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## **A Performance Approach to the Design and Specification of Foundations for Industrial Ground Bearing Slabs and Pavements**

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### **ABSTRACT**

The foundations for industrial flooring and pavements are normally designed based on measurements, or prediction, of the California Bearing Ratio (CBR) of the subgrade, and from this the design thickness of the foundation is chosen utilising long established empirical relationships. The modulus of subgrade reaction ( $k$ ) measured by static plate bearing tests may also be used, and is correlated to CBR. The thickness design charts are the same as those used for the design of highway foundations and are based primarily on observed performance. The foundations are then constructed to a recipe specification whereby specific (tightly graded) materials are placed and compacted upon the subgrade with specified plant.

The soil CBR can only be regarded as an index property and does not directly or explicitly assess the primary functional performance parameters, of stiffness or strength. If CBR were replaced with direct measurement of these parameters, then the current empirical approach could be replaced with more powerful analytical design. Performance of the as-built foundation could then be better assured by compliance testing (end product) on site during construction. By moving to a performance-based specification approach, requiring some analytical foundation design, it is anticipated that more appropriate and efficient use of plant and materials can be made. This should enable better quality construction to be achieved, more efficient use of recycled materials or stabilisation of weak subgrades, hence leading to more sustainable construction.

Recent research at Loughborough University has developed such a performance-based specification approach for the design of (major) highway foundations, and has assessed those devices suitable to measure the performance parameters for both design and compliance testing. In this paper the transfer of this technology to industrial flooring and paving is suggested. The benefits of a performance-based approach to foundation design and specification are explained. The loading and function of a foundation is described and the performance parameters required to perform these functions are detailed. Suitable methods currently available to measure these performance parameters are described in brief. Finally, the implications and benefits of a move to a performance-based specification approach are discussed.

## **INTRODUCTION**

The philosophy for the design of foundations for industrial ground bearing slabs and pavement structures, such as industrial hard standing and aircraft pavements, are predominately based on the traditional empirical foundation design approach adopted for road pavements. In the UK the specification is based on a recipe approach whereby selected materials are laid and compacted with specified plant in a specified manner, and a minimum level of performance is assumed based on past experience. The pavement foundation design thickness is based primarily on the use of the California Bearing Ratio (CBR) to characterise the subgrade soil and also the overlying (granular) foundation materials (i.e. the capping and sub-base).

A two-stage design approach is adopted for the majority of pavement structures and ground bearing slabs whereby the foundation is designed empirically and is assumed to give an adequate minimum level of performance. The structural layers are then designed separately. Such a recipe approach to foundation design based on CBR is unlikely, therefore, to result in the most efficient use of materials and plant. In addition it does not easily allow for the use of recycled, new or marginal materials and does not readily permit the use of analytical design procedures for the full pavement structure.

The use of CBR as a design performance parameter is widely acknowledged as being not wholly satisfactory. However, the CBR has been correlated with pavement performance in many countries over many years and has arguably provided a trusted empirical indicator of adequate behaviour for many conventional materials and design.

It is now becoming appreciated within the floor slab construction industry that the empirical design approach to foundations is limiting the use of analytical floor slab design, and can not guarantee slab performance. An initial proposal for a performance specification for floor structures was suggested by Pearson (1999), and more recently the need for a move to a performance-based foundation design and specification has been appreciated (Cudworth and Pearson, 2000). This paper presents the philosophy of such a performance specification recently developed for highway pavement foundations for the UK Highways Agency, and suggests a possible way forward for other paving and floor slabs.

The design of foundations for ground bearing slabs (Chandler and Neal, 1988, and TR34, 1994) and heavy duty pavements (Knapton, 1996) is similar to that for road foundations (Powell et al 1984), and they sustain similar loading. Thus, the potential for transfer of the recent highway foundation research into these fields is proposed as realistic. The paper details the drawbacks of the CBR test, identifies the loading sustained by these foundations and hence parameters that need to be assessed. It then explains how these parameters fit into a performance specification approach to foundation design and construction. The test methods developed that measure these parameters both in the laboratory and in the field are then reviewed.

If such a move to performance-based specifications can be made it is anticipated that more effective use may be made of materials, such as stabilised or those recycled and

also waste products, hence reducing the requirement for high quality quarried aggregate. In addition, by directly measuring the performance parameters of the materials greater assurance of as-built quality and efficiency of site operations is also anticipated.

