CONCRETE BLOCK PAVEMENT EVALUATION WITH THE FALLING WEIGHT DEFLECTOMETER

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1. INTRODUCTION

The structural evaluation of pavements can be carried out in many ways, but the Falling Weight Deflectometer (FWD) has become established as one of the most effective testing devices. This equipment has the ability to accurately measure the deflected shape of the pavement surface which results from the application of a transient load, similar to the load applied by a moving wheel. The FWD is also very mobile, being towed behind a normal road going vehicle, and the automatic testing sequence enables maximum utilisation of the equipment once mobilised to a site.

Data from FWD surveys can be used to determine the "effective elastic stiffness" (also known the "resilient modulus" and "modulus of elasticity") of all the significant pavement pavers and also of the subgrade. These values of elastic stiffness can then be used to make judgements about the structural integrity of the various pavement layers. They also form a basis for determining the residual pavement life using a combination of analytical techniques and knowledge of material properties. Such an approach has been described by Brown et al (1), using a multi-layer linear elastic model to represent the pavement structure. Developments of this approach, including its implementation to the design of pavement strengthening and remedial work on bituminous surfaced roads, have also been described by Brown et al (2).

This paper presents case studies using the same approach, and utilising the computer programs given by Brown et al (2), applied to pavements with a block surfacing - in particular those pavements designed for heavy duty port areas. Such pavements often have either a cement bound or bituminous bound base, and therefore the block surfacing layer makes a small contribution to overall pavement strength. In contrast, the block surfacing layer has much more significance if incorporated in a pavement with a granular base.

2. BASIC ANALYTICAL APPROACH

The FWD loads the pavement in a controlled manner over the area of a 300mm diameter parcular plate which is in contact with the pavement surface. This loading is effected by means of weights falling through a pre-determined drop height. Both the magnitude of the weights and the drop height can be varied in order to obtain a load on the plate which simulates the wheel loading of the vehicles using the pavement. Deflections of the pavement surface, at increasing radial distances from the loaded plate, are recorded automatically. A total of seven deflections are involved, with deflection dj^ being measured at the centre of the loaded plate and deflection d? furthest from the loaded plate.

The location of the deflection measuring instruments ("geophones") can be adjusted to suit the particular pavement structure being tested. For example, where the pavement consists of very stiff or very thick layers, the load spreading ability of the structure is high. In this case the measurement for deflection d_7 is made at a radial distance from the centre of the loaded plate in excess of 2 metres. For a weak structure the measurement of d_7 may be made at only 1.5 metres from the loaded plate.

Multi-layer linear elastic theory is then used to match theoretical "deflection bowls" to those measured in the FWD survey. A computer program is used which accounts for the non linear behaviour of the subgrade, the stiffness of which is stress dependent. The thickness of each pavement layer is required for this procedure, and is obtained from construction records if available or, preferably, from selected coring or trial pitting of the pavement. The "back-analysis" procedure determines an "effective elastic stiffness" of the pavement layers and the subgrade.

The term "effective elastic stiffness" is used in recognition of the non-homogeneous nature of pavement layers and the damage they accumulate with trafficking, notably due to the initiation and propagation of cracks. The effective stiffness obtained from the back-analysis procedure therefore represents elements of bound material, with a modulus of elasticity similar to an undamaged material, separated by discontinuities at cracks. Similarly for a block surfacing each block is a discrete element with high modulus of elasticity, separated by a joint, a few millimetres wider with low modulus of elasticity.

If the stress regime in the block surfacing was to be considered in detail, such an approximation would give a wildly inaccurate assessment of the stresses and strains generated in the block surfacing layer and underlying bedding sand. Apart from vertical wheel loading, tangential forces at the navement surface, due to braking of vehicles, would also have to be considered. However, for the pavements with which this paper is primarily concerned - those with bound bases - the assessment of the stress regime in the block surfacing is less important. Although localised failures can occur due to rutting within the block and sand layers, this can be rectified quickly by removal and relaying of blocks. In contrast, overstressing of the bound base - perhaps by an occasional overloaded vehicle - can be more difficult rectify.

Clearly, for pavements incorporating a block surfacing layer, some basic assumptions made in multi-layer elastic theory do not hold:-

(a) the block layer is not a homogeneous, isotropic material,

(b) the block layer is not able to sustain tensile strains.

The most common alternative to multi-layer elastic theory for analysis of FWD data is the use of a finite element technique (3). However, the FWD is especially useful for the evaluation of complex pavement structures which may consist of up to four pavement layers and the subgrade. The modelling of such a structure by means of finite elements would be much more time consuming and expensive (due to greater computing time), than by using multi-layer elastic theory. In addition the FWD is often used to fulfil a "troubleshooting" role, to investigate pavement failures or help resolve contractual claims. In such cases analysis of data is often required urgently. If based on multi-layer elastic theory, the computer programs to carry this out can be run on portable micro-computers.

