Performance parameters and target values for construction of UK road foundations

PERFORMANCE PARAMETERS AND TARGET VALUES FOR CONSTRUCTION OF UK ROAD FOUNDATIONS

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ABSTRACT

There is impetus in the UK to move away from empirical design of road foundations and method specification towards analytical design assured by end product testing during construction. Current research at Loughborough University, sponsored by the Highways Agency, is aimed at introducing such a performance based specification. This paper introduces the philosophy behind the research and explains the primary objectives. Selective results are presented from a full-scale field trial construction of a road foundation on a soft subgrade, which was characterised by a variety of field devices and subsequently trafficked. This paper focuses on insitu stiffness modulus (E_R), measured by several devices for comparison. The setting of suitable target values for field E_R is seen as a key factor and the influence of inherent variability in material response a concern. The discrepancy between devices and the problem of long-term stability are discussed and highlighted as a key focus for the remainder of the work.

KEYWORDS: Foundation, Insitu Stiffness, Design, Trafficking, Triaxial.

INTRODUCTION

UK road foundations often consist of an improvement layer of unbound granular materials (capping) compacted onto a soil subgrade, which is either in its natural state or has been treated and/or compacted during the earthworks. This provides the *formation* upon which sub-base is laid and compacted to complete the *foundation*, which aims to provide a suitable platform to construct the upper structural pavement layers. UK road foundations are designed in accordance with HD25/94[1]. The foundation layer thicknesses are designed according to the equilibrium California Bearing Ratio (CBR), which is based on empirical data and experience and aims to ensure the long-term performance of the pavement. The road foundation is then constructed in accordance with the method specification included in the Specification for Highway Works[2]. The use of a recipe specification gives assurance of the performance of closely regulated materials that are known to be adequate.

This approach to design and construction precludes the use of functional soil and granular material performance parameters, which are required for analytical pavement design and for a truly performance based specification for road foundation construction. However, such a specification is desirable to permit the inclusion of alternative materials and/or alternative construction methods. A consortium of Scott Wilson Pavement Engineering Ltd and Loughborough and Nottingham Universities are researching and developing a performance based specification for subgrade and capping materials, funded by the UK Highways Agency. The broad specification philosophy is:

- measure performance parameters of the subgrade and potential capping materials at the site investigation stage,

- incorporate these into a foundation design procedure that provides a stable platform on which to construct and in the long term, and

- measure the performance parameters during construction to assure compliance with the design.

If a specification based on ‘end product’ testing can be implemented and linked to functional design parameters, marginal materials that do not meet the requirements of the current specification could be permitted. This would facilitate the use of more recycled materials and secondary aggregates, thus deriving desirable environmental benefits.

PERFORMANCE PARAMETERS

Road foundations must be designed to meet three critical loading conditions:

- Relatively few (≤ 1000 standard axles) large stress pulses applied directly to the formation surface by construction traffic.

- A small number of very high stresses applied by compaction plant.

- A very large number of small applied stresses caused by trafficking of the completed pavement.

Clearly the first two conditions are applied to the subgrade and compacted capping materials in their state at the time of construction, whereas the third condition is applied to the soil and capping materials in their long-term equilibrium state.

To meet these loading requirements the foundation must possess adequate stiffness (i.e. low resilient deformation) and sufficient strength to prevent permanent deformation. Adequate stiffness is required to allow satisfactory compaction of the overlaying pavement layers, and is achieved using appropriate materials that are well compacted, combined with sufficient thickness to spread the applied transient surface stress over a sufficiently large area to avoid distress to the underlying layers. Equally, the foundation must be able to sustain the applied stress without significant permanent deformation (rutting). If rutting does occur during construction, this can lead to ponding of water at the top of cohesive subgrades. This in turn results in weakening and a reduction in subgrade stiffness in the long term, causing the third loading condition to become more critical. This loss of stiffness can result in high resilient in-service deformations, leading to fatigue cracking of the overlying bound layers.

There are significant problems in measuring these two performance parameters accurately. Both resilient and permanent deformations caused in a foundation are controlled by the nature of the applied loading, in terms of applied stress (axle load), duration of stress pulse (vehicle speed) and direction of vehicle pass. In addition, different soils will behave in different ways to each combination of the above factors. Therefore the tests used to measure performance must match the loading conditions in practice as closely as possible.

