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Abstract

UK Pavement foundations are currently designed using a method specification whereby tightly specified materials are constructed using specific compaction methods and layer thickness. This process does not necessarily guarantee the performance of the materials, but it is assumed to be adequate based on past experience. However, it can be inefficient, leading to unnecessary restrictions when using stabilised, recycled or marginal materials and/or the inappropriate use of good quality aggregates.

The UK Highways Agency (HA) funded a recently completed three-year research project to produce a draft performance-based specification for road foundations. The performance-based specification aims to enable more appropriate and efficient use of a wider range of materials, both natural and recycled. The performance parameters required of the materials were established as the stiffness and the resistance to permanent deformation, with both measured, ideally, in the laboratory for design purposes and during construction to ensure their performance on site. Pre-construction trials to demonstrate adequate material performance (both as individual layers and as a composite structure) are expected to feature prominently when the new approach is adopted. A further HA-funded project started in January 2000 to evaluate the implementation of this new specification.

This paper outlines the philosophy of the draft performance-based specification produced, including *what* needs to be measured and *how* and *when* it should be measured. Its impact on the highways industry is then discussed.

1.0 Introduction

UK road pavements are traditionally designed in two stages, using a series of empirically designed road foundation layers that provide a foundation upon which to construct the (bound) structural pavement layers (Powell et al, 1984). The road foundation layers consist of capping (where necessary on low-strength subgrades) and sub-base, to protect the natural soil subgrade. The capping layer is essentially a subgrade improvement layer, and is regarded as a construction expedient to facilitate good support, and hence good compaction, of the overlying layer(s). The capping is often a granular material won locally or made by stabilising the subgrade with either lime or cement or both. Frequently, however, it is an imported crushed rock from a quarry. The sub-base is normally an imported, well-graded and very good quality crushed rock, and is regarded as a structural layer. It also acts as a regulating course upon which to compact the bound layers as well as a frost protection layer.

The current UK specification for road foundations (MCHW Vol.1, 1998) is based on a recipe approach, whereby selected materials are laid and compacted with specified plant in a specified manner to achieve a minimum level of performance. This performance is not *measured*, but is *assumed* to have been achieved from previous experience. The pavement foundation designs are based primarily on the use of the California Bearing Ratio (CBR) to characterise the subgrade, capping and sub-base materials. The CBR is used as a measure of both material strength and stiffness. Although the use of CBR as a performance parameter is widely acknowledged as being not wholly satisfactory (Brown, 1996), CBR has been correlated with pavement performance over many years, in many countries, and has arguably provided a trusted empirical indicator of adequate material behaviour. Such an empirical approach based on CBR is unlikely, however, to result in the efficient use of materials and plant, does not easily allow for the use of recycled, new or marginal materials, and does not permit the use of rigorous analytical design procedures.

Environmental considerations in construction have grown in prominence, and the cost of good quality crushed rock will soon rise due to the introduction of the 'aggregate tax'. Many 'waste' materials and industrial by-products were overlooked in the past because their use in road pavement structures had not been proven empirically, and these are now being considered for reuse due to the Landfill Tax. However, if a performance-based specification can be implemented that measures directly the required material performance parameters, the use of many previously untried materials can be more readily introduced. In addition, by directly measuring the performance parameters of the foundation materials, as they are constructed, greater assurance of the design and efficiency of site operations is anticipated.

The Highways Agency has funded a programme of research (undertaken by Loughborough University in association with Scott Wilson Pavement Engineering Ltd. and the University of Nottingham), aimed at producing an appropriate performance-based specification for pavement foundations. This work has the long-term aim of superseding the current empirical CBR-based road foundation design and specification. A draft performance-based specification has been produced and the implementation of this specification started in January 2000. This paper details the philosophy behind the performance-based specification developed from the initial research contract. The parameters that need to be measured are discussed, together with how they should be measured and when. The draft performance-based specification is described, and the objectives of the current implementation work are presented. Finally, the implications of the new performance approach for material producers, suppliers and end users, both in the short- and longer-term, are discussed.

