Recent developments in pavement foundation design

Développements récents dans la conception des fondations des chaussées

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ABSTRACT: For many years the design of flexible pavements was heavily dependent on use of the California Bearing Ratio (CBR) of the soil subgrade within an empirical method that dated back to the 1920's. Recent changes to design practice in the UK have at last recognised that the key parameters are the resilient stiffness modulus (E_r) and the resistance to permanent (plastic) deformation under repeated loading of the subgrade and foundation materials. The foundation platform on which the asphalt layers are placed is characterised by a 'Surface Modulus', which is measurable on site using a dynamic plate test. Resistance to rutting under construction traffic is determined from proof loading with a truck. The surface modulus is a function of E_r for the individual foundation layers. To aid the selection of materials, a simplified version of the repeated load triaxial test has been developed to quantify both resilient and plastic strain characteristics. This apparatus is known as the PUMA and is similar to the Springbox device that has been successfully used in recent years. It can accommodate both soils and lightly stabilised materials for use in sub-base construction.

RÉSUMÉ : Pendant de nombreuses années la conception des chaussées souples a été fortement tributaire de l'utilisation de l'indice portant californien (CBR) de la plate-forme du sol par le biais d'une méthode empirique qui remontait à 1920. Les changements récents dans la pratique du dimensionnement au Royaume-Uni ont enfin reconnu que les paramètres clés sont le module de rigidité élastique (E_r) et la résistance à la permanente déformation (plastique) sous charge répétée des matériaux du sol de fondation et de fondation. La plate-forme de fondation sur laquelle les couches d'asphalte sont placées se caractérise par un «Module Surfacique», qui est mesurable sur le site en utilisant un essai à la plaque dynamique. La résistance à l'orniérage sous trafic est déterminée à partir d'un essai de chargement référence avec un camion. Le module de surface est fonction de E_r pour les couches de fondation individuelles. Pour faciliter le choix des matériaux, une version simplifiée du test triaxial à charge répétée a été développée pour quantifier à la fois les caractéristiques de déformation résilientes et plastiques. Cet appareil est connu comme le PUMA et est une version améliorée de l'appareil Springbox qui a été utilisé avec succès ces dernières années. Il peut être utilisé à la fois pour des sols et des matériaux stabilisés utilisés comme couche de fondation.

KEYWORDS: Pavement foundations, laboratory testing, repeated loading, resilient modulus, plastic strain, design.

1 INTRODUCTION.

The California Bearing Ratio (CBR) continues to be used to characterise subgrades in modern flexible pavement design methods in most parts of the World (eg. Highways Agency, 2006, AASHTO, 2008) despite the fact that it has long been recognised as, at best, a simple index of undrained shear strength. The mechanical properties of subgrade soils and of capping and sub-base materials that are relevent to pavement design are, however, the resilient stiffness modulus (E_r) and the resistance to plastic strain under repeated loading, concepts that are gradually being incorporated into pavement design methods. Developments both in laboratory and field testing have assisted this process. This has allowed a wider choice of materials to be used in construction within a framework of performance related specifications. While field testing using some form of dynamic plate load represents the end-product performance test for resilient characteristics on the as-built foundation, engineers also require element tests that can be used on candidate materials for the individual layers and the subgrade as part of the design process. Combining this information within an elastic analysis of the foundation can deliver a target value for what is known as the 'Surface Modulus', which is the parameter determined from the dynamic plate loading test.

The repeated load version of the triaxial test was developed in the 1960s to determine resilient modulus but it has proved time consuming to use and has essentially remained a research tool. By contrast, simplified methods of testing asphalt were developed for use in engineering practice in the 1990s against a sound research background (Brown, 1995). These have been adopted within European Standards. A similar philosophy has since been used to provide an appropriate test method for soils, granular materials and lightly stabilised materials.