Therefore, the use of multi-layer elastic theory is clearly worth pursuing for evaluation of concrete block pavements. The significance of the various differences between idealised theory and the realities of pavement engineering need to be understood by the engineer carrying out the evaluation. Some of these will be considered below by reference to actual projects in which the FWD has been involved. It should be noted that these projects primarily relate to pavement structures with bound bases, where the blocks effectively only act as a surfacing layer.

3. INITIAL BEHAVIOUR OF BLOCK LAYER

Although blocks are generally laid in such a way that they interlock by means of their geometry, the physical process of "lock-up" (4,5), (such that the blocks are thought to act as a composite whole rather than individual units), only occurs with time and is thought to be due to the action of traffic and weathering.

This is graphically illustrated by FWD results obtained during testing of a newly laid port area pavement. Figure 1 shows the construction details and Figure 2 shows the shape of a typical deflection bowl A, (as defined by the seven FWD measured deflections), superimposed with a deflection bowl B.

100 mm	Concrete blocks
50 mm	Bedding sand.
400 mm	Cement bound granular material.
	Sea dredged sandy gravel (reclaimed land)

Figure 1 : Construction details - port area pavement.

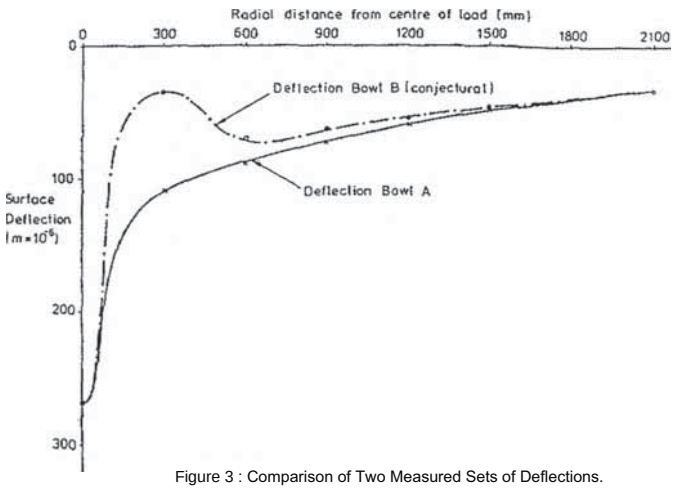

Figure 3 : Comparison of Two Measured Sets of Deflections.

In deflection bowl 8, deflection d_2 (at 300mm from the centre of the loaded plate is less than deflection d_3 (at 600mm from the centre of the loaded plate). This can be compared with the normal behaviour shown by deflection bowl A, where deflection d_2 is greater than deflection d_3. In bowl B, the blocks located around the edge of the loaded plate had not developed sufficient lock-up to prevent them moving independently from the remainder of the pavement structure. It is thought that much of this movement resulted from stresses generated in the bedding sand under the impulse load applied by the FWD, which reduced interparticle friction and allowed the sand to behave in a similar manner to a fluid. (Figure 3).

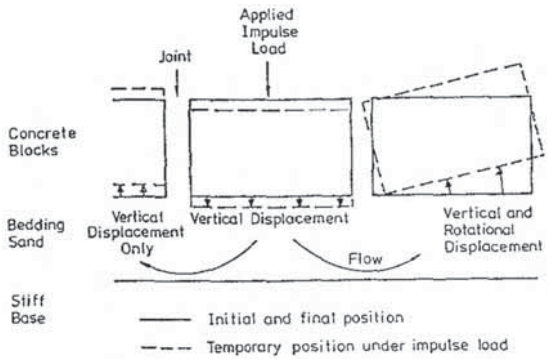

Figure 3 : Possible Mechanisms of Block Movement Adjacent to Load, for Newly Laid Pavement. (Exaggerated).

Clearly it would be impossible to model pavement behaviour for deflection bowl B using elastic theory, and viscous effects would have to be taken into account in any analysis method chosen. Fortunately there is little need to model deflection bowl B, since a second visit to the site, 9 months later, showed that the accurrence of this behaviour began to disappear once the pavement was opened to traffic. In other words, the homogeneity of the block layer began to improve.

Average effective stiffnesses for the pavement structure in Figure 1 are given in Table 1. although testing was not carried out in precisely the same areas, the results appear to indicate that an increase in the effective stiffness for the cement bound layer had occurred during the 9 months between the two site visits. Only in this way, through calculation of effective stiffnesses, can changes with time be assessed for each layer.

