fibre mix C1S, and so comparisons with the fine concretes would have been impossible. This specimen size would also be difficult to cut accurately from an in-situ sprayed panel and so comparisons between cast and sawn specimens would also have been impossible.

Plastic shrinkage tests to BS6319: Part12: 1992 were also conducted on some of the pre-blended mortars. However, reproducible results were difficult to obtain and so the results are not included here.

A restrained shrinkage test was also developed to represent a typical on-site sprayed repair. Second-hand 593x897x50 mm paving slabs, which would minimise substrate drying shrinkage, were grit-blasted on the face to be repaired. Half the substrate was covered with reinforcing mesh at a depth of 30 mm and half was left un-reinforced. The substrate was saturated surface dry and sprayed to a depth of approximately 60 mm. The repair was floated and a curing membrane applied. Three pairs of measuring studs with a 200 mm gauge length were fixed on both the reinforced and un-reinforced sections and strain readings were taken at similar intervals as for the drying shrinkage. The shrinkage value quoted is an average of these three readings. The back of the substrates were also instrumented on some of the mixes to monitor the movement of the substrates.

3.7.6 Air permeability

The air permeability test used was based upon equipment used by Lovelock (1970) and further developed by Hudd (1989). An air pressure of 50 psi (3.45x10^5 N/m^2) was applied to 20 mm x 55 mm diameter samples, that had been wet cured for 28 days,
cored, sawn to length, and oven dried at 50°C for 14 days. Samples were cored from cast mortar, sprayed mortar and mortar which had been sprayed into a mould. These same specimens were also used to measure the sorptivity (Section 3.7.7). Each result reported is the average of four samples, two from each of two cores.

3.7.7 Sorptivity

This simple test is based upon the procedure described by RILEM (1974) and used the specimens from the air permeability test (Section 3.7.6). The dried samples were weighed, placed in 2 mm of water and the weight gain was measured after 5, 15, 30, 60, 120, 180 and 240 minutes. The following formula can be used to calculate the sorptivity:

\[ i = S \sqrt{t} \]

Where, \( i \) = increase in mass of sample in g/mm\(^2\) since the beginning of the test;
\( t \) = time, measured in minutes, at which the mass is determined; and
\( S \) = Sorptivity, in mm/min\(^{0.5}\).

A logarithmic graph can be drawn of time against weight and the gradient of this line taken as the sorptivity. Each result reported is the average of four samples, two from each of two cores.

3.7.8 Modulus of elasticity

The secant modulus of elasticity was measured using cast and sawn 75x75x229 mm specimens which had been wet cured for 28 days. The test was based upon BS1881: Part121: 1983 and work recently completed by Jones (1998). The specimen strains were recorded over a gauge length of 85 mm using four LVDTs, the average of which was used to calculate the modulus. The load was applied at a rate of 0.5 mm/min and the load and deformations were digitally recorded using a data acquisition system. These values were then copied into a spreadsheet and the elastic modulus calculated. Each result reported is the average of two specimens. The Dennison compression machine and test specimen are shown in Figure 3.16.
3.7.9 Density

The hardened densities of the 100 mm cubes and 55 mm and 100 mm diameter cores were calculated at 7 and 28 days by weighing in air and determining their volume from measured dimensions. The densities for cast, sawn and sprayed cubes were all calculated and the results reported are the average of two specimens. Care was taken to ensure that no voids were present, especially with the specimens obtained from a sprayed cube mould.

3.8 SUMMARY

This Section has described the development of the equipment, materials and mix designs used in the experimental investigation, together with the development of the mixing, casting, pumping and spraying methods used to obtain both the cast and sprayed specimens. In addition, it has described the pumping and spraying trials completed both in the laboratory at Loughborough and in the field trials. Also described are the test methods and the specimen preparation used to measure both the fresh properties and the hardened properties of the mortars and concretes. The data obtained from these tests will now be presented, analysed and discussed in Chapters 4 and 5.
Figure 3.1 Spraying chamber at Loughborough University

Figure 3.2(a) Putzmeister TS3EVR worm pump and compressor
Optional extras:
- Compressed air control, part no. 002708.009
- Sack mangle, part no. 002711.009

1. Vario drive 2.2 kW, 400 V (on request 230 V, 50 cycles) or E-gear motor, 3 x pole-changing
2. Hopper
3. Cardan shaft
4. Worm pump
5. Pressure outlet
6. Hose coupling
7. Discharge connection piece
8. Supporting frame with wheel
9. Supporting foot
10. Supports
11. El. switchbox
12. Hinge
13. Undercarriage

Figure 3.2(b) Putzmeister TS3EVR worm pump

Figure 3.3 Reed B-10 piston pump
Figure 3.4(a) Plastic collar nozzle and air line

Figure 3.4(b) Stainless steel nozzle
Figure 3.5 Gradings (of the combined aggregate and cementitious components) of the pre-blended proprietary mixes

Figure 3.6 Combined grading of mix D9 and D10
Figure 3.7 Combined grading of mix D11 and D12

Figure 3.8 Mortar stream taken by high-speed camera

Figure 3.9 Rheological audit
Figure 3.10 Tattersall 2-point test apparatus

Figure 3.11 2-Point test - down curve
Figure 3.12 Viskomat apparatus 1

Figure 3.13 Pressure bleed apparatus
Figure 3.14 Reinforcement encasement (a) plan view (b) core cross-section

Figure 3.15(a) Constant head permeameter (b) Falling head permeameter (Craig, 1990)
Figure 3.16 Elastic modulus apparatus
4 FRESH PROPERTIES

4.1 INTRODUCTION

This chapter examines the influence of rheology on the pumping and spraying of mortars and concretes. The performance of seven commercially available pre-blended repair mortars, 12 laboratory-designed fine mortars and eight laboratory-designed fine concretes were examined using the Tattersall two-point and Viskomat rotational viscometers, the pressure bleed test, the slump test, a build test and a vane shear strength test. Several types of pump were used to pump and spray the mixes to assess their suitability and to measure their adhesion to a substrate by build thickness. This value is a measure of sprayability and is converted into values of maximum shear and bending stress which are then compared with the workability parameters in order to determine their inter-relationship. Two methods of measuring the degree of reinforcement encasement were also used.

Sections 4.2 and 4.3 present an initial analysis of the rheological data for the mortars and fine concretes respectively. The values for the mortars and fine concretes are compared in Section 4.4 and a deeper investigation of trends and underlying causes is presented. Some of the data presented here has been published in the papers listed in Appendix A.8.

4.2 MORTARS

4.2.1 Rheological Overview

This Section presents and discusses the rheological properties of the mortars described in Section 3.4 using the tests described in Section 3.6. These results are compared with the fine concretes in Section 4.4 and their influence on the pumpability and sprayability of the mixes is discussed. The hardened performance of these fine mortars is presented in Section 5.2. Eight rheological tests were conducted, two for workability (slump and shear vane), three for pumpability (two-point, Viskomat and pressure bleed) and three for sprayability (build, core grading and reinforcement
encasement). The results for most of these tests are presented in Table 4.1. This table includes every mortar that had at least two of its rheological properties measured. It should be remembered that the mortars have different mix designs, some of which would not realistically be used, either due to their mix design (e.g. D7w) or due to their workability (e.g. D1w-2 and D1w-3). These have been tested to increase the understanding of the relationships between the rheological properties and the influence of the mix design on these properties. Due to these variable workabilities and mix designs some of the relationships and trends are not distinct, although if a result does not follow the trend then this is mentioned and discussed.

4.2.2 Workability (slump and vane shear strength)

The shear vane provides a basic measure of the shear strength (in kN/m²) of a mortar and this is plotted against slump (in mm), as shown in Figure 4.1. This shows a decrease in shear strength for an increase in slump, as would be expected, and a correlation coefficient $R^2$ of 0.89. The standard deviations for the slump tests were in a range 3.5 to 7.1, with an average of 5.3 and in a range of 0.04 to 0.21 for the vane shear strength tests with an average of 0.13. The shear vane test can provide an instantaneous result exactly where the rheological properties of the mortar needs to be measured, e.g. in the hopper of the pump. This relationship is examined further in Section 4.4 together with the similar relationship for the fine concretes.

These mortar workability properties of slump and vane shear strength will be compared with the other rheological properties (e.g. flow resistance and build etc.) in Sections 4.2.3, 4.2.4 and 4.2.7 and with the fine concretes in Section 4.4.
<table>
<thead>
<tr>
<th>Mix</th>
<th>Build Length (mm)</th>
<th>Build Mass (kg)</th>
<th>Failure Stress (kN/m²)</th>
<th>Vane Shear Strength (kN/m²)</th>
<th>Slump (mm)</th>
<th>g-2 Point h (Nms)</th>
<th>g-Visko h (Nmm)</th>
<th>Failure description</th>
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<td>D1w</td>
<td>210</td>
<td>21.4</td>
<td>3.5</td>
<td>1.52</td>
<td>57.5</td>
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<td>D1p</td>
<td>230</td>
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<td>3.2</td>
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<td>3.00</td>
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<td>75</td>
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<td>75</td>
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<td>D5w</td>
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<td>--</td>
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<td>75</td>
<td>1.22</td>
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<td>--</td>
</tr>
<tr>
<td>D12-1</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.1</td>
<td>25</td>
<td>--</td>
<td>--</td>
<td>Too stiff to pump</td>
</tr>
<tr>
<td>P1w</td>
<td>320</td>
<td>41.5</td>
<td>3.82</td>
<td>1.37</td>
<td>60</td>
<td>3.2</td>
<td>0.89</td>
<td>Cohesive (wide base)</td>
</tr>
<tr>
<td>P2w2</td>
<td>270</td>
<td>26.2</td>
<td>4.3</td>
<td>1.52</td>
<td>50</td>
<td>--</td>
<td>--</td>
<td>Cohesion</td>
</tr>
<tr>
<td>P2w1-1</td>
<td>210</td>
<td>22.8</td>
<td>3.7</td>
<td>1.14</td>
<td>70</td>
<td>1.68</td>
<td>0.53</td>
<td>Cohesive (Wetted up P2w1)</td>
</tr>
<tr>
<td>P2w</td>
<td>220</td>
<td>13</td>
<td>3.7</td>
<td>1.82</td>
<td>60</td>
<td>--</td>
<td>--</td>
<td>Cohesive (Small cross/section)</td>
</tr>
<tr>
<td>P2w1</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.52</td>
<td>50</td>
<td>--</td>
<td>--</td>
<td>Too stiff to pump</td>
</tr>
<tr>
<td>P2-1</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>3.6</td>
<td>0.4</td>
<td>Not sprayed</td>
</tr>
<tr>
<td>P2-2</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>82.5</td>
<td>2.5</td>
<td>Not sprayed</td>
</tr>
<tr>
<td>P2-3</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>120</td>
<td>2.5</td>
<td>Not sprayed</td>
</tr>
<tr>
<td>P2-4</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2.1</td>
<td>0.59</td>
<td>Not sprayed</td>
</tr>
<tr>
<td>P3w</td>
<td>230</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.6</td>
<td>0.79</td>
<td>Not sprayed</td>
</tr>
<tr>
<td>P4w2</td>
<td>290</td>
<td>26.6</td>
<td>4.3</td>
<td>--</td>
<td>--</td>
<td>2.4</td>
<td>0.60</td>
<td>Adhesion</td>
</tr>
<tr>
<td>P4w1</td>
<td>180</td>
<td>18.7</td>
<td>3.1</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Adhesion</td>
</tr>
<tr>
<td>P6w</td>
<td>250</td>
<td>32.2</td>
<td>5.3</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Adhesion</td>
</tr>
<tr>
<td>P7w</td>
<td>350</td>
<td>23.5</td>
<td>3.8</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Probably cohesive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Probably adhesion</td>
</tr>
</tbody>
</table>

Table 4.1. Rheological test results - Mortars
4.2.3 Flow resistance and torque viscosity – Two-point test

Figure 4.2(a) shows the results obtained from the Tattersall two-point test on mix P1. They show a distinct upcurve and downcurve which was typical for all the mortars tested. However, approximately half way along the downcurve the torque appears to increase as the impeller speed decreases. This is due to the mortar not falling into the impeller sufficiently and therefore not creating enough resistance to produce a high enough reading above the idling pressures. A regression line drawn through these points, as shown in Figure 4.2(a) provides misleading values of flow resistance (g) and torque viscosity (h). As the speed is increased during the test (producing the upcurve) structural breakdown takes place, and so the results from the downcurve are used for calculating g and h (Figure 4.2(b)). The points at the bottom of the downcurve are not used as at these low speeds sufficient resistance is not provided by the mortar to give a representative reading. Using the results this way gave a correlation coefficient (R) of 0.994 compared with 0.63 when using all the data points.

The values of g and h for the mix D1 at different slumps are shown in Figure 4.3(a). As would be expected, the mix with the lowest slump (50 mm) had the highest flow resistance and the lowest plastic viscosity. A greater distinction between the values for g and h for the 82.5 mm and 120 mm slumps would be expected but these results suggest that the apparatus is less sensitive for mortars at higher slumps. However, Figure 4.4 seems to indicate that this flow resistance/slump relationship may not be representative of most mortars. Figure 4.4 shows a decrease in the flow resistance with an increase in slump, as would be expected. The spread of results is due to the data being produced from many different mix designs (including pre-blended and designed). Figure 4.3(b) shows the g and h for the mortar P2 after it has been mixed, pumped or sprayed. The increase in both g and h as the mortar is pumped and then sprayed would be expected as the excess air is forced out of the mortar.

The two-point test results for all the mortars in this study are shown in Figures 4.5 and 4.6. The pre-blended mortar with both the highest g and highest h was mix P1 which had the most ‘basic’ mix design of all the pre-blended mortars tested, and contained no polymers, fibres or lightweight fillers. The mix with the next highest value of g,
P4, also had a relatively basic mix design and together they were the cheapest commercially of all the pre-blended mortars that were tested. The two highly polymer-modified mixes (P6 and P3) had the lowest values of \( g \), although their corresponding values of \( h \) were very different. The mix P3 is a two-part (powder and liquid) re-profiling mortar which had been formulated to enable it to be applied in thin layers without it separating or being too 'sticky', which could explain the low value of \( g \). The designed mixes in Figure 4.6 show a clear trend dependent upon the mix design: the greater the proportion of crushed Portland stone within the mix compared with the building sand then the greater the value of \( g \). This agrees with work by Banfill (1994) who concluded that an increase in fines produced an increase in \( g \) and \( h \), although a distinct increase in \( h \) was not found here. The addition of SBR to a mix, in this case mix D5 having no SBR and mix D1 being an identical mix containing a 3:1 water:SBR solution, appears to have little effect on either \( g \) or \( h \). This is in contrast with the pre-blended mortars where the highly polymer-modified mortars possessed a lower value of \( g \).

4.2.4 Flow resistance and torque viscosity - Viskomat

Existing data published on the Viskomat (Banfill, 1994 and Wolter, 1995) is on mortars with a workability higher than those in this study and several different measurement profiles of speed against time are documented. A standard profile had to be chosen for this study and mix D1 was tested in the Viskomat at speeds of 200, 180, 160 and 140 rpm for 20 minutes at a stiffness at which it would be sprayed. The changes in torque against time for these different speeds are shown in Figure 4.7. The tests conducted at 180 and 200 rpm experienced structural breakdown for approximately seven and eight minutes respectively. The tests conducted at 140 and 160 rpm also demonstrated structural breakdown for up to two minutes but this breakdown was significantly smaller than for the higher speeds and so a speed of 200 rpm for a time of 10 minutes was chosen for the structural breakdown duration of the testing profile. The remainder of the profile consisted of decreasing steps of 20 rpm every 2 minutes down to a minimum speed of 60 rpm. At speeds lower than this the mortar ceased rotating with the pot.
Figure 4.8 shows the torque against time graph for mix P4 using breakdown speeds of 180, 160, 140 and 120 rpm and it can be seen that decreasing the breakdown speed decreases the value of \( h \). The values recorded at the speeds of 160 and 180 rpm (on the x-axis) have been excluded as their recorded torques increased as their speeds decreased due to the mortar rotating with the pot occasionally at high speeds. This was the main problem encountered when testing low-workability mortars with the Viskomat.

The pre-blended mortars P1, P2, P4, P6 and P7 are shown in Figure 4.9. As some of the mortars did not flow sufficiently (due to their low workability), a profile was used that increased the initial speed in increments, with one minute at 50 rpm, one minute at 100 rpm, one minute at 150 rpm and then finally 10 minutes at 200 rpm (for the breakdown period). The speed then decreased in steps of 20 rpm every 2 minutes as before. The mortar P1 was initially tested at the stiffness used for spraying, but it would not breakdown at any of the breakdown speeds or rotate sufficiently with the pot. It was therefore tested at a higher workability than would typically be used for spraying, which explains why this produced the lowest value for \( g \) of all the mortars tested. This mortar was also the most difficult to pump of the pre-blended mortars tested (at a stiffness typically used for spraying) and it was the only polymer-free pre-blended mix tested.

Mortar P2 broke down quickly and produced the highest value for \( g \). Mortars P4 and P7 broke down but began to trap air within the sample after 17 and 13 minutes respectively causing the mortar to rise within the pot and so these tests were ended prematurely. These two mortars had the lowest values for \( h \) of the pre-blended mortars tested which agrees with the work of Beaupré (1994), who reported that \( h \) decreases with the addition of air entrainment, although the opposite effect has also been reported by Wolter (1995). The mortar with the next lowest value of \( h \), P1, had the highest workability which is consistent with the low values of both \( h \) and \( g \). Another problem encountered with mortars P4, P7 and P6 was that the polypropylene fibres became trapped around the paddle and the scraper within the pot, which increases the torque on the paddle due to the enlarged surface area. This also alters the mix proportions of the mortar as some of the fibres have effectively been 'removed' from
the mix. Mix P4 took the longest to break down (with the exception of P1), the mortar not beginning to flow until a speed of 100 rpm. The final mix, P6, broke down easily and did not trap any air.

4.2.5 Comparison of Two-point and Viskomat results

Figures 4.10(a) and (b) compare the values obtained with the Two-point test and the Viskomat. The apparatus and the units are different and so direct comparisons of the numerical results for each mortar can not be made. As mentioned earlier, the values for P1 of both g and h are significantly lower when using the Viskomat due to the higher workability of the mix than when tested in the Two-point. This mix did produce the highest value of g with the Two-point test which suggests that this material may have a flow resistance at this water content which is too high for testing in the Viskomat. The material that produced the next highest value of g with the Two-point test, P4, was also the second most difficult to break down with the Viskomat. Figure 4.10(b) shows that the two mixes with the lowest values for h in the Viskomat (P4 and P7) trapped the air during the test although the corresponding values for g do not seem to have been affected. This Figure also shows that mixes P2 and P6, which broke down quickly in the Viskomat, have relatively higher values of h, compared with the other materials, in the Viskomat than in the Two-point.

Comparing the two tests, the Two-point was more effective at the low workabilities used for spraying as it was difficult to break down the mortars sufficiently in the Viskomat and the basic mixes containing no polymers (such as P1) could not be tested in the latter. The polymer-modified mortars (such as P2 and P6) could be tested effectively in the Viskomat although some of these mortars (P4 and P7) trapped air during testing.

4.2.6 Pressure bleed test

Figure 4.11(a) shows that the total liquid emitted from the pre-blended repair mortars in the first 30 minutes at a pressure of 10 bar (12.2 kN) ranged from 20 to 140 ml. This liquid was a combination of water, SBR, Portland cement, silica fume and very fine (<75 μm) sand particles. The relatively basic mortars (P1 and P4) that contain little or no polymers emitted the largest total amount of liquid at the fastest rate and
the highly polymer-modified mixes (P6 and P7) emitted a smaller total amount of liquid at a slower rate. The polymer-modified two-part re-profiling mortar (P3) emitted a small amount of liquid (20 ml) very quickly in the first 2.5 minutes but then the rate of bleeding decreased rapidly. As stated in section 4, the resistance of a mix to bleeding is dependant upon the mix composition, especially the grading of the constituents. Comparing the gradings of the mixes it can be seen that the mixes with the lowest proportion of fine material emitted the most liquid and vice versa. The smoothness of the grading is also important as any gaps in the grading allow the liquid and the fine particles to flow through.

Figure 4.11(b) shows that the total amount of water emitted from the designed mixes at a pressure of 10 bar ranged from 45 to 120 ml. The mixes containing no SBR (D5 and D6) emitted a larger volume of liquid at a much higher rate than the mixes with SBR. As can be seen from Table 3.9, mix D5 is identical to mix D1 except that the latter contained SBR. The table also shows that mixes D1 to D4 contained varying proportions of crushed stone and building sand. The mix with the most fines (D1) emitted the most liquid at the quickest rate and the mix with the least fines (D4) emitted the least liquid at the slowest rate. This is due to the higher water content needed when a greater proportion of fines are present in order to obtain the same workability. It would have been informative if the amount of water emitted could have been plotted against the percentage of free water within the mix. However, most of the mixes were mixed to a typical workability for pumping rather than a particular water/cement ratio and so the water content was not always recorded.

Figure 4.12(a) shows mix D1 tested at constant pressures of 5, 10, 15 and 20 bar (6.1, 12.2, 18.3 and 24.4 kN) for 30 minutes. Figure 4.12(b) shows the first 30 seconds of these tests and it can be seen that the initial rate of liquid emitted increases with increasing pressure with the rate at 20 bar being almost three times the rate at 5 bar. However, over 30 minutes the pressure seems to have only a small effect on the total amount of liquid emitted with 53 ml being emitted at 5 bar and 63 ml at 20 bar.
4.2.7 Adhesion and build thickness

The build value (in mm) and corresponding mass of mortar at the point of failure for each of the mixes is shown in Table 4.1. The shear stress at the substrate at failure was then calculated using these values and the cross-sectional area at the base of the mortar (approximately 300 mm square). The maximum tensile stress on the mortar at failure due to the moment was also calculated by idealising the mortar on the substrate into the frustum of a square-based pyramid. The volume, and therefore the dimensions of this frustum, could be calculated using the mass, the fresh wet density, the area of the base and the height of the frustum (i.e. the build value). This shape was then used to calculate the moment and hence the maximum tensile stress at failure on the mortar. The relationship between the build value and the maximum shear and tensile failure stresses is shown in Figure 4.13. The failures were visually recorded as either adhesive (at the substrate) or cohesive (in the mortar) failures. Each of these failures can then further be classed as either tensile or shear failures. An example of the failure stress calculations for P2w2 is given in Appendix A.9. It should be remembered that the failure stresses reported here are the stresses that the mortar is subjected to due to its own weight, and they are not a measure of the tensile or shear strength of the mortar, which was not measured in this work. However, these properties are obviously related.

The method shown in Appendix A.9 is based on simple bending theory and would not normally be applied to a short frustrum, such as the one we have here. However, it is an idealisation and intended as an approximate method for comparing the build of the different materials and not as an exact method of structural analysis. The structural theory assumes: plane sections remain plane, linear elastic behaviour takes place, a homogenous material and no cracking. However, these conditions are not met here. It also does not take into account edge effects and the effect of the substrate/fresh material interface, which the structural theory assumes is continuous and homogeneous.

The build frustrum could alternatively have been analysed as a nib, a corbel or as a beam/column connection. Appendix A.9 shows the forces that are assumed to be
acting on the element, depending on which method of analysis is used. As can be seen from these diagrams, none of these methods illustrate completely the build up of fresh material on a hardened substrate. The simple elastic bending described above was therefore applied as an idealised solution.

A poor correlation is found between the slump of the mortar before pumping and the maximum tensile and shear stresses at failure (Figure 4.14). The build compared with slump is shown in Figure 4.15 and this indicates an increase in build as the slump increases from zero until a slump of approximately 60 mm is reached, at which point the build begins to decrease. Unfortunately, the failure stresses for the 5 mm slump mix (D1w-2) were not calculated (due to the mass of the build not being recorded) and so this result does not appear in Figure 4.14. These results are compared with the fine concretes in Section 4.4 and the reasons for this relationship are discussed.

Beaupré (1994) also reported that an increase in the value for $g$ (the flow resistance, obtained from the Two-point test) produced a corresponding increase in the build value, which agrees with the data presented here (Figure 4.16). This value of $g$ obtained from the Two-point test is also plotted against the maximum shear and bending stresses in Figure 4.17. No discernible trend is apparent and more tests would be needed to establish a relationship (if one exists). Mortar D1w-3 had a very high slump of 95 mm, which would explain the low value for both $g$ and for the failure stresses. It could be possible that a similar trend exists here to that shown in Figure 4.15. This possible trend is discussed in Section 4.4.

Figure 4.18 presents the relationship between the vane shear strength immediately before pumping and the maximum tensile and shear stresses at failure. These results appear to show no correlation between the vane shear strength and the failure stresses. However, if just the maximum failure stress for each mix is considered and the Figure is studied in conjunction with the build/vane shear strength relationship in Figure 4.19 then it could be suggested that the maximum failure stress (and the corresponding build) at first increases with increasing vane shear strength, and then begins to decrease at a vane shear strength of approximately $1.4 \text{kN/m}^2$. This trend is discussed in more detail in conjunction with the fine concretes in Section 4.4.
The mix design, water content and spraying conditions (pump type, velocity etc.) all have an influence on the build and rheological properties of the mortars and so it is difficult to establish definite trends when the data is collected using different mortars and pumping systems. Tests were therefore conducted on mix D1 (Table 4.2) to further examine the relationship between slump, vane shear strength and build (Figures 4.15 and 4.19). The same mix design was tested at 3 different water/cementitious ratios and pumped and sprayed using the TS3EVR worm pump. As the water/cementitious ratio increased the slump also increased and the vane shear strength decreased, as would be expected. The value for g also seems to decrease in a similar way to Figure 4.4, although the mix with the lowest water content was too stiff to test in the Two-point apparatus.