Excessive resilient deformation can be guarded against by measuring stiffness *in situ* using dynamic measuring devices. To guard against excessive permanent deformation the foundation layers must possess sufficient shear strength. This can be controlled in practice by limiting the applied stress transmitted to the subgrade, i.e. by providing a capping of sufficient thickness and by ensuring that this capping material is sufficiently well compacted to have achieved an adequate stiffness and internal shear strength. Capping thickness can be designed according to the strength and stiffness of the subgrade, which can be assessed *in situ* during construction by an appropriate test or possibly predicted from laboratory tests. The capping behaviour is more difficult to estimate from laboratory tests but can be controlled by measuring density and stiffness. Direct measurement of subsurface rutting to limit the quantity of permanent deformation induced by trafficking during construction (i.e. rutting at the top of the subgrade and within the capping itself), however, remains a challenge for future research.

TARGET VALUES

Target values for stiffness and shear strength must be determined for construction compliance. It is anticipated that the target values will be specific to the device used to measure them due to variations in their operation. Values of target stiffness have been suggested from other work. For example, a stiffness of 50 to 60 MPa measured on the completed capping and 100 MPa on the completed sub-base have been suggested by the current authors[3]. In Germany, a minimum static plate bearing test modulus (E_{V2}) of 45 MPa is required at the top of formation, although this is negated by a requirement for a thick frost protection layer above the formation. Chaddock and Brown[4] suggested a value of 80 MPa as an acceptable top of capping stiffness, as measured by the Falling Weight Deflectometer with a 450 mm plate and 200 kPa contact stress, whereas a value of 30 MPa as measured by the Lightweight Weight Drop Tester is suggested[5].

Three dynamic stiffness measuring devices have been recommended for detailed evaluation[3] of their ability to confirm the stiffness achieved during construction at the top of the formation:

- The Falling Weight Deflectometer (FWD)
- The TRL Foundation Tester[4] (TFT, developed at Loughborough)
- The Lightweight Drop Tester (LDT)

The TFT and LDT are similar small scale dynamic devices which comprise a 10kg falling mass that impacts via a rubber damper seated on a 300mm bearing plate. The TFT measures the force applied and deflection of the ground (directly) whilst the LDT assumes a constant stress and measures the deflection of the plate. The LDT applies a peak stress of 100 kPa and as a result the TFT and FWD were configured to match this for the field trial described later. The FWD has been included as a benchmark device against which to judge the measurements from the other devices as it appears to be widely accepted by pavement engineers. However it is considered too sophisticated to be proposed in the new specification.

A target composite formation stiffness has been set initially at 50 MPa, based upon field observations and static linear elastic analyses. The achieved formation stiffness depends upon the stiffness of the subgrade, and the thickness and stiffness of the capping layer. Controlled compaction trials are currently being undertaken to refine this target value using the TFT and LDT.

Current UK design guidance[6] requires the formation of ruts in the sub-base, when used as a haul road, to be limited to 40mm to prevent excessive damage to the subgrade beneath. A similar approach for capping is proposed, thus requiring that the formation surface rut be monitored. The proportion of the surface rut that will occur in the subgrade will clearly depend upon the nature of the capping used, although this is difficult to predict and thus the general recommendations given in Table 1 have been suggested to limit rutting in the subgrade to 20mm.

Table 1. Permissible Rutting at the Surface of Capping Materials

Capping thickness, t (mm)	Maximum permissible surface rut (mm)
$t \leq 250$	20
$250 < t \leq 500$	30
$t > 500$	40

FIELD VALIDATION

A series of controlled field trials is being undertaken to validate and/or revise the target values suggested for the performance specification. These will also determine the strength of the relationship between the laboratory parameters used for design and the site compliance tests. To date, one controlled field trial and selective testing on live construction sites have been carried out. The controlled trial site consisted of a reasonably consistent, relatively soft sandy clay subgrade onto which three good quality standard crushed rock capping materials were constructed. Both rutting response to repeated lorry loading and stiffness were measured.

The trial foundations were constructed in twelve 3m long bays. The capping thickness design was based upon laboratory repeated load triaxial test data for undisturbed samples taken during the site investigation. The capping was 450mm deep for nine bays, each material being laid with poor (4 passes), medium (8 passes) and good (16 passes) compaction using a Benford TV 800H twin drum roller. Three bays were constructed as a wedge ranging in thickness from 300 to 600mm and given 16 passes (good compaction) of the same roller. After subgrade exposure, Dynamic Cone Penetrometer (DCP) tests were performed in each bay to provide strength profile measurements *in situ* and undisturbed samples were taken and subjected to repeated load triaxial testing in the laboratory for further correlations. Stiffness was then measured on the exposed subgrade and on the completed capping layer *directly above* the subgrade test positions. Insitu density measurements were also carried out on the completed capping. The road was then trafficked with 1000 passes of a 15 tonne, two axle lorry to examine rutting, which was monitored.