2.0 The Function of Pavement Foundations and their Required Performance

The pavement foundation performs several functions both during construction and when in-service. In particular it acts as a series of load-spreading layers to reduce to acceptable levels the stresses transmitted to the subgrade, particularly when used as a temporary haul road during construction, and as a construction base on which the overlying pavement layers can be adequately compacted (Figure 1). In the long term the foundation must provide sufficient support to prevent premature flexural fatigue cracking in the structural layers (Figure 2).

To enable the pavement foundation to fulfil these functions the foundation materials must have adequate strength and resistance to permanent deformation, to prevent the accumulation of permanent strain within the materials. For the subgrade not to deform excessively the applied stress transmitted to it must be reduced by adequate stiffness and thickness of the overlying layers. Adequate provision of these parameters will allow the pavement layers to be constructed to an acceptable standard, prevent the generation of excessive cumulative subgrade rutting and also limit the extent of cracking in the structural layers in service.

Significant subgrade rutting is a real problem as it can cause loss of stiffness and strength due to disturbance (i.e. remoulding/loss of structure). Also, and in the case of clay subgrades, it can result in longer-term softening and weakening of the subgrade due to ponding of water on the depressed subgrade surface.

The most serious loading conditions occur during construction, since the applied stresses in the foundation are much higher than when protected by the structural layers, and it is for this condition, while satisfying the requirements of an adequate construction platform, that the foundation layers are primarily designed. It is important also, however, to consider the effects that environmental changes can have in the long term (e.g. water content changes) and to ensure that the designs and the materials utilised are sufficiently robust to deal with them.

The materials must also be inherently non frost-susceptible and provide adequate frost protection to the subgrade and must not degrade. In addition, they must have adequate drainage capabilities in order to avoid high levels of saturation, leading to loss of strength and stiffness. Adequate surface and subsurface drainage is also evidently vital in achieving this objective.

3.0 Requirements of a Performance-Based Specification

For a full performance-based specification to be implemented the following five criteria must be satisfied:

- an ability to measure the performance parameters of the subgrade in the laboratory for both the short-term construction condition and the long-term in service condition,
- a method(s) of predicting accurately the environmental changes in the pavement,
- a means of incorporating the measured parameters in the design process,
- an ability to measure the same parameters on the subgrade and pavement layers in the field to assess compliance, and
- the setting of suitable target values for construction to provide assurance of the quality of the final product.

The two primary targets, for in-situ assessment, are assurance that the overlying layers can be adequately compacted and that acceptable trafficking performance will be achieved during construction (i.e. control of rutting/material disturbance). This requires the assessment of both the stiffness and resistance to permanent deformation of the composite foundation as it is constructed. However, predicting the likely long-term behaviour from measurements made during construction is not currently feasible and represents a significant challenge.

4.0 Measurement of Performance Parameters

It is widely recognised that there is no unique measurement of resilient elastic stiffness of a soil or granular aggregate, and thus any measurement must be qualified by the (e.g. stress) conditions under which it is measured. In addition, the stiffness that any one material can achieve will be dependent on the stiffness of the material that underlies it (composite behaviour), and thus the materials cannot be considered in isolation.

In the case of strength/resistance to permanent deformation there is a large dependency on the applied stress regime. In this case, however, the dependency on the behaviour of the underlying or overlying layer properties is even greater. For example, in the case of a weaker lower layer it may control the initial permanent strain. Both the onset and propagation of rutting are dependent on the interaction between the layers (e.g. the capping and the subgrade) as well as both their individual strength and stiffness properties. Thus the individual material stability under trafficking is insufficient as a measurement of performance (It is for this reason that the term 'resistance to permanent deformation' is often used to describe the composite behaviour.) Therefore the measurements of the relevant parameters, both in the field and in the laboratory, should take place under conditions that match as closely as possible those that they will be subjected to *in situ* (i.e. a moving wheel load, see Fleming and Rogers, 1995).