The data also shows that as the slump increases (and the vane shear strength decreases) the build value increases initially and then begins to decrease, as shown in Figures 4-15 and 4.19. The cast cube strength also decreased as the water content increased (as would be expected). The sprayed mould strengths were higher than the cast due to the greater compaction achieved by spraying and these also decreased with increasing water content with exception of the mix with the lowest water content which was so stiff that voids were formed when sprayed into the mould, thus decreasing the compressive strength.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Water/ Cementitious Ratio</th>
<th>Slump (mm)</th>
<th>Shear Vane (kPa)</th>
<th>Build (mm)</th>
<th>2-Point Test g (Nm)</th>
<th>h (Nm/s)</th>
<th>Cube Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1w-2</td>
<td>0.56</td>
<td>5</td>
<td>3.0 (adhesive)</td>
<td>150</td>
<td>--</td>
<td>--</td>
<td>44.2</td>
</tr>
<tr>
<td>D1w</td>
<td>0.58</td>
<td>57.5</td>
<td>1.5 (adhesive)</td>
<td>210</td>
<td>3.43</td>
<td>0.40</td>
<td>37.6</td>
</tr>
<tr>
<td>D1w-3</td>
<td>0.60</td>
<td>95</td>
<td>1.1 (cohesive)</td>
<td>180</td>
<td>1.05</td>
<td>0.81</td>
<td>34.3</td>
</tr>
</tbody>
</table>

The results of the rheology tests and pumping trials on mixes D7w and D8w (see Table 3.9 for mix design) are shown in Table 4.3. Mix D7w was tested to investigate the pumpability of a simple single-aggregate mix with a low cement content (6:1 aggregate:cement ratio) which had an overall total grading (aggregate and cementitious) that was within the grading zone established from the pre-blended
mortars (Section 3.4.3). It pumped through the TS3EVR and down the line, but too slowly (approximately 0.06 m$^3$/hour) to be of practical use. This was probably due to the resistance of the aggregate on the wall of the hose as there were not enough cement fines available to produce a lubricating layer around the inside of the hose.

Mixes D8w and D8w-1 were tested to investigate the use of entrained air in mortars as a pumping aid when using the TS3EVR worm pump. The air content of D8Aw-1 and D8Aw was 15% before pumping and 12% after pumping. Mix D8Aw-1 pumped through the worm pump but not down the line. Additional liquid (3:1 water:SBR suspension) was therefore added to increase the workability (mix D8Aw) and the mix was pumped again. This mix pumped approximately 3m down the line. All the mixes pumped too slow to perform either a build test or to spray into cube moulds for compressive strength testing.

<p>| Table 4.3 Influence of mix design on rheological parameters and pumpability |
|---------------------------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Mix</th>
<th>Water/Cementitious ratio</th>
<th>Slump (mm)</th>
<th>Shear Vane (kPa)</th>
<th>2-Point Test g (Nm)</th>
<th>2-Point Test h (Nm/s)</th>
<th>Cast Cube Strength (MPa)</th>
<th>Pumping Distance/Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>D7w</td>
<td>0.93</td>
<td>75</td>
<td>1.7</td>
<td>1.22</td>
<td>1.15</td>
<td>17.6</td>
<td>Very slow flow rate</td>
</tr>
<tr>
<td>D8Aw-1</td>
<td>0.57</td>
<td>40</td>
<td>2.1</td>
<td>---</td>
<td>---</td>
<td>42.4</td>
<td>Through pump but not line</td>
</tr>
<tr>
<td>D8Aw</td>
<td>0.60</td>
<td>70</td>
<td>1.4</td>
<td>1.68</td>
<td>0.53</td>
<td>---</td>
<td>Approx. 3m down line</td>
</tr>
</tbody>
</table>

4.2.8 Reinforcement encasement

Sorptivity

The influence of the density of reinforcement on the sorptivity (of the top of the core, i.e. the material just behind the bars) is shown in Figure 4.20. Note that the sorptivity of all the mortars except P2W and P2d increases between bar overlaps of zero and 96 mm$^2$, and then levels off and only increases slightly as the bar overlap area increases. Several methods for quantifying the density of reinforcement were compared including: summing the bar diameters, summing the bar cross-sectional areas, calculating the total projected bar area within the core and calculating the area of bar overlap. The area of bar overlap was chosen as it was a value that could be easily understood and which gave a broad spread of results. In general, the sorptivity of the pre-blended mortars does not increase greatly as the density of reinforcement increases. The tops of the cores produced a wider sorptivity range than the corresponding bottom slice of the core, probably due to the voids produced in the
mortar being concentrated directly beneath the bars. A reinforcement encasement test was conducted on mortar P4w using bars with overlap areas up to 576 mm² (equivalent to 2x12 mm bars overlapping 2x12 mm bars). This showed a much steeper increase in sorptivity with bar area with a correlation coefficient of 0.901 (Figure 4.21).

The piston-pumped laboratory-designed mortar D1p had the highest sorptivity in this test, probably due to the higher absorption of the aggregate (2.5% at 30 minutes compared to approximately 1% with the aggregate from mix P4 as shown in Figure 4.22). Mortar P2 had the lowest sorptivity, the large-diameter worm-pumped P2W being lower than the small-diameter worm-pumped P2w, especially at the denser levels of reinforcement. This could be attributed to the higher velocity, and therefore more complete encasement, of the larger-diameter worm pump. This higher velocity can also explain the lower sorptivity of the piston-pumped D1p compared with the worm-pumped D1 (Table 5.2). However, the difference between P1p and P1d is very small with the higher-velocity piston pump producing only slightly lower sorptivity than the dry process pump.

Core Grade

Figure 4.23 shows the core grades for three of the pre-blended mortars. Note that the P4w cores that produced a grade 5 were so badly voided that sorptivity tests could not be carried out and so this data does not appear in Figure 4.20. There is a contrasting behaviour between the two worm-pumped mortars, P2W and P4w. P4w core grades increase significantly with increasing overlap area, whereas P2W grades do not. The most probable reason for this is the difference in the stream velocity of the different worm pumps; P4w being applied with a small-diameter low-output pump, and P2W with a larger-diameter medium-output pump. The mortar P1d applied by the dry process exhibits a less well defined trend, though an increase in core grade with increasing overlap area is discernible.

The two methods of assessing the encasement (Figures 4.20 and 4.23) show similar trends, with P2W producing little change in encasement with increasing overlap area, and P4w showing the largest changes. These reinforcement encasement results are
compared with the results for the fine concretes in Section 4.3.5. When discussing reinforcement encasement of sprayed concrete and mortars, it should be remembered that, (a) encasement (and core grade values) is related to the flow (and hence slump and workability) of the material, and (b) the degree of compaction affects the sorptivity (along with the water/cement ratio, which is also linked to the slump and workability).

4.2.9 Observations during the pumping and spraying process

During each spray trial observations were recorded regarding the spraying process and high-speed video was used to record the streams of some of the mortars (Table 4.4). An example still from one of the videos is shown in Figure 3.8. The information obtained can be classed as quantitative (stream velocity and angle of dispersion) and qualitative (such as the visual assessment of the amount of rebound and atomisation). Observations were recorded on the flow consistency (with a constant, even stream being more favourable to one which 'pulsates'), the degree to which the material atomises and the amount of rebound.

Velocity

The highest velocity was produced by the dry process pump (36 m/s) and the lowest by the low-volume worm pump (7.4 m/s). This is due to the high air/mortar ratio for the dry-process pump compared with the worm and piston pumps (see Table 4.6). The different sized particles also travelled at different velocities, with the smallest having the highest velocity. A balance needs to be obtained, as high velocities produce good compaction but high rebound from the substrate. A negligible difference in velocity was found between horizontal and vertical spraying for mix P7w at this spraying distance (approximately 1 m).

The angles of dispersion in Table 4.4 were all narrow and small enough for the range of spraying generally used in repair (1-2 m). Pulsing of the mortar flow with the worm pump was only slight at most due to the continuous action of the worm. The piston pump created more pulsing (as expected) due to the cyclic action of the pistons which made directing the stream more difficult.
Table 4.6 Air/mortar ratio for different pump types

<table>
<thead>
<tr>
<th>Pump</th>
<th>Mortar Output (l/min)</th>
<th>Air Output (m$^3$/s)</th>
<th>Air/mortar ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry process</td>
<td>50</td>
<td>0.172</td>
<td>206</td>
</tr>
<tr>
<td>Piston</td>
<td>80</td>
<td>0.172</td>
<td>129</td>
</tr>
<tr>
<td>Small worm</td>
<td>6</td>
<td>0.00472</td>
<td>47</td>
</tr>
</tbody>
</table>

The most user-friendly mix/pump/nozzle combination used in this study was mix P1w with the 9 mm aperture brass nozzle and the TS3EVR low-volume worm pump. It produced an even, continuous, directable stream with good atomisation, no pulsing and with very little material falling away from the nozzle or stream.

Effect of nozzle design

The best atomisation was produced by mix P1w with the 9 mm aperture brass nozzle. The atomisation of the highly polymer-modified mixes P3w and P7w was very poor, especially P7w which was also very sticky and difficult to handle. Large flocs of material were observed to build up on the nozzle and peel away with the stream before falling away from the stream flow. This is uneconomic due to the wasted material and the additional time needed to clear up wasted material.

Table 4.5 shows the results of a study of the effects on the mortar stream of different nozzles when used with the TS3EVR worm pump. Mix P1 with a 60 mm slump was used with all the nozzles and the streams recorded with a High-Speed camera. Inappropriate nozzles can result in wide streams of poorly-atomised material which are difficult to direct (thereby increasing overspray) and wasteful of material.

The 16 mm aperture plastic nozzle (Figure 3.4(a)) produced the widest angle of dispersion ($60^\circ$) which made the stream difficult to direct. The steel (Figure 3.4(b)) and brass nozzles produced the narrowest and most directable streams. The maximum velocities were very similar (as was expected) as the same mix, pump and compressor were used with each nozzle. The plastic nozzles slowed down some of the stream due to poor atomisation producing larger (and therefore slower) flocs of material. The 9 mm aperture brass nozzle produced the best atomisation and therefore the highest minimum particle speed. This was the best nozzle of the four tested in Table 4.5, producing an even, directable stream with good atomisation and no pulsing. The pulsation was minimal with all the nozzles due to the continuous action of the worm pump.
<table>
<thead>
<tr>
<th>Mix</th>
<th>Nozzle Type</th>
<th>Angle of Dispersion</th>
<th>Velocity (m/s)</th>
<th>Pulsation</th>
<th>Atomisation</th>
<th>Rebound</th>
<th>Observations</th>
<th>General</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1w</td>
<td>9mm Brass</td>
<td>25°</td>
<td>12.6</td>
<td>High</td>
<td>Very</td>
<td>n/a</td>
<td>Good stream</td>
<td>no loss of material</td>
</tr>
<tr>
<td></td>
<td>22° Rubber</td>
<td></td>
<td>14.4</td>
<td>High</td>
<td>Good</td>
<td></td>
<td>Spray was</td>
<td>intermittent and uneven 'bursts' therefore difficult to work with</td>
</tr>
<tr>
<td></td>
<td>10° Steel</td>
<td></td>
<td>36.0</td>
<td>Slight</td>
<td>Good</td>
<td></td>
<td>Narrow stream</td>
<td>but large cloud of dust along path of stream, therefore difficult to distinguish rebound</td>
</tr>
<tr>
<td>P2p</td>
<td>Rubber</td>
<td>n/a</td>
<td>25.0</td>
<td>Slight</td>
<td>Poor</td>
<td>n/a</td>
<td>Generally good atomisation with small proportion of large flocs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>piston</td>
<td></td>
<td>22.5</td>
<td></td>
<td></td>
<td></td>
<td>Very large flocs of material and very little material falling away from stream</td>
<td></td>
</tr>
<tr>
<td>P3w</td>
<td>9mm Brass</td>
<td>25°</td>
<td>12.5</td>
<td>Slight</td>
<td>Poor</td>
<td>Low</td>
<td>Vertical (overhead) spraying. Greater pulsation, larger flocs of material and higher rebound than when spraying horizontally</td>
<td></td>
</tr>
<tr>
<td>P7w-H</td>
<td>9mm Brass</td>
<td>25°</td>
<td>12.1</td>
<td>Slight</td>
<td>Very poor</td>
<td>Low</td>
<td>Horizontal. Large flocs observed falling away from the nozzle and the stream. Continual build up of material on the nozzle which peels off and is projected away (out of the stream)</td>
<td></td>
</tr>
<tr>
<td>P7w-V</td>
<td>9mm Brass</td>
<td>30°</td>
<td>12.2</td>
<td>Medium</td>
<td>Very poor</td>
<td>Medium</td>
<td>Large flocs observed falling away from the nozzle and the stream</td>
<td></td>
</tr>
<tr>
<td>D1p</td>
<td>Rubber</td>
<td>n/a</td>
<td>27.0</td>
<td>Medium</td>
<td>Poor</td>
<td>High</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: 1 See Section 3.3.3 for a description of the nozzles used  
2 P1w mix with 9 mm aperture nozzle taken from Table 4.5 for comparison  
3 No substrate used therefore no rebound possible  
4 Nozzle not in camera shot therefore difficult to measure angle of dispersion and pulsation
Table 4.5 Nozzle trial with Mix P1w and low-volume worm pump

<table>
<thead>
<tr>
<th>Mix</th>
<th>Nozzle Type</th>
<th>Angle of Dispersion</th>
<th>Velocity (m/s)</th>
<th>Pulsation</th>
<th>Atomisation</th>
<th>Rebound</th>
<th>Observations</th>
<th>General</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1w</td>
<td>9mm Steel</td>
<td>20°</td>
<td>12.1</td>
<td>Slight</td>
<td>Good</td>
<td>n/a</td>
<td>Small amount of material falling away from stream</td>
<td></td>
</tr>
<tr>
<td>P1w</td>
<td>9mm Brass</td>
<td>25°</td>
<td>12.6</td>
<td>None</td>
<td>Very</td>
<td>n/a</td>
<td>Good stream - no loss of material</td>
<td></td>
</tr>
<tr>
<td>P1w</td>
<td>16mm Plastic</td>
<td>60°</td>
<td>12.5</td>
<td>Very</td>
<td>Poor</td>
<td>n/a</td>
<td>Very large (up to 10 mm) flocs of material in stream and small amount of material falling away from stream</td>
<td></td>
</tr>
<tr>
<td>P1w</td>
<td>9mm Plastic</td>
<td>45°</td>
<td>13.0</td>
<td>Very</td>
<td>Average</td>
<td>n/a</td>
<td>Large amount of material falling away from stream</td>
<td></td>
</tr>
</tbody>
</table>

NOTE: 1 No substrate used therefore no rebound possible
The large worm-pumped P2W with the 9 mm steel nozzle (Figure 3.4(b)) was a good balance between output and an even flow with no pulsation and little rebound. The dry-process sprayed mortars P5d and P8d produced a high amount of rebound. The highly polymer-modified mix P6w did not atomise well and produced a large amount of wasted material falling away from the stream.

Mix D5w pumped and sprayed adequately but at a higher pressure than the similar mix D1w. D6w also pumped and sprayed adequately but at a slower rate and with more rebound than the similar mix D1w. D2w also pumped slightly slower than D1w due to the coarseness of the mix and D3w was slower still. These coarser mixes also produced more rebound than D1w. The low cement content mix D7w had an output too low to be of practicable use (<1 l/min) and produced very high rebound. Approximately 65% of the material also fell away from the stream during spraying.

The designed mortars on the boundary of the recommended grading zone (D10w and D11w, see Section 3.4.3 and Figures 3.7) pumped adequately although the finer aggregate mix (D10w) was dense, sticky and difficult to handle. The coarser mix D11w just below the grading zone (Figure 3.7) pumped very slowly at first (approximately 0.7 l/min), then blocked. The finer mix D12w just above the grading zone pumped slowly (3.0 l/min) at a high pressure but was sticky and difficult to work with.

**Particle image analysis**

An attempt was made to quantify the mortar stream using particle analysis software. Two still images were taken (such as the one in Figure 3.8) from the High-Speed video 0.7 milliseconds apart, and inputted into the Power-view PIV System Insight 2.10 flow analysis software produced by TSI Inc. This produces vector data which can be imported into Tec-plot 7.5 (Amtec Engineering) which produces the vector diagram shown in Figure 4.24. The vectors show the direction of the particles and the length corresponds to the velocity of the particles. The software divides the chart into 100 equally-sized zones with each vector representing the average of 10 particles.
within each zone. However, problems were encountered with the software identifying all the individual particles due to their fineness, the imperfect focusing of the camera and the 'coloured' backdrop, which ideally needed to be completely white. These reasons, together with the rebound (which travels in the opposite direction to the stream) being included in the 10-particle average for each zone, account for the loose material falling down from the nozzle having a longer vector (and hence apparently 'higher' velocity) than the particles in the centre of the stream (which in reality have the higher velocity). The software does have potential for analysing the particle streams of sprayed mortars and concretes but it was acquired at the end of the research programme, after the streams had all been filmed.

4.2.10 Summary
This Section has presented and discussed a variety of data on the rheological performance of wet-process mortars. A rheological audit has been developed and tests for each stage within this audit have been used to characterise the pumpability and sprayability of each mortar. The relationships between the rheological properties and the pumpability and sprayability of the mortars will be examined further in Section 4.4, together with the fine concretes. A shear vane test has been developed which can give an instantaneous measurement of the shear strength of the mortar wherever this property needs to be assessed and a good correlation with the slump of a mortar has been found.

The Two-point test apparatus produced satisfactory results with fine mortars with low workabilities, although care needed to be taken in both conducting the test and interpreting the results. Both the grading of the constituents and the presence of polymers had a significant effect on the flow resistance and torque viscosity. A procedure was developed for the Viskomat apparatus but the results obtained from the pre-blended mortars were inconclusive, with difficulties being encountered due to their low workability and the tendency of some mixes to entrain air or trap polypropylene fibres around the measuring paddle.

The pressure bleed test demonstrated that the presence of an SBR significantly influences both the rate and total emission of liquid from the mix under pressure. The
proportion of fine material and the water content of the mix were also crucial factors in the amount and rate of liquid emitted. The pressure of the test for the initial 30 seconds of the pressure bleed test influenced greatly the rate of bleeding, but this influence was diminished after 30 minutes.

The results of pumping and spraying trials on different mortars have been presented together with the associated values for slump, build, vane shear strength and flow resistance. A new method that defines the build in terms of the maximum shear and tensile bending stresses generated at failure has been outlined which enables a more detailed and scientific analysis of the sprayability of the mortar to be made and the relationship between these stresses, the build, the slump, the flow resistance and the vane shear strength of the mortars has been discussed. These relationships will be discussed further and compared with the fine concretes in Section 4.4.

Two new methods of quantifying the encasement of reinforcement have been proposed and investigated and a relationship has been found between the density of reinforcement and the encasement. Mix design and spraying velocity were both found to influence the encasement.

High speed video was used to record the mortar stream and from this both quantitative and qualitative data was taken. The most user-friendly mix/pump/nozzle combination was found to be mix P1w with a 9 mm aperture brass nozzle and the TS3EVR low-volume worm pump which produced an even, continuous, directable mortar stream with good atomisation, no pulsing and very little wastage. A nozzle study with the TS3EVR and high speed camera was also conducted and the 9 mm aperture brass nozzle was found to produce the best atomisation and the highest minimum particle speed. An attempt was made to quantify the mortar stream using particle analysis software and the images from the high speed camera. Interesting data was produced but more work would be needed to film the mortar stream especially for use with the analytical software in order to obtain reliable quantitative data.
4.3 FINE CONCRETES

4.3.1 Rheological overview

This Section reports on the influence of rheology on the pumping and spraying of the fine concretes described in Section 3.4 using the tests described in Section 3.6. Used together, these tests form part of a rheological audit of each concrete (Section 3.6). The hardened performance of these fine concretes is presented in Section 5.3. Five rheological tests were conducted, two for workability (slump and shear vane), one for pumpability (Two-point) and three for sprayability (build, core grading and reinforcement encasement). The results of these tests are presented in Table 4.7.

4.3.2 Workability (slump and vane shear strength)

The shear vane provides a basic measure of the shear strength of fresh concrete and this is plotted against slump in Figure 4.25. This shows that, for the concretes that pumped, a decrease in shear strength corresponded to an increase in slump and a correlation coefficient $R^2$ of 0.947 (compared with $R^2=0.89$ for the mortars). The standard deviations for the slump tests were in a range 3.9 to 7.1, with an average of 5.5 and in a range of 0.08 to 0.17 for the vane shear strength tests with an average of 0.13. The slump values for the pumpable fine concretes presented here ranged from 30-130 mm, which shows the broad range of slumps at which well-designed mixes can be pumped at. Most reference sources recommend a slump of between 50-150 mm, with a loss of 10-25 mm caused by compaction by the pumping process. A target slump of 75 mm ± 25 mm is common which is used by ready-mix companies who produce concrete for pumping. A slump of 50-80 mm is seen as a good compromise between pumpability and shootability (Beaupré, 1994).

Three of the mixes that would not pump are also shown. These mixes contained air entrainment and were thought not to have pumped due to the pressure from the pistons causing the entrained air to be compressed rather than forcing the concrete down the line. All the mixes with an air content greater than 12.5% failed to pump satisfactorily.
These fine concrete workability properties of slump and vane shear strength will be compared with the other rheological properties (e.g. flow resistance and build etc.) in Sections 4.3.3 and 4.3.4 and with the mortars in Section 4.4.
<table>
<thead>
<tr>
<th>Mix</th>
<th>Build</th>
<th>Mass (kg)</th>
<th>Failure Stress kN/m²</th>
<th>Vane Shear Strength-kN/m²</th>
<th>Slump mm</th>
<th>Two-point test g - Nm</th>
<th>h - Nms</th>
<th>Failure description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Substrate</td>
<td>Floor</td>
<td>Total</td>
<td>Shear</td>
<td>Bending</td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>Clp</td>
<td></td>
<td>200</td>
<td>--</td>
<td>--</td>
<td>28.8</td>
<td>4.70</td>
<td>5.47</td>
<td>--</td>
</tr>
<tr>
<td>ClSp</td>
<td></td>
<td>320</td>
<td>--</td>
<td>--</td>
<td>11.6</td>
<td>2.73</td>
<td>4.51</td>
<td>--</td>
</tr>
<tr>
<td>C1Ap-1</td>
<td></td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.25</td>
<td>10</td>
<td>1.6</td>
</tr>
<tr>
<td>C1Ap-2</td>
<td></td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.92</td>
<td>80</td>
<td>--</td>
</tr>
<tr>
<td>C1Ap</td>
<td>285</td>
<td>--</td>
<td></td>
<td>45.4</td>
<td>5.45</td>
<td>6.96</td>
<td>0.54</td>
<td>--</td>
</tr>
<tr>
<td>C3p</td>
<td></td>
<td>220</td>
<td>9.8</td>
<td>18.5</td>
<td>28.3</td>
<td>4.63</td>
<td>5.66</td>
<td>2.5</td>
</tr>
<tr>
<td>C3Ap-1</td>
<td></td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.74</td>
<td>50</td>
<td>5.0</td>
</tr>
<tr>
<td>C3Ap</td>
<td>130</td>
<td>--</td>
<td></td>
<td>15.0</td>
<td>2.45</td>
<td>1.68</td>
<td>0.86</td>
<td>1.85</td>
</tr>
<tr>
<td>CP1p</td>
<td>160</td>
<td>--</td>
<td></td>
<td>24.0</td>
<td>3.92</td>
<td>3.72</td>
<td>1.96</td>
<td>75</td>
</tr>
<tr>
<td>CP2p</td>
<td>180</td>
<td>19.8</td>
<td>7.2</td>
<td>27.0</td>
<td>4.42</td>
<td>4.74</td>
<td>2.23</td>
<td>60</td>
</tr>
<tr>
<td>C4p</td>
<td>260</td>
<td>--</td>
<td></td>
<td>--</td>
<td>--</td>
<td>2.39</td>
<td>30</td>
<td>--</td>
</tr>
<tr>
<td>C5p</td>
<td>160</td>
<td>17.0</td>
<td>35.0</td>
<td>52.0</td>
<td>3.78</td>
<td>2.32</td>
<td>1.19</td>
<td>100</td>
</tr>
</tbody>
</table>

*Table 4.7. Rheological test results- Fine concretes*
4.3.3 Flow resistance and torque viscosity - Two-point test

Figure 4.26(a) shows the values of flow resistance $g$ and torque viscosity $h$ for mix C3Ap before pumping and after spraying. The increase in both $g$ and $h$ as the concrete is pumped and then sprayed is expected as the excess air is forced out of the mix on impact (in this case, reduced from 12.5 to 8.5%). This is also reflected in the reduction in slump (from 130 to 60 mm) and increase in vane shear strength (from 0.76 to 1.63 kN/m²). Also shown is a mix made with the same proportions as mix C3Ap but with a higher initial air content of 15%. This would not pump due to this high initial air content and the high value of $g$ (5.0 Nm). These results show that the two-point apparatus could be helpful in predicting the pumpability of air-entrained concrete mixes.

The two-point test results for four of the mixes before pumping are shown in Figure 4.26(b). The air-entrained mixes C3Ap and C1Ap possessed the lowest values of $g$ and $h$, which was to be expected (Tattersall and Banfill, 1983). The non-superplasticised mix C3p had the highest $g$. This was to be expected as the mix had the lowest slump (50 mm) and the highest shear strength (2.2 kN/m²) of the mixes in this investigation. These results suggest that the value of $h$ could have a large influence on the pumpability of air-entrained concretes. The addition of air entrainment seems to reduce the values of $g$ and $h$, but a too greater reduction in the value of $h$ (approximately 0.50 and below) may render a concrete unpumpable.

4.3.4 Adhesion and build thickness

The build value (in mm) and corresponding mass of concrete sprayed onto the substrate for each of the mixes is shown in Table 4.7. Figure 4.27 shows an increase in the build value for a decrease in slump before pumping with a correlation coefficient $R^2$ of 0.95. These values are discussed and compared with the mortars in Section 4.4.

The maximum shear stress at failure was then calculated from the cross-sectional area at the base of the concrete (approximately 300 mm square) in the same way as for mortars. The maximum tensile stress at failure due to the bending moment was also
calculated by idealising the concrete on the substrate into the frustum of a square-based pyramid. The volume, and therefore the dimensions of this frustum, could be calculated using the mass, the fresh wet density, the area of the base and the height of the frustum (i.e. the build value). These dimensions were then used to calculate the moment and hence the maximum tensile bending stress at failure in the freshly sprayed concrete. The relationship between the maximum tensile and shear stresses at failure and the build is shown in Figure 4.28. At the higher builds the maximum tensile stress is greater than the maximum shear stress for each concrete and at lower builds the opposite is true. The steel-fibre mix C1Sp appears to have a lower maximum shear and bending stress than would be expected, possibly due to the steel fibres increasing the cohesiveness of the concrete, thus producing a high build with a narrow cross-section. The build value was therefore high (320 mm) and the mass was low (11.6 kg), thus producing a low maximum shear and tensile bending stress.

