THE EFFECT OF CONCRETE BLOCK LOCK-UP ON PAVEMENT PERFORMANCE

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1. SUMMARY

Lock-up in a concrete block pavement has been referred to by many researchers in the past decade. The phenomenon is essential to the proper performance of a CBP. It is important therefore to further investigate the lock-up mechanism, which has been reliably reported to :

* increase with time and pavement useage'
* vary considerably when expressed as the modulus of the layer (between 400 and 7500 N/mm^2)

This paper attempts to determine firstly the parameters that cause progressive lock-up, and secondly the effect that such lock-up has on the performance of the total pavement. It is suggested that the degree of lock-up is in fact the (measurable) amount of pre-compression in the block layer. Such prestress modifies its structural behaviour from truly flexural, at low stress levels, to semi-rigid not unlike prestressed concrete slabs. The prestress enables the layer to transfer shears through the joints and to provide a degree of fixity resulting in smaller rotations and deflections.

The concept of a balanced pavement is introduced. When a balance is obtained, the base layers below the block course provide support just sufficient for the blocks to be structurally utilised to their ultimate capacity when the surface loads are applied.

The link between block course modulus, thickness and load is presented in graphical form to arrive at indicative values of load spread for balanced conditions.

2. INTRODUCTION

This paper was prompted by the Author’s confusion caused by, what appeared to be, conflicting expert opinions and findings with regard to concrete block paving (CBP) parameters such as lock-up, material equivalencies, load spread and modulus.

As all these experts were experienced and well qualified, could they all be correct? That would only be possible if their findings were based on a wide range of circumstances. The answer seems to be that a CBP performs in different ways for different base and subgrade conditions and combinations.

For instance, placed on a rocky or heavily stabilised unyielding foundation, the blocks merely act as a wearing course. Deflections under the wheels are nil to minute and the CBP will not spread the load by beam-action.

On the other side of the spectrum, consider a CBP on a highly compressible base. The block course is called upon to distribute a heavy load over a large area, well beyond its capacity to sustain the subsequent stresses, shears and rotations. The pavement fails in the joints. This situation may also arise if, due to operational activities, the bedding material has washed away.

In between these two extremes, there exists a CBP structure in which the structural capacity of the block course matches that of the underlying base. The surface load is distributed over an area of such proportions as not to cause joint failure and the block course is utilised to its maximum capacity.

The three cases discussed above are shown in Figure 1.