### **THE FUNCTIONAL REQUIREMENTS OF GROUND BEARING SLAB AND PAVEMENT FOUNDATIONS**

To resist the applied loading from either static or moving loads the foundations must fulfil the following mechanical functions (Powell et al, 1984, Chandler, 1982):

- i) It must support construction vehicles during the construction of the overlying layers. It must not deform significantly (resilient deformation) under this loading as to reduce the effectiveness of the compacted structure. It must dissipate the applied stresses from the (repeated) construction loads to a sufficiently low level to ensure that the subgrade does not sustain significant permanent deformation. For external works if excessive rutting of the subgrade occurs, ponding of water may occur within the subsurface rut, which may in turn lead to further softening and weakening of the subgrade in the long-term.
- ii) It must provide an adequate base for the placing and compaction of the overlying structural layers, (i.e. not deform excessively so reducing the effectiveness of the completed structure).
- iii) It must provide adequate and consistent support across the site to the overlying layers when in-service and distribute the stresses transmitted through the structural layers reducing the applied stress to the subgrade to a sufficiently low level. If not, cracking of the upper layers can propagate leading to deterioration of the complete structure.

In addition the foundations materials used must possess chemical and physical stability in the long-term and must remain adequately drained, and for external works they must have sufficient thickness to provide frost resistance to the subgrade.

To perform these mechanical functions satisfactorily it is clear that the materials used in foundations must possess the two primary performance parameters of adequate stiffness and sufficient resistance to permanent deformation.

### **CURRENT PAVEMENT FOUNDATION DESIGN METHODS**

The design of foundations for ground bearing slabs is normally based upon the subgrade CBR, measured either in the laboratory or inferred on site from a plate bearing tests via a relationship with Modulus of subgrade reaction (K) (TR 34, 1994). The foundation design thickness is assessed from empirical design charts based on information developed for road pavements (DMRB Volume 7 1994). For heavy duty hard standing a similar approach is adopted, (Knapton, 1996). The foundations are then constructed based on the current recipe specification used for highways (Volume 1, MCHW, 1994), whereby specified materials are compacted with specific plant for a certain number of passes.

## FOUNDATION MATERIALS

### *Subgrade*

The subgrade is often a natural soil, which may express variability across the site, and with depth. It may comprise cohesive or cohesionless soils or a mixture of both. The effects of loading in the short- and long-terms are different and should be allowed for.

### *Capping*

If the value of subgrade CBR chosen for design is low (<5%), then an additional subgrade improvement layer known as ‘capping’ is often provided (or thickened sub-base). Capping is used to provide an adequate working platform upon which to construct the sub-base layer.

Capping materials are described in the Specification (MCHW1, 1994). Granular capping is currently specified in terms of material grading and durability requirements, either a 6F1 fine capping (graded from 75 mm particle size down) or 6F2 coarse capping (graded from 125 mm particle size down) or 6F3 recycled capping material. Stabilisation of the subgrade with either lime or cement, or both, is also permitted though it may not be cost effective for sites that are relatively small, however. These different materials are treated as providing equal performance under current guidance.

It is advised (DMRB, 1994) that a capping, once placed and compacted, should achieve a minimum CBR of 15%. This is an indicator only, and is rarely utilised in specifications however.

### *Sub-base*

The sub-base is regarded as a structurally important layer that forms a working platform upon which to transport and build the upper structural layers. It also acts as a regulating course to establish final levels and tolerances. To achieve the required functions, the sub-base needs to be a stiff and strong layer, and thus is usually a tightly-graded and good quality crushed granular material (maximum specified particle size of 37.5 mm) and is normally imported. It may also be cement stabilised, however. The recommended minimum CBR for sub-base is 30%, which is rarely measured.

The full benefit of the actual strength and stiffness of the foundation materials utilised is not realised through the current system either for the foundation or full structure design.