Figure 4.29 shows the relationship between the slump of the concrete before pumping and the maximum tensile and shear stresses in the concrete at failure in the build test, which indicates a decrease in both stresses for an increase in slump with a correlation coefficient $R^2$ of 0.959. Note that at higher slumps the maximum shear (flow) stress is higher than the tensile stress, which is consistent with the visual observations as at higher slumps the concrete failed cohesively (i.e. it shears) rather than adhesively (see Table 4.7).

Figure 4.30 shows that an increase in flow resistance before pumping (or $g$, from the Two-point test) produces an increase in the build value (with a correlation coefficient $R^2$ of 1), which agrees with work published by Beaupré (1994). However, more tests are needed to confirm this as in this study only three two-point tests were conducted before spraying on concretes that pumped and sprayed successfully (and hence produced a measurable build value).

Figure 4.31 shows that an increase in the vane shear strength immediately before pumping produces an increase in the maximum tensile and shear stresses at failure. As the vane shear strength increases, the maximum stress at failure changes from shear to tensile, which agrees with the data presented in Figures 4.29 and 4.25. The air-
entrained mix C1Ap has a low vane shear strength before mixing due to the lubrication of the air bubbles but a high failure strength after spraying due to the compaction of the pumping and spraying process forcing the air out of the concrete. A similar trend for the vane shear strength of the fine concretes (including C1Ap) is shown with build in Figure 4.32.

An increase in the maximum tensile and shear stresses with an increase in the flow resistance (g) before pumping was also found, which was expected (Figure 4.33). Comparing Figures 4.33, 4.32 and 4.31, it would be expected that the vane shear strength, flow resistance and slump would all be related and these relationships (for both fine concretes and mortars) are investigated in Section 4.4.

4.3.5 Reinforcement encasement

Sorptivity

The influence of the density of reinforcement on the sorptivity (of the top of the core, i.e. the material just behind the bars) is shown in Figure 4.34. The tops of the cores produced a wider sorptivity range than the corresponding bottom slice of the core, probably due to the voids produced in the concrete being concentrated directly beneath the bars. In general, the sorptivity of the mixes does not increase greatly as the density of reinforcement increases. The sorptivity appears to reach a maximum at a bar overlap area of 128 mm², which is equivalent to two 8 mm diameter bars overlapping an 8 mm bar, and then decreases slightly up to a bar overlap of 192 mm².

The fine concretes produced higher values for sorptivity (0.09-0.29 mm/min⁰.⁵) compared with the mortars (0.01-0.09 mm/min⁰.⁵), mainly due to the finer grading and higher cement and silica fume content of the mortars. C2d produced the highest sorptivity, possibly due to the lower velocity of the dry-process pump producing less compaction and therefore more voids compared with the piston-sprayed mixes. The other mix with a high sorptivity was the non-superplasticized mix C3p. This could be attributable to the higher water/cement ratio of this mix compared with the other wet-sprayed mixes. Similarly, the low water/cement ratio of C4p could contribute to it’s relatively low sorptivity.
Figure 4.35 shows cores taken from four of the mixes graded on a scale of one (good encasement) to five (poor encasement). C4p shows a clear increase in core grade (therefore poorer encasement) with an increase in area of bar overlap, possibly due to the low water/cement ratio and the low slump (30 mm) compared with the other mixes. C3p produced very little voidage, even at bar overlap areas of 288 mm² (equivalent to a 12 mm bar overlapping two other 12 mm bars), possibly due to the high water/cement ratio of the mix, although the slump of the mix (50 mm) was only average. CP1p and CP2p exhibited very similar degrees of encasement, the only difference being at the highest area of bar overlap (288 mm²) where mix CP2p produced more voids than mix CP1p. This is the reverse of what would be expected as the mixes are identical except for the higher proportion of polypropylene fibres in CP1p compared with CP2p. However, mix CP1p did have a slightly higher slump (75 mm compared to 60 mm).

The sum of the core gradings for these four mixes is compared with the water/cementitious ratio in Figure 4.36 and it clearly shows that an increase in the water/cementitious ratio decreases the total number of voids (i.e. better encasement of the reinforcement). The core grading is again compared with the water/cementitious ratio in Figure 4.37. This Figure shows that as you increase the density of reinforcement for a mix with a particular water/cementitious ratio then the core grade value will increase (i.e. poorer encasement). This illustrates that if you have a high density of reinforcement then there will be a minimum water/cementitious ratio at which you can adequately encase the bars.

The two methods of assessing the encasement (sorptivity and core grading) show similar, but less defined, trends for the fine concretes than for the mortars in Section 4.2. The core grading method highlights changes in voidage with respect to reinforcement whereas the sorptivity method reflects the rate of ingress of water into the concrete, both of which are important. The mix with the smallest number of voids (C3p) possessed some of the highest sorptivity values and the mix with the largest number of voids (C4p) possessed some of the lowest sorptivity values. However, it is the durability and integrity of the concrete which is important together with the
protection of the reinforcement from corrosion and so these results should be used together when assessing the quality of a sprayed repair.

4.3.6 Observations during the pumping and spraying process

Four fine concrete streams were filmed with a High-Speed camera in the same way as the mortars in Section 4.2.9 and the results are shown in Table 4.8. The piston-pumped mixes all had a similar maximum velocity (22.8-26.5 m/s) and the dry-process mix C2d had the highest (31.5 m/s) due to the higher air/mortar ratio of this process (Table 4.6). The air-entrained mix C1Ap produced a broad range of particle velocities. All the mixes pulsated to some degree due to the cyclic action of the pistons, although not as much as mortar D1p (Table 4.4). Mix C1S produced the most pulsing of the mixes in Table 4.8, probably due to the steel fibres creating ‘balls’ of material within the line. The rebound of these mixes was generally large due to the high velocity of the streams, with the dry-process mix C2d producing a significantly high amount. It should be noted that these mixes were sprayed onto a concrete substrate before the build up of any fresh material, the rebound being reduced when a layer of fresh material had been built up. A large proportion of steel fibres can be seen rebounding when spraying mix C1S. All the mixes atomised adequately with mix C1Ap producing a fine continuous stream which was easy to direct, although the rebound was high. However, mix C2d produced a large dust cloud whilst spraying and a large amount of rebound and so was difficult, as well as uneconomic, to spray.

The fine concretes C3p and C3Ap, which were not filmed with the High-Speed camera, pumped intermittently with the 35 mm diameter line and the streams were difficult to direct effectively. Mix C3Ap pumped and sprayed more smoothly when the slump was increased (from 50 mm to 130 mm). Mix CP1p was extremely difficult to spray with the 35 mm line as the high proportion of polypropylene fibres caused the pressure to build up within the line and then be suddenly released, causing large (and dangerous) ‘bursts’ of material. The pumppability increased when a 50 mm line was used but was still intermittent. Mixes CP2p, C4p and C5p were pumped with the 50 mm diameter line and all pumped and sprayed smoothly. In hindsight, the 50 mm diameter line would have improved the pumppability of all the fine concretes tested and would have been used from the start. Care needs to be taken when pumping mixes that
contain either steel fibres, high contents of polypropylene fibres or high levels of air entrainment.
Table 4.8 Observation of fine concrete streams

<table>
<thead>
<tr>
<th>Mix</th>
<th>Nozzle Type</th>
<th>Angle of Dispersion</th>
<th>Velocity (m/s)</th>
<th>Observations</th>
<th>General</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>High</td>
<td>Low</td>
<td>Pulsation</td>
</tr>
<tr>
<td>C1p</td>
<td>Rubber</td>
<td>n/a</td>
<td>22.8</td>
<td>21.0</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Piston</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1S</td>
<td>Rubber</td>
<td>n/a</td>
<td>23.6</td>
<td>20.1</td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>Piston</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1Ap</td>
<td>Rubber</td>
<td>( \approx 20^\circ )</td>
<td>26.5</td>
<td>9.3</td>
<td>Slight</td>
</tr>
<tr>
<td></td>
<td>Piston</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2d</td>
<td>Steel</td>
<td>n/a</td>
<td>31.5</td>
<td>26.0</td>
<td>Slight</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE:

1. Nozzle not in camera shot therefore difficult to measure angle of dispersion and pulsation
4.3.7 Summary

This Section has presented and discussed a variety of data on the rheological performance of wet-process fine concretes. A rheological audit has been presented and tests for each stage within this audit have been used to characterise the pumpability and sprayability of each concrete. The results for the fine concretes are compared with the corresponding results for the mortars in Section 4.4 and the relationships between the rheological parameters will be further discussed.

A shear vane test was used which can give an instantaneous measurement of the shear strength of the concrete wherever this property needs to be assessed and a good correlation with the slump has been found for pumpable fine concretes.

The Two-point test apparatus produced satisfactory results with fine concretes, although care needed to be taken in both conducting the test and interpreting the results. Superplasticiser and air entrainment were both seen to affect the results and they indicated that the apparatus could be used to help in predicting the pumpability of air-entrained concrete mixes. The values for slump, build and vane shear strength for different concretes have been presented and these parameters can be seen to be related. The method presented in Section 4.2 that measures the build in terms of the maximum shear and tensile bending stresses generated at the point of failure has been applied to the fine concretes and a relationship between these failure stresses, the slump and the vane shear stress of the concretes has been found. A relationship between the build and the value of g from the two-point test was also found. The relationship between all these parameters are investigated further in Section 4.4.

Two methods for assessing the reinforcement encasement were investigated, visual core grading and sorptivity measurement. The density of reinforcement appeared to have only a small effect on the sorptivity of the concrete compared with the sorptivity of the un-reinforced material. The visual grading was a simple test that accurately measured the encapsulation of the bars. The two methods should be used together when assessing the quality and durability of a sprayed concrete repair.
Taken collectively, these results show that tests on these fresh fine concretes can be used to indicate the workability (slump and shear vane), pumpability (two-point test) and sprayability (build, maximum failure stresses, sorptivity and visual grading) of the different concretes. The results from these tests are presented together with the results from the mortars in Section 4.4 and there interrelationship examined.
4.4 COMPARISON OF MORTARS AND FINE CONCRETES

4.4.1 Introduction

The results of the fresh properties of the mortars (both pre-blended and designed) and the fine concretes were presented in Sections 4.2 and 4.3 respectively. This Section examines the relationship between the rheological properties and compares the values obtained from the mortars and the fine concretes. The effect of these properties on the pumpability and sprayability of the materials is also considered. The final part of this Section discusses the influence of particle grading and proportions on the pumpability and sprayability of mortars. The mix designs are described in Sections 3.4.2 (pre-blended mortars) and 3.4.3 (designed mortars and fine concretes) and the test methods in Section 3.6.

A rheological audit was presented in Section 3.6.1 and the results presented here show the rheological properties of the mortars and concretes as they progress through each stage of the mixing, pumping and spraying process. The rheological test results are presented in Tables 4.1 (for mortars) and 4.7 (for concretes). Properties measured before pumping (and after mixing) include slump, vane shear strength and flow resistance and plastic viscosity (from the Tattersall 2-point test and the Viskomat rotational viscometer) and these can be related to pumpability. Slump rather than water/cement ratio was taken as the principal measure of water content due to the widely varying mix proportions of the mixes (e.g. aggregate/cementitious ratios between 2.7:1 and 6:1). The fine concretes produced less variable results than the mortars due their mix designs and workabilitys being more similar than those for the mortars.

4.4.2 Pumpability – as measured by slump, vane shear strength, flow resistance and plastic viscosity before spraying

*Slump and vane shear strength*

In general, the slump decreases as the vane shear strength increases (Figure 4.40). Three of the air-entrained fine concretes would not pump and had a combination of
low vane shear strength and low slump. The mortar D12w-1 would not pump and D12w pumped with difficulty. This mortar had a large proportion of lightweight filler (Table 3.10) which seems to have significantly altered the rheological properties of the mix. If just the mixes that pumped are considered then the fine concretes had a higher vane shear strength for a particular slump than the mortars, probably due to the restraining action of the larger aggregates in the fine concretes. Consideration should therefore be given to the mix design of a material when comparing values of slump and shear strength. This relationship between the slump and the vane shear strength can be used together to provide a good indication of the pumpability of a mortar or fine concrete, especially if considered together with the mix design (e.g. the presence of air entrainment, constituent grading etc.).

**Slump and flow resistance (g)**
Excluding the un-pumpable mixes, g decreased as the slump increased (Figure 4.41). This agrees with similar results published by Beaupré (1994). The fine concretes had a higher g for a particular slump compared with the mortars (excluding the un-pumpable mixes) and the mortars and fine concretes with a low slump and a low g would not pump. The pumpable fine concretes and mortars agree with work by Morinaga (1973) who reported a simple linear relationship between slump and g. It should be remembered that the type of cement can cause the values of g and h for a cement paste to double in size and that the type of aggregate can also effect the value of g by the order of 35% (see Section 2.4.6). This could explain the variability in the results for the mortars (compared with the fine concretes) due to the different types of cement and aggregate used (especially in the pre-blended mortars which were supplied by four different manufacturers). Beaupré also emphasised the influence of cement type on the values of g and h and the setting time of the mix. These values of g compare well with results obtained by Dimond (1980) (1.4-3.5 Nm) and Yeoh (1982) (3.4-5.25 Nm) which were reported by Tattersall (1991). Beaupré (1994) presented values for g of 0.4-4.2 Nm for slumps of 15-260 mm for pumpable concretes.

**Slump and plastic viscosity (h)**
For the pumpable fine concretes, h decreases with an increase in slump, as would be expected (Figure 4.42). Again, the un-pumpable air-entrained fine concretes have a
low h and a low slump. There seems to be no correlation between slump and h for mortars, whether pumpable or not. The values of h obtained are similar to results obtained by Dimond (1980) (0.5-1.3 Nm/s) and Yeoh (1982) (0.58-1.63 Nm/s), which were both reported by Tattersall (1991).

Flow resistance and plastic viscosity

No correlation was found between g and h for either mortars or fine concretes (Figure 4.43), which agrees with data published by Beaupré (1994). He also concluded that for air-entrained mixes h was always below 1.0 Nms, which was also found here. Beaupré introduced the idea of a 'pumpability box' (which encompassed mixes with g < 4.2 and h < 2.9). However, the mixes in his study were all pumped with the same pump, line and compressor at the same speed (unlike this study) and so direct comparisons with the data presented here cannot be made. However, a 'pumpability zone' does appear to exist in the data presented here and so this data (in conjunction with Figure 4.41) could be used to approximately predict the pumpability and sprayability of a mix. It should be remembered however, that the mortars and fine concretes here represent a large variety of mix designs at a wide range of water contents (or slumps) and it is difficult to define criteria that will satisfy all possible mix designs.

As discussed in Section 2.5.3, pumpability is a complex phenomena and is influenced by the grading of the material and its permeability as well as its workability. The pumpability zones presented in Figures 4.43 and 4.41 should therefore only be used in conjunction with the grading zone for pumpable mortars established in Section 3.4 and the pressure bleed test results (for permeability) presented in Section 4.2.6.

Vane shear strength and flow resistance (g)

For pumpable fine concretes, an increase in g corresponds to an increase in vane shear strength (Figure 4.44). A narrow band of vane shear strengths (1-1.5 kN/m²) for the mortars corresponds to a wide range of flow resistance (1.2- 3.6 Nm), although at low values of g the mortars would not pump. For the fine concretes, an increase in the vane shear strength and the flow resistance produces a change in failure mode from cohesive to adhesive.
4.4.3 Sprayability – as measured by the build test

Once mixed, and after the first set of rheology tests were conducted (slump, vane shear strength, 2-point test), the mixes were pumped and sprayed as described in Section 3.5. Quantitative data (such as velocity) and qualitative data (such as failure mode of the built-up material) were recorded and the results are presented in Sections 4.2.7 and 4.3.4.

After spraying, the maximum build obtained and the failure mode were recorded. The mass of material still adhered to the substrate after failure was recorded together with the mass fallen away from the substrate. Observations were also recorded of the shape of the build 'frustum' (e.g. a small or large cross/section). The sprayed mortars and concretes appeared to fail either cohesively (mainly the high slump mixes), or adhesively at the substrate (mainly the low slump mixes).

**Build and slump**

Beaupré (1994) found no correlation between slump before pumping and build, although he did conclude that a correlation could exist between concretes of the same mix design. However, the fine concretes tested in this study show a distinct increase in build for a decrease in slump (Figure 4.45). As the slump decreases the fine concretes and mortars change from a cohesive failure to an adhesive failure. This change in failure mode could possibly account for the build of the mortars increasing as the slump decreases until a slump of approximately 60 mm when the build appears to fall for a decrease in slump. This trend is shown schematically in Figure 4.46. All the mixes (mortars and fine concretes) that did not fail cohesively can be grouped together (as shown in Figure 4.45) except for D3w which failed adhesively despite being in the cohesive failure 'zone'. This could be due to the coarseness of the mix (see Table 3.9). This decrease in build with a decrease in slump did not appear in Beaupré's work due to the build test being conducted on a series of steel vanes which ensured a cohesive failure compared with the grit-blasted substrate used in this work.
Vane shear strength and build

Similarities can be found between Figures 4.47 and 4.45, which would be expected due to the relationship between slump and vane shear strength (Figure 4.40). Discounting the air-entrained C1Ap, the build of the fine concretes increases as the vane shear strength increases. The build of the mortars also appears to increase and then decrease with an increase in vane shear strength in a similar way to the change in the build with a decrease in slump, as shown in Figure 4.45.

Build and flow resistance (g)

Figure 4.48 shows that the build increases with the flow resistance (g) before pumping for both the fine concretes and the mortars. The results for the fine concretes have similar values to those presented by Beaupré (1994) but the mortars in this work produced a higher build for a particular value of g than the concretes. The mortars in Figure 4.48 lie on the right of the curve in Figure 4.45 and so for these mortars an increase in build corresponds to an increase in g and a decrease in slump, as seen in Figure 4.41. This trend is stronger for the fine concretes.

Build mass, length and slump

Figure 4.45 showed that for the fine concretes a decrease in slump produced an increase in build and so it would be expected that a decrease in slump would also produce an increase in the build mass, as is shown in Figure 4.49. The exception is C5p, which had a larger cross/section (450x450 mm) compared with the other mixes and so had a higher mass for a particular build. Similar exceptions can be found for some of the other mixes, such as P2p and P1p. This is illustrated in Figure 4.50 where the build mass is roughly proportional with the build length for the mortars and fine concretes, except when the cross/section is larger or smaller than the standard 300 mm square. The trend is stronger for the fine concretes due to the greater variation in the mix designs and densities of the mortars. The build mass seems smaller than it should be for P7w due to the low density of the material (1433 kg/m$^3$). The fine concretes have a greater build mass for a particular build length than the mortars due to their higher densities (see Tables 5.3 and 5.6).
Vane shear strength and build mass

If the air-entrained mix and those mixes with cross/sections different from 300 mm square are ignored then a good correlation for the fine concretes can be found between build mass and vane shear strength (before pumping) (Figure 4.51). However, the trend is less defined for mortars, although the range of values is smaller and the densities and mix designs are more varied. The values for the mortars can be compared with Figures 4.47, 4.40 and 4.45 and it could be suggested that the build mass initially increases for an increase in vane shear strength before decreasing as the vane shear strength increases further, although more data would be needed to confirm this trend.

Maximum tensile and shear stresses

The maximum tensile and shear stresses within the built up material at failure were calculated using the build length and build mass, as explained in Section 4.2.7. Simple elastic analysis was used to calculate the maximum shear and bending stresses in the mass of material just before it fails. The maximum shear stress increased with the maximum tensile stress (both at failure), for both the mortars and the fine concretes, as would be expected (Figure 4.52(a) and (b)).

It can be assumed that the maximum shear stress occurs in the centre of the specimen and the maximum bending stress occurs at the top edge of the sample. When the bending stress exceeded the maximum tensile strength of the material, cohesive failure occurred within the material. The material could also fail cohesively when the maximum shear stress exceeded the shear strength of the material. These were both recorded as cohesive failures. When the bending stress exceeded the adhesive strength of the material, adhesive failure occurred at the substrate. The material could also fail adhesively when the maximum shear stress exceeded the adhesive strength of the material. These were both recorded as adhesive failures. In practice, most of the failures were cohesive.

As would be expected, the shear and tensile stresses increase with an increase in build. This method of quantifying the sprayability of a material was deemed to be more scientific and more reliable than simply measuring the build length. It also takes into
account the different densities of the materials and any differences in the shape of the build 'frustum', as can be seen by comparing these results with the build mass and build length (Figure 4.50 and 4.53). It should also be noted that for the fine concretes and most of the mortars, as the maximum shear and tensile stresses increase the failure mode of the material changes from cohesive to adhesive. Figure 4.53 also shows how the size of the base of the build ‘frustrum’ affects the maximum failure stresses, with a large base enabling a large mass to be built up with no increase in failure stress.

Jolin et al. (1999) also tried to measure the in-situ shear strength of sprayed concretes and mortars (although with the dry process, they can still be used as a comparison). This was done by measuring the penetration resistance of a Proctor penetration needle (termed the consistency) which was closely related to the shear strength of the material. A poor correlation was found between this penetration stress and build length but a good correlation was found between the penetration stress and the average tensile stress (Figure 2.29), which he calculated using the mass and cross-sectional area of an overhead build test at failure. He stated that although in failure terms, tension and shear are related, there was a distinct curve for each type of mix, with the addition of silica fume increasing the tensile strength of the mix for a given shear (penetration) strength. The addition of air-entrainment reduced the tensile strength for a given shear (penetration) strength. He also measured the fresh tensile stress by spraying into a 1000x300x75 mm mould equipped with a load cell and displacement transducer. This tensile stress also produced a good correlation with the shear (penetration) stress. The range of values obtained by Jolin et al. (1999) for the maximum tensile stress obtained from the overhead build test and the maximum tensile stress measured using the load cell and displacement transducer are shown in Table 4.9. This shows that the tensile stress measured directly from a dynamic build test can be up to five times smaller than what he terms "pure tension" measured using a load cell. Care should therefore be taken when quoting and discussing shear and tensile stresses for sprayed concretes and mortars. However, the stresses obtained in this work show a wider range than those obtained from the build test in Jolin’s work and are nearer the results obtained using the load cell. Unfortunately, no data is available from Jolin on the stresses for the shotcrete obtained from the load cell.
Table 4.9 Fresh tensile stresses (Jolin et al., 1999)

<table>
<thead>
<tr>
<th>Tensile stress at failure (kN/m²)</th>
<th>Mortar</th>
<th>Mortar + Silica Fume</th>
<th>Mortar + Air Entrainment</th>
<th>Shotcrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>From build test</td>
<td>1.5 - 2.3</td>
<td>1.3 - 2.3</td>
<td>0.7 - 1.2</td>
<td>1.2 - 1.6</td>
</tr>
<tr>
<td>From load cell</td>
<td>5 - 11.3</td>
<td>4 - 11.3</td>
<td>3.2 - 9</td>
<td></td>
</tr>
<tr>
<td>This work</td>
<td></td>
<td>1.9 - 6.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Tables 4.1 and 4.7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Maximum failure stresses compared with slump (before pumping)

Figure 4.54 shows that the maximum failure stresses (either shear or tensile stress taken from Figure 4.52, whichever the greater) of the fine concretes increase steadily as the slump decreases in a similar way to the build (Figure 4.45). However, the mass of the fine concrete with the lowest slump (C4p) was not recorded and so we do not know if this trend continues or if the maximum failure stress begins to fall, in a similar way to the build for mortars shown in Figure 4.45. A similar trend for the mortars could exist but the range is too small to be confident. The trend for the mortars is similar to the trend in Figure 4.45 with the exception of P1p which had a large cross/section and so possessed a low maximum failure stress compared with its build length (Figure 4.55) and P2w2, which built up in a frustum with a large 'nose' compared with the other mixes and so had a large maximum failure stress for a given build length.

Maximum failure stress and build

The maximum failure stresses for both the mortars and the fine concretes increase with an increase in build, as would be expected, with the fine concretes having a slightly larger maximum failure stress for a particular build than the mortars due to their higher densities (Figure 4.55). As the build and the maximum failure stresses increase, both types of material progress from a cohesive to an adhesive type failure mode in a similar way to Figure 4.52. The relationship appears to be more consistent for the fine concretes than the mortars, possibly due to the mix designs of the fine concrete being more similar than the mortars. Some of the mixes appear to have a disproportionately low maximum failure stress for a particular build. This can be due to a narrow (C1Sp) or large (P1p) cross/section, low density (P7w), the build 'frustum' being very narrow (D2w) or a low fines aggregate mix causing an early adhesive failure (D3w). Mix D1w also seems to have a disproportionately high maximum...
failure stress for a given build, possibly as this was the only mix sprayed onto steel vanes rather than a grit-blasted substrate.

The above trends can be explained using the schematic model shown in Figure 4.56. At a high slump (e.g. 95 mm, mortar D1-3) the mortar will fail cohesively and will have a low build and therefore a low maximum failure stress (Figure 4.54 and 4.55). As the slump decreases (from 95-60 mm), the build (Figure 4.45) and the maximum failure stresses (Figure 4.54) increase (e.g. from D1-3 to D2w). At a slump of 60-45 mm the mortar can fail either cohesively or adhesively depending on the mix design (e.g. the density, cement and fines content etc.) and the spraying apparatus and technique (e.g. from D2w, to D5w and P2w2, to D6w). As the slump decreases further (45-5 mm) the mortar fails adhesively (Figure 4.46) and the build and maximum failure stress will decrease (e.g. from D6w to D1w-2).

**Maximum failure stresses and flow resistance (g)**

For the fine concretes the maximum failure stresses increase for an increase in flow resistance before pumping and the failure mode changes from a cohesive to a combined adhesive/cohesive failure (Figure 4.57). No definite trend is obvious for the mortars. However, comparing with Figures 4.45, 4.47 and 4.46 it could be suggested that as the flow resistance increases from zero the maximum failure stresses increase and the mortar fails cohesively. As the flow resistance increases further, the stiffness of the mortar makes an adhesive failure more likely and so the maximum failure stresses begin to decrease. More data would be needed to confirm this theory. In contrast, the increase in flow resistance in Figure 4.48 produces an increase in build for fine concretes and mortars.

**Maximum failure stress and vane shear strength**

Figure 4.58 shows that with the exception of the air-entrained mix CIAp, the maximum failure stress of the fine concretes increased with an increase in vane shear strength, as would be expected when compared with Figure 4.47. The air is compacted out of CIAp on impact and so a high build (and therefore maximum failure stress) is possible with a low vane shear strength before pumping. No obvious relationship exists for the mortars although the relationship suggested in Figures 4.47 and 4.45
could be applied due to the known relationships between vane shear strength, slump, build and maximum failure stress (Figures 4.40 and 4.55).