	Average effective stiffnesses of pavement layers in MN/m^2		
Visit	Blocks + Bedding Sand	Cement Bound Granular Material	Sandy Gravel Subgrade
1	675	11,500	240
2	630	18,500	200

Table 1 : Comparison of average effective stiffnesses for each visit

4. MODELLING OF BLOCK LAYER

Modelling the whole elastic response of the pavement structure, including the subgrade, involves back-analysis, or matching of theoretical deflection bowls to those actually measured in-situ. Although Figure 2 shows a very abrupt change in deflections near to the centre of the load, it is still possible to accurately match the measured deflection bowl by a theoretical one (2). In common with most engineering models the result involves some simplification of the real pavement structure. The user should be aware of any assumptions made, especially the sensitivity of these assumptions to changes in other variables.

A consistency of approach should also be applied, so that the method adopted for back-analysis of the deflection bowl, including basic input data such as pavement layer thicknesses, should be identical to the method adopted for calculation of stresses and strains (from which residual lives can be assessed).

For bituminous bases, extensive work (2,6) has shown that one of the most important parameters governing the pavement life is horizontal tensile strain at the bottom of the bituminous layer. For cement-bound bases, the equivalent parameter is tensile stress (7). These parameters are mostly governed by the ratio of effective stiffnesses between the base and underlying supporting layer, and the effective stiffness of the block surfacing layer in isolation is not normally required. The blocks and underlying bedding sand can be combined into a single layer for the back-analysis procedure. Table 2 shows some typical effective stiffnesses that have been obtained by modelling the block layer separately from the bedding sand, as well as combined. (Results not for same deflection bowls).

	Effective stiffnesses of pavement layers in MN/m^2			
Description	100mm Concrete Blocks	50mm Bedding Sand	80mm Concrete Blocks	40mm Bedding Sand
Separate	3100	60	2500	50
Combined	Range 450 - 950		800	

TABLE 2 : Effective stiffnesses of pavement layers.

5. CALCULATION OF PAVEMENT LIFE

Once the pavement model has been obtained, calculations can be performed which determine the stresses and strains at critical points in the structure, from which an assessment of remaining life can be made. Any magnitude of wheel load or combination of wheel loads can be considered, which is particularly useful for port area pavements where vehicle loads are often augmented by braking and turning forces.

A description of the methods employed for assessment of pavement life and the design of strengthening measures is given by Brown et al (2,8). In particular, the methods enable the engineer to :-

(a) allow for the combined effect of several different vehicle types (that is, take into account the loading spectrum).

(b) allow for any fatigue damage that has already occurred, in the bound base materials, resulting from trafficking prior to testing with the FWD

(c) allow for different degrees of canalisation of vehicles

(d) choose a suitable rut depth, (appropriate to the vehicles using the site, surface water drainage provisions, etc) to define a failure condition resulting from overall permanent deformation.

The elastic analysis method employed for these calculations does not automatically prevent the generation of tensile strains in the block layer. If tensile strains occur, the joints between blocks will open up and a reduction in effective stiffness will result.

In this analysis, no account is taken of any compressive stresses which may build up in the block layer with time and trafficking (5). Fortunately, for those pavements with a bound base the effect of any reduction in the effective stiffness of the block layer can usually be ignored.

6. INFLUENCE OF DIFFERENT BASE MATERIALS

Different base materials have different effective elastic stiffnesses and consequently the distribution of stresses in pavement structures will vary, even if the pavement layer thicknesses are the same. In order to illustrate this, an elastic analysis was carried out on the pavement structure shown in Figure 4, with three different base types - cement bound, bituminous bound and granular. The pavement layer thicknesses and effective stiffnesses were chosen to represent a typical, middle-of-the-range pavement that might be designed for a port area.

	Description	Effective stiffness (MN/m^2)
80 mm	Concrete bocks	3000
50 mm	Bedding sand	50
300 mm	(a) Cement bound	20000
	Base (b) Bituminous bound	7000
	{c) Granular	200
300 mm	Granular sub - base	100
	Subgrade (poor granular/ good clay)	150

Figure 4 : Pavement structure used for comparison of strains.

Figure 5 compares the variation with depth of the vertical strain induced by a 40 kN dual wheel load (ie. an 80 kN "standard" axle), for each base type. Since the area under each curve gives a measure of the surface deflection on the centreline of the load, it is clear that the pavement with a granular base will have significantly greater deflection. This movement may, in turn, increase the likelihood of localised failure in the block surfacing layer.