4.1 Laboratory Assessment

Routine laboratory assessment of materials of the size and nature of those used as capping is currently impractical, due both to the large particle size and the complicated cyclic loading required to simulate traffic loading (Frost, 2000). This is an area requiring further research. Laboratory testing of capping materials is essentially limited to physical index and chemical tests to guard against particle degradation under trafficking and adverse effects of water content changes in the long-term, and assessment of compaction properties (MCHW Vol.1, 1998). However assessment of the compaction behaviour of materials containing particles greater than 80mm in size is problematic (Rockliff, 2000).

For fine grained materials, typical of those found in UK subgrades, the Repeated Load Triaxial Test has been developed to assess both their stiffness and permanent deformation behaviour. The latter parameter is defined by determining a 'threshold' stress (q_{thresh}, see Brown and Dawson, 1992) below which the development of permanent deformation remains stable (i.e. accumulates at an ever-decreasing rate). Whilst this form of testing does not model the true loading experienced under a rolling wheel, (i.e. rotation of principal stresses) and is limited to cycling the deviator stress. Permanent deformation of the subgrade can thus be controlled by limiting the applied vertical stress, transmitted through the overlying layers, to a level *below* which the accumulation of permanent deformation remains stable.

4.2 Field Assessment

Considerable research has been undertaken over the past few years to develop dynamic stiffness measuring devices that can quickly measure the stiffness of the subgrade and the pavement layers during construction. These devices measure a composite stiffness under a transient load pulse, which is applied to the ground by dropping a weight onto a bearing plate via a rubber buffer. The deflection of the ground is measured and combined with the applied load, which is either measured or is assumed to be constant (by means of a constant drop height), to calculate the stiffness using conventional Boussinesq static analysis. Such devices include the trailer-mounted Falling Weight Deflectometer (FWD, Figure 3), the portable prototype TRL Foundation Tester (TFT, Figure 4) , German Dynamic Plate (GDP, sometimes termed the lightweight drop tester, Figure 5) and the recently developed Prima 100. The portable devices typically apply a stress of 100 to 200kPa via a 300mm diameter plate over a period of approximately 20 milliseconds, and are suggested to be more suitable for testing subgrade and capping. The three portable devices measure deflection via a central geophone (or accelerometer) only, thus assessing the foundation's composite stiffness only and precluding individual layer stiffness by backanalysis. However, by testing each layer as it is constructed their contribution can be indirectly assessed (SWPE, 1999).

It is proposed that the laboratory-derived threshold stress of a soil can be linked to its undrained shear strength (q_{max}) and that this can then be used for correlation to shear strength measurements on site. The indirect measurement of strength in the field is possible using the portable Dynamic Cone Penetrometer (DCP). However, the DCP is not suitable for penetrating very strong materials or those containing very large particles, and only measures the properties of the individual material layers as they are being penetrated, i.e. it cannot measure the composite foundation performance.

The mechanisms that lead to the development of rutting in two-layer systems are not well understood and the ability to model rutting is consequently lacking. Therefore, it is proposed that the only practical means, currently, of guarding against excessive permanent deformation is to monitor the development of surface rutting in the "as-constructed" road foundation and to place a limit on the amount allowed (Figure 6). As a consequence a pre-construction trial section is required, which includes controlled trafficking, to prove the competence of the proposed materials and methods.

Although density is not a performance parameter, its measurement is considered important for assessing the adequacy of compaction of unbound materials. A material, once laid within a pavement foundation, may possess sufficient stiffness to allow the adequate compaction of the subsequent layers, but may deform excessively during trafficking because of poor strength due to inadequate compacted density, and therefore particle interlock. It is consequently recommended that density should be measured on site and compared to the maximum density that is achievable, from either a laboratory test or in the pre-construction field trial. Measurement of dry density is not uncommon in practice, the Nuclear Density Gauge (NDG) being an accepted method.

5.0 Specification Approach Adopted

It is clear from the above discussion that it is not currently possible for the complete requirements of a fully analytical performance specification to be implemented, due primarily to the lack of widely available commercial equipment that is suitable for practical use for tests of such complexity. Therefore appropriate compromises are necessary. In addition it is acknowledged that the performance specification developed from this research would need to undergo a phased introduction into practice. This is considered necessary both to engender confidence in the new approach and to make best use of the considerable empirical experience that has been generated over many years with the traditional method specification.

Experience needs to be gathered of the proposed test methods and data produced, and the performance-based specification produced therefore currently accommodates two different approaches (SWPE, 1999):

- A CBR performance-based approach, to assess the subgrade, with the traditional two phase design process (short- and long-term) and the new elements of field compliance testing *(standard approach).*
- A fully analytical performance-based approach substituting a new laboratory soil characterisation test for the CBR test (*detailed approach*).

The detailed approach is regarded as a longer-term goal. Currently only the standard approach is being evaluated for implementation and is described in detail below.

6.0 The Performance-Based Specification (Standard Approach)

A flow chart of the design and assessment process is presented in Figure 7. It features three iterative stages:

- design,
- a Pre-construction field trial, and
- construction compliance testing.

6.1 Target Values for Compliance Testing

To ensure that the subgrade properties found in the field are as good as, or better than, those assumed in the design it is proposed that CBR measurements are made in the field and must at least match the long-term design CBR values (the short-term design is the contractor's responsibility). These values will be design/site specific.

To ensure adequate capping performance during construction, it is proposed that various specification targets are set. A target composite stiffness of 50MPa (measured with a 300mm-diameter dynamic plate test) is proposed to facilitate adequate compaction of the sub-base. The dry density after compaction should be at least 95% of the laboratory maximum dry density. A limit on the surface rutting caused by construction vehicles is proposed to protect the subgrade and this is detailed in Table 1. The values have been chosen on the assumption that approximately 50% of the capping surface rut is transferred to the surface of the subgrade). These targets and limits are proposed values only and are being assessed in the current implementation work.

6.2 Design

The design requirements for the standard approach are similar to those for the existing method specification (DMRB Vol.7 HD25/94, 1994) for the in-service full pavement, though resulting in lower capping requirements than at present. This long-term design requirement utilises the CBR (based on prediction of the equilibrium water content in accordance with current guidance). However, for the short-term design of the foundation (which will be the contractor's responsibility to ensure that the foundation can be built and provide a good platform for the construction of the upper structural layers) the CBR, or an alternative parameter such as stiffness, can be utilised. The design thicknesses are established for these two conditions using charts included in the new specification. These are based on static linear elastic theory and are for guidance only for the short-term case, but are compulsory for the long-term case. The greater of the two thicknesses should be chosen.

6.3 Field Trial

To demonstrate that the selected materials and design are adequate, a site trial is to be performed prior to construction using the proposed materials and methods on a *representative* section of subgrade. A complete programme of in-situ testing is to be performed on the subgrade and capping to determine the performance of the trial relative to the design data and target values (i.e. measurement of CBR, stiffness, strength and density). The trial section will then be trafficked to determine its resistance to permanent deformation by monitoring the rutting of the capping surface. In the event of large surface ruts occurring, the proportion of rutting transmitted to the subgrade surface can be determined by excavation, and any adjustment to the specified rut limits agreed. At this stage the contractor can consider different thicknesses and combinations of materials to optimise his design. Once the standard testing is complete, consideration should be given to artificial saturation of a limited area of the trial section, particularly if the materials are considered to be seriously water susceptible, and further assessment to examine the possible effects of poor weather during construction.

If the trial proves unsuccessful, the design thicknesses and/or choice of materials must be re-evaluated and a further trial should be carried out. Finally, after successful confirmation of the design and the specification values from the trial, construction can begin.