### **CBR**

The test measures the resistance of a sample of soil to a 51mm diameter plunger forced at a constant rate of 1mm/minute. The CBR value is evaluated by comparing the load required to cause two specified penetrations (2.5 and 5.0 mm) relative to the comparable performance of a standard crushed rock. For the laboratory-based test samples are remoulded and re-compacted into a steel mould, often at predicted or assumed worst case water contents (i.e. soaked tests). The CBR test can also be performed *in situ* with the

51mm plunger and the apparatus being mounted on a vehicle, providing the necessary dead weight, or by larger diameter static plate bearing testing (whereby CBR is inferred from the modulus of subgrade reaction, k). The in-situ tests have very different confining conditions to the laboratory based test and are seldom used for design purposes (Croney, 1997). Correlations have also been proposed that empirically link the CBR of subgrades to measurable parameters such as Consistency Index (CI), related to soil suction and hence strength, by regarding the CBR test as a measure of bearing capacity (Black, 1962). This allows the use of soil plasticity data to derive a design CBR value (without performing a CBR test) (DMRB Volume 7, 1994, Chandler and Neal, 1988) .

The CBR is therefore a (relative) measure of the resistance to penetration of the material. This is a function of the strength and stiffness of the material under test (i.e. for a strong material such as a crushed rock it is more ‘stiffness related’, whereas for a wet clay it is more ‘strength related’) (Croney, 1997). However, where its measurement is more ‘stiffness related’ it infers stiffness at often larger strains and a lower strain rate than that caused by the structural loading sustained. In addition it does not model the application of repeated loading that occur under trafficking (Brown et al, 1990). The test does not guarantee failure of the material under the plunger, and thus cannot be regarded as a true measure of strength either (Hight and Stevens, 1982). Nonetheless, the CBR test is relatively quick and inexpensive and much experience has been gained of its use.

For semi-analytical pavement foundation design (which is allowed in the current UK, with approval) the CBR has been empirically related to stiffness via the equation:

$$E=17.6 (\text{CBR})^{0.64} \quad (\text{MPa})$$

This equation is a lower bound solution and is reportedly valid for CBR values between 2 and 12 % (Powell et al, 1984). Other CBR/stiffness correlations have been proposed for different materials and over different ranges of subgrade CBR, for example  $E=10 \text{ CBR}$  (Heukelom and Klomp, 1962). The stiffness value calculated is used to derive design thicknesses via static linear elastic analysis using assumed capping and sub-base material parameters that limit the critical design strains.

Brown (1996) states that these correlations are unsatisfactory. Soil stiffness varies with soil type, applied load, stress history and with rate of load application, due to the influence of deviator stress, soil suctions and soil type, and therefore concludes that there can be no unique relationship between CBR and resilient modulus. Sweere (1990), could find no correlation between CBR and stiffness for a range of granular materials.

The CBR test does not directly measure a fundamental material property required for analytical design or assessment nor at appropriate loading magnitude or rate. Therefore, new tests are required to supersede the CBR and facilitate the use of performance parameters and analytical design.

## **REQUIREMENTS OF A PERFORMANCE-BASED SPECIFICATION**

For a full performance-based specification to be implemented the following five criteria must be satisfied (Fleming et al 2001):

- 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 structural 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 objectives, for the foundation assessment in-situ, are assurance that the overlying layers can be adequately constructed and that acceptable resistance to the damaging effects of construction traffic will be achieved (i.e. control of rutting). This requires the assessment of both the stiffness and resistance to permanent deformation of the composite foundation, as it is being constructed. However, predicting the likely long-term behaviour from measurements made *during* construction represents a significant ongoing research challenge.

## **MEASUREMENT OF PERFORMANCE PARAMETERS**

It is widely recognised that there is no unique value of resilient elastic stiffness of a soil or granular aggregate, and that any measurement must be qualified by the test conditions (e.g. principal stresses, or strain magnitude). In addition, the stiffness that any one material can achieve in the field is somewhat dependent on the stiffness of the substrate (i.e. composite behaviour), and thus the material behaviour cannot be considered in isolation.

In the case of strength/resistance to permanent deformation there is a large dependency on the applied stress regime, relative to the allowable ultimate stresses. Both the onset and propagation of permanent deformation are dependent on the individual strength and stiffness properties of each layer and, importantly, their interaction. For example, a weaker lower layer may initiate and thus control the initial permanent strain of the composite, even for a competent upper layer. Thus the individual material stability under loading is insufficient as a measurement of performance and it is for this reason that the term 'resistance to permanent deformation' is often used to describe the composite behaviour. As a consequence of these effects, the measurement of the relevant performance parameters should take place under conditions that match as closely as possible the actual live loading (Fleming and Rogers, 1995).