2 PAVEMENT FOUNDATION DESIGN

The concept of designing a pavement in two stages was proposed by Brown and Dawson (1992). The first stage involves all layers up to and including the sub-base, known as the pavement foundation, and requires that a relatively small number of heavy wheel loads should be accommodated from construction traffic. The second stage involves design of the completed pavement for the long term incorporating bound layers over a foundation of known, measured effective stiffness; the 'Surface Modulus'.

The UK Highways Agency (2009) have introduced an interim design guide for pavement foundations following these principles (Highways Agency, 2009). Four classes of foundation are defined in terms of minimum values for the Surface Modulus; Class 1 ≥ 50MPa, Class 2 ≥ 100MPa, Class 3 ≥ 200MPa and Class 4 ≥ 400MPA. The top two classes generally require the use of stabilized aggregates of some type. A similar approach is used in France (LCPC and SETRA, 1994).

The definitive test method for measuring the Surface Modulus is the Falling Weight Deflectometer (FWD) which applies load pulses that are simulative of moving heavy wheel loads. Given the non-linear resilient characteristics of soils and granular materials, it is important to use an appropriate stress level when testing. If a hand-held Lightweight Deflectometer (LWD) is used, the stress level will be lower and the zone of influence smaller so a correlation exercise with the FWD has to be carried out and this is site specific.

In order to assess resistance to rutting, a standard truck of known axle load is operated on the completed foundation to deliver the equivalent of 1000 standard 80kN axle loads. The accumulated permanent deformation in the wheel tracks is measured and assessed against allowable values which depend on the layer thicknesses and material types.

During the design phase, it is convenient to use a simple laboratory test to determine the resilient characteristics of potential materials for use in the foundation. This provides input data to the design analysis which can generate a combination of layers of particular thicknesses with an overall effective surface modulus to satisfy the design specification for one of the foundation classes. A site trial involving one or more potential solutions can then provide confirmation that the target surface modulus has been achieved.

3 LABORATORY TESTING

3.1 *Background*

The testing philosophy is an extension of that adopted for asphalt, which resulted in the Nottingham Asphalt Tester (NAT), (Cooper and Brown, 1989) being developed as a simple low cost facility for use in engineering practice. It consisted of a pneumatically driven loading frame into which different test modules could be placed in order to measure various mechanical properties of an asphalt test specimen under repeated loading, including stiffness modulus, resistance to fatigue cracking and to permanent strain accumulation.

Using similar principles to those applied by Semmelink and de Beer (1995) for their K-Mould, Edwards et al (2005) developed a test module for unbound and weakly stabilized materials (known as a 'Springbox') that fitted into the NAT test frame. This involved a 170mm cubical specimen contained in a box with one opposite pair of vertical faces rigid and the other pair spring loaded to simulate the confining situation insitu for an element of compacted aggregate. Vertical loading was applied through a square loading platen at a frequency of 1Hz by the pneumatic actuator and measurements of both resilient and plastic deformations were taken under repeated loading.

3.2 *The Precision Unbound Materials Analyzer (PUMA)*

One of the perceived disadvantages of the Springbox is its square cross-section, raising the possibility of non-uniform compaction and non-homogeneous stress conditions. The PUMA, shown in Figure 1, therefore, adopts a similar 150mm diameter circular shape to that of the K-Mould but with a slightly increased height of 150mm. Like the K-Mould it is confined within eight curved wall segments. The specimen, which is compacted using standard equipment (e.g. a vibrating hammer) at a desired water content, is then loaded on its top surface by a circular platen. Side walls are confined within a rubber-lined steel band, the rubber providing the possibility of wall movement under load, simulating the elasticity of surrounding material in-situ. Under repeated vertical loading a residual horizontal stress will accumulate, typically between 10kPa and 50kPa, again simulating the in-situ condition.

Measurements are taken as follows: a) vertical load from a load cell; b) vertical displacement of the top surface from LVDTs, optionally inserted through holes in the top platen; c) horizontal strain in the steel confining band from a strain gauge. This last measure is directly proportional to the stress in the steel band and, therefore, to the horizontal stress in the specimen. It is also proportional to the horizontal strain in the specimen, via the known compressibility of the rubber lining. Thus, while only vertical stress is controlled, vertical and horizontal stress and strain are all monitored during the test.

