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The effect of construction pattern and unit interlock on the structural behaviour of block pavements

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ABSTRACT

The maintenance or even replacement of cracked pavements requires considerable financial resources and puts a large burden on the budgets of local councils. In addition to these costs, local councils also face liability claims arising from uneven or cracked pedestrian pavements. These currently cost the Manchester City Council and Preston City Council around £6 million a year each. Design procedures are empirical. A better understanding of the interaction between paving blocks, bedding sand and subbase was necessary in order to determine the mode of failure of pavements under load. Increasing applied stress was found to mobilise "rotational interlock", providing increased pavement stiffness and thus increased load dissipation resulting in lower transmitted stress on the subgrade. The indications from the literature review were that pavements are designed to fail by excessive deformation and that paving blocks remained uncracked at failure. This was confirmed with experimental data which was obtained from tests on segments of pavements that were laid/constructed in a purpose built test frame in the laboratory.

1. Introduction

A light duty block pavement consists of the following layers: (a) surface course of concrete blocks, (b) laying course, (c) roadbase, (d) subbase, and, (e) subgrade. Concrete block pavements are recommended for areas, where traffic speed is less than 70 km/h (43 miles/h) [1]. Hence, concrete block pavements are normally used in built-up areas, i.e. residential roads, where a speed limit less than 40 miles/h is normally imposed.

According to Knapton [2], "a considerable amount of research has been directed towards producing design charts relating thickness of base and subbase material required based on the properties of the subgrade and the traffic characteristics". Design criteria are based on experience and adjusted, if needed, by means of on site observation and accelerated trafficking tests [3]. However, the accuracy of these methods is limited because they are simplified/empirical procedures that ignore certain parameters such as the discontinuous nature of blocks [3,4].

1.1. Factors influencing the structural performance of concrete block pavements

Static load tests, accelerated trafficking pavement tests and full-scale field tests have been carried out to investigate how different factors affect the performance of concrete block pavements. These factors are:

- **Block strength**: Panda et al. [5], Knapton [6] and Shackel [7] advocated that the structural performance of concrete block pavements is independent of the compressive strength of concrete blocks. This indicates that the compressive strength of concrete blocks is not the critical parameter to be considered when designing pavements. A compressive strength of 49 N/mm^2 is usually targeted by precast factories which appears to ensure that a tensile splitting strength of 3.9 N/mm^2 is achieved, i.e. the specified value in BS EN 1339 [8]. The requirement for the compressive or tensile splitting strength appears to be for ensuring adequate durability performance, e.g., freeze–thaw resistance and resistance to sulphate attack from aggressive ground conditions, rather than ensuring that concrete blocks remain crack free during the loading of the pavement. This implies that failure of the pavement is governed by deformation and that deformation deemed to have made the pavement unserviceable will not cause cracking of the paving blocks [9].
- **Block thickness**: Shackel [9] advocated that concrete block pavements can tolerate a significantly larger deflection than asphalt pavements without cracking. This implies again what was mentioned above, i.e. deformations deemed to make the pavement unserviceable will not cause cracking of the paving blocks. Panda et al. [5] showed that the use of a thicker block, 80 or 100 mm compared to 60 mm, will result in lower

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deformations of the pavement. Relationships between the resilient pavement deformation and the block and subbase thicknesses have been proposed by Shackel [10]. Similar relationships between the stress at the top of the subgrade and the block and subbase thicknesses have also been proposed. Festa et al. [11] attributed the more effective dissipation of load with thicker blocks to friction acting between them which prevents a loaded paving block from sliding easily past adjacent blocks. This results in a spreading of the load over a greater area before it reaches the bedding sand, i.e. the blocks are acting together as a slab and thus the load is no longer a concentrated load but is spread over several blocks. Tests carried out by Festa et al. [11] indicated that an angle of friction of 36° or a shear stress of 0.44 N/mm^2 is the maximum that can be achieved with well constructed pavements. According to Knapton [12], concrete block pavements do not merely act as a wearing surface, like bituminous pavements that are flexible, but act as a single structural element, i.e. the individual paving blocks interlock and act to dissipate a concentrated load. Three forms of interlock have been identified:

  - *Vertical interlock*: The spaces between blocks are normally filled with jointing sand and this is achieved by agitating the paving blocks with a plate vibrator [13]. This practice results in the jointing sand being compressed in between the paving blocks creating a horizontal or "dilatancy" force. This force prevents adjacent blocks from sliding past each other independently. It can therefore be expressed in terms of a friction force.
  - *Horizontal interlock*: Vehicles suddenly braking or accelerating can cause significant horizontal forces on pavements which may lead to local tensile stresses and cracking of the blocks. Certain paving patterns may be better than others and are therefore preferred for car parks.
  - *Rotational interlock*: Blocks may be loaded eccentrically causing the blocks to rotate [2]. However, this rotation will be prevented by the adjacent blocks if the pavement is restrained along its edges. Pavements without edge restraints have been reported to deflect 1.6 times more [14]. Panda et al. [15] and Sun [16] reported noticing blocks rotating with increasing applied loads. This rotation can cause "arching thrust", preventing further rotation of the blocks and therefore resulting in higher load bearing capacities. The beneficial effect of "arching thrust" was known since the first century A.D. and was utilised in the construction of relatively flat "arches" [17].

- **Block shape**: Debate continues into the influence of block shape on interlock with some favouring complex shapes [9] whilst others consider that there is no evidence to suggest that shape is a relevant factor [6].
- **Laying pattern**: Panda et al.'s experimental data [5] showed that the load bearing capacity of a pavement is unaffected by the laying pattern. It was, however, believed that the herringbone pattern may perform better than the others in car parks because it can resist horizontal forces due to vehicles braking or accelerating.
- **Jointing sand**: Panda et al. [15] observed lower pavement deformations with coarse grading of sands. This was attributed to the mobilisation of a higher shear resistance. The effect of increasing the joint width, from 2 to 8 mm, was also found to allow greater rotation of the blocks and therefore a reduction in the rotational interlocking effect. Knapton [2] and Dutruel et al. [18] confirmed this. A joint width of 2 mm–4 mm has been recommended [18].
- **Bedding sand (grading and thickness)**: Bedding sand not only provides a smooth surface for laying the paving blocks but it also partly fills the block joints. Panda et al. [15], Shackel [7] and Knapton [19] advocated that the use of coarse sand improves the performance of the pavement by providing higher shear resistance to vertical movement. BS 7533-3 [20] recommends the use of coarse sand for heavy duty applications such as bus stations and aircraft pavements. Panda et al. [15] observed that the deformation of a pavement was not affected greatly with bedding sand thicknesses up to 50 mm. However, a bedding thickness beyond 50 mm increased significantly the pavement deformation. As a result, Lekso [21] recommended a bedding sand thickness of 30 mm.
- **Subbase**: A stronger subbase material such as cement-treated or crushed rock subbase will have improved pavement performance over a weaker subbase material such as asphalt or blast-furnace slag [22,23].

1.2. Multi-layer elastic pavement models

Mathematical models have been developed which enable an evaluation of the performance of concrete block pavements and these are described next.

1.2.1. Boussinesq's equation

Block pavements can be modelled as a succession of linear elastic layers. The stress and overall displacement/deformation can be determined using Boussinesq's half space model and the corresponding equation for vertical stress is:

$$\sigma_z = \sigma_0 \left\{ 1 - \frac{1}{\left[1 + \left(\frac{r}{z}\right)^2\right]^{3/2}} \right\} \tag{1}$$

where σ_z is the vertical stress at depth z, σ_0 is applied pressure, r is radius of load acting over a circular area, z is the depth, where σ_z is determined.

Modular block pavements are complicated multi-layer systems as a result of a combination of different layers of widely varying properties meeting at common interfaces under complicated applied vehicular loading. Thus, in order to devise rational design and analysis tools for these systems, engineering simplifications are necessary. One such means of a simplified analysis technique has been provided by Boussinesq who devised equations for calculating physical phenomena, i.e. stresses, strains and displacements, at any point in a homogeneous, linear, elastic semi-infinite space defined by its elastic modulus and Poisson's ratio.

Interestingly, Boussinesq's equations for vertical and principal stresses are independent of the elastic parameters and are, thus, not affected by the elastic modulus. Furthermore, equations for stresses and strains reveal an important difference in variation with depth with that for displacement. Whilst the latter is inversely proportional to depth below the applied load, stress and strain are inversely proportional to square of the depth. The knock on effect of this difference is that surface deflection at the top of a layered system is poorly correlated to stresses and strains in individual layers [24]. A further complication is created due to the fact that a block pavement has distinct layers with different properties, which does not allow Boussinesq's equations to be applied.

1.2.2. Winkler-spring model

A pavement can be modelled as a series of springs, where the deflection/deformation of each spring/layer is given by:

$$\delta = \frac{\sigma}{k_w} \tag{2}$$

where δ is the overall settlement per unit area (mm), σ is the compressive stress applied to a unit area of soil (N/mm^2); k_w is