	Row A	*Row B*	*Row C*
Lightweight Drop Tester	x	x	x
TRL Foundation Tester *Lightweight Drop Tester* *Falling Weight Deflectometer*	x	x	x
Falling Weight Deflectometer	x	x	x

Figure 1. Layout of Dynamic Stiffness Test Points for Each Test Bay

The test layout was devised to give 9 locations per bay, to allow each test to be carried out three times on nominally similar freshly compacted capping and such that three sets of tests were carried out at the same point. (Figure 1).

During the course of the trial the weather became very hot causing a firm crust to be formed on the subgrade surface when exposed. Repeat stiffness measurements on the subgrade in the last bays to be covered showed it to have increased in stiffness by 50%.

No more than 30mm of rutting was caused in any bay during trafficking. This excellent foundation performance under trafficking, was primarily attributed to two factors. Firstly, the materials improved during construction due to drying out, rendering the parameters obtained from the site investigation tests no longer relevant at the time of construction. Secondly, the capping material stiffness used in calculating the required layer thickness to give a composite modulus was assumed, from experience, to be 80 MPa. Back-analysis of the FWD stiffness data indicated that the actual capping layer stiffness was in most cases higher than 80 MPa, possibly due to the greater stiffness achievable when compacting onto a stiffer substrate and due to the induction of larger suction stresses as the capping dried. Further research is required to produce a method of estimating site values for capping stiffness.

Subgrade stiffness measurements exhibited relatively high variation with all three devices, despite the fact that the subgrade could be regarded as being reasonably consistent. Figure 2 shows the stiffness readings on the subgrade for Row A. The variability observed was attributed to both natural variations in the subgrade and differences between devices including rate of loading, transducer type, analysis method and adequacy of plate/ground contact. This variability illustrates the problems of obtaining repeatable measurements of an absolute value of subgrade stiffness for comparison with a target value.

Stiffness readings for the TFT and FWD on top of capping typically exceeded the site target value set for the composite foundation stiffness of 50 MPa. An unusual result is exhibited by Bay 10, though this was probably caused by the presence of backfill to a buried service. The LDT values however typically fell below this target value, yet the excellent performance of the trial road suggests that the target value set for testing by the LDT (only) should be reduced.