**Maximum failure stress and flow resistance from the Viskomat**

For mortars (only mixes with aggregate < 2 mm can be tested in the Viskomat) an increase in the flow resistance (g) before pumping produces a slight reduction in the maximum failure stress (Figure 4.59). However, no slump or vane shear strength values were recorded and so it is not possible to identify where on the curve presented in Figure 4.56 the mixes might be. These results should correlate with the 2-point results in Figure 4.57, but different mixes are shown and the number and range of samples is small and so comparisons are difficult to make.

**Vane shear strength, slump and flow resistance of C3Ap**

Slump, vane shear strength and 2-point tests were conducted on mix C3Ap before pumping and after spraying. As would be expected, the action of pumping and spraying causes the mix to stiffen, thus increasing the flow resistance (g) and vane shear strength and decreasing the slump (Figure 4.60). Beaupré (1994) reported a similar increase in flow resistance after pumping and spraying, although he did not measure slump or vane shear strength after spraying. Although these trends would be expected for all the mixes, the differences are pronounced here due to the entrained air being forced out of the concrete during spraying.

**4.4.4 Effect of particle grading, permeability and void content**

As explained in Section 3.4, two mortars (D9 and D10) were designed so that their combined gradings (aggregate, cement and silica fume) were at the boundary of the gradings for the pre-blended mortars (Figure 3.6) to investigate the effect of the combined grading on the pumpability and sprayability of the mortars. Two more mortars (D11 and D12) were designed to be just outside these boundarys (Figure 3.7). The mix designs are given in Table 3.10 and the results for all four mixes are given in Table 4.10.
Pumpability

Mortars D9w and D10w which lay at the lower and upper boundaries of the grading zone respectively were expected to pump satisfactorily, which they did, although at a high pumping pressure (9 bar). The rheological properties of these two mortars suggested that the mixes would be pumpable. The output rates are reasonable, that for D10w being lower due to the resistance in the line because of the high proportion of fines in the mix. The sprayed cube strengths of 51.3 and 56.4 MPa are also more than adequate.

The coarse mix D11w was not expected to pump due to the combined grading being outside of the grading zone for the pre-blended mortars. However, if just the rheological properties were examined and the results compared with the data presented in Figures 4.40, 4.42 and 4.43 then the mortar could have been presumed to have been pumpable and sprayable. It is therefore important to analyse a materials combined grading as well as its rheological properties when attempting to assess its pumpability. Mortar D12w had a large proportion of lightweight filler and cement which made the grading very fine. This high fines content made the output very low (and virtually unusable) due to the resistance within the line. The rheological properties, when compared with the data presented in Figure 4.40, suggested that the mix might not pump. The hardened density and the sprayed cube strength were both low, as expected, due to the high proportion of lightweight filler. From these mixes and results it seems that if the combined grading is kept within the grading 'zone' (i.e. between the gradings for D9w and D10w) then a mortar can be produced that is pumpable, sprayable and with adequate hardened properties.
Table 4.10 Grading study mix results

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>D9w</th>
<th>D10w</th>
<th>D11w</th>
<th>D12w</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Before w/c Ratio</strong></td>
<td></td>
<td>0.45</td>
<td>0.51</td>
<td>0.38</td>
<td>0.43</td>
</tr>
<tr>
<td><strong>Pumping</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vane Shear Strength</td>
<td>kN/m²</td>
<td>1.52</td>
<td>1.55</td>
<td>1.11</td>
<td>0.87</td>
</tr>
<tr>
<td>Slump</td>
<td>mm³</td>
<td>50</td>
<td>45</td>
<td>90</td>
<td>65</td>
</tr>
<tr>
<td>Fresh Density</td>
<td>kg/m³</td>
<td>2218</td>
<td>2091</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Flow Resistance (g)</td>
<td>Nm</td>
<td>2.4</td>
<td>--</td>
<td>1.42</td>
<td>--</td>
</tr>
<tr>
<td>Plastic Viscosity (h)</td>
<td>Nms</td>
<td>0.59</td>
<td>--</td>
<td>0.86</td>
<td>--</td>
</tr>
<tr>
<td><strong>During Pumping and Spraying</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Pump Pressure</td>
<td>bar</td>
<td>9</td>
<td>9</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Output</td>
<td>l/s</td>
<td>7.9</td>
<td>5.7</td>
<td>--</td>
<td>3.0</td>
</tr>
<tr>
<td>Build</td>
<td>mm</td>
<td>227</td>
<td>200</td>
<td>--</td>
<td>180</td>
</tr>
<tr>
<td><strong>Hardened Properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cast Cube Strength</td>
<td>MPa</td>
<td>41.6</td>
<td>44.4</td>
<td>37.0</td>
<td>--</td>
</tr>
<tr>
<td>Sprayed Cube Strength</td>
<td>MPa³</td>
<td>51.3</td>
<td>56.4</td>
<td>--</td>
<td>23.5</td>
</tr>
<tr>
<td>Cast Cube Density</td>
<td>kg/m³</td>
<td>2053</td>
<td>1960</td>
<td>2037</td>
<td>--</td>
</tr>
<tr>
<td>Sprayed Cube Density</td>
<td>kg/m³</td>
<td>2198</td>
<td>2187</td>
<td>--</td>
<td>1496</td>
</tr>
</tbody>
</table>

Water Permeability

The results for the falling head water permeability test on mixes D1, D2, D3 and D4 and their aggregate components are shown in Table 4.11. As would be expected, the building sand on its own is the most permeable of the aggregate combinations and the finer, well-graded Portland stone is the least permeable. Although this order of results was expected, this test could be used to assess the water permeability of different aggregate combinations to provide an indication of a mix's ability to retain its liquid component (i.e. its resistance to bleeding). It was anticipated that the mortars D1 to D4 would follow the same trend as for their aggregate components, i.e. the coarse mix D4 having the highest permeability and the fine mix D1 the least. However, this was not the case and the mix with the highest proportion of fines (D1) had the highest permeability. From observing the test it is thought that the fine mixes were so impermeable that the water could not flow evenly through the sample and instead it found a gap through which to flow between the sample and the external casing. Hence the flow rate and resulting permeability value of the finer mixes are higher than the coarser mixes.

Table 4.11 Falling head water permeability

<table>
<thead>
<tr>
<th>Mix type</th>
<th>Mix design</th>
<th>Permeability (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Only</td>
<td>Portland stone only</td>
<td>$2.3 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>1:2 Building sand : Portland stone</td>
<td>$6.3 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>2:1 Building sand : Portland stone</td>
<td>$21 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>Building sand only¹</td>
<td>$360 \times 10^{-6}$</td>
</tr>
<tr>
<td>Aggregate, cement and silica fume</td>
<td>D1</td>
<td>$0.53 \times 10^{-6}$</td>
</tr>
<tr>
<td>(3 : 1 : 0.05)</td>
<td>D2</td>
<td>$0.31 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>D3</td>
<td>$0.15 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>D4</td>
<td>$0.22 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

1. Building sand permeability test conducted with the constant head test
Voids content

The voids content of the dry constituents for the proprietary pre-blended mortars were presented in Table 3.13. There appears to be no correlation between the voids content and the mix designs in Table 3.7. However, correlations can be made with the pressure bleed test results for the pre-blended mortars in Figure 4.11. It would be expected that the mortars with the highest voids content would bleed the most liquid, and vice versa. However, the opposite was true, with the lower voids content mortars P1, P2 and P4 bleeding the most and the higher voids content mixes P3, P5, P6 and P7 bleeding the least.

4.4.5 Summary and Conclusions

This Section has presented, discussed and compared a variety of data on the rheological performance of wet-process mortars and fine concretes. These rheological properties and relationships have been used to characterise the pumpability and sprayability of each mortar or fine concrete. The effect of the combined particle grading, the permeability of the aggregate and aggregate/cementitious combinations, and the voids content of the combined dry constituents have all been discussed.

When assessing a materials pumpability, the rheological properties should be considered together with the combined grading of the constituents. The main rheological properties to consider are the slump and the vane shear strength (Figure 4.40), and the flow resistance and plastic viscosity from the two-point test (Figure 4.43). The relationship between the flow resistance and the slump can also be used to give an indication of pumpability (Figure 4.41). For mortars, these results can be used together with a comparison of the combined grading of the mix with the grading zone presented in Figure 3.6. If the combined grading fits inside this grading zone, and also lies within the areas of the pumpable mixes in Figures 4.40, 4.41 and 4.43, then a confident prediction can be made that the mix is pumpable. However, a pumping trial is still recommended before the mix can be said to be definitely pumpable.

Sprayability can be measured by the mass and length of material that can be built up on the substrate. This can be further expressed in terms of the maximum shear and
bending stresses generated at failure (Figure 4.52). The build test has also
demonstrated how the failure mode changes between a cohesive and an adhesive
failure as the rheology of the mix changes (Figures 4.45 and 4.46). Most of the mixes
failed cohesively and in general a stiffer mix (i.e. lower slump and higher vane shear
strength) had a higher cohesive strength and therefore a higher build. This trend
continues until there is a switch from cohesive to adhesive failure when the build will
begin to decrease. These results suggest that it is the shear strength of the material
after spraying that is controlling the cohesive failure and therefore the build. However,
this fresh state after spraying is complex and has not been studied extensively in this
work. There is a possibility that the freshly built-up material may be acting more like a
partially saturated soil than a mortar or concrete.

The reinforcement encasement is also a measurement of the sprayability of a material
and this has been shown to increase as the workability increases (Figure 4.36). An
informed balance must therefore be made to obtain a mix which is both pumpable and
sprayable, yet which has good build and encasement properties.
4.5 FIGURES

Figure 4.1. Vane shear strength compared with slump for mortars

Figure 4.2. Two-point test, mix P1 (a) Upcurve and downcurve (b) Initial downcurve
Figure 4.3. Two-point test (a) Effect of slump on mix D1 (b) Effect of mix P2 being mixed, pumped and sprayed

Figure 4.4. Flow resistance (g) from the 2-Point test compared with slump

Figure 4.5. Two-point test: Pre-blended mortars
Table 4.1: Designed mixes

<table>
<thead>
<tr>
<th>Mix</th>
<th>g</th>
<th>h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Nm)</td>
<td>(Nmm)</td>
</tr>
<tr>
<td>D1</td>
<td>3.4</td>
<td>0.40</td>
</tr>
<tr>
<td>D2</td>
<td>2.9</td>
<td>0.52</td>
</tr>
<tr>
<td>D3</td>
<td>2.8</td>
<td>0.46</td>
</tr>
<tr>
<td>D4</td>
<td>2.4</td>
<td>0.51</td>
</tr>
<tr>
<td>D5</td>
<td>3.4</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Figure 4.6: Two-point test: Designed mixes

Figure 4.7: Viskomat breakdown speeds
Table 4.8: Viskomat: Torque compared with speed, mix P4

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>g (Nmm)</th>
<th>h (Nmm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>37.9</td>
<td>0.39</td>
</tr>
<tr>
<td>160</td>
<td>50.8</td>
<td>0.27</td>
</tr>
<tr>
<td>140</td>
<td>43.2</td>
<td>0.25</td>
</tr>
<tr>
<td>120</td>
<td>49.1</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Figure 4.8. Viskomat: Torque compared with speed, mix P4

Table 4.9: Viskomat: Torque compared with speed, pre-blended mixes

<table>
<thead>
<tr>
<th>Mix</th>
<th>g (Nmm)</th>
<th>h (Nmm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>32.6</td>
<td>0.06</td>
</tr>
<tr>
<td>P2</td>
<td>66.4</td>
<td>0.07</td>
</tr>
<tr>
<td>P4</td>
<td>48.9</td>
<td>0.06</td>
</tr>
<tr>
<td>P6</td>
<td>37.4</td>
<td>0.10</td>
</tr>
<tr>
<td>P7</td>
<td>48.1</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Figure 4.9. Viskomat: Torque compared with speed, pre-blended mixes
Figure 4.11. Pressure Bleed Test (a) Pre-blended mixes  (b) Designed mixes
Figure 4.12. Pressure bleed test at different pressures on mix D1 (a) over 30 minutes (b) over 30 seconds

Figure 4.13. Failure stresses compared with build
Figure 4.14. Failure stresses compared with slump (before pumping)

Figure 4.15. Build compared with slump (before pumping)
Figure 4.16. Build compared with flow resistance (g) before pumping

Figure 4.17. Failure stresses compared with flow resistance (g) before pumping
Figure 4.18. Failure stresses compared with vane shear strength

Figure 4.19. Build compared with vane shear strength (before pumping)
Figure 4.20. Reinforcement encasement: Sorptivity compared with area of bar overlap.

Figure 4.21. Mix P4w reinforcement encasement: Sorptivity compared with area of bar overlap.

Figure 4.22. Aggregate absorption of P4 and D1.
Figure 4.23. Core grade compared with area of bar overlap

Figure 4.24. Velocity vectors from particle analysis of sprayed concrete
Figure 4.25. Vane shear strength compared with slump for fine concretes

<table>
<thead>
<tr>
<th>Mix</th>
<th>g (Nm)</th>
<th>h (Nm/s)</th>
<th>Slump (mm)</th>
<th>Air (kN/m²)</th>
<th>Shear (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpumpable</td>
<td>5.0</td>
<td>0.13</td>
<td>50</td>
<td>15</td>
<td>1.53</td>
</tr>
<tr>
<td>After pumping</td>
<td>2.0</td>
<td>1.19</td>
<td>60</td>
<td>8.5</td>
<td>1.63</td>
</tr>
<tr>
<td>Before pumping</td>
<td>0.94</td>
<td>0.62</td>
<td>130</td>
<td>12.5</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Figure 4.26. Two-point test

<table>
<thead>
<tr>
<th>Mix</th>
<th>g (Nm)</th>
<th>h (Nm/s)</th>
<th>Slump (mm)</th>
<th>Shear (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3p</td>
<td>4.27</td>
<td>1.04</td>
<td>50</td>
<td>2.2</td>
</tr>
<tr>
<td>C5p</td>
<td>2.25</td>
<td>1.00</td>
<td>100</td>
<td>1.05</td>
</tr>
<tr>
<td>CIAp</td>
<td>1.60</td>
<td>0.50</td>
<td></td>
<td>0.48</td>
</tr>
<tr>
<td>C3Ap</td>
<td>0.94</td>
<td>0.62</td>
<td>130</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Figure 4.25. Two-point test
Figure 4.27. Slump compared with build

Figure 4.28. Build value compared with maximum shear and tensile stresses at failure

Figure 4.29. Slump value compared with maximum shear and tensile stresses at failure
Figure 4.30. Build value compared with flow resistance (g)

\[ Y = 125 + 0.74x + 3.79x^2 \]

R^2 = 1

g: Two-Point Test (Before pumping) (Nm)

Figure 4.31. Vane shear strength compared with maximum shear and tensile stresses at failure

\[ y = 0.4 + 2x \]

R = 0.988

Failure stresses (kN/m^2) (Before pumping)

Vane Shear Strength (kN/m) (Before pumping)
Figure 4.32. Build vs vane shear strength

Figure 4.33. Failure stresses compared with flow resistance (g)
Figure 4.34. Sorptivity compared with area of bar overlap

Figure 4.35. Core grade vs area of bar overlap
Figure 4.36. Sum of core gradings compared with w/c ratio

Figure 4.37. w/c ratio compared with core grade
Figure 4.40. Vane shear strength compared with slump for mortars and fine concretes

Figure 4.41. Flow resistance (g) from the 2-Point test compared with slump

Figure 4.42. Plastic viscosity (h) from the 2-Point test compared with slump
Figure 4.43. Plastic viscosity (h) from the 2-Point test compared with slump

Figure 4.44. Vane shear strength compared with flow resistance (g)

Figure 4.45. Build compared with slump (before pumping)
Figure 4.46. Model of change in failure mode with change in slump

Figure 4.47. Build compared with vane shear strength (before pumping)

Figure 4.48. Build compared with flow resistance (g) before pumping
Figure 4.49. Slump (before pumping) compared with build mass

Figure 4.50. Build length compared with mass of build

Figure 4.51. Build compared with vane shear strength (before pumping)
Figure 4.52. Maximum failure stresses (a) mortars labelled (b) fine concretes labelled

Figure 4.53. Maximum failure stress compared with mass of build

Figure 4.54. Maximum failure stress compared with slump (before pumping)
Figure 4.55. Maximum failure stress compared with build

Figure 4.56. Schematic model of change in failure mode with change in slump

Figure 4.57. Maximum failure stress compared with flow resistance (before pumping)
Figure 4.58. Maximum failure stress compared with vane shear strength

Figure 4.59. Maximum failure stress for mortars compared with flow resistance (g) from the Viskomat

Figure 4.60. Change in slump, vane shear strength and flow resistance of C3Ap after spraying
5 HARDENED PROPERTIES: RESULTS AND DATA ANALYSIS

5.1 INTRODUCTION
This Chapter presents the results and analysis of the hardened property testing on the mortars and fine concretes. Eight commercially available pre-blended repair mortars, twelve laboratory-designed mortars and ten laboratory-designed fine concretes were pumped and sprayed. Several of the laboratory-designed mortars described in Section 3.4.3 and presented in Table 4.1 were produced primarily for rheology testing and therefore only limited (and sometimes no) hardened property testing was conducted. The hardened properties measured include compressive and flexural strength, tensile bond strength, hardened density, modulus of elasticity, air permeability, sorptivity and drying and restrained shrinkage. Details of the test methods and specimen preparation are described in Section 3.7 and the fresh properties of these mixes are discussed in Chapter 4. A comparison between the mortars and fine concretes and the influence of the mix constituents on the fresh and hardened properties are discussed in Sections 6.1 and 6.2 respectively. The implications for practice with reference to the repair scenarios are discussed in Section 6.3. Some of the data presented here has been published in the papers listed in Appendix A.8.

5.2 MORTARS
This Section presents the hardened properties of the mortar mixes described in Section 3.4 using the test methods described in Section 3.7. The fresh properties of these mortars were presented and discussed in Section 4.2. A comparison between the wet and dry processes for mortars is included in Section 5.2.8.

5.2.1 Compressive strength
Figure 5.1(a) shows the average equivalent cube strengths (based on two samples) of the worm-pumped pre-blended mortars (and the dry-process sprayed mortar P8d) obtained from in-situ cores, cubes cut from panels, and the cast and sprayed cubes. Each reported value is the average of two specimens and the standard deviations were in the ranges of 1.03 to 4.79 for cores, 0 to 2.33 for in-situ cubes, 0.14 to 1.63 for cast cubes and 0.92 to 3.32 for sprayed cubes with average standard deviations of 2.91,
The mortars with the lowest strengths of 26.8-33.9 MPa were, as expected, obtained with the render/profiling and lightweight repair mortars (P3w and P7w). The simple laboratory-designed mix D1w produced the highest strengths compared to the more sophisticated (and expensive) pre-blended mortars. The relationship between the in-situ compressive strength and the water/cement ratio is as expected (Figure 5.2). The trend produced by Hills (1982) is shown for comparison.

The fall in the cast cube values as the w/c ratio decreases is typical for insufficiently compacted concrete (Neville, 1995), adequate compaction by vibration being difficult to obtain with several of the mortars (P5, P6 and P7). The lightweight mortar P7 had a high water/cementitious ratio due to the low proportion of cement and the high proportion of lightweight filler. The in-situ cube strengths are generally higher than the corresponding cast cubes, due mainly to the greater compaction (and therefore greater densities, see Table 5.2) obtained with the spraying process. It is generally agreed that in-situ sprayed concretes produce higher strengths than for similarly cast mixes (SCA, 1990 and Gordon, 1995), although the opposite has also been observed (Banthia et al., 1994b). P5w, P6w and P7w have low cast cube strengths as these specimens contained a large number of air voids, even after considerable vibration. There is a good correlation between the in-situ cube strengths and the cubes sprayed in moulds, despite the difficulty in obtaining a sample with no voids and low rebound (samples with excessive voidage being discarded).

The cast and sprayed mould compressive strengths of the designed mortars are shown in Figure 5.1(b). The sprayed specimens have greater compressive strengths compared with the cast specimens, as would be expected, except for mix D1w-2 which was very stiff (with a 5 mm slump, see Table 4.1) and therefore could not be sprayed into a cube mould without creating any voids. Mix D7w produced the lowest compressive strength (17.6 MPa), as was expected, due to the low cement content (see Table 3.9). The highest strength was produced by mix D5w (56.5 MPa). This mix was similar to mix D1w in Figure 5.1(a) with the exception that it contained no SBR. The inclusion of SBR seems to have increased the compressive strength slightly from between 52.3-56.5 MPa for mix D5w (cast and sprayed mould specimens) to 56.7-57 MPa for mix
D1w. P2w1-1 was simply mix P2w2 with an increased water content (which decreased the vane shear strength from 1.52 to 1.14 kN/m², see Table 4.1) which therefore produced a more workable mix. This mix could then be sprayed into a cube mould with less voids and entrapped rebound, thus producing a higher compressive strength than the stiffer mix (46.5 MPa compared with 40.2 MPa) despite the higher water/cement ratio. These values also correspond to the values for the identical mix P2w in Figure 5.1(a), which had a sprayed mould compressive strength of 42.2 MPa.

If the cast compressive strengths of mixes D1w, D2w and D3w are compared then it can be seen that the strength increases as the Portland stone/building sand ratio increases (see Table 3.9). Also, comparing the cast compressive strengths of mixes D1w, D6w and D7w, it can be seen that as the proportion of Portland stone increases compared with the cement (i.e. the mixes become leaner, see Table 3.9), the strength decreases, as would be expected.

Figure 5.3 shows the compressive cube strengths of mixes P2, D1, P1 and P5 sprayed through different pumps. This shows a small difference in the in-situ cube strengths for the wet-process pumps (small and large-diameter worms and a piston pump) for both P1 and P2 but a larger increase when mixes P1 and P5 are sprayed with the dry process, the latter being expected due to their lower water/cementitious and aggregate/cementitious ratios resulting from the high aggregate rebound with this process. The higher values for the sprayed-mould cube strengths using the small-diameter worm pump, compared with the piston pump for D1 and P1, could be attributed to the difficulty in spraying a 100 mm cube mould with the larger nozzle and higher output of the piston pump.

5.2.2 Bond strength
The vertical and overhead bond strengths of the small worm-pump mortars (average of five samples) are shown in Figure 5.4(a) and the 7 and 28 day bond strengths of mortars P1, P2 and P5 sprayed with different pumps are shown in Figure 5.4(b). Each value reported is the average of five tests and the standard deviations were in a range of 0.085 to 0.245 at 7 days and 0.085 to 0.385 at 28 days, with an averages of 0.165 and 0.235 respectively. All the pre-blended mortars achieved at least 1.7 MPa at 28
days (with the exception of the lightweight mortar P7) which comfortably exceeds the Concrete Society minimum bond strength of 0.8 MPa. Interestingly, the laboratory-designed mix D1w achieved a vertical 28 day bond strength as high as any of the more expensive proprietary pre-blended mortars. Figure 5.4(b) shows that the type of pump affected the bond strength. Due to the large amount of aggregate rebound the dry process produces a repair that is rich in cement with a correspondingly higher bond strength (P1d and P5d). The piston-pumped P1p produced a lower bond strength than the worm-pumped P1w and the compressive strength was also lower (Figure 5.3(b)). In contrast, mix P2W (large worm pump) produced a much lower bond strength than P2w and P2p, despite having a similar compressive strength.

The vertical bond strengths are compared with compressive strength in Figure 5.5. This shows that the mortars in this study (except P7) possess a relatively narrow range of vertical bond strengths (1.7-2.25 MPa), despite having a broad range of in-situ compressive strengths (32-57 MPa). As previously mentioned, P7 was a lightweight material and had both a low vertical and overhead bond strength.

5.2.3 Flexural strength
The average flexural strengths (of two samples) in Figure 5.6 (and the numerical data in Appendix A.10) show a similar trend to the compressive strength results, with the cast beams in general having the lowest flexural strengths and the in-situ beams the highest. Problems were again encountered with voidage and rebound when spraying into the beam moulds, badly affected beams being discarded. Each reported result is the average of two tests and the standard deviations were in ranges of 0.007 to 0.071 for the cast, 0.134 to 0.389 for the in-situ specimens and 0.042 to 0.615 for the sprayed specimens, with average deviations of 0.039, 0.262 and 0.329 respectively. The relationship between the flexural and compressive strength (Figure 5.7) is in line with previously published data for cast concrete (Neville, 1995).

5.2.4 Drying and restrained shrinkage
The rates of drying shrinkage for three types of prism (from an average of two samples) are shown for mix D1 in Figure 5.8(a) and for mix P3w in Figure 5.8(b). The larger (75x75x229 mm) in-situ prisms had the highest total drying shrinkage for the
designed-mix D1w (approximately 1200 microstrain at 1 year), possibly due to the greater compaction and slightly lower aggregate content (due to differential rebound) compared with the cast samples. However, the shrinkage-compensated pre-blended mix P3w expanded before it began to shrink. This Figure shows that care should always be taken when quoting drying shrinkage values, especially when shrinkage-compensating chemicals are present, as the dimensional change of the sample can be very different depending on the age and size of the sample.

The drying shrinkage results for the 75x75x230 mm in-situ prisms for the mortars are shown in Figure 5.9. A wide range of results were obtained, despite all the proprietary pre-blended mixes being described as ‘low shrinkage’. P3w contained a shrinkage compensator (as did P2W) which explains the initial expansion of the specimen - minimum shrinkage being vital for a re-profiling render designed to be applied in thin layers. The mortar which shrank the greatest at the fastest rate was the lightweight mortar P7, which would be expected due to the very high water/cementitious ratio. Figure 5.10 shows the 28 day shrinkage for mortars P1, P2 and P5 after they have been cast, sprayed with the dry process and worm and piston pumped and sprayed. The first shrinkage measurement for P1w was taken 2 days after spraying and so the 28 day shrinkage would be expected to be greater than shown when compared with the results taken 1 day after spraying, as a large proportion of the shrinkage occurs within the first 24 hours. However, mortar P2 contains a shrinkage compensator and so the overall 28 day shrinkage shown for P2 and P2w is actually lower than shown. The dry process mixes, P1d and P5d, shrank considerably less than their equivalent wet process or cast specimens, probably due to their lower water/cement ratio compared with wet spraying. The results for mortar P5 (Figure 5.11) show very little difference in the shrinkage rates between cast and in-situ prisms when wet-sprayed but a lower initial rate of shrinkage when sprayed using the dry process, probably due to the lower water/cement ratio produced.