Figure 1. The Precision Unbound Material Analyzer (PUMA)

3.3 *Analysis of Test Conditions*

In order to maximize the information that could be derived from a single test during the development of the equipment, specimens were loaded in four stages each involving 1000 load applications. Vertical stress levels up to about 250kPa were used, above an initial preload of typically 5kPa. Since horizontal stress is not controlled, values varied according to the material tested. Figure 2 illustrates stresses measured during a typical test on a natural gravel.

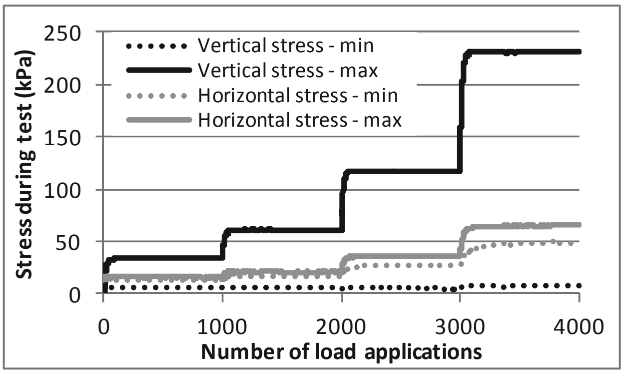

Figure 2. Stresses measured during a typical PUMA test

As a first approximation, friction between the walls and the specimen could be neglected and the measured stresses and strains converted directly into a stiffness modulus and Poisson's ratio, treating the material as a linear elastic solid. This is the method specified in EN 13286-7 (CEN, 2004) in relation to interpretation of triaxial data. Nevertheless, it is self-evidently inaccurate to ignore friction between the walls and the specimen as well as friction against the upper and lower platens. Direct measurements taken during development of the PUMA equipment suggested that a coefficient of friction of around 0.5 could be expected. The effect of this would be to transfer vertical load to the walls, reducing the stress at the lower platen. Similarly, platen friction would mean that not all the internal horizontal stress within the specimen would reach the walls and be measured. An approach to take account of this has been outlined by Thom et al (2012) who developed the following correction equations.

$$\Delta\sigma_{v(corrected)} = \Delta\sigma_{v(measured)} - 0.5\mu h\,(\sigma_{hmax}+\sigma_{hmin})/r \qquad (1)$$

$$\Delta\sigma_{h(corrected)} = \Delta\sigma_{h(measured)} + 2\mu r\,(\sigma_{vmax}+\sigma_{vmin})/15h \qquad (2)$$

where: σ_{vmax} = vertical stress at full load
σ_{vmin} = vertical stress on unloading (slightly > 0)
σ_{hmax} = horizontal stress at full load
σ_{hmax} = horizontal stress on unloading
$\Delta\sigma_v$ = $\sigma_{vmax} - \sigma_{vmin}$
$\Delta\sigma_h$ = $\sigma_{hmax} - \sigma_{hmin}$
μ = coefficient of friction (0.5 assumed)
h = specimen height (approximately 150mm)
r = specimen radius (75mm)

With these corrected stresses, the stiffness modulus and Poisson's ratio can be calculated with greater accuracy. Figure 3 shows a typical set of results from a PUMA test on a gravel aggregate. On the figure, these are compared with a set of predictions based on equations for the resilient non-linear stress-strain behaviour of a gravel aggregate contained in Thom (1988), providing a degree of added confidence that the measurements and their interpretation are approximately correct.