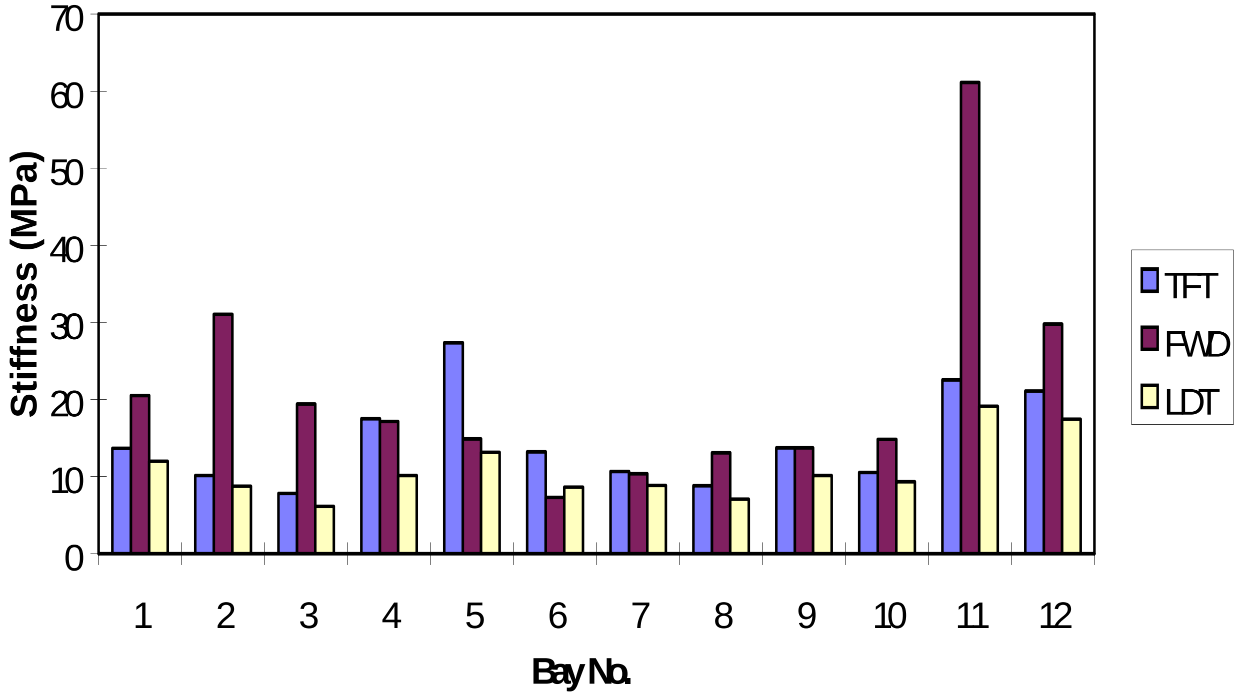

Figure 2. Comparison of Measured Stiffness along Row A on the Subgrade (Three Tests at a Single Point)

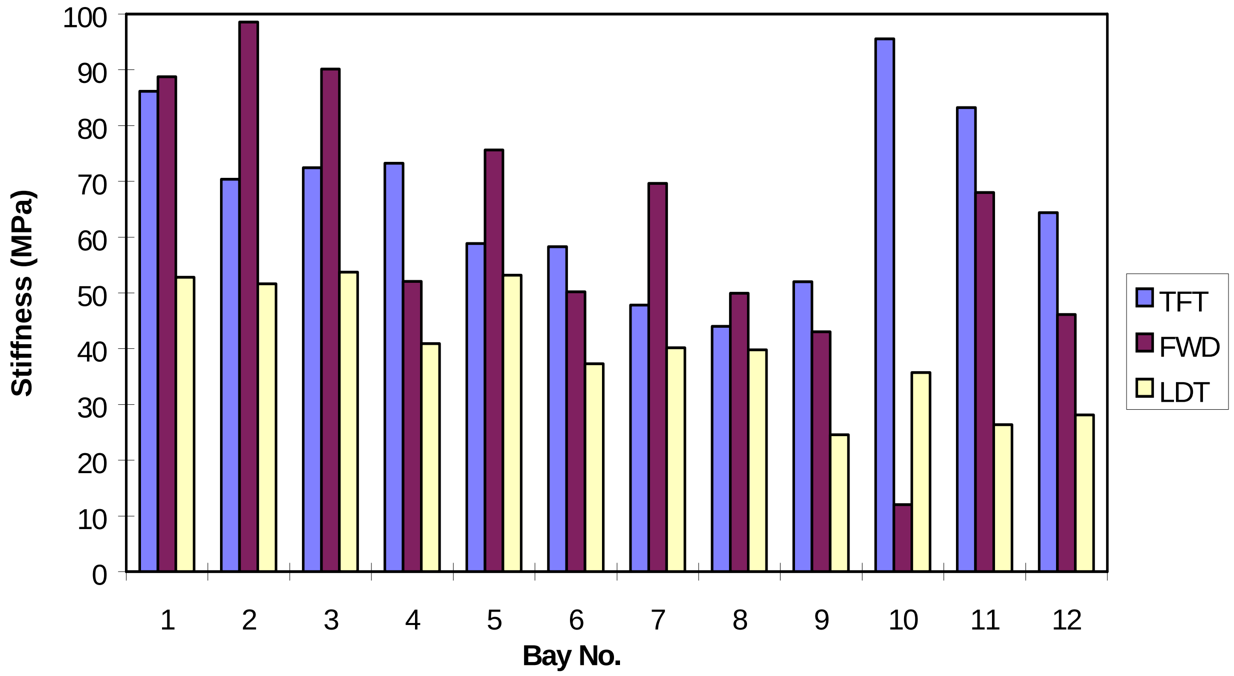

Figure 3. Comparison of Measured Stiffness along Row A on the Surface of the Capping (Three Tests at a Single Point)