The restrained shrinkage of several mortars stored in ambient conditions, with and without mesh reinforcement, is shown in Figure 5.12. The results are the average of three gauge readings on a single slab measured directly from the face of the repair, with no allowance for the movement of the substrate. Mortars D1p and P2p were
sprayed 6 months before P1p and P1d and were therefore cured under very different temperature and humidity conditions. This could explain the large difference in the shrinkage rates for the mortars in the two spray trials. Mortars D1 and P2 expanded in the first few days, partly due (for P2 only) to the presence of shrinkage compensators but also due to the ambient temperature and humidity fluctuations. This influence of the ambient conditions could also explain the sharp decrease in the rate of shrinkage for mortars P1p and P1d after 42 days and the expansion of mortars D1p and P2p after 14 days. The much greater shrinkage rate of P1p and P1d compared with D1p and P2p could be attributed to the dates on which they were sprayed. P1p and P1d were sprayed on the 18 and 19th of June (i.e. the beginning of summer, therefore a faster rate of shrinkage due to a higher ambient temperature) and D1p and P2p were sprayed on the 18th of November (i.e. the beginning of winter, therefore a correspondingly slower rate of shrinkage). The laboratory-designed D1p and the shrinkage-compensated pre-blended P2p had very similar shrinkage profiles until approximately 250 days.

The reinforcement mesh had very little influence on the shrinkage profiles for all the mortars, with the mesh-reinforced P1p, P1d and D1p actually shrinking slightly more than the corresponding un-reinforced mortars. The main purpose of reinforcement mesh is to eliminate cracking, yet no cracking was observed on either the reinforced or un-reinforced sections of the slabs.

5.2.5 Air permeability and sorptivity
The results for the air permeability and sorptivity tests are shown in Figures 5.13 and 5.14 respectively and are summarised in Table 5.1. Their relationship with the in-situ compressive cube strength is shown in Figure 5.15. The air permeability and sorptivity tests were carried out on the bottom 20 mm thick section of the core and it is these results that are presented in the figures. A relationship between permeability and compressive strength for concretes that have been wet-cured for 28 days is shown for comparison (Neville, 1995). As would be expected, the air permeability decreases as the compressive strength increases, with most of the mortars having a lower permeability than concrete. However, the sorptivity does not show a clear relationship with the compressive strength. Recent work by Al-Kindy (1998) has shown that
sorption decreases with an increase in compressive strength, with the sorptivity of a 50 MPa concrete being 1.5-2 times lower than similarly cured 30 MPa concrete, the decrease being attributable to the increased cement content and lower w/c ratio. The lack of a clear relationship in the current study between compressive strength and sorptivity is possibly a result of the difference in mix constituents and proportions of the pre-blended mortars, Al-Kindy's results being based on concretes made with the same constituents.

Mix P3 had the lowest sorptivity of all the mortars, which was expected as this is a rendering and re-profiling mortar. It also had the lowest air permeability of the wet-process pre-blended mortars. It would be expected that the in-situ specimens would have the lowest sorptivity (compared with the cast and sprayed mould specimens) due to their higher density (Table 5.3) and greater compaction. However, although this is true for mix P3, it is not so for the other mortars in Table 5.1. The laboratory-designed mortar D1 had the lowest air permeability, although conversely, it also had the highest sorptivity of all the mortars. Spraying seemed to improve the permeability, with the cast specimens consistently producing the highest air permeability values.

### Table 5.1 Air permeability and sorptivity

<table>
<thead>
<tr>
<th>Mortar</th>
<th>Air Permeability (x10^{-17} \text{ m}^2)</th>
<th>Sorptivity (mm/min(0.5))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cast</td>
<td>In-situ</td>
</tr>
<tr>
<td></td>
<td>Top</td>
<td>Bottom</td>
</tr>
<tr>
<td>P1p</td>
<td>0.040</td>
<td>0.034</td>
</tr>
<tr>
<td>P1d</td>
<td>0.033</td>
<td>0.027</td>
</tr>
<tr>
<td>P2p</td>
<td>0.027</td>
<td>0.017</td>
</tr>
<tr>
<td>P3</td>
<td>0.013</td>
<td>0.014</td>
</tr>
<tr>
<td>P4</td>
<td>0.023</td>
<td>0.022</td>
</tr>
<tr>
<td>P5d</td>
<td>0.013</td>
<td>0.011</td>
</tr>
<tr>
<td>P6</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>P7</td>
<td>0.016</td>
<td>0.019</td>
</tr>
<tr>
<td>P8d</td>
<td>0.028</td>
<td>0.028</td>
</tr>
<tr>
<td>D1</td>
<td>0.036</td>
<td>0.040</td>
</tr>
<tr>
<td>D1p</td>
<td>0.033</td>
<td>0.023</td>
</tr>
</tbody>
</table>

#### 5.2.6 Modulus of Elasticity

The elastic modulus is compared with the in-situ compressive strength in Figure 5.16. The results shown are from the average of two specimens and the standard deviations were in the range of 1.04 to 1.72 for the cast and 0.006 to 0.86 for the in-situ specimens with average deviations of 1.38 and 0.433 respectively. There is no
agreement on the precise form of this relationship for sprayed concrete (Neville, 1995), but that from ACI 363R-92 (1994) for concrete is shown for comparison. The results obtained show significantly lower modulus values, especially at lower strengths. This is due to the lower density combined with the type and proportion of aggregate within the mortars. The data is important, however, as it is desirable for the elastic modulus of the repair and the substrate to be as similar as possible.

5.2.7 Hardened Density

The densities in Table 5.2 show that in general the in-situ mortars possess the highest densities and the cast mortars the lowest. The results shown are from the average of two specimens and the standard deviations were in the range of 0.71 to 14.1 for the cast, 8.49 to 39.6 for the in-situ specimens and 0.71 to 48.8 for the sprayed mould specimens. The average deviations were 7.4, 24.0 and 24.8 respectively. A large number of voids were present in the cast cubes for P5, P6 and P7, even after several minutes vibration and these specimens therefore possess a significantly lower density than the corresponding in-situ and sprayed cubes. The dry-process mortars all had a higher density than the wet-process worm- or piston-pumped mortars. The piston-pumped mortars (P2p and D1p) produced higher densities than the corresponding worm-pumped mortars (P2w and D1w) although the density of the piston-pumped mortar P1p was lower than P1w.

The densities in the third section of the Table correspond very closely to the compressive strengths in Figure 5.1(b), with the sprayed mould specimens all having higher densities than the corresponding cast specimens (except for D1w-2).

<table>
<thead>
<tr>
<th>Table 5.2 Mortar density</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kg/m³)</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Cast Cube</td>
</tr>
<tr>
<td>In-situ Cube</td>
</tr>
<tr>
<td>Sprayed Mould</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>P5w</th>
<th>P5d</th>
<th>P6w</th>
<th>P7w</th>
<th>P8d</th>
<th>D1w</th>
<th>D1p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Cube</td>
<td>1400</td>
<td>1662</td>
<td>1278</td>
<td>2088</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-situ Cube</td>
<td>1654</td>
<td>1895</td>
<td>1783</td>
<td>2200</td>
<td>2096</td>
<td>2230</td>
<td></td>
</tr>
<tr>
<td>Sprayed Mould</td>
<td>1660</td>
<td>1792</td>
<td>2118</td>
<td>2193</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.2.8 Wet- and dry-process sprayed mortars compared

Table 5.3 shows the properties of the three mortars that were sprayed using the dry process together with comparable wet-process data where available. The values for compressive, bond and flexural strength for mix P5 are shown graphically in Figure 5.17. As expected, these strengths are all higher for the dry process mixes, as are the values for elastic modulus and density. This is due to the lower water/cementitious ratio and higher in-situ cement content of the dry process mixes (this lower water/cementitious ratio was also the reason for the strengths and density of P1 being lower when piston pumped than when worm pumped). The compressive and flexural strengths, hardened density and elastic modulus were also all lower for the cast specimens compared with both the dry and wet process mixes due to the compaction of the spraying process. The mixes also had a lower drying shrinkage at 28 days when sprayed using the dry process than with the wet. The initial shrinkage measurements for Plw and P8d were taken 2 days after spraying, compared with 1 day for the other mortars and so the 28 day drying shrinkage could be expected to be higher for these two mixes than is shown in the table. The dry-process mortars also produced much lower air permeability values compared with the wet process mortars (Table 5.1.) although these mortars cannot be compared like-for-like.

<table>
<thead>
<tr>
<th>Mortar</th>
<th>Cube Strength (MPa)</th>
<th>Density (kg/m²)</th>
<th>Flexural Strength (N/mm²)</th>
<th>Max. Bond Strength (MPa)</th>
<th>Elastic Modulus (kN/mm²)</th>
<th>Sorptivity (mm/min 0.5)</th>
<th>28 Day Shrinkage (microstrain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 cast</td>
<td>35.8</td>
<td>1815</td>
<td>4.8</td>
<td>-</td>
<td>21.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P1 worm</td>
<td>38.8</td>
<td>1973</td>
<td>6.2</td>
<td>1.85</td>
<td>23.5</td>
<td>-</td>
<td>663*</td>
</tr>
<tr>
<td>P1 piston</td>
<td>33.6</td>
<td>1843</td>
<td>5.4</td>
<td>1.40</td>
<td>-</td>
<td>0.037</td>
<td>828</td>
</tr>
<tr>
<td>P1 dry</td>
<td>53.0</td>
<td>2115</td>
<td>7.3</td>
<td>2.80</td>
<td>24.7</td>
<td>0.030</td>
<td>643</td>
</tr>
<tr>
<td>P5 cast</td>
<td>40.0</td>
<td>1400</td>
<td>4.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1331</td>
</tr>
<tr>
<td>P5 worm</td>
<td>45.7</td>
<td>1654</td>
<td>6.4</td>
<td>2.00</td>
<td>-</td>
<td>-</td>
<td>1367</td>
</tr>
<tr>
<td>P5 dry</td>
<td>58.1</td>
<td>1895</td>
<td>9.1</td>
<td>2.76</td>
<td>25.9</td>
<td>0.012</td>
<td>840</td>
</tr>
<tr>
<td>P8 dry</td>
<td>71.0</td>
<td>2220</td>
<td>9.2</td>
<td>-</td>
<td>36.6</td>
<td>0.028</td>
<td>742*</td>
</tr>
</tbody>
</table>

Note: * denotes first shrinkage sample reading taken 2 days after spraying
5.2.9 Summary

This Section presented the hardened properties of the mortar mixes (both pre-blended and laboratory-designed) described in Section 3.4 using the test methods described in Section 3.7.

The relatively simple laboratory-designed mortars possessed high compressive and flexural strengths compared with the commercially available pre-blended mortars and a good correlation exists between the in-situ and the sprayed mould compressive cube strengths, providing that no large voids or excessive rebound is present (Figure 5.1). However, it was very difficult to remove all the voids from several of the pre-blended mortars, even with substantial vibration. The different types of wet-process pumps (small- and large-diameter worms and piston pump) seemed to have little effect on the compressive and flexural strengths of the mortars (Figure 5.3). However, the output of the pump and the size and design of the nozzle did influence properties such as bond strength and the compressive strengths of the sprayed moulds; the small worm pump being best able to spray directly into a cube mould with minimum voids, therefore producing a higher compressive strength.

The mortars all possessed a relatively narrow range of bond strengths compared with their compressive strengths (Figure 5.5). The different types of wet-process pump affected the bond strength, but this was probably due more to the stream velocity and water/cementitious ratio than the actual pumping process (Figure 5.4). The results for the modulus of elasticity, when compared with the compressive strength, show significantly lower values than published formulas of this relationship would suggest, especially at lower strengths.

The dry-process mixes exhibited less drying shrinkage than the equivalent wet-process or cast mixes, as was expected (Figure 5.11). The cast and the in-situ prisms had very similar rates of drying shrinkage, suggesting that cast prisms could be used for quality control purposes to measure and monitor in-situ drying shrinkage (Figure 5.8). The restrained shrinkage strains suggest that the shrinkage of a sprayed repair is influenced more by the ambient conditions (mainly temperature and humidity, but also rain, wind and sunlight) than by the composition of the mix itself (Figure 5.12). The inclusion of
mesh within the repair also seems to have little effect on the measured values of shrinkage taken from the face of the repair. The air permeability decreased with an increase in compressive strength, as would be expected (Figure 5.15). However, sorptivity did not appear to show a clear relationship with the compressive strength.

Though slightly out-performed by the dry-process mortars in terms of compressive, flexural and bond strengths, the strengths obtained (30-60 MPa compressive, 4-9 MPa flexural and 1.7 MPa bond for non-lightweight mortars) are adequate enough for the majority of repair applications. Of particular attraction to the designer/specifier are the knowledge that the mix specified, once pumped and sprayed, will be the mix in-situ (without the uncertainty of the water content controlled by the nozzleman in the dry process, and the further effect of differential rebound). Furthermore, with the low-volume pumps used in this study, the ability to obtain representative quality control specimens by spraying directly into steel moulds is another advantage in terms of convenience and cost.

The hardened property results for the mortars presented here will be compared with the fine concretes in Section 6.1 and the influence of the mix constituents on the fresh and hardened properties of these mortars will be discussed in Section 6.2.
5.3 FINE CONCRETES

This Section presents the hardened properties of the fine concretes described in Section 3.4.3 using the tests described in Section 3.7. The fresh properties of these fine concretes were presented and discussed in Section 4.3 and the hardened properties presented here will be compared with those for mortars in Section 6.1. The effect of the constituents on the fresh and hardened properties and the implications for practice (with reference to the repair scenarios) will be discussed in Sections 6.2 and 6.3 respectively.

5.3.1 Compressive strength

Figure 5.18 shows the cube and core strengths of the piston-pumped concretes and the dry-process sprayed concrete C2d, obtained from in-situ cores, cubes sawn from panels and cast and sprayed cubes. Each reported value is the average of two specimens and the standard deviations were in the ranges of 0.354 to 7.58 for 58 mm diameter cores, 0.63 to 3.39 for in-situ cubes, 1.06 to 2.40 for cast cubes with average standard deviations of 3.97, 2.02 and 1.73 respectively. The concrete with the lowest strength (30.1 MPa) was CP2p which was sprayed into a cube mould. However, there are large differences in compressive strength for the sprayed cube specimens (compared with the other methods of specimen preparation) due to the difficulties of spraying into a 100 mm cube mould with a high-volume, large-nozzle piston pump. In contrast, the cast and in-situ cube strengths for each mix were very similar. However, it is generally agreed that in-situ sprayed concretes produce higher strengths than for similarly cast mixes due to the greater compaction obtained with the spraying process (SCA, 1990 and Gordon, 1995). This trend was found for mortars (Section 5.2.1). However, the opposite has also been observed (Banthia et al., 1994). The 58 mm diameter core compressive strengths were consistently lower than the other methods of measurement, suggesting that this diameter of core may be too small to accurately measure the compressive strength of these fine concretes.

Mix C3Ap had the lowest in-situ strength, possibly due to the lack of superplasticiser compared with the other mixes (which would increase the water/cement ratio for the
same workability) and the presence of air voids (8.5% after spraying). However, the addition of air to mix C1p (i.e. mix C1Ap, see Table 3.12) appears to have increased the compressive strength. The highest cast and in-situ cube strengths were obtained by mixes C4p and C5p, mainly due to the larger aggregates used in these mixes and their low water/cement ratios (Table 3.12).

The relationship of the in-situ cube strength with the water/cement ratio is as expected (Figure 5.19), the trend being similar to data produced for sprayed concrete by Hills (1982). However, the trend for the sprayed cubes seems opposite to what would be expected. This could be due to the increase in water/cementitious ratio producing a more workable mix, which when sprayed into a 100 mm cube mould produces less voids with less trapped rebound, and therefore a higher compressive strength.

5.3.2 Tensile bond strength

The 7 and 28 day vertical bond strengths of the piston-pumped concretes are shown in Figure 5.20(a) and the 28 day vertical bond strengths are compared with the in-situ compressive strengths in Figure 5.20(b). All the concretes achieved at least 2.1 MPa at 7 days and at least 2.3 MPa at 28 days, comfortably exceeding the Concrete Society minimum bond strength of 0.8 MPa. Each value reported is the average of five tests and the standard deviations were in a range of 0.162 to 0.339 at 7 days and 0.271 to 0.359 at 28 days, with averages of 0.250 and 0.315 respectively. The lowest bond strength was obtained with the dry-process mix C2d, the opposite of what would be expected. Figure 5.20(b) shows that the concretes in this study possess a relatively narrow range of vertical bond strengths (2.3-3.1 MPa at 28 days), despite having a broad range of in-situ compressive strengths (40.1-80.3 MPa).

5.3.3 Flexural strength

Table 5.4 shows similarly variable results to the compressive strength results with no apparent trends. The sprayed mould compressive strengths for C1Ap and CP2p are very similar to their in-situ strengths, but the sprayed mould strength for C1Sp is significantly lower. This shows the problems that can occur with voidage and rebound when spraying into beam moulds, especially with a high-volume piston pump. Each
reported result is the average of two tests and the standard deviations were in ranges of 0.057 to 0.474 for the cast, 0.057 to 0.474 for the in-situ specimens, with average deviations of 0.265 and 0.332 respectively. The sprayed mould results are from one specimen only. The relationship between the flexural and compressive strengths for both cast and in-situ specimens (Figure 5.21) is in line with data for cast concrete (Neville, 1995). CP2p had a lower sprayed-mould compressive strength than would be expected from this Figure due to the difficulty in spraying into a cube mould with the high-volume piston pump, which was even more difficult than spraying into a beam mould without creating significant voids and rebound entrapment.

### Table 5.4. 28 day flexural strength

<table>
<thead>
<tr>
<th>Material</th>
<th>C1p</th>
<th>Chp</th>
<th>C1Ap</th>
<th>C2d</th>
<th>C3p</th>
<th>C3Ap</th>
<th>CP1p</th>
<th>CP2p</th>
<th>C4p</th>
<th>C5p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Beam</td>
<td>7.0</td>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>3.8</td>
<td>4.9</td>
<td>6.2</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>In-situ Beam</td>
<td>5.9</td>
<td>6.8</td>
<td>7.9</td>
<td>6.2</td>
<td>5.9</td>
<td>4.1</td>
<td>6.8</td>
<td>5.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprayed Mould</td>
<td>3.5</td>
<td>7.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note 1: Bad voids in C1S sprayed mould

### 5.3.4 Drying and restrained shrinkage

The drying shrinkage results for the 75x75x229 mm in-situ prisms are shown in Figure 5.22. The fine concretes with the lowest rates of drying shrinkage were C4p and C5p. This was due to their relatively high proportions of coarse aggregate and low water/cementitious ratios compared with the others. The dry-process mix C2d also had a low rate of drying shrinkage due to its low water/cementitious ratio (as was expected). The highest rates of drying shrinkage were for the two mixes containing polypropylene fibres (CP1p and CP2p). This indicates that polypropylene fibres can be used in a mix design to minimise plastic shrinkage, but does little to limit drying shrinkage.

The results for mix C1p (Figure 5.23) show little difference in the rates of drying shrinkage between cast and in-situ prisms when wet sprayed. The dry-process mix C2d exhibited a slightly lower rate of drying shrinkage compared with the wet-process mix C1p.

The restrained shrinkage of eight fine concretes, with and without mesh reinforcement, is shown in Figure 5.24. The results are the average of three gauge
readings measured directly from the face of the repair, with no allowance for the movement of the substrate. The high rates of shrinkage of C1Ap and C2d compared with the other mixes could be attributed to the dates on which they were sprayed: C1Ap and C2d being sprayed in the middle of June (i.e. the beginning of summer, therefore a faster rate of shrinkage due to a higher ambient temperature) and the other fine concretes being sprayed in the middle of November (i.e. the beginning of winter, therefore a slower rate of shrinkage). This was also apparent for the wet-process mortars (Section 5.2.4). This influence of the ambient conditions could also explain the expansion of mixes CP2p, C4p and CP1p after 150 days and mixes C2d and C1Ap after approximately 290 days.

The reinforcement mesh had very little influence on the rates of shrinkage, with the mesh-reinforced C3p, C2d and C1Ap mixes shrinking slightly more than the corresponding un-reinforced mixes. However, the main purpose of reinforcement mesh is to eliminate cracking, yet no cracking was observed on either the reinforced or un-reinforced sections of the slabs. Similar results were also found for the wet-process mortars.

The free drying shrinkage of the 76x76x229 mm prisms taken from in-situ and stored at 20°C and 50% relative humidity are shown for comparison with the restrained shrinkage specimens for mix C4p in Figure 5.25(a). The shrinkage of these laboratory-stored prisms is considerably greater (more than four times in this case) than the restrained specimens left outside in ambient conditions. However, the shrinkage rate for the laboratory-stored prisms for mix C1Ap (Figure 5.25(b)) is considerably closer to the restrained specimens. Clearly quoting shrinkage results from tests conducted under laboratory conditions should be done with caution when discussing in-situ repairs and their performance.

5.3.5 Sorptivity

The results for sorptivity are shown in Table 5.5 and the relationship with the in-situ compressive cube strength is shown in Figure 5.26. The sorptivity test was carried out on the bottom 20 mm thick section of the core and it is these results that are presented. As mentioned in Section 5.2.5, sorptivity has been shown to decrease with an increase
in compressive strength, with the sorptivity of a 50 MPa concrete being 1.5-2 times lower than similarly cured 30 MPa concrete, the decrease being attributable to the increased cement content and lower w/c ratio (Al-Kindy, 1998). However, the trend here is poor. The difference in mix constituents and proportions between the mixes presented here both contribute to the spread of results, Al-Kindy's results being based on concretes made with the same constituents.

The sorptivity of the fine concretes compared with their water/cementitious ratios is shown in Figure 5.27. This shows a clear increase in sorptivity for an increase in water/cementitious ratio for both the top and bottom slices of the core. It also shows higher sorptivity values for the top slice (i.e. the slice just behind the reinforcement) than the bottom slice (i.e. the slice next to the back of the panel), mainly due to the voids within the core being concentrated directly beneath the reinforcement. Mix C1Ap appears to have a slightly higher sorptivity than it's water/cementitious ratio would suggest, possibly because of the entrained air within the mix.

<table>
<thead>
<tr>
<th>(mm/min$^{0.5}$)</th>
<th>C1p</th>
<th>C1Sp</th>
<th>C1Ap</th>
<th>C2d</th>
<th>C3p</th>
<th>CP1p</th>
<th>CP2p</th>
<th>C4p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top slice</td>
<td>0.117</td>
<td>0.096</td>
<td>0.138</td>
<td>0.202</td>
<td>0.204</td>
<td>0.179</td>
<td>0.140</td>
<td>0.107</td>
</tr>
<tr>
<td>Bottom slice</td>
<td>0.060</td>
<td>0.068</td>
<td>0.122</td>
<td>0.184</td>
<td>0.133</td>
<td>0.105</td>
<td>0.085</td>
<td>0.073</td>
</tr>
</tbody>
</table>

5.3.6 Modulus of Elasticity

The modulus of elasticity is compared with the in-situ compressive strength in Figure 5.28. The results shown are from the average of two specimens and the standard deviations were in the range of 0.32 to 2.55 with an average of 1.47. There is no agreement on the precise form of this relationship for sprayed concrete (Neville, 1995), but that from ACI 363R-92 (1994) for concrete is shown for comparison. However, a definite trend is difficult to establish due to the narrow range of cube strengths presented here. This data for the fine concretes is also more in line with this published relationship than the mortars (Section 5.2.6). The data is important, however, as it is desirable for the modulus of elasticity of the repair and the substrate to be as similar as possible.
5.3.7 Hardened Density

The values of density for all the types of cube show no definite trend (Table 5.6), although the values for density correspond very closely to the values for compressive strength shown in Figure 5.18. The results shown are from the average of two specimens and the standard deviations were in the range of 21.2 to 75.0 for the cast and 2.83 to 15.6 for the in-situ specimens with average deviations of 48.0 and 9.2 respectively. The sprayed mould results are from one specimen only. The mix with the highest hardened densities were C4p and C5p, which was expected due to their large proportion of coarse aggregate. The densities obtained from the sprayed moulds were variable compared with the other types of specimen due to the difficulty of spraying directly into a 100 mm cube mould.

<table>
<thead>
<tr>
<th>Table 5.6. Hardened density</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kg/m³) C1p C1Sp C1Ap C2d</td>
</tr>
<tr>
<td>Cast Cube 2167 2221 -- --</td>
</tr>
<tr>
<td>In-situ Cube 2162 2247 2222 2245</td>
</tr>
<tr>
<td>Sprayed Mould 2084 2165 2239 --</td>
</tr>
</tbody>
</table>

5.3.8 Wet and dry-process sprayed concretes compared

Table 5.7 shows the properties of the dry-process sprayed mix C2d together with the comparable wet-process mix C1p. The mix designs were the same except for the presence of a superplasticiser in mix C1p and the method of spraying. The values for compressive strength for C2d are higher than the in-situ C1p but lower than the cast C1p and the flexural strength is slightly higher. The bond strength of the dry-process mix C2d is lower than the wet-process C1p, which is the opposite of what would be expected.

<table>
<thead>
<tr>
<th>Table 5.7. Dry-process sprayed concrete comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>C1p in-situ</td>
</tr>
<tr>
<td>C1p cast</td>
</tr>
<tr>
<td>C2d dry</td>
</tr>
</tbody>
</table>

For the dry-process sprayed mix it would be expected that the compressive, flexural and bond strengths would be higher, as well as the elastic modulus and hardened density due to a lower water/cementitious ratio and a higher in-situ cement content.
compared with the wet-process sprayed concrete. However, the presence of the superplasticiser in the wet-process mix would decrease the water/cementitious ratio. The hardened density, flexural strength and elastic modulus were all higher for the dry-process mix, but the compressive cube and bond strengths were lower. The lower drying shrinkage for the dry process compared with the wet process and the cast specimen was as expected.

5.3.9 Summary

This Section presented the hardened properties of the fine concretes described in Section 3.4.3 using the tests described in Section 3.7.

The correlation between the in-situ and the sprayed mould compressive cube strengths is not as consistent as that for the wet-process mortars, although comparisons can be made providing that no large voids or excessive rebound is present (Figure 5.18). The fine concretes all possessed a relatively narrow range of bond strengths (2.3-3.1 MPa at 28 days) compared with their compressive strengths (Figure 5.20).