### *Laboratory Assessment*

Routine laboratory assessment of granular materials is currently difficult and often 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 granular materials is essentially limited to physical index

and chemical tests to determine compaction behaviour, guard against particle degradation under trafficking and the adverse effects of water content changes in the long-term (MCHW Vol.1, 1998).

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 under cyclic loading. The latter parameter is defined by determining a 'threshold' stress,  $q_{\text{thresh}}$ , (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 only. The permanent deformation of the subgrade can potentially be controlled by this method, limiting the applied vertical stress transmitted through the overlying layers to a level *below* which the accumulation of permanent deformation remains stable.

Recent research (Frost 2000) proposed a simplified analytical design method, using routine (triaxial) apparatus. This work has shown that the threshold stress is reached at a deviator stress of approximately half the ultimate (i.e.  $0.5q_{\text{max}}$ ) and that this deviator stress also matches that for the commencement of the stiffness asymptote for cohesive materials. Therefore it is suggested that a simple single measure of stiffness and strength may provide sufficient data for a performance-based design. However the inability to routinely assess the stiffness response of granular materials is still a significant limitation.

#### *Field Assessment*

Considerable research has been undertaken over the past few years to develop and routinely use dynamic stiffness measuring during construction (superseding static plate tests). 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 or plate) is measured, as is the applied load in most cases (or assumed constant by means of a constant drop height for the weight). The stiffness is then determined using conventional Boussinesq static analysis. The dynamic devices include the trailer-mounted Falling Weight Deflectometer (FWD), the portable prototype TRL Foundation Tester (TFT), German Dynamic Plate (GDP), also known as the lightweight drop tester, and the recently developed Prima. 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 foundation materials as they apply a loading pulse approximate to that from a vehicle (Fleming, 2000).

The indirect measurement of strength (and hence  $q_{\text{max}}$ ) 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.

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 a pre-construction field trial. Measurement of dry density is not uncommon in practice, the Nuclear Density Gauge (NDG) being an accepted common method.

#### *Comparison between Laboratory and Field Testing*

Differences between the laboratory and field measured values of performance parameters might be expected to show poor comparison, especially from sample preparation differences. However, various researchers, reviewed by Frost (2000), have shown the two sources of data collected to show comparable trends. The natural variability of soils, difficulty in control of construction tolerances and material repeatability often produces significant scatter, especially in field data, and thus frequently obscures direct comparisons between data points.

### **IMPLICATIONS FOR DESIGN**

Currently the structural layers of paving are designed separately with little consideration given to the actual performance response of the foundation. An immediate improvement to this situation would be from a simplified performance-based specification using the tools described above, to monitor the construction consistency and adequacy and which has been shown to be practical for highways (Fleming et al, 2001). A longer-term goal would be to introduce the required analytical design, and new laboratory testing to supersede CBR, to enable a full performance-based specification to be used. This would facilitate the paving structure to be designed as a whole unit, giving greater assurance of overall performance, more (sound) flexibility in the materials used, and potentially allow the benefit of a high-performance foundation to be realised and perhaps allow a reduction in structural layer thickness.

### **CONCLUSIONS**

The CBR based empirical design is limiting the use of recycled and marginal materials in foundations for ground bearing slabs and pavements, and does not guarantee performance of the structure nor utilise the actual performance which may exceed that assumed.

A move toward performance-based specification, and associated analytical foundation design, requires complementary laboratory and field assessment of the required performance parameters of stiffness and resistance to permanent deformation. This should give better assurance of 'as constructed' quality and performance of the foundation. This would enable a wider range of materials such as recycled materials to be used to form the foundation based on sound engineering.

Direct assessment of the support provided by the foundation and incorporating this into a holistic slab/pavement design approach will allow the full benefit of a high strength and stiffness foundation to be realised, possibly reducing paving thickness. Conversely where a poor subgrade or foundation is identified a more appropriate thickness/treatment could be designed with greater confidence of performance.

Compliance testing during construction, using dynamic plate stiffness measuring devices and assessment of the compacted materials density, can be routinely and quickly performed upon the foundation *in situ*. The introduction of such tests will give better assurance of the consistency of construction quality and highlight potential problem areas in the foundation immediately during construction.

Laboratory testing to determine stiffness and permanent deformation behaviour *routinely* for design still requires further development, especially for granular materials. This currently limits the implementation of a detailed performance-based design and specification, however it is anticipated that a simplified analytical design approach *can* be developed.

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