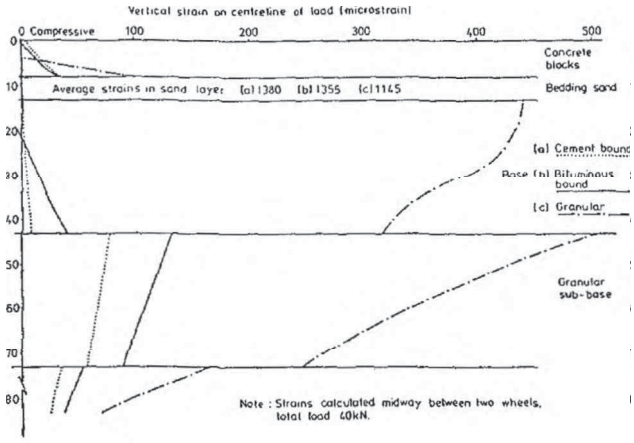

Figure 5 : Vertical strain variation with depth.

7. CASE STUDIES

In order to illustrate further aspects of concrete block pavement evaluation with the FWD, three case studies are briefly discussed below.

A : Comparison between brick paviors and concrete blocks

An evaluation of a trial site was carried out with the FWD, where the surfacing consisted of concrete blocks or brick paviors, and the base has bituminous bound (hot rolled asphalt (HRA)). The site was located on the access road to an industrial estate, which was trafficked by heavy goods vehicles.

A comparison of material types, thicknesses and effective stiffnesses are given in Table 3; location A1 refers to 80mm concrete blocks, location A2 refers to 65mm brick paviors.

	Effective stiffnesses of pavement layers in MN/m^2				
Location	Rectangular Blocks/ Bricks	50mm Bedding Sand	195mm HRA Base	150mm Granular Sub-base	Silty Clay Subgrade
A1	7200	40	13800	130	150
A2	9600	50	7000	80	100

Table 3 : Comparison of effective stiffnesses for blocks and bricks.

For these two individual locations, the effective stiffness of the block and brick layers are comparable. Both values are above average, indicating that a high degree of "lock up" has been established between the blocks. Location A1 has above average stiffness for the HRA base, but it was not possible to obtain material samples in order to ascertain the cause.

B : Comparison of two different applied stress levels

During the evaluation of a pavement with 80mm concrete block surfacing, 50mm bedding sand and 600mm granular sub-base and base, two different stress levels were applied by altering the height from which the FWD weights were dropped. The pavement had not carried much traffic and back-analysed stiffnesses for the block layer indicated a poor degree of "lock-up".

A comparison of the mean deflections obtained from 18 test locations, for three deflection criteria, is given in Table 4.

	Applied Stress Level (kN/m)	Mean Deflection (m x 10^{-6})		
		d_1	(d_1-d_3)	d_7
	600	560	351	22
	400	418	252	15
Ratio	1.50	1.34	1.47	1.39

TABLE 4 : Mean deflections at different applied stress levels.

As might be expected from a pavement with a granular base, (the stiffness of which is stress dependent), the ratio of deflections differs from the ratio of applied stress. With a much stiffer, bound base, closer agreement would be expected. The importance of choosing an appropriate loading for in-situ testing with the FWD can therefore be seen.

C : Evaluation of granite setts overlaid by bituminous materials.

In the United Kingdom during the 19th and early 20th century, granite setts were a common surfacing for urban roads. Generally, these are now overlaid by bituminous materials. The FWD was used to test such a pavement in order to evaluate the residual life and recommend remedial measures, if required.

Table 5 gives material types, average thicknesses and average back-analysed effective stiffnesses for this pavement.

	Effective stiffnesses of pavement layers in MN/m^2		
70mm Bituminous Material	100mm Granite Letts + 20mm Ash	175mm Unreinforced Concrete	Ash Fill and Subgrade
7000	500	12000	90

TABLE 5 : Average effective stiffnesses of pavement layers

The range of effective stiffnesses for the granite setts and ash was 270-800 MN/m^2. Comparison with other results, especially the concrete blocks in Table 2, indicates a lower effective stiffness obtained for the granite setts and ash, even though a thin (20mm) "bedding " layer was used. Since the stiffness of individual setts would be expected to be greater than individual blocks, this implies wide joints (hence poor degree of "lock-up") and possibly a very weak ash bedding layer.

It is of interest to note that on this site there was no evidence of reflection cracking in the surfacing. It is understood that the use of similar constructions are now being investigated in an attempt to overcome the problem of reflection cracking through bituminous overlays on concrete pavements.

8. CONCLUSIONS

(1) Use of the FWD, for the evaluation of pavements with concrete block surfacings, requires a method of analysing the deflection data. Multi-layer elastic theory provides a practical, and quick, method for carrying this out, and is able to accurately match theoretical and measured deflection bowls.

(2) Although multi-layer elastic theory does not permit detailed modelling of the stress regime in the block and bedding sand layers, this is not considered to be of significance for heavy duty pavements with bound bases, where the blocks only act as a surfacing material.

(3) Analysis of FWD data using multi-layer elastic theory has enabled the application of analytical design methods, that were originally developed for other types of pavement structure, and now widely used by engineers, to be applied to block pavements.

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