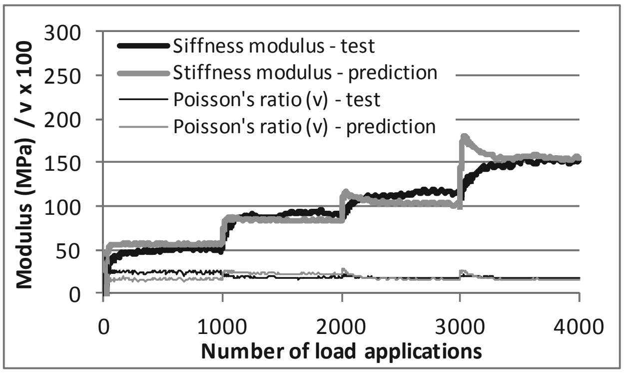

Figure 3. Stiffness modulus and Poisson's ratio – corrected for friction

Figure 4 shows some typical results for the accumulation of permanent strain under the four stages of repeated loading. Use of data of this type is not presently catered for in the Highways Agency's design method but it can be useful at the material selection stage for use on a comparative basis.

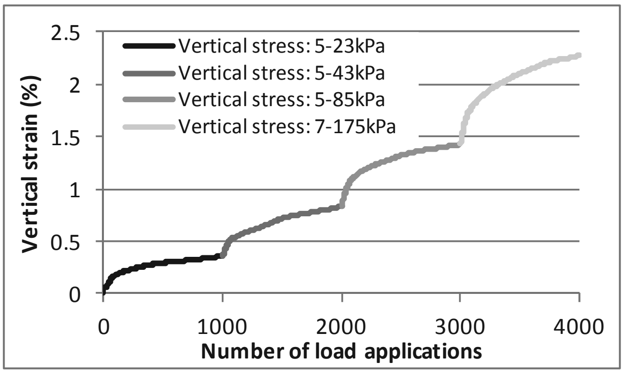

Figure 4. Accumulation of permanent strain in a typical PUMA test

4 USE OF DATA

4.1 *Selection of Appropriate Stress Level*

A key requirement for a realistic stiffness modulus test is that the stress conditions should be representative of those in the pavement. For a completed pavement, an estimate of such conditions can be derived from multi-layer linear elastic analysis and this was carried out for two cases, one with 140mm of asphalt (Case 1) and the other with 240mm (Case 2), assuming a temperature of around 20°C. At mid-depth in a 200mm base layer below the asphalt, the computed stresses due to a 100kN axle (50kN wheel) load were found to be as shown in Figure 5.

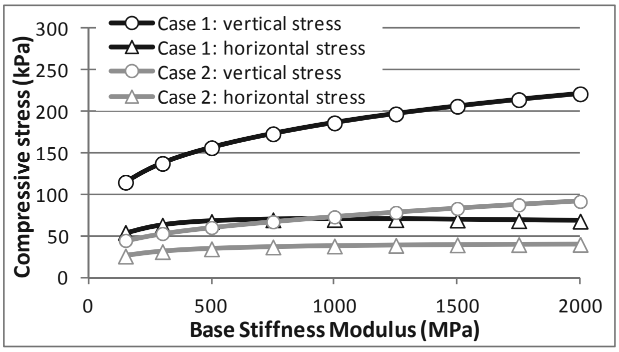

Figure 5. Predicted traffic induced stresses at mid-depth in the base layer

Although the stresses in Figure 5 only represent a limited range of examples, they suggest the sort of stress levels that should be applied to achieve a realistic stiffness modulus for pavement design. For example, using the data in Figures 2 and 5 and taking the case of a 300MPa base layer, the stress conditions would be similar to Stage 3 of the test routine in the case of a 140mm asphalt pavement and Stage 4 with 240mm of asphalt.

It is also necessary to consider the case of insitu testing using an LWD, which typically applies a vertical stress of about 100kPa, and for which it is difficult to predict the appropriate horizontal stress due to the non-linear nature of granular materials. Nevertheless, adopting an earth pressure coefficient approach the situation is akin to an active rather than passive state, in which case the ratio of vertical to horizontal stress is likely to be of the order of 4 to 5. This gives a likely horizontal stress of 20kPa to 25kPa near to the surface under an LWD load. Since it is known that the horizontal stress state has a controlling influence on measured stiffness modulus, similar to the effect of confining stress in a triaxial test, it is logical to ensure that this is correctly simulated. This suggests that either Stage 1 or 2 of the proposed test routine is likely to give a stiffness modulus suitable for inclusion in a foundation surface modulus prediction. Stage 1 is likely to be most appropriate for the uppermost layer, while Stage 2 may represent conditions in an underlying foundation layer.