The dry-process mixes and the mixes containing the larger (8 mm) aggregate (C4p and C5p) exhibited less drying shrinkage than the other mixes, as was expected (Figure 5.22). The cast and in-situ prisms exhibited very similar rates of drying shrinkage, suggesting that cast prisms could be used for quality control purposes to measure and monitor in-situ drying shrinkage (Figure 5.23). The dry-process sprayed mix exhibited a slower rate of drying shrinkage than the similar wet-process mix. The restrained shrinkage measurements of the repairs suggest that the shrinkage of a sprayed repair is influenced more by the ambient conditions than by the composition of the mix itself in a similar way to the mortars (Figure 5.24). The inclusion of mesh within the repair also seems to have little effect on the measured values of shrinkage taken from the face of the repair.

The sorptivity showed a slight decrease with increasing in-situ compressive strength (although the range of results was large) and a distinct increase with an increase in the water/cementitious ratio (Figures 5.26 and 5.27). The results for the modulus of elasticity, when compared with the compressive strength, show a similar trend.
compared with published formulas of this relationship, although a wider range of compressive strengths would be needed to accurately reinforce this trend (Figure 5.28). The hardened density for all the types of cube showed no definite trend, although they did correspond closely to their relative values for compressive strength.

The results of the hardened property tests on these fine concretes (pre-blended and designed) suggest that the hardened properties of these mortars (e.g. compressive, flexural and bond strength) are adequate enough for them to be used as repair materials for wet-process application. However, the ability to obtain representative quality control specimens by spraying directly into steel moulds is not as consistent as it is when spraying mortars with a low-volume worm pump (Section 5.2), although it can still be used if care is taken in both spraying the specimen and interpreting the results.

The hardened property results for the fine concretes presented here will be compared with those obtained for the mortars in Section 6.1 and the effect of the constituents on the fresh and hardened properties of these mixes will be discussed in Section 6.2.
Figure 5.2. Compressive cube strength compared with water/cementitious ratio
Figure 5.3. Compressive Cube Strengths: Different Pump Types

Figure 5.4. Bond Strength (a) Overhead and Vertical at 28 days (b) Different Pumps at 7 and 28 Days
Figure 5.5. In-situ compressive cube strength compared with vertical bond strength.

Figure 5.6. 28 day flexural strength of mortars.

Figure 5.7. Compressive cube strength compared with flexural strength.
Figure 5.8. Drying shrinkage of mortars (a) mix D1 (b) mix P3w

Figure 5.9. Drying shrinkage of prisms taken from in-situ material
Figure 5.10. Effect of pump type on 28 day shrinkage

Figure 5.11. Drying shrinkage of P5w and P5d
Figure 5.12. Restrained shrinkage

Figure 5.13. Air permeability of mortars

Figure 5.14. Sorptivity of mortars
Figure 5.15. Sorptivity and air permeability compared with in-situ compressive strength

Figure 5.16. Modulus of elasticity compared with insitu cube strength (mortars)

Figure 5.17. Effect of pump type on properties of mix P5 (a) Compressive strength (b) Bond strength (c) Flexural strength
Figure 5.18. Compressive strengths of fine concretes

Figure 5.19. Compressive cube strength compared with water/cementitious ratio
Figure 5.20. Bond strength (a) 7 and 28 day (b) compared with in-situ compressive cube strength

Figure 5.21. Flexural strength compared with compressive cube strength

Figure 5.22. Drying shrinkage of prisms taken from in-situ material
Figure 5.23. Drying shrinkage of Clp and C2d

Figure 5.24. Restrained shrinkage

Figure 5.25. Restrained and drying shrinkage of (a) C4p and (b) C1Ap
Figure 5.26. Sorptivity compared with in-situ compressive strength

Figure 5.27. Sorptivity of core compared with water/cementitious ratio

Figure 5.28. Modulus of elasticity compared with in-situ cube strength

\[ E = 3.32 f_c^{0.5} + 6.9 \]
Figure 5.29. In-situ hardened density compared with in-situ compressive strength
6 COMPARISONS AND IMPLICATIONS

6.1 COMPARISON BETWEEN MORTARS AND FINE CONCRETES

The hardened property results for the mortars (both pre-blended and designed) and the fine concretes were presented in Sections 5.2 and 5.3 respectively. This Section compares the values obtained for the mortars with those for the fine concretes and briefly examines the relationships between the different properties.

Compressive strength

In general, the fine concretes produced higher compressive strengths than the mortars, as would be expected due to their larger aggregate size and lower water/cement ratios. The highest cast and in-situ cube strengths were obtained by the large-aggregate fine concretes C4p and C5p. Of all the mortars and fine concretes, the lowest cast and in-situ compressive strengths of 26.8-33.9 MPa were obtained with the render/profiling and lightweight repair mortars (P3w and P7w), as would be expected (Figure 5.1). The lowest compressive strengths obtained for the fine concretes were for the sprayed cube moulds (30.1 MPa for CP2p and 34.2 MPa for C1S) due to the difficulty of spraying into a small 100 mm cube mould with a high-output, large-nozzled piston pump (Figure 5.18). This is in contrast to the worm-pumped mortars where a good correlation between the in-situ cube strengths and the specimens obtained from sprayed moulds was found.

The in-situ cube strengths for the mortars were generally higher than the corresponding cast cubes, but for the fine concretes the strengths were very similar. This was partly due to the problems with compacting some of the cast pre-blended mortars, particularly mixes P5, P6 and P7. The highest compressive strength for the mortars was the dry-process mix P8d (54.6 MPa), but the fine concrete dry-process mix C2d had a compressive strength very similar to the wet-process mixes. The core compressive strengths were consistently lower for the fine concretes than the other methods of measurement, a trend not found with the mortars. This could possibly be
due to the larger aggregate size of the fine concretes and the small diameter of the cores.

Although the fine concretes had a slightly higher compressive strength for a given water/cementitious ratio than the mortars, the trends were very similar (Figures 5.2 and 5.19).

**Bond strength**

Figure 5.20(b) shows that the fine concretes possess a relatively narrow range of vertical bond strengths (2.3-3.1 MPa at 28 days), despite having a broad range of in-situ compressive strengths (40.1-80.3 MPa). This compares with a similarly narrow, yet lower, range for the worm-pumped mortars (Figure 5.5), which show a spread of 1.7-2.2 MPa for in-situ compressive strengths of 32.9-53.1 MPa. The piston-pumped mortars in Figure 5.4(b) show a wider range of bond strengths (1.4-2.3 MPa) for a smaller range of in-situ compressive strengths (33.5-44 MPa).

**Flexural Strength**

For the mortars the cast beams generally had the lowest flexural strengths and the in-situ beams the highest (Figure 5.6) but the fine concretes showed no visible trend. For both types of mix the trends in the flexural strength corresponded to the trends in the compressive strength. Problems were also encountered with voidage and rebound for both types of mix when spraying into the beam moulds, although less so when the mortars were sprayed with the low-volume worm pump.

The relationship between the flexural and compressive strengths for both the mortars and the fine concretes (Figures 5.7 and 5.21 respectively) is in line with data for cast concrete (Neville, 1995). However, the concretes presented in Neville followed a trend more similar to the mortars (Figure 5.7) than the fine concretes (Figure 5.21).

**Drying shrinkage**

A narrower range of shrinkage values were obtained with the fine concretes compared with the wet-process mortars (approximately 900-1500 microstrain at 200 days for the
fine concretes compared with 250-2400 microstrain for the mortars (Figures 5.24 and 5.9 respectively)). This is mainly due to the restraining action of the larger aggregates in the fine concretes and the presence of shrinkage compensators in several of the proprietary mortars.

Both the fine concretes (Figure 5.23) and the mortars (Figures 5.8(b) and 5.11) showed little difference in the rates of drying shrinkage between cast and in-situ prisms when wet-sprayed. Differences in the rates of restrained drying shrinkage due to the time of year at which the mixes were sprayed were apparent in both the mortars (Figure 5.12) and the fine concretes (Figure 5.24). The dry-process fine concrete (Figure 5.23) and mortar (Figures 5.11) both had a lower rate of drying shrinkage than when wet-sprayed, as was expected.

The reinforcement mesh had very little influence on the rates of restrained shrinkage for both the mortars and the fine concretes. However, the main purpose of reinforcement mesh is to eliminate cracking, yet no cracking was observed for the mortars or the fine concretes on either the reinforced or unreinforced section.

Sorptivity

Research has shown that sorptivity decreases with an increase in compressive strength due to the increased cement content and lower w/c ratio. This relationship with compressive strength is only slight for the fine concretes (Figure 5.26) and no trend is visible for the mortars (Figure 5.15). The stronger trend for the fine concretes could be due to the mix designs for the mortars being more variable than those for the fine concretes. A clear increase in sorptivity for an increase in water/cementitious ratio for the fine concretes is also visible (Figure 5.27), for both the top and bottom slices of the core.

Modulus of elasticity

The results for the wet-process mortars (Figure 5.16) show lower modulus of elasticity values compared with the in-situ cube strengths than for the fine concretes (Figure 5.28), although a definite trend is difficult to establish for the fine concretes due to the
narrow range of compressive cube strengths. These lower values for the mortars could be due to the lower density of the mortars for a particular compressive strength (Figure 5.29) and the type and proportion of aggregate used.

**Hardened Density**

For the wet-sprayed mortars, the in-situ densities were consistently higher than their cast equivalents (Table 5.3) but no definite trends were visible for the fine concretes (Table 5.6). The range of in-situ hardened densities was also much narrower for the fine concretes (2147-2312 kg/m³) than for the mortars (1433-2230 kg/m³) for a similar range in in-situ compressive strengths (Figure 5.29). This is probably due to the fine concretes having more similar mix designs (in terms of aggregate types and aggregate/cement ratio) than the mortars.

**Wet and dry processes compared**

The hardened density and the elastic modulus were higher for both the mortars and the fine concretes when sprayed with the dry-process compared with the wet process (Tables 5.3 and 5.7). However, the bond strengths were higher for the mortars when sprayed with the dry process (compared with the wet process), but lower for the fine concretes. Also, the compressive cube strengths were higher with the dry process for the mortars, but not significantly different for the fine concretes. This could possibly be due to the dry-process fine concretes containing no superplasticiser (compared with the wet-process fine concretes), which would increase the water/cementitious ratio and therefore the strength. This is in contrast to the dry-process mortars where exactly the same mix design was sprayed as the wet-process mortars, with the only difference being in the water content. All the dry-process mixes (both the mortars and the fine concretes) had a lower drying shrinkage rate than their equivalent wet process mix.

This seems to show that the superior properties traditionally associated with the dry process compared with the wet (higher compressive and bond strengths and lower drying shrinkage) are evident here for the mortars, but the difference is less distinct for the fine concretes. However, it is the authors view that the in-situ compressive strengths and bond strengths produced here with the wet process (38.8 MPa minimum
and 1.4 MPa minimum, for a mortar which is not a lightweight or rendering mortar) are more than adequate for the majority of repair applications. Furthermore, problems can be encountered when the compressive strengths are appreciably higher than the substrate concrete with regard to differential loading caused by the differences in the modulus of elasticity.
6.2 EFFECT OF CONSTITUENTS ON THE FRESH AND HARDENED PROPERTIES

The fresh and hardened properties for the mortars and fine concretes were presented in Chapters 4 and 5 respectively. This Section examines the effect of the constituents on the fresh and hardened properties of the mortars and fine concretes together with the factors that need to be considered when specifying and proportioning these constituents. The effect of these constituents on the pumpability and sprayability of the materials is also considered. Some of these relationships have been presented and discussed in previous Sections (e.g. water/cement ratio and compressive strength) and so will not be discussed here. The mix designs are presented in Sections 3.4.2 (pre-blended mortars) and 3.4.3 (designed mortars and fine concretes) and the test methods in Sections 3.6 and 3.7.

It should be remembered that this work is based upon concrete and mortar and that many of the relationships between the different properties (both fresh and hardened) and constituents are already known and have been researched and proven many times (e.g. cement content and compressive strength, water content and slump). This Section therefore concentrates on the constituents and properties most relevant to wet-process sprayed repair work.

Cement

Cement obviously has a great influence on the hardened properties of a mortar or concrete, but it also has an effect on the rheological properties. A low cement content (and therefore high aggregate content) decreases the cohesiveness of a mortar and increases the rate of bleeding (Figure 4.11, mortars P1, P4, D5 and D6). However, too high a cement content can cause increased resistance within the line and hence a lower pumping rate, or even blockage. This is illustrated by mortar D12w (Tables 3.10 and 4.10) which had an aggregate:cement ratio (by weight) of 1:1 which resulted in a comparatively low output (3 l/min) and a high pumping pressure (10 bar), despite the mix having a low vane shear strength (0.87 kN/m²) and an average slump (65 mm). Also, a low cement content can create a low output due to the inadequate thickness of
lubricating layer around the ‘plug’ of material. For example, mortar D7w pumped too slowly to conduct a build test, despite having a low vane shear resistance (1.03 kN/m²) and average slump (75 mm) (see Tables 3.9 and 4.1). It is known that increased cement contents facilitate adhesion and build thickness and this is shown here by comparing the cement contents (Table 3.9) and the build length and mass of mortars D5 and D6 (Table 4.1). An increase in cement content obviously also increases many of the hardened properties, such as the compressive, flexural and bond strengths (e.g. Figure 5.1(b)). An increased cement content is also known to increase the drying and restrained shrinkage, but no trends were found in this work (Figure 5.9). However, comparisons are difficult to make due to the presence of shrinkage compensators in some of the proprietary mixes.

Aggregate

The aggregate grading is critical to the rheological properties of fresh mortars and concretes and to the structure of the hardened product. The proportion of aggregate within a mix is connected to the cement content and so many of the relationships discussed in the previous paragraph are also relevant here (e.g. the high bleed rate of mortars P1, P4, D5 and D6 due to their low cement content (and therefore high aggregate content)). Aggregate grading, as well as proportion, affects the bleed rate, as shown in Figure 4.11. The aggregate in mortar D1 has more fines than mortar D4 and hence required a higher water content for the same workability which resulted in a higher total bleed. However, in practice, mortar D4 would not pump due to excessive bleeding, as even though the water content was low, the aggregate grading was poor and so the small amount of liquid in the mix bled out. This compares with mortar D1, where even though the water content was higher, it was effectively ‘locked in’ by the good aggregate grading. The fine concrete C4p had a large proportion of coarse aggregate compared with the other mixes and was the worst mix at encasing the reinforcement (Figures 4.35 and 4.36), although this is more likely to be attributable to the low water/cement ratio and low slump.

The pumpability and other properties of mortars D9w, D10w, D11w and D12w were greatly effected by the grading of the aggregates, despite the mixes having the same aggregate/cement ratio (Table 3.10 and 4.10). These mixes illustrated that if the total
grading of the dry constituents is outside of the band in Figure 3.7 then pumping problems are likely to occur.

The coarse aggregate in the fine concretes C4p and C5p increased the compressive strength and hardened density of the mixes (Figure 5.18 and Table 5.6 respectively), even though the total aggregate/cement ratios were very similar to the other fine concretes. These mixes also had the lowest rate of drying shrinkage of all the fine concretes (Figure 5.22) and one of the lowest rates of restrained shrinkage (Figure 5.24).

The lightweight filler in mortar P7w had little effect on the pumpability of the mortar as it is generally the grading and proportion of the aggregate or filler that is important, rather than the density. P7w did however, have one of the lowest bleed rates of the mortars tested (Figure 4.11(a)). As would be expected, high build values were achieved with the lightweight mortar (Table 4.1), although low compressive strengths (Figure 5.1(a)), very low bond strengths (Figure 5.4(a)) and high drying shrinkages (Figure 5.9) were also observed, probably due to the high water/cement ratio of the mix (Figure 5.2).

Water content

The water content of a mortar or concrete is obviously critical to its rheological and hardened properties, and relationships such as the water/cementitious ratio and compressive strength are well known (Figures 5.2 and 5.19). However, the water content and water/cementitious ratio are even more critical for sprayed mortars and concrete. Generally, as the water content increases, the slump increases and the vane shear strength decreases (Figures 4.1 and 4.25). A higher water content also increases the probability (and potential volume) of bleeding, although this is also dependant upon the grading and proportions of the other constituents (Figure 4.11). Figures 4.45 and 4.46 show that the water content (or slump) affects the build of the material, with the build decreasing as the slump increases for the fine concretes (in the range shown) and the build increasing then decreasing for the mortars. A balance therefore has to be obtained to ensure that the material is workable enough to pump yet is stiff enough to produce an adequate build. This increase and decrease in build with increase in slump
is shown in Table 4.2, which also shows the decrease in cast compressive strength with increasing slump (due to the increasing water/cementitious ratio). Interestingly, the stiffest mix in this study (with a 5 mm slump) would not spray effectively into the cube moulds without producing air voids and so despite having a low water/cementitious ratio it had a low compressive strength. This relationship is investigated further in Figures 4.36 and 4.37, where an increase in voids for a decrease in the water/cementitious ratio is shown. Clearly a balance for the water content needs to be obtained, not only for the build (as previously mentioned) but also between achieving good reinforcement encasement (where a high water content is beneficial) and adequate hardened properties (where a low water content is beneficial). Superplasticisers and water-reducers can obviously be used to help achieve this balance, but care is still required.

Silica fume

Silica fume is known to increase cohesiveness, reduce bleeding and improve the hardened properties of mortars and concretes. However, the rate of addition in this study was 5% by weight of cement for all the mixes and so the effect of the silica fume was difficult to assess.

SBR

All the laboratory-designed mortars contained SBR in a 1:3 SBR:water solution except for mixes D5 and D6 (Table 3.9). Mortar D5 had very similar rheological properties in terms of g and h as the similar mix D1, which was the same as D5 except for the presence of SBR (Figure 4.6). However, the inclusion of SBR greatly reduced both the rate, and total amount bleeding (Figure 4.11(b)). This figure shows the relatively low cement content and lack of SBR contributing to the high rate of bleeding of mortar D6. However, mortar D5 had a build value (270 mm) and maximum failure stress higher than D1 (Table 4.1), suggesting that the presence of SBR hindered build. D6w also had a similar build to D1, despite having a lower cement content. D5 also had a slightly lower compressive strength than the similar mix D1w (Figure 5.1). These results suggest that SBR increases the pumpability (by reducing bleeding) but may reduce the sprayability (by reducing the build attainable).
However, more testing would be needed at different dosage rates to investigate this further, as would additional testing of the hardened properties (compressive and bond strength, and permeability and sorptivity).

Fibres

Most of the pre-blended mortars (except P1) contained small amounts of polypropylene fibres, mainly to reduce plastic shrinkage (which was not measured in this study) and to increase the cohesiveness. However, the fibres seemed to have little effect on the other rheological and hardened properties, when compared with the mortars with no fibres (P1 and all of the laboratory-designed mixes). The fibres had more of an effect in the fine concretes, mainly due to the increased proportion added. The polypropylene and the steel fibres had little effect on the compressive strength of the fine concretes (Figure 5.18), although they were associated with a slight increase in the bond strength (Figure 5.20(a)) and the flexural strength (Table 5.4). However, the polypropylene fibre-reinforced fine concretes CP1p and CP2p both had the highest rates of drying shrinkage of all the fine concretes (Figure 5.22), possibly due to their high water/cementitious ratios (Table 3.12). The high proportion of polypropylene fibres in CP1p caused the mix to pump in bursts (Table 4.7), which made it very difficult to use, and liable to block. However, the similar mix CP2p which contained less fibres, pumped well. The steel fibre-reinforced fine concrete C1S built up on the substrate in a very narrow cross/section (Figures 4.28, 4.50 and 4.55) and obtained the highest build of all the mixes in this study of 320 mm (Table 4.7). In contrast, CP1p and CP2p had relatively low build values (160 mm and 180 mm respectively). However, a large proportion of the steel fibres were present in the rebound (Table 4.8).

Superplasticiser

All of the fine concretes contained superplasticiser, except for mixes C2d, C3p and C3Ap. None of the mortars contained superplasticiser. It would be expected that the increased water/cementitious ratio of the fine concrete C3p (compared with the similar mix C1p) would affect the properties of the mix. However, only small differences were evident and most properties, such as the drying shrinkage, were very similar.
(Figure 5.22), despite the higher water/cementitious ratio. The hardened density of C3p compared with C1p (for all types of specimen) was higher (Table 5.6). As would be expected, the sorptivity of C3p was higher than for mix C1p (Figure 4.34 and Table 5.5), although the reinforcement encasement was very good (Figure 4.36).

**Air entrainment**

Air entrainment was used in this study in mixes C1Ap, C3Ap and D8Aw to try to increase their pumpability. For all these mixes a balance for the level of air entrainment had to be obtained. Mortar D8Aw-1 had an initial air content of 15% and a slump of 40 mm and would not pump, even when water was added to increase the slump to 70 mm (Table 4.3). Similarly, C1Ap-1 had an air content of 23% and would not pump, and the similar mix C1Ap-2 would still not pump with an air content of 18%. The air content was reduced further to 15% for mix C1Ap and this pumped and sprayed effectively and a high build value of 285 mm was obtained. C3Ap-1 would also not pump due to the high air content, but the similar mix C3Ap pumped and sprayed with an air content of 12.5%. However, the build produced was very low (130 mm) due to the high workability of the mix (60 mm slump after spraying (Table 4.7)).

A balance has therefore to be obtained so that a mix has an air content high enough to make it workable and therefore pumpable, but low enough so that the air does not compress in the line and cause a blockage. The water content has also to be considered so that the mix is stiff enough to produce an adequate build. The air-entrained mix C1Ap produced very good atomisation but high rebound (Table 4.8). C1Ap produced the highest compressive and flexural strengths and densities compared with the similar fine concretes in Figure 5.18 and Tables 5.4 and 5.6 (except the larger aggregate mixes C4p and C5p). However, mix C3Ap (with no superplasticiser) produced some of the lowest compressive strengths.

Care should be taken with air entrained mixes when assessing a mix’s pumpability from its rheological properties (slump, vane shear strength, g and h etc.) as the mixes can seem workable enough to pump, yet will still cause a blockage as the air in the mix is compressed (Figure 4.25). However, the two-point test does seem to give an indication with regards to the pumpability of air-entrained mixes (Figure 4.26) and the other rheological tests can be used in combination to also give an indication of
pumpability (Figures 4.40, 4.41 and 4.43). Air-entrainment also makes it difficult to predict the build (Figure 4.32) and failure stresses (Figure 4.31) of a mix before pumping.
6.3 IMPLICATIONS FOR PRACTICE

This Section examines the Repair Scenarios discussed in Section 3.2 and discusses the properties (both fresh and hardened) required by a mix design to satisfy these scenarios. Examples of possible mix designs for each scenario (from this work), both laboratory-designed and proprietary mixes, are also provided. It should be remembered that the fresh and hardened properties required from a mix are the same whether if it is site-batched or pre-blended. Other factors which would influence the choice of materials such as cost and quality control are not discussed here.

Many of the properties of fresh and hardened mortars and concretes are usually desirable, if not essential, for all the repair scenarios and so these are not discussed in depth e.g. low bleeding, cohesiveness, good adhesion and bond strength, low rebound and dust, low air permeability and sorptivity, comparative elastic modulus etc. These properties are only mentioned when they are particularly relevant to a repair scenario e.g. good bond strength in overhead applications. Similarly, the constituent properties for a repair scenario are only listed when they have an influence on the application. Good mix design practice and good site practice should always be followed regardless of the application. The main constituents (such as cement and aggregate) are not mentioned unless specifically relevant to a scenario. Constituents not studied in this work (e.g. retarders and shrinkage compensators) are only briefly mentioned and are not discussed in depth. The discussion also concentrates on wet-process sprayed concrete properties, not conventional cast concrete or hand-applied repairs.

The repair scenarios are shown in Table 6.1 together with the parameters to consider when selecting a mix design for each application, grouped under headings of fresh and hardened properties, pumpability and sprayability. The building repairs (cover and structural) have been brought together into one category for simplification. Suggestions for alternative constituents for each mix design are provided, as are possible mix designs from this work. It should be remembered that every mix design is a balance and compromise between the constituents, properties, performance and cost.
Bridge soffit

The main considerations for this scenario are good strength (compressive, flexural and bond), low permeability and shrinkage (due to the presence of chlorides), overhead working, and difficult access (possibly at restricted times). This means that a cohesive, rapid setting, low density and low slump mix is preferable with good build, good reinforcement encasement and low rebound. These properties could be enhanced with the use of silica fume, SBR and possibly accelerators or air entrainment. Steel fibres are also an option in place of the mesh if access is especially difficult. Possible mixes from this work are C1p, C1Sp, C1Ap, P2p and D1p or derivatives of these. The other pre-blended mixes would satisfy most of the requirements but a piston pump would ideally be needed due to the size and elevation of the repairs. The pre-blended proprietary mortar P7w, although being lightweight and having adequate strength and permeability properties, had a very low bond strength (Figure 5.4) and so would not be recommended.

Bridge abutment

This scenario is similar to the previous scenario (the bridge soffit) except that the surfaces are vertical, access is easier and less restricted and therefore the requirements for cohesiveness, setting rate and build are less. The main criteria are therefore strength and chloride resistance. The mixes mentioned previously are therefore suitable, together with mixes C4p, C5p and D1w. Most of the wet-process pre-blended mortars (except P7w) would also be suitable and the choice of pump would depend upon the size and quantity of the repairs. Increased silica fume and the addition of SBR could also both be used to improve the permeability (and the cohesiveness) of the mixes.

Arch bridge

Excellent bond, restricted access and good strength are the main considerations for this scenario and so high-quality mixes such as C4p and C5p are recommended. Steel fibres could also be incorporated if mesh is difficult to fix and a bonding agent and possibly an accelerator at the nozzle may be helpful. Steel mesh would be useful (if possible to fix) to provide initial support for the concrete before it sets as deteriorated
masonry is a very poor substrate. Careful substrate preparation would therefore be critical.

Building
The building scenario is a combination of vertical and overhead surfaces, and internal and external environments. Ideally (and usually) the same mix will be used for all of a structure and so the choice of mix depends upon the balance between the size of the internal/external and vertical/overhead repairs. A worm pump (small or large) would probably be easier to handle inside a building and so most of the pre-blended mixes could be used. If structural strength and chloride resistance is required then the higher grade mortars such as P2w, P4w or P6w or the laboratory-designed D1w are most suitable. If internal cover is all that is needed (i.e. non load-bearing with no chlorides present) then a cheaper grade of mortar could be used such as P1w, D2w, D5w or D6w. If thin overlays and renders are required then P3w would be an obvious (though expensive) option. Fillers and silica fume could be used if low permeability and a good finish are required and polypropylene fibres could be added to improve the fire resistance. Pigments can also be added to the mix to provide a colour match if necessary.