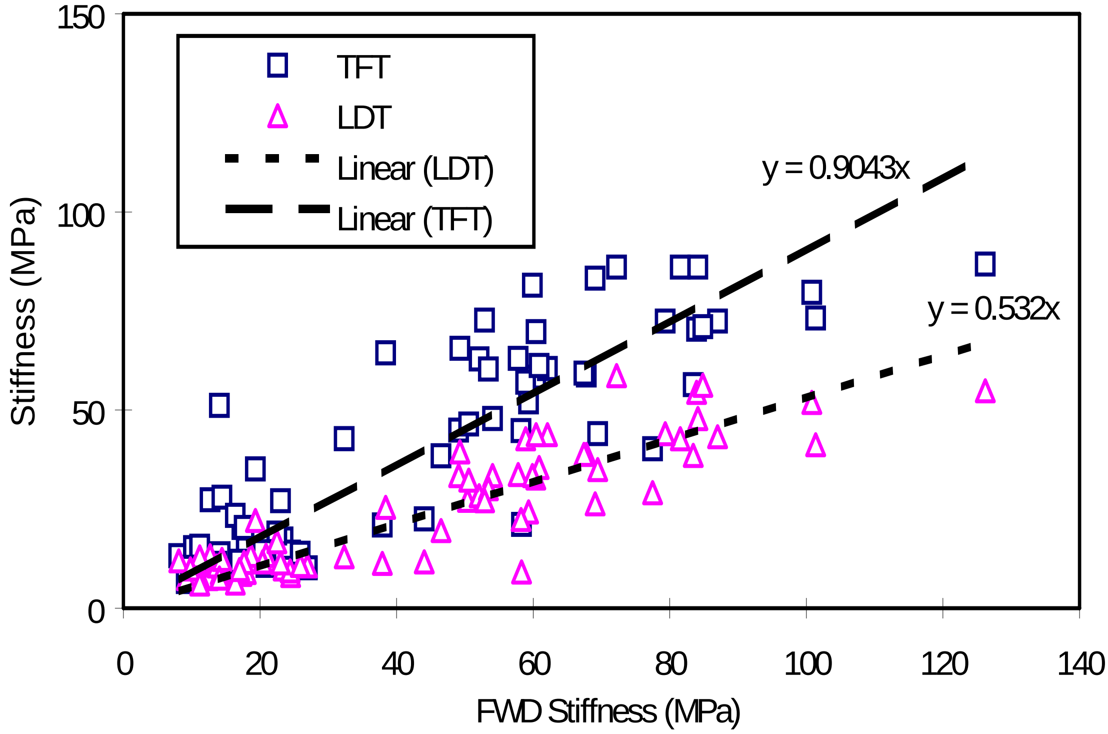

Figure 4. Stiffnesses Measured by the TFT and LDT Compared with that Measured by the FWD on the Capping and Subgrade

The test data from each of the devices, when tested at the same point, were plotted against those from the FWD to seek a correlation between devices. An example is presented in Figure 4, which includes data on both subgrade and capping. It shows that relatively poor correlation to the lines of best fit are obtained (i.e. R<0.8). The LDT showed less scatter than the TFT, although this might be partly due to the data smoothing that occurs during its data processing routine. The TFT measured stiffness values were generally 90% of those measured with the FWD, whereas those with the LDT were approximately 50% of the FWD measurements.

CONCLUSIONS AND RECOMMENDATIONS

A performance based specification for road foundation layers would provide greater assurance of adequate construction and long-term performance. This would allow the use of more marginal capping materials as their in-service performance could be assured. However its success requires accurate measurement of the elastic stiffness of subgrade, capping and sub-base materials, as well as provision to restrict rutting under construction traffic loading. In parallel with the need for suitable site assessment methods, a laboratory test is required to measure the stiffness of subgrade, and ideally also the capping and sub-base materials, under cyclic load and low confining stress, to include the use of measured stiffness in a more analytical design.

The capping thickness designed for the field trial was based upon laboratory triaxial tests on the subgrade. The design was more than adequate in terms of stiffness and resistance to permanent deformation. However, this may have partly been due to weather induced changes in the subgrade, thus confirming that site conditions can improve material performance in the short term but prudent design must always be based on a worst case condition possibly that relating to subgrade equilibrium water content. Further full-scale field trials are currently underway, with efforts focused on establishing lower bound laboratory and field values for stiffness and strength, aiming to design foundations that are close to or at failure for further validation of this work. The fieldwork also showed that significant scatter of the data was produced by all the dynamic stiffness measuring devices, therefore care must be taken in setting target values and field test protocols. Most scatter was observed on the subgrade.

The LDT consistently measured a lower stiffness (approximately 50%) than the FWD or TFT, whereas the TFT measured slightly lower stiffness (approximately 90%) than the FWD. Nevertheless the TFT and LDT are lightweight, portable and simple to use for repeated testing and provide a potentially valuable way forward for stiffness measurement *in situ*.

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