4.2 *Design example*

By way of example, the data shown in Figure 3 have been used to generate a design for a UK Highways Agency Class 2 foundation (Highways Agency, 2009) which requires an equivalent surface modulus of 100MPa under a 240mm thick asphalt layer. The designation 'Class 2' represents the condition in the finished pavement and it is, therefore, appropriate to use Stage 4 of the PUMA test, which gives a material stiffness modulus of 150MPa.

It is also necessary to evaluate the stiffness modulus of the subgrade soil. This can also be carried out in the PUMA, again taking Stage 4 conditions for the completed pavement and it is assumed here that this gave a stiffness modulus of 60MPa.

It is now possible to use multi-layer linear elastic analysis to determine the equivalent foundation modulus under the completed pavement. It is suggested here that the most appropriate design methodology is to compare computed asphalt tensile strains (the asphalt fatigue cracking design criterion) under a given load, first with the intended 2-layer foundation, then with a single layer only, representing the equivalent foundation with a single stiffness value. On this basis, 260mm of the gravel material in Figure 3 is required.

The surface modulus obtained from testing with an LWD will however be significantly less than 100MPa due to material non-linearity. Stage 1 of the PUMA test generated a stiffness of just 50MPa for the gravel. For the subgrade, had it been tested, Stage 2 would be appropriate due to the increased level of confinement at depth which, if Stage 4 had given 60MPa, would be likely to have given a value of around 40MPa. Turning to multi-layer linear elastic analysis once more, with 260mm of material of 50MPa stiffness overlying a subgrade of 40MPa stiffness, the equivalent surface modulus is calculated to be 46MPa. This value would therefore represent the direct LWD test equivalent of a Class 2 foundation.

4.3 *Discussion*

The design approach described in Highways Agency (2009) represents a considerable step forward in that it puts pavement analysis onto a sound basis. Nevertheless, implementation in the UK has given rise to questions as to the appropriate in-situ measured surface modulus requirement for a given foundation class. For example, the limits currently included in Highways Agency (2009) for a Class 2 foundation are an absolute minimum LWD modulus of 50MPa and a mean value (from groups of 5 tests) of 80MPa which, from the foregoing example, would appear to be an unnecessarily conservative requirement. It is understood that a similar point has been made on several occasions by contractors who have found the 80MPa mean value difficult to achieve with standard unbound crushed rock aggregates. Clearly this is an issue that would benefit from further comparative study, including tests carried out on completed pavements using a Falling Weight Deflectometer.

Nevertheless, judgments have to be made in order to move forward and testing in a PUMA or similar confined compression test (Springbox, K-Mould) can provide suitable information on which to base such judgments. The evidence put forward in this paper suggests that the LWD-measured stiffness modulus on a granular pavement foundation should typically be less than half the value that would apply in the finished pavement, although it is clearly important to ensure that limits placed in specifications are suitably robust.

Once appropriate limits are agreed, including suitable factors of safety, the PUMA or similar tests can then be very useful in allowing a designer to evaluate alternative foundation material combinations in order to achieve a desired foundation class. The challenge for any highway authority is to allow road construction and design organizations to innovate and, thereby, save resources and costs while maintaining an appropriate degree of conservatism.

5 CONCLUSIONS

This paper represents a snapshot of developments in the UK that are still ongoing. It is believed that the generic test type, one version of which has been described, could be widely used in pavement foundation design. This is, however, reliant on there being a specification that commands the trust of the industry and that ensures the designed long-term in-service foundation stiffness modulus is achieved subject to matters that are outside the remit of direct testing, notably the provision of appropriate drainage.

6 ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Cooper Research Technology in obtaining data from the PUMA equipment.

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