RC chimneys
Access problems due to the height is the main consideration in this scenario and so the mix needs to be cohesive, with low bleeding and a long workable life to enable it to be pumped high up the structure. Depending upon the chimney, either a large piston pump on the ground could be used or a small (and light) worm pump could be lifted up with the scaffold as the work progressed. Steel fibres are also an option (with the piston pump only) if access is a problem with fixing steel mesh. High-grade mixes are not needed as the repairs are not structural and so the cheaper mixes D1w, D2w, P1w or P4w could be used with the worm pump and C3p with the piston pump, all of which would produce adequate hardened properties.

Water-retaining structures
Low permeability and good tensile strength (to resist cracking) are the main considerations for this scenario, and possibly rapid placement depending upon the
time available for the repair. Mesh or steel fibres are needed for crack control, and silica fume, SBR and a superplasticiser to enhance the permeability. Air entrainment would improve freeze/thaw resistance if this is required (depending upon the environment). The mortars D1p, P2p, P3w P4w, P5w and P6w and the fine concretes C1p, C1Sp, C1Ap, C4p or C5p are most suitable, or derivatives/combinations of these.

**Marine structures**
The main points to consider with this scenario are the presence of chlorides, abrasion resistance, good bond strength and restricted access (due to the tides). This therefore requires a cohesive mix which could be rapidly placed and have good adhesion, low permeability, sorptivity and shrinkage and high chloride, abrasion and freeze/thaw resistance. Steel fibres could improve abrasion resistance and air entrainment the freeze/thaw resistance. Silica fume and SBR are needed for cohesiveness and to enhance the permeability and sorptivity characteristics. A high grade mix is therefore recommended, such as C4p, C5p, C1Sp or C1Ap, or a combination, which would include the well-graded aggregates of C4p and C5p, the steel fibres of C1Sp and the air entrainment of C1Ap.

**Tunnels**
Tunnel repairs are found to be mainly structural and so a strong mix is required. Other considerations include the presence of chlorides, a damp atmosphere, overhead working, restricted access and long pumping distances. A mix with a high compressive, flexural and bond strength and low permeability is therefore needed which also has good cohesion, adhesion and build, low rebound, good encasement and a long workable life. A high grade mix such as C4p or C5p would be most suitable possibly with a retarder (with or without an accelerator at the nozzle) to extend the setting time.

**Sewers**
A sewer is basically a small masonry tunnel with the same problems as mentioned above, except that access is usually even more restricted and the environment is more aggressive. A similar mix to above is therefore required, possibly with increased silica
fume and some SBR for enhanced permeability, sorptivity and chemical resistance characteristics. Steel fibres could also be considered as a replacement for reinforcing steel due to the access problems.
<table>
<thead>
<tr>
<th>TYPE OF REPAIR</th>
<th>FRESH PROPERTIES</th>
<th>PUMPABILITY</th>
<th>SPRAYABILITY</th>
<th>HARDENED PROPERTIES</th>
<th>CONSTITUENTS</th>
<th>POSSIBLE MIXES</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge soffit</td>
<td>low density, high cohesiveness, low slump, possibly rapid setting</td>
<td>Rapid placing, possibly small pump and nozzle</td>
<td>Excellent adhesion, cohesion and build - stiff on impact Good build Low rebound Good encasement (if mesh) Possibly good environment</td>
<td>Good compressive, flexural and bond strength for strengthening, low permeability and low sorptivity due to chlorides Low density</td>
<td>Lightweight aggregate and fillers? Possibly steel fibres silica fume for strength, cohesiveness, rebound and low permeability SBR - bond and low permeability air-entrainment as slump-killer Possible accelerators</td>
<td>C1p, C1Sp, C1Ap, P2p and D1p</td>
<td>Mesh difficult to place overhead, therefore steel fibres</td>
</tr>
<tr>
<td>Bridge abutment</td>
<td>Possibly rapid setting</td>
<td>Rapid placing, high output, possibly small pump and nozzle</td>
<td>Low rebound and dust, Possibly good environment (if over water or rail lines)</td>
<td>Good compressive, flexural and bond strength for strengthening, low permeability and low sorptivity due to chlorides</td>
<td>silica fume for strength, cohesiveness, rebound and low permeability SBR – bond and low permeability Large aggregates for strength (and economy) Possible accelerators</td>
<td>C1p, C1Sp, C1Ap, P2p, D1p, C4p, C5p and D1w</td>
<td>Economic to use same mix as for soffit if applicable</td>
</tr>
<tr>
<td>Arch bridge</td>
<td>Low density, high cohesiveness, low slump, possibly rapid setting</td>
<td>Rapid placing, possibly small pump and nozzle</td>
<td>Excellent adhesion, build and cohesion - stiff on impact Good build Low rebound Good encasement (if mesh) Possibly good environment</td>
<td>Good compressive and flexural strength for strengthening, excellent bond strength Low density</td>
<td>Lightweight aggregate and fillers? Possibly steel fibres, silica fume for strength, cohesiveness and rebound, SBR – as a bond primer, air-entrainment as slump-killer, Possible accelerators</td>
<td>C4p and C5p</td>
<td>Mesh difficult to place overhead, therefore steel fibres. Careful substrate preparation needed</td>
</tr>
<tr>
<td>Buildings</td>
<td>For overhead-low density, high cohesiveness and low slump</td>
<td>Possibly small pump and nozzle (confined space)</td>
<td>Low rebound and dust, Good environment if inside Good encasement needed if mesh or lapped bars Good adhesion, cohesion and build for overhead</td>
<td>Good compressive, flexural and bond strength for structural, low permeability and low sorptivity if chlorides, Low density if overhead</td>
<td>Colour match if required, Good grading with small aggregate, fillers and silica fume if good finish required, or a flash coat, Possible poly fibre and air entrainment for fire resistance Possible steel fibres</td>
<td>P2w, P4w, P6w or D1w or P1w, P3w, D2w, D5w or D6w</td>
<td>Possible internal access problems</td>
</tr>
<tr>
<td>r.c. chimneys</td>
<td>Low slump, long open time, cohesiveness, no bleeding</td>
<td>Pump able to pump to a large height or light pump and nozzle to be used on scaffold</td>
<td>Low rebound and dust, Possibly good environment</td>
<td>General good concrete properties</td>
<td>Retarders, pumping agents, Possibly steel fibres, Possibly lightweight aggregates, Silica fume &amp; SBR for cohesiveness and to prevent bleeding</td>
<td>D1w, D2w, P1w or P4w or C3p</td>
<td>Mesh difficult to place at high level, therefore steel fibres. Access difficult</td>
</tr>
</tbody>
</table>
**Table 6.1 Repair Scenarios - Parameters to Consider - Part 2 of 2**

<table>
<thead>
<tr>
<th>TYPE OF REPAIR</th>
<th>FRESH PROPERTIES</th>
<th>PUMPABILITY</th>
<th>SPRAYABILITY</th>
<th>HARDENED PROPERTIES</th>
<th>CONSTITUENTS</th>
<th>POSSIBLE MIXES</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water retaining structures</td>
<td>Low slump, possibly rapid setting</td>
<td>Rapid placing, high output, probably piston pump</td>
<td>Possibly good environment, good encasement (if mesh)</td>
<td>Good tensile strength if cracking possible, low drying shrinkage, low permeability and sorptivity</td>
<td>Possible accelerators, small aggregates and fillers for thin sections, possibly steel fibres, silica fume and SBR for permeability, possibly air entrainment for freeze/thaw</td>
<td>D1p, P2p, P3w, P4w, P5w or P6w or C1p, C1Sp, C1Ap, C4p or C5p</td>
<td>Cracks possibly injected before application of repair, caution with steel fibres due to corrosion. Care to be taken with substrate preparation</td>
</tr>
<tr>
<td>Marine structures</td>
<td>Cohesive (low wash-out), low slump, possibly rapid setting</td>
<td>Rapid placing, high output, probably piston pump</td>
<td>Low rebound, good encasement (if mesh), good adhesion</td>
<td>Good tensile strength if cracking possible, low drying shrinkage, low permeability and sorptivity, high chloride and abrasion resistance, freeze/thaw resistance</td>
<td>Possible accelerators, possibly steel or poly fibres, silica fume and SBR for cohesiveness, low permeability &amp; sorptivity, possibly air entrainment for freeze/thaw and as a slump-killer</td>
<td>C4p, C5p, C1Sp or C1Ap</td>
<td>Access problems due to tides, very aggressive environment, care to be taken with substrate preparation</td>
</tr>
<tr>
<td>Tunnels</td>
<td>Low slump, long open time, cohesiveness, no bleeding, possibly rapid setting</td>
<td>Pumping long distances, piston pump, high output</td>
<td>Low rebound and dust, good build and cohesion, good environment, good encasement (if mesh), good adhesion</td>
<td>Good compressive, flexural and bond strength, low permeability and sorptivity, preferable low density for overhead</td>
<td>Possibly a retarder and SP and accelerator system, possibly air-ent. as a slump-killer, steel fibres for flexural strength and toughness, silica fume &amp; SBR for cohesiveness, low permeability &amp; sorptivity, good grading required for pumpability, flash coat possibly</td>
<td>C4p or C5p</td>
<td>Access problem therefore possibly fibres not mesh, long pumping distances and open times often needed</td>
</tr>
<tr>
<td>Sewers (masonry tunnels)</td>
<td>Low slump, long open time, cohesiveness, no bleeding</td>
<td>Pumping long distances, possibly small pump inside tunnel or larger pump externally</td>
<td>Low rebound and dust, good build and cohesion, good environment essential, excellent adhesion, good encasement</td>
<td>Good compressive and flexural strength, excellent bond strength, low permeability and sorptivity, preferable low density, low shrinkage, abrasion resistance</td>
<td>Possibly a retarder and SP and accelerator system, possibly air-ent. as a slump-killer, steel fibres for flexural strength, toughness and abrasion resistance, silica fume &amp; SBR for cohesiveness, very low permeability &amp; sorptivity, good grading required for pumpability</td>
<td>C4p or C5p</td>
<td>Access very difficult therefore possibly fibres not mesh, long pumping distances and open times often needed, water/chemical abrasion resistance needed</td>
</tr>
</tbody>
</table>
7 CONCLUSIONS AND RECOMMENDATIONS

7.1 INTRODUCTION

Concrete repair in general and the durability of concrete has been well researched in the past but little of this has dealt with low-volume wet-process sprayed mortars and fine concretes. Research has also been conducted on the rheology of cement pastes, mortars and concretes, but little of this is related to low-volume pumping and spraying. Pumping has also been investigated, but this has been mainly concerned with high-volume and large-aggregate mixes. Only a limited amount of research exists that investigates both the pumping process, the spraying process and their influence on the hardened performance of the in-situ repair material. The study aimed to address this lack of knowledge and this chapter presents the conclusions drawn, together with the recommendations for further study. The conclusions are presented in four sections: fresh properties of mortars and fine concretes; hardened properties of mortars and fine concretes; effect of constituents on the fresh and hardened properties and the repair scenarios.

The recommendations are principally aimed at four areas: materials and mixes, pumping and spraying, fresh property test methods and hardened property test methods.

7.2 CONCLUSIONS

7.2.1 Fresh properties of mortars and fine concretes

Shear vane strength

A shear vane test has been developed which can give an instantaneous measurement of the shear strength of a material at a variety of points in the process (mixer, pump, sprayed etc.) and a good correlation with slump has been found for pumpable materials (Figure 4.40).
Flow resistance and flow viscosity

The Two-point rotational viscometer produced satisfactory results with mortars and fine mortars with low workabilities, although care needs to be taken in both conducting the test and interpreting the results (Sections 4.2.3 and 4.3.3). It can be concluded that the grading of the constituents and the presence of polymers both had a significant effect on the flow resistance and plastic viscosity. Superplasticiser and air-entrainment both affected the results and they indicated that the apparatus could be used in predicting the pumpability of air-entrained mixes. The results obtained with the Viskomat for the pre-blended mortars were inconclusive, difficulties being encountered due to their low workability and the tendency of some mixes to entrain air or trap polypropylene fibres around the measuring paddle.

Build and failure stress

A new method which measures the build in terms of the maximum shear and bending stresses generated at failure has been applied to the mortars and fine concretes and a relationship between these failure stresses, the build, the slump, the flow resistance and the vane shear stress of the mixes has been found (Sections 4.2.7 and 4.3.4). The build test also demonstrated how the failure mode changes from a cohesive to an adhesive failure as the workability of a mix decreases.

Pressure bleed test

It can be concluded that the presence of an SBR reduces both the rate and total emission of liquid from a mortar under pressure in the pressure bleed test (Section 4.2.6). The proportion of fine material and the water content of a mix were also crucial factors in the amount and rate of liquid emitted: the coarser the mix and the higher the initial water content of a mix then the higher the bleed.

Rheological audit

A rheological audit has been developed and tests for each stage within this audit have been used to characterise the pumpability and sprayability of each mortar and fine concrete (Section 4.2.1). The results presented show that tests can be used to indicate the workability (slump and shear vane), pumpability (two-point test and pressure
bleed test) and sprayability (build, maximum failure stresses, sorptivity and visual grading) of the different materials.

**Reinforcement encasement**

Two methods for assessing the reinforcement encasement were investigated, visual core grading and sorptivity measurement (Section 4.2.8 and 4.3.5). Once an initial density of reinforcement had been reached, the sorptivity of the material did not increase greatly as the density of reinforcement increased. The visual grading was a simple test that accurately measured the encapsulation of the bars. The two methods should be used together when assessing the quality and durability of a sprayed concrete repair. It can also be concluded that the mix design and spraying velocity both influenced the encasement, with an increase in slump and an increase in the velocity both improving the encasement.

**Equipment**

Tests on the different nozzles concluded that the 9 mm aperture brass nozzle produced the best atomisation and the highest minimum particle speed of the worm pump nozzles tested (Section 4.2.9).

The different types of wet-process pumps (small- and large-diameter worms and piston pump) had little effect on the compressive and flexural strengths of the mortars. However, the output of the pump and the size and design of the nozzle influenced properties such as bond strength and the compressive strengths of the sprayed moulds; the small worm pump being best able to spray directly into a cube mould with minimum voids, therefore producing a higher compressive strength. These specimens could then be used for quality control purposes such as compressive cube strength.

**7.2.2 Hardened properties of mortars and fine concretes**

**Compressive strength**

The laboratory-designed mortars possessed high compressive and flexural strengths compared with the commercially available pre-blended mortars and a good correlation exists between the in-situ and the sprayed mould compressive cube strengths, providing that no large voids or excessive rebound is present (Sections 5.2.1 and
5.3.1). The type of wet-process pump (small- and large-diameter worms and piston) had little effect on the strengths of the mortars (Figure 5.3). However, the output of the pump and the size and design of the nozzle did influence properties such as bond strength and the compressive strengths of the specimens sprayed into moulds; the small worm pump was best for spraying directly into a cube mould with minimum voids, thereby producing a higher compressive strength. Generally, it can be concluded that the fine concretes produced higher compressive strengths than the mortars. The lowest cast and in-situ compressive strengths for the mortars were obtained with the render/profiling and lightweight repair mortars, as expected.

**Bond strength**

The fine concretes had a relatively narrow range of vertical-surface bond strengths, despite having a broad range of in-situ compressive strengths. This compares with a similarly narrow, yet lower, range for the worm-pumped mortars (Figures 5.5 and 5.20). The type of wet-process pump affected the bond strength, but this was due more to the stream velocity and water/cementitious ratio than the pumping process itself.

**Flexural Strength**

It can be concluded that for both the mortars and the fine concretes the trends in the flexural strength corresponded to the trends in the compressive strength. Greater standards of deviation were obtained with the fine concretes compared with the mortars due to voids and rebound entrapment when spraying into the beam moulds with the piston pump.

**Shrinkage**

It is concluded that the dry-process sprayed mixes (both mortars and fine concretes) exhibited less drying shrinkage than their equivalent wet-process or cast mixes (Figures 5.9 and 5.22). The cast and in-situ prisms had very similar rates of drying shrinkage, suggesting that cast prisms could be used for quality control purposes to measure and monitor in-situ drying shrinkage. A narrower range of shrinkage values was obtained with the fine concretes compared with the wet-sprayed mortars. The reinforcement mesh had very little influence on the rates of restrained shrinkage for both the mortars and the fine concretes. The restrained shrinkage strains suggest that
the shrinkage of a sprayed repair is influenced more by the ambient conditions (mainly temperature and humidity, but also rain, wind and sunlight) than by the composition of the mix itself.

_Sorptivity and air permeability_

The air permeability of the mortars decreased with an increase in compressive strength, as would be expected (Figure 5.15). However, the sorptivity did not show such a clear relationship: the fine concretes showed a slight decrease with increasing compressive strength and a distinct increase with an increase in the water/cementitious ratio.

_Modulus of elasticity_

The wet-process mortars had lower modulus of elasticity values (for a given in-situ cube strength) than the fine concretes, possibly due to their lower density and the type and proportion of aggregate used (Figures 5.16 and 5.28).

_Hardened Density_

The mortar in-situ densities were consistently higher than their cast equivalents, but no definite trend was found for the fine concretes. The range of densities was also much narrower for the fine concretes.

_Sample type_

The correlation between in-situ and sprayed mould compressive cube strengths is not as consistent for the fine concretes as for the mortars, although comparisons can be made providing that no large voids or excessive rebound are present. The lowest strength fine concretes were from the sprayed cube moulds, due to the difficulty of spraying. This is in contrast to the worm-pumped mortars where a good correlation between the in-situ cube strengths and the specimens obtained from sprayed moulds was found. The in-situ cube strengths for the mortars were generally higher than the corresponding cast cubes, but for the fine concretes the strengths were very similar. For mortars, it can be concluded that the cast beams generally produced the lowest flexural strengths and the in-situ beams the highest, but the fine concretes showed no visible trend.
**Wet and dry processes compared**

The hardened density and elastic modulus were higher for both the mortars and the fine concretes when sprayed with the dry process compared with the wet process, as were the bond strengths of the mortars (Section 5.3.8). However, the dry process fine concretes produced lower bond strengths. Also, the mortar compressive cube strengths were higher with the dry process, but not significantly different for the fine concretes. All the dry-process mixes (both mortars and fine concretes) had a lower drying shrinkage than their equivalent wet-process mix.

It can be concluded therefore that there is some evidence to support the traditional view of the superior properties associated with the dry process compared with the wet (such as higher strengths and lower drying shrinkage) in the case of mortars, but the difference is less distinct with fine concretes. Even so, the compressive and bond strengths produced with the wet process (30-60 MPa compressive and 1.7 MPa bond strength minimum for non-lightweight mortars) are more than adequate for the majority of repair applications. Of particular attraction to the designer/specifier is the knowledge that the mix specified, once pumped and sprayed, will be the mix in-situ (without the uncertainty of the water content controlled by the nozzleman in the dry process, and the further effect of differential rebound).

**7.2.3 Effect of constituents on fresh and hardened properties**

**Cement content**

It can be concluded that a low cement content (and therefore high aggregate content) decreases the cohesiveness of a mortar, increases the rate of bleeding and decreases the output. However, too high a cement content causes increased resistance within the line and hence a lower pumping rate, or even blockage. An increased cement content facilitates adhesion and build and obviously also increases many of the hardened properties, such as the compressive, flexural and bond strengths.
**Aggregate**

It can be concluded that the aggregate grading, as well as proportion, affects the bleed rate, with finer, well graded aggregates bleeding less than coarser aggregates. The finer the aggregate then the higher the water content required to obtain the same workability which can result in a higher total bleed. However, in practice, the coarse mortar would not pump due to excessive bleeding, as even though the water content was low, the aggregate grading was poor and so the small amount of liquid in the mix would bleed out. This compares with the fine mortar where, even though the water content was higher, it was effectively ‘locked in’ by the good aggregate grading. If the total grading of the dry constituents of a mortar is outside of the pumpable grading zone presented in Section 3.4.3 then pumping problems are likely to occur.

The fine concretes containing 8 mm coarse aggregate had the highest compressive strength and hardened density of all the mixes. These mixes also had the lowest rate of drying shrinkage and one of the lowest rates of restrained shrinkage.

Lightweight filler had little effect on the pumpability of the mortar (except in large proportions, such as mix D12w). As would be expected, high build values were achieved with the lightweight mortar, although low compressive strengths, very low bond strengths and high drying shrinkage was also observed.

**Water content**

It is concluded that in general, as the water content increases, the slump increases and the vane shear strength decreases, for both mortars and fine concretes. A higher water content also increases the probability (and potential volume) of bleeding. The build decreases as the slump increases for the fine concretes and the build increases then decreases for mortars (in the range presented here). A balance therefore has to be obtained to ensure that the material is workable enough to pump yet is stiff enough to produce an adequate build. A balance also needs to be obtained between achieving good reinforcement encasement (where a high water content is beneficial) and adequate hardened properties (where a low water content is beneficial).
Additives and additions

It can be concluded that the inclusion of SBR reduces both the rate, and total amount bleeding.

The polypropylene and steel fibres slightly increased the bond and flexural strength in the fine concretes. However, the polypropylene fibre-reinforced fine concretes had the highest rates of drying shrinkage of all the fine concretes. At high proportions of polypropylene fibres the piston-pumped fine concrete mix pumped in bursts, which made it very difficult (and dangerous) to use. The steel fibre-reinforced fine concrete obtained the highest build of all the mixes in this study. In contrast, the polypropylene fibre-reinforced fine concretes had relatively low build values.

Initial air contents of 15% for mortars and 18% and 23% for the fine concretes would not pump. A fine concrete initial air content of 15% pumped and sprayed effectively and a high build value was obtained. In conclusion, a balance has to be obtained so that a mix has an air content high enough to make it workable and therefore pumpable, but low enough so that the air does not compress excessively in the line and cause a blockage. Care should be taken with air entrained mixes when assessing a mixes pumpability from its rheological properties (slump, vane shear strength, g and h etc.) as the mixes can seem workable enough to pump, yet will still cause a blockage as the air in the mix is compressed. However, the two-point test does give an indication with regards to the pumpability of air-entrained mixes and the other rheological tests can also be used in combination with the two-point test to give a further indication of pumpability.

7.2.4 Repair scenarios

A survey of eleven local authorities, consultants, contractors and material suppliers was used to identify a set of ten generic repair scenarios and their performance requirements. Advice is given on possible mixes and methods which are suitable for these scenarios. A designer/specifier should now be able to identify a repair scenario, select a mix design from this work and with minimal alterations make it suitable for use on that particular scenario.
7.3 RECOMMENDATIONS FOR FURTHER RESEARCH

This research has demonstrated that low-volume wet-process sprayed mortars and fine concretes can be successfully used for repair work. However, this work has also highlighted the need for additional research to both continue the work presented here and to develop the process further. The recommendations for further research can be divided into four areas: materials and mixes, pumping and spraying, fresh property test methods and hardened property test methods.

7.3.1 Materials and mixes

A pumpable combined grading zone was successfully identified in this work for mortars. Further work could be done to identify a similar zone for fine concretes.

Air entrainment was utilised in this work as a pumping aid. However, more work is needed to identify the levels of air entrainment that are needed in each type of mix before pumping, to produce a specified level of entrained air after pumping (and spraying). This needs to be investigated for mortars and fine concretes using both piston pumps and small- and large-diameter worm pumps. Also, further rheological testing could be conducted on these air-entrained mixes (with the 2-point, Viskomat, slump and shear vane etc.) to enable their pumpability to be predicted.

A fine concrete mix was pumped and sprayed in this work with a high proportion (5 kg/m³) of polypropylene fibres. This mix was very difficult to pump smoothly and further work could be conducted to improve the pumpability and sprayability of this and similar high-fibre mixes.

7.3.2 Pumping and spraying

The relationship between the bending and shear failure stresses obtained from the build test and the shear and tensile strengths of the material both before pumping and after spraying could be investigated, for both mortars and fine concretes. It may be possible to analyse the in-situ sprayed material from a soil mechanics perspective in terms of shear strength and pore pressure and relate this to the materials rheological properties.
A nozzle study could be conducted with a fine concrete, a piston pump and a high-speed camera in a similar way to the study presented here for mortars, to identify a nozzle design which minimises rebound, dust and overspray. Similar work could also be conducted with a dry process gun. The initial work on the particle and vector analysis of the mortar streams presented here could also be extended to produce a technique capable of analysing and assessing the quality of a mortar or concrete particle stream.

The work presented here suggested that the particle stream velocity affected properties such as reinforcement encasement, bond strength and compaction. Optimum stream velocities might be determined for different mixes, applications and equipment.

7.3.3 Fresh property test methods

Due to the low workabilities of the mortars in this work, it was difficult to obtain consistent results with the Viskomat rotational viscometer. Further work could be conducted to modify the apparatus for use with low workability mortars and pastes e.g. altering the shape or configuration of the blades.

Two types of reinforcement encasement test were used successfully in this work: sorptivity and core grading. However, the bar overlap area was limited to 296 mm² (except for mortar P4) and further work could be done to measure the encasement up to approximately 600 mm², for both mortars and fine concretes. The effect of the water/cement ratio of mortars on the encasement could also be investigated, in a similar way to the fine concretes presented here.

Pressure bleed tests could be conducted on the fine concretes in this work to assess their resistance to bleeding in a similar way to the mortars. Different pressures could also be used to find the optimum pumping pressure for bleeding resistance and pumpability. The addition of an SBR to the fine concretes to reduce bleeding could also be investigated, as could the influence of grading and the constituent proportions on the bleeding of both fine concretes and mortars.
7.3.4 Hardened property test methods

This work showed that the ambient conditions had a large effect on the restrained shrinkage of in-situ sprayed repairs. This effect could be investigated further to try to predict the behaviour of an in-situ repair depending upon its ambient conditions. The measurement of in-situ restrained shrinkage and the development of a standard restrained shrinkage test which incorporates the possible movement of the substrate could also be investigated.

Air permeability of the fine concretes presented here could be measured and the effect of different constituents on the permeability investigated.