6.4 Construction

The subgrade is to be tested *in situ* immediately prior to capping placement to check that it meets the design values for the long term. However, if the parameters measured on the subgrade lie below the long-term design values (or any other pre-determined values, based on laboratory test data, which suggest that the equilibrium values will subsequently fall below the design values), then the long-term design may need to be amended as construction takes place. ’Soft spots’, if these are the problem, will need to be isolated and treated accordingly. If the targets for the subgrade fall below the short-term requirements for site construction (this is the contractor’s responsibility, and he needs to balance the construction costs versus risks for these situations), then either additional excavation and addition/thickening of capping or subgrade stabilisation may be needed. If either of these solutions is adopted, it may be possible to take account of this in the long-term design and reduce the thickness of the sub-base, or even pavement layers, accordingly. However this course of action needs careful consideration and is not presently covered in the specification.

Once the subgrade is shown to be acceptable the capping can be constructed. The amount of surface rutting under construction trafficking should be monitored as construction works proceed and compared to the limiting values given in Table 1. Capping density is checked to guard against long-term deformation, and the top of capping composite stiffness is measured immediately prior to sub-base construction to ensure that adequate compaction of the sub-base can be achieved.

If the capping exhibits excessive rutting or has an insufficient stiffness, then it must be re-compacted or replaced by an acceptable capping prior to sub-base construction. Where the degree of rutting gives cause for concern, the subgrade surface should be investigated locally to ensure that the subgrade has not been compromised (i.e. excessively disturbed or deformed to allow water ponding). Trafficking thereafter must be carefully controlled and restricted if necessary. Where a sacrificial layer is used to allow for more site traffic the guidance in Table 1 should still be adhered to for the full thickness placed, and the stiffness measured after its removal and immediately prior to placing the sub-base.

7.0 Implementation Trials

Evaluation and refinement of the draft performance-based specification is now taking place. The development of the draft specification was based on many measurements at several 'live' construction sites and purpose-built full-scale 'controlled' field trials. Consequently the current implementation work is focussing on how the proposed specification fits in with the many different forms of contract, and its impact on the construction operations, standard testing regimes and general project management procedures. Thus to evaluate the difficulty of implementing the specification, several live sites using different forms of contract have been identified. The first of these trials is now underway. It is hoped that some findings from this work will be available for presentation at the conference to supplement the paper contents.

8.0 Implications of a Performance Approach

In the near future it is considered that the proposed change in the standard performance-based specification approach will not significantly affect the material suppliers, for the traditional materials, but will open up new possibilities for other materials. The current specification clauses for capping materials will remain largely unchanged. However, the new specification will allow contractors to use a wider range of materials, if their performance can be demonstrated to be acceptable. The most significant change will be that materials provided will have to be shown to be able to perform *in situ*, i.e. that the materials can be trafficked (as per the site requirements) without excessive rutting and that a target stiffness can be achieved when compacted onto a typical subgrade. Therefore a greater appreciation of the performance of supplied aggregates will be needed from their suppliers and contractors in general.

In the medium-term it is anticipated that the suppliers will be required to provide performance data relating not only to the durability of their materials but also the performance parameters of stiffness and permanent deformation. Similarly constructors will be required to provide assurance of a material's suitability and performance once placed.

In the longer-term the move towards a fully analytical approach to pavement foundation design will require a much greater understanding of both the performance of the materials supplied and appropriate performance test methods. In addition, the performance of stabilised materials has to date been investigated to a lesser extent than unbound foundation materials, and this is an area for further work for research and for the on-going implementation trials.

9.0 Acknowledgement

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Table 1. Proposed Maximum Permissible Surface Rut Limits at the Surface of Formation During Construction

Capping Thickness X (mm)	Maximum Surface Rut Depth (mm)
250 >X	30
250≤ X ≤500	40
X> 500	50

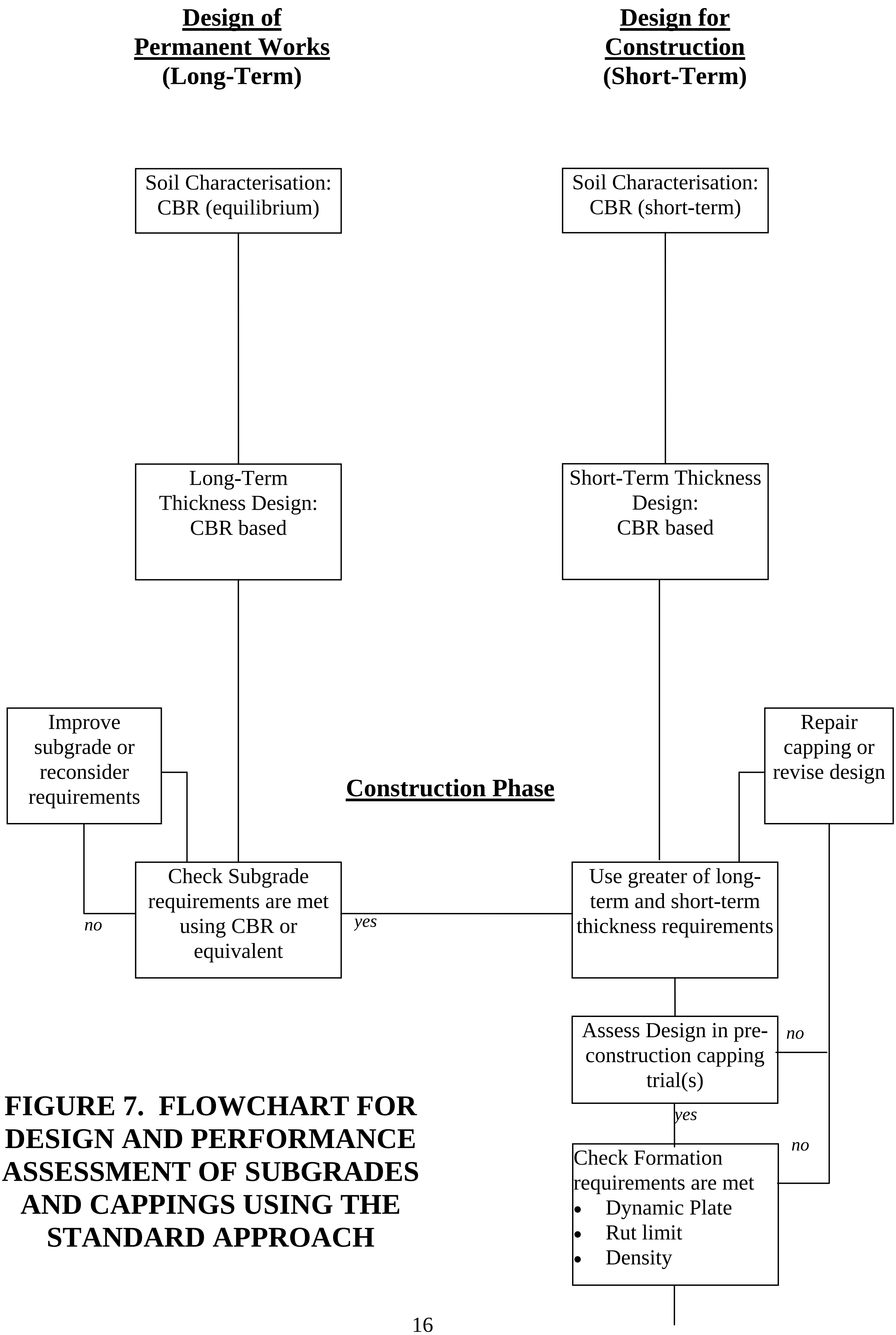

FIGURE 7. FLOWCHART FOR DESIGN AND PERFORMANCE ASSESSMENT OF SUBGRADES AND CAPPINGS USING THE STANDARD APPROACH