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268


APPENDIX A.1

Conversion to fundamental units

The constants \( g \) and \( h \) are not in fundamental units of yield (\( \tau_o = \text{Pa} \)), or plastic viscosity (\( \mu = \text{Pa.s} \)). It is not necessary to convert to fundamental units unless results obtained from two different apparatus are to be compared. This is because \( g \) and \( h \) values are affected by the geometry of the apparatus in which they are measured. It is possible to convert to calibrate each apparatus with liquids known viscosity to relate these immediate values of \( g \) and \( h \) to the fundamental properties of \( \tau_o \) and \( \mu \). As summarised by Tattersall and Banfill (1983):

The rate of shear in a mixer varies from point to point and it is not possible to carry out full analysis. However, some progress may be made if it is assumed that there is an average effective shear rate that is proportional to the speed of the impeller so that;

\[
\gamma = KN
\]

(equ. 9.1)

and by suitable calibration it is possible to determine the value of \( K \). A knowledge of this constant and another calibration constant \( G \) permits the expressing of yield value and plastic viscosity in fundamental units by the following equations:

\[
\tau_o = (K/G) g \quad \text{(equ. 9.2)}
\]

\[
\mu = (1/G) h \quad \text{(equ. 9.3)}
\]

This means that the values of \( g \) and \( h \) are, respectively proportional to \( \tau_o \) and \( \mu \), but the constants of proportionality are different.

By using different oils at different temperatures, Bloomer (1979) has been able to obtain numerical values \( G \) and \( K \) from the two-point workability apparatus, as shown in Table 9.1. To obtain the yield value \( \tau_o \) in Pascal, the \( g \) value must first be multiplied by 135 for the MkII apparatus. Similarly, to obtain the viscosity \( \mu \) in Pascal-second, the \( h \) value must be multiplied by 22.2.
Table A.1 G and K values for the MkII two-point apparatus (Bloomer, 1979)

<table>
<thead>
<tr>
<th>Constant</th>
<th>MkII apparatus</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>0.045</td>
</tr>
<tr>
<td>K</td>
<td>6.09</td>
</tr>
<tr>
<td>K/G</td>
<td>135</td>
</tr>
<tr>
<td>1/G</td>
<td>22.2</td>
</tr>
</tbody>
</table>
## APPENDIX A.3 Repair Scenarios

<table>
<thead>
<tr>
<th>TYPE OF REPAIR</th>
<th>PURPOSE</th>
<th>GEOMETRY</th>
<th>SUBSTRATE</th>
<th>ENVIRONMENT</th>
<th>ORIENTATION</th>
<th>REINFORCEMENT</th>
<th>SURFACE FINISH</th>
<th>ACCESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>bridge soft</td>
<td>1 cover</td>
<td>&lt;2m²</td>
<td>50-100mm</td>
<td>(+/-10mm)</td>
<td>hydro-demolition + grit blasting</td>
<td>concrete</td>
<td>Carbonation Chlorides</td>
<td>atmos.</td>
</tr>
<tr>
<td>bridge abutment</td>
<td>1 cover</td>
<td>&lt;2m²</td>
<td>50-100mm</td>
<td>(+/-10mm)</td>
<td>hydro-demolition + grit blasting</td>
<td>concrete</td>
<td>Carbonation Chlorides</td>
<td>atmos.</td>
</tr>
<tr>
<td>arch bridge strengthening</td>
<td>1m²+</td>
<td>50-100mm</td>
<td>NA</td>
<td>grit blasting</td>
<td>masonry</td>
<td>deteriorated masonry</td>
<td>atmos.</td>
<td>curved surface</td>
</tr>
<tr>
<td>building cover</td>
<td>&lt;2m²</td>
<td>50-100mm</td>
<td>(+/-10mm)</td>
<td>mechanical (hydro-demolition) + grit blasting</td>
<td>concrete</td>
<td>Carbonation (chlorides in car parks)</td>
<td>atmos.</td>
<td>60:40 vertical</td>
</tr>
<tr>
<td>building structural</td>
<td>&lt;2m²</td>
<td>50-100mm</td>
<td>(+/-3mm (visible))</td>
<td>(+/-10mm (covered))</td>
<td>hydro-demolition + grit blasting</td>
<td>concrete</td>
<td>Fire-damage</td>
<td>atmos.</td>
</tr>
<tr>
<td>r.c. chimneys cover</td>
<td>50-100mm</td>
<td>(+/-10mm)</td>
<td>mechanical (hydro-demolition) + grit blasting</td>
<td>concrete</td>
<td>Carbonation</td>
<td>atmos.</td>
<td>vertical</td>
<td>mesh (possibly fibre)</td>
</tr>
<tr>
<td>water retaining structures 1 cracking</td>
<td>25-100mm</td>
<td>(+/-10mm)</td>
<td>hydro-demolition + grit blasting</td>
<td>concrete</td>
<td>Carbonation</td>
<td>atmos. + wet substrate</td>
<td>mainly vertical</td>
<td>mesh (possibly fibre)</td>
</tr>
<tr>
<td>marine structures 1 cover</td>
<td>25-100mm</td>
<td>(+/-10mm)</td>
<td>hydro-demolition + grit blasting</td>
<td>concrete</td>
<td>Chlorides</td>
<td>Carbonation Abrasion</td>
<td>atmos. + wet substrate</td>
<td>vertical</td>
</tr>
<tr>
<td>tunnel structural</td>
<td>&lt;1m²</td>
<td>100mm</td>
<td>2-4m</td>
<td>(+/-10mm)</td>
<td>hydro-demolition + grit blasting</td>
<td>concrete</td>
<td>Carbonation Chlorides</td>
<td>cool (ventilation fans). can be damp</td>
</tr>
<tr>
<td>sewer (masonry tunnels) strengthening</td>
<td>1m²+</td>
<td>25-50mm (&lt;100mm)</td>
<td>(+/-10mm)</td>
<td>grit blasting</td>
<td>masonry</td>
<td>Deteriorated masonry</td>
<td>warm &amp; damp</td>
<td>curved surface</td>
</tr>
</tbody>
</table>
APPENDIX A.4 Aggregate gradings

- Portland stone
- River gravel
- Coarse smooth

Particle size (mm)

- Sand (<300µm)
- Fillite
- Soft building sand
- Coarse building sand

Particle size (mm)

- Sand 1
- Sand 2
- Sand 5

Particle size (mm)
APPENDIX A.5 Pre-blended Aggregate Gradings

Pre-blended mortar gradings - aggregate only (excluding filler)

Pre-blended mortar gradings - aggregate and filler only
APPENDIX A.6 Vane shear strength calculations

The shear vane was calibrated with a torque wrench and the torque/scale reading relationship obtained is shown in the Figure below.

Gradient of Torque/Vane shear strength graph (see below) = 1/7.4519
Therefore, Torque = reading from scale on shear vane divided by 7.4519

From BS1377: Part9: 1990:

\[
\tau = \frac{M}{K}
\]

Where \( \tau \) = shear strength (kPa)
\( M \) = torque required to produce shear (Nm)
\( K \) = a constant depending upon the dimensions of the vane

From BS1377: Part9: 1990:

\[
K = \frac{D^2 H}{2} \left(1 + \frac{D}{3H}\right) \times 10^{-8}
\]

Where \( D \) = width of the vane = 90 mm
\( H \) = height of vane = 67 mm

Therefore, for the vane used in this work, \( K = 1.234 \)

Therefore, \( \tau = \frac{M}{1.234} \) and \( \tau = \frac{\text{Vane reading}}{7.4519} \times \frac{1}{1.234} \)

and \( \tau = 0.10875 \times \text{Vane reading} \)
### APPENDIX A.7 Test method Investigation

**COMPRESSIVE STRENGTH**

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Description</th>
<th>Source</th>
<th>Sample Type</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TEST METHOD 1</strong></td>
<td><strong>CUBE TEST FOR MORTAR.</strong></td>
<td>EN-ISO4012/1-1994</td>
<td>60x60x60mm min. square cubes cut from sprayed test panel or cubes cast 100,150,200,250 or 300mm square.</td>
<td>The cube is placed between the platens of the testing machine and a compressive load is applied at a constant stress of 0.2-1.0 MPa/s until failure occurs.</td>
</tr>
<tr>
<td><strong>SOURCE 1</strong></td>
<td></td>
<td></td>
<td>150mm square preferred.</td>
<td></td>
</tr>
<tr>
<td><strong>SAMPLE TYPE</strong></td>
<td></td>
<td></td>
<td>150mm square preferred.</td>
<td></td>
</tr>
<tr>
<td><strong>METHOD</strong></td>
<td></td>
<td></td>
<td>As above but at a load rate of 0.045 MPa/s.</td>
<td></td>
</tr>
<tr>
<td><strong>SOURCE 2</strong></td>
<td>BS6319:Part 2:1983 Method for Measurement of Compressive Strength of Mortars.</td>
<td>40x40x40mm square cube prepared in a mould.</td>
<td>As above but at a load rate of 0.045 MPa/s.</td>
<td></td>
</tr>
<tr>
<td><strong>SOURCE 3</strong></td>
<td>ASTM C109 : Test Method for the Compressive Strength of Hydraulic Cement Mortars.</td>
<td>50x50x50mm square cube prepared in a mould.</td>
<td>As above but at a load rate of 0.045 MPa/s.</td>
<td></td>
</tr>
</tbody>
</table>

**TEST METHOD 2** | **CUBE TEST FOR CONCRETE.** | BS1881:Part116:1983 Method for Determination of Compressive Strength of Concrete Cubes. | 100mm^3^ or 150mm^3^ square cubes prepared in a mould. | Compressive load of 0.2-0.4 MPa/s applied until failure occurs. |
| **SOURCE 2** | | | | ASTM - Cylinders only used for compressive strength. |

**TEST METHOD 3** | **CYLINDER TEST.** | EN-ISO4012/1-1994 | Drilled cores with a minimum diameter of 50mm and a height/diameter ratio between 1.0 and 2.0. Each end of the cored sample needs to be capped with a high strength compound to ensure an even load distribution. | As per cube test with a loading of 0.2-0.4 MPa/s. |
| **SOURCE 2** | | | | BS1881:Part120:1983 Method for Determination of the Compressive Strength of Concrete Cores. |
SAMPLE TYPE: 100mm or 150mm diameter capped cores.
METHOD: As per cube test with a loading of 0.2-0.4 MPa/s.

SOURCE 3: ASTM C39 Compressive Strength of Cylindrical Concrete Specimens.
SAMPLE TYPE: Diameter must be at least 3 times greater than the maximum aggregate size. The length 'ideally' needs to be twice the diameter. Cores need to be capped.
METHOD: As per cube test but with a loading of 0.14-0.34 MPa/s.
SAMPLE: Spray panel and cut cube or core cylinder;
MANUFACTURE: Spray mould (Cube, beam or cylinder);
             Hand cast pumped, sprayed or pre-pumped mix.

EQUIPMENT NEEDED: 'Denison' testing machine;
AND AVAILABILITY: 'Clipper' concrete saw;
                   'Dymodrill' core drill: 55mm and 100mm int. diameter;
                   Capping material and capping jig.
NOTES: Also Equivalent Cube Test on beams - easier to spray possibly?

MODULUS OF ELASTICITY

UNITS: N/mm².

TEST METHOD 1
NAME: Determination of elastic modulus in compression.
SOURCE: EN104-823-2
SAMPLE TYPE: Preferably cylinders of 150mm dia. and 300mm height. Testing of cubes also possible.
METHOD: Place the sample in the compression test machine and apply a load until a strain of approx. 0.002m/m is indicated. Record the applied load. Zero the strain gauges at 10% of the initial load then measure the increase in compressive strain as the load is cycled. Record 4 cycles. Test at least 3 specimens from the same mix.
SAMPLE MANUFACTURE: Spray panel and core cylinder or saw cube.
                     Spray mould (Cube, beam or cylinder).
                     Hand cast pumped, sprayed or pre-pumped mix.

EQUIPMENT NEEDED AND AVAILABILITY: Compression test machine with strain gauges;
                                    'Clipper' concrete saw;
                                    'Dymodrill' core drill: 55mm and 100mm int. diameter available - 150mm possibly better?
DRYING SHRINKAGE

UNITS : mm/m.

**TEST METHOD 1** : SHRINKAGE TEST.
**SOURCE 1** : EN 104-816-4:1995
**SAMPLE TYPE** : 160x40x40mm fresh concrete sample.
**METHOD** : Install the measuring pegs into the ends of the mould. Pour in the concrete and compact with a tamping rod. Cure for approx. 24 hours then strike. Initial mass and initial length are then recorded. Length is then recorded at intervals, commonly 1,3,7,14,28 and 56 days.

**SAMPLE TYPE** : A trapezoidal sample cast in a PTFE trough and tested whilst freshly mixed. Sample stored in air at 20°C.
**METHOD** : Measurements taken using electronic transducers up to 100 hours from casting. At least 3 samples needed.

**SOURCE 3** : BS1881:Part 5:1970 Methods of Testing Hardened Concrete for Other Than Strength (Withdrawn).
**SAMPLE TYPE** : 75x75x150-300mm fresh concrete sample. At least 4 samples needed.
**METHOD** : Soak sample at 20°C for 28 days then. Dry in oven for 14 days then record the length every 2 days.

**SAMPLE TYPE** : Mortar : 25x25x285mm fresh sample. Concrete : 100x100x285mm fresh sample.
**METHOD** : Store and test at least 3 samples at 23°C and 50% RH. Take readings at 4,7,14 and 28 days and at 8,16,32 and 64 weeks.

**SAMPLE TYPE** : At least 2 freshly mixed samples 100, 150 or 300mm in length.
**METHOD** : A ball is placed on top of the freshly mixed sample and is continuously examined with a magnifying lens.
**SOURCE 6**

Fosroc Research, Test Method N°82 : Coutinho Shrinkage Ring.

**SAMPLE TYPE**

Cylindrical ring - 112mm int., 175mm ext. and 60mm high.

**METHOD**

Time recorded for sample to crack and the width of the crack.

**SAMPLE MANUFACTURE**

Spray concrete into mould.

**EQUIPMENT NEEDED:**

Unrestrained movement mould; Measurement studs and measuring apparatus; Compaction tools and equipment. We have moulds of sizes 285x25x25mm and 229x75x75mm.

**REFERENCES**


**NOTES**

CIRIA report recommends storing the sample at 20°C and 50%RH. It also recommends measuring the length and the weight after 1, 2, 3, 4, 7, 14, 21 and 28 days and then at 7 day intervals until a constant length is achieved.

Fosroc prepared a test sample by cutting a 70x70x270mm section from a 100x100x500mm sprayed sample after 24 hours. 2 locating discs 200mm apart were then glued onto 3 faces of the beam and the strain was measured at intervals with a de-mountable strain gauge. The sample was stored at 20°C and 65%RH.

**TENSILE SPLITTING STRENGTH**

**UNITS**

MPa or N/mm².

**TEST METHOD 1**

**NAME**

Splitting tension test.

**SOURCE**

EN-ISO4108-1994

**SAMPLE TYPE**

Cylindrical, cube or prismatic.

**METHOD**

The sample is placed in the jig and then into the testing machine. It is then compressed until failure by indirect tension occurs in the form of splitting down the vertical axis of the specimen.

**SAMPLE MANUFACTURE**

Spray panel and saw cube or core cylinder; Spray mould (cube, beam or cylinder);
HAND CAST PUMPED, SPRAYED OR PRE-PUMPED MIX.

EQUIPMENT NEEDED AND AVAILABILITY:
- Compressive testing machine;
- Jig - 150mm deep jig available but 100mm or 55mm jig needs to be made to test cored samples;
- ‘Dymodrill’ core drill.

NOTES:
- Only small amounts of data are available on the cube or prismatic splitting tests. Cylinders are usually used.

PERMEABILITY

UNITS: m²

TEST METHOD 1
NAME: Air permeability test.
SOURCE: EN7031.
SAMPLE TYPE: 50mm dia. sample cored and then cut. The samples need to be pre-conditioned as the moisture content affects the permeability of the sample.
METHOD: The sample is placed into the cell and held in place by the confining pressure provided by the compressed Nitrogen. The compressed air is then allowed to flow through the sample under steady state conditions and the resultant pressure head is then measured.
SAMPLE MANUFACTURE: Spray panel and then core sample; Hand cast pumped, sprayed or pre-pumped mix and then core a sample.

EQUIPMENT NEEDED AND AVAILABILITY:
- Air permeability test rig;
- Compressed air and compressed nitrogen;
- Testing cell and flow meter;
- ‘Dymodrill’ core drill with 55mm dia. bit;
- ‘Clipper’ concrete saw.

NOTES: Average of at least 2 samples recommended.
Test is very quick to do and non destructive.

DURABILITY FACTOR (FREEZE/THAW TEST)

UNITS: No units.

TEST METHOD 1
NAME: Rapid freezing and thawing in water.
SAMPLE TYPE : 76-127mm in width, depth or diameter, prisms or cylinders. 279-406mm in length. Normally tested at 14 days.

METHOD : Freeze and thaw for 300 cycles or until the Dynamic Modulus of Elasticity is reduced to 60% of its original value. The reduction in compressive strength and the change in dimensions can also be measured.

TEST METHOD 2
NAME : Rapid freezing in air and thawing in water.
SAMPLE TYPE : As above.
METHOD : As above but the sample is surrounded by air during the freezing phase of the cycle.

SAMPLE MANUFACTURE : Spray panel and cut cube or core cylinder; Spray mould(cube, beam or cylinder); Hand cast pumped, sprayed or pre-pumped mix.

EQUIPMENT NEEDED AND AVAILABILITY : Freeze/thaw cabinet; Thermometer/thermocouples; Electronic balance; Vernier callipers. ‘Dymodrill’ coring machine; ‘Clipper’ concrete saw.

NOTES : Good for comparing results but not indicative of actual in-situ conditions.

TENSILE BOND STRENGTH

UNITS : N/mm² or MPa.

TEST METHOD 1 : PULL OFF TEST FOR CONCRETE.
SAMPLE TYPE : A sample of 50-60mm dia. is cored through into the substrate to a depth of approx.15mm. Care must be taken that the core is perpendicular to the surface concrete.
METHOD : A steel disc is glued onto the top of the core with epoxy resin. A tensile pull-off load is applied to pull the core from the substrate. 5 bond tests should be carried out from each specimen.

SAMPLE TYPE : 50mm diameter dolly epoxy glued to concrete.
METHOD : Load applied at a 'steady' rate. At least 6 tests needed.

TEST METHOD 2 : PULL OFF TEST FOR MORTAR.
SAMPLE TYPE : Composite specimen that is in the form of a 2.7:1 aspect rectangular prism that is scarf jointed at 30°. Total size: 55x150x150mm.
METHOD : Sample loaded as per BS6319:Part2. At least 4 samples needed.

SOURCE 2 : C952-86 Bond Strength of Mortar to Masonry Units.
SAMPLE TYPE : Cross-brick couplets and concrete block assemblies secured together with mortar.
METHOD : Load applied at 2.7 KN/min. and the force needed to pull apart the masonry units is measured.

SOURCE 3 : C321-83 Bond Strength of Chemical-Resistant Mortars.
SAMPLE TYPE : Cross-brick couplets only.
METHOD : The cross-brick couplets are pulled apart at a rate of 5-6.4 mm/min. until failure occurs.

TEST METHOD 3 : PULL OFF TEST FOR ADHESION
SAMPLE TYPE : 20mm diameter dolly glued to mortar.
METHOD : Loading at 1N/mm² maximum. 3 tests minimum.
SAMPLE MANUFACTURE : Spray panel lined with sample substrate;
HAND CAST PUMPED, SPRAYED OR PRE-PUMPED MIX ONTO SAMPLE SUBSTRATE.

EQUIPMENT NEEDED: ‘Dymodrill’ core drill with 55mm dia. bit;
‘Limpet’ pull off machine;
Vernier callipers.

NOTES : Can also be used to measure tensile bond strengths between shotcrete layers. Standard substrate needs to be agreed.

CUMULATIVE WATER ADSORPTION - 'i'

283
UNITs : g/mm² or mm.

TEST METHOD 1
NAME : Capillary suction (by measurement of weight gain).
SAMPLE TYPE : 100mm diameter cylindrical specimen with a thickness of at least 20mm or 3 times the maximum aggregate size. Moisture content and temperature important and a standard needs to be set. Sides of sample possibly coated with a bituminous material.
METHOD : The sample is held with water approx. 2mm above the base. The quantity of water absorbed is measured at intervals by weighing the specimen. The surface water should be wiped off and the specimen weighed within 2 minutes. A minimum of 6 measurements are needed over a period of up to 4 hours.

TEST METHOD 2 (If Applicable)
NAME : Capillary suction (measurement of inflow).
SOURCE : EN104-837:1995
SAMPLE TYPE : As above
METHOD : As above but instead of weighing the specimen the depth of the inflow of water into the specimen is measured.
SAMPLE MANUFACTURE : Spray panel and core sample; Hand cast pumped, sprayed or pre-pumped mix.
EQUIPMENT NEEDED : 'Dymodrill' coring machine;
AND AVAILABILITY : Water bath with demineralised water and supportive rack for the specimens;
Electronic balance;
'Clipper' concrete saw;
Tape measure and stopwatch.

DENSITY OF HARDENED CONCRETE

UNITs : Kg/m³.

TEST METHOD 1
NAME : Determination of density by calculation.
SOURCE : EN-ISO6275-1994
SAMPLE TYPE : The sample should be a regular shape to make the calculation of the volume more accurate.
**METHOD**

The sample should be dried at 105°C until constant mass is achieved. The sample is then cooled and weighed. The volume is then calculated using the dimensions of the possible or the dimensions of the actual mould if sample.

**TEST METHOD 2 (If Applicable)**

<table>
<thead>
<tr>
<th>NAME</th>
<th>Water displacement method.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAMPLE TYPE</td>
<td>As above although a regular shape is not critical.</td>
</tr>
<tr>
<td>METHOD</td>
<td>The sample and the stirrup are both fully immersed in the tank and weighed. The weight of the empty stirrup is also measured in water. The sample is then wiped dry and weighed in air.</td>
</tr>
</tbody>
</table>

**COMPARISON OF THE 2 METHODS**

The water displacement method is the preferred method for cut or cored samples.

**SAMPLE MANUFACTURE**

- Spray a panel and cut a cube or core a sample;
- Spray a panel or mould;
- Hand cast pumped, sprayed or pre-pumped mix.

**EQUIPMENT NEEDED AND AVAILABILITY**

- Balance with stirrup;
- Vernier callipers;
- Water tank;
- Ventilated oven;
- ‘Dymodrill’ coring machine;
- ‘Clipper’ concrete saw.
APPENDIX A.8 Published papers


Appendix A.9 Failure stress calculations

This appendix contains an example set of calculations for mix P2w2 (see Table 4.1) to calculate the bending and shear failure stresses at failure:

Base height: 0.300 m  
Base width: 0.300 m  
Build length: 0.270 m  
Mass mortar: 26.2 kg  
Density (Table 5.3): 1876 kg/m³

Average shear stress at substrate at failure
= Mass x g / area  
= Mass x 9.81 / (w x h)  
= 26.2 x 9.81 / (0.3 x 0.3)  
= 2855 N/m²

Maximum shear stress at substrate at failure
= Average shear stress x 1.5  
= 2855 x 1.5  
= 4.3 kN/m²

Volume of a square-based frustrum = (L(A + √A.a + a)) / 3

If area a is assumed to be square then:
Volume(V) = (L(w.h + √w.h.H.H + H.H)) / 3

If w is assumed to equal h then:
H = \left(\frac{3V}{L}\right) - H.h - h²

Volume = mass/density, therefore:
Volume (V) = 26.2/1876 = 0.0140 m³

Build Length (L) = 0.270 m, therefore H can be found by iteration:
H = 0.15 m

From simple bending theory:
\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{R}, \text{ therefore the bending stress } \sigma = \frac{M.y}{I}
If \( w = h \) then and \( I = \) second moment of area \( = \frac{bd^3}{12} \), then

\[
I = \frac{h^4}{12}
\]

also, \( y = \) distance from neutral axis, therefore \( y = \frac{h}{2} \)

Therefore, \( \sigma = \frac{M_y}{I} = \frac{M \times \frac{h}{2}}{\frac{h^4}{12}} = \frac{6M}{h^3} \)

The moment of the frustrum can be assumed to be the moment of the extended total cone of length \( L_2 \) minus the moment of the cone ‘C’

The length \( L_2 \) can be calculated by similar triangles:

\[ \tan \theta = \frac{h(H-h)}{L} = \frac{h}{L_2} \]

Therefore, for mix P2w2, \( L_2 = 0.54 \text{ m} \)

Moment = Force x distance to centre of gravity
therefore, moment of total cone = weight of total cone x g x \( L_2 \)
= density x Volume of total cone x g x \( L_2/4 \)
= 1876 x (1/3 x w x h x L2) x g x \( L_2/4 \)
= 1876 x (1/3 x 0.3 x 0.3 x 0.54) x 9.81 x 0.54/4
= 40.2 Nm

Moment of end cone = Force x distance to centre of gravity
= (density x g x Volume of cone) x (\( L + \frac{1}{4} (L_2-L) \))
\[
= \frac{\text{density}}{12} \times g \times H^2 \times (L2-L) \times (L2+3L)
\]
\[
= \frac{1876}{12} \times 9.81 \times 0.15^2 \times (0.54-0.27) \times (0.54 + (3 \times 0.27))
\]
\[
= 12.6 \text{ Nm}
\]

Therefore moment of the frustrum = 40.2 - 12.6
\[
= 27.6 \text{ Nm}
\]

Therefore, from \( \delta = \frac{6M}{h^3} \),
\[
\delta = \frac{(6 \times 27.6)}{(0.3 \times 0.3 \times 0.3)}
\]
\[
= 6.1 \text{ kN/m}^2
\]

**Alternative Analysis**

**Nib**

**Corbel**

**Beam/column**
Appendix A.10 Hardened property results

28 day flexural strength

<table>
<thead>
<tr>
<th></th>
<th>P1w</th>
<th>P2w</th>
<th>P2p</th>
<th>P3w</th>
<th>P4w</th>
<th>P5w</th>
<th>P6w</th>
<th>P7w</th>
<th>D1w</th>
<th>D1p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Beam</td>
<td>4.8</td>
<td>5.9</td>
<td>6.5</td>
<td>7.2</td>
<td>5.1</td>
<td>4.6</td>
<td>--</td>
<td>3.4</td>
<td>6.7</td>
<td>--</td>
</tr>
<tr>
<td>In-situ Beam</td>
<td>6.2</td>
<td>6.2</td>
<td>7.9</td>
<td>8.8</td>
<td>5.5</td>
<td>6.4</td>
<td>6.2</td>
<td>5.3</td>
<td>8.0</td>
<td>7.3</td>
</tr>
<tr>
<td>Sprayed Mould</td>
<td>6.0</td>
<td>7.7</td>
<td>7.1</td>
<td>8.4</td>
<td>4.7</td>
<td>5.9</td>
<td>7.0</td>
<td>4.7</td>
<td>6.1</td>
<td>5.6</td>
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</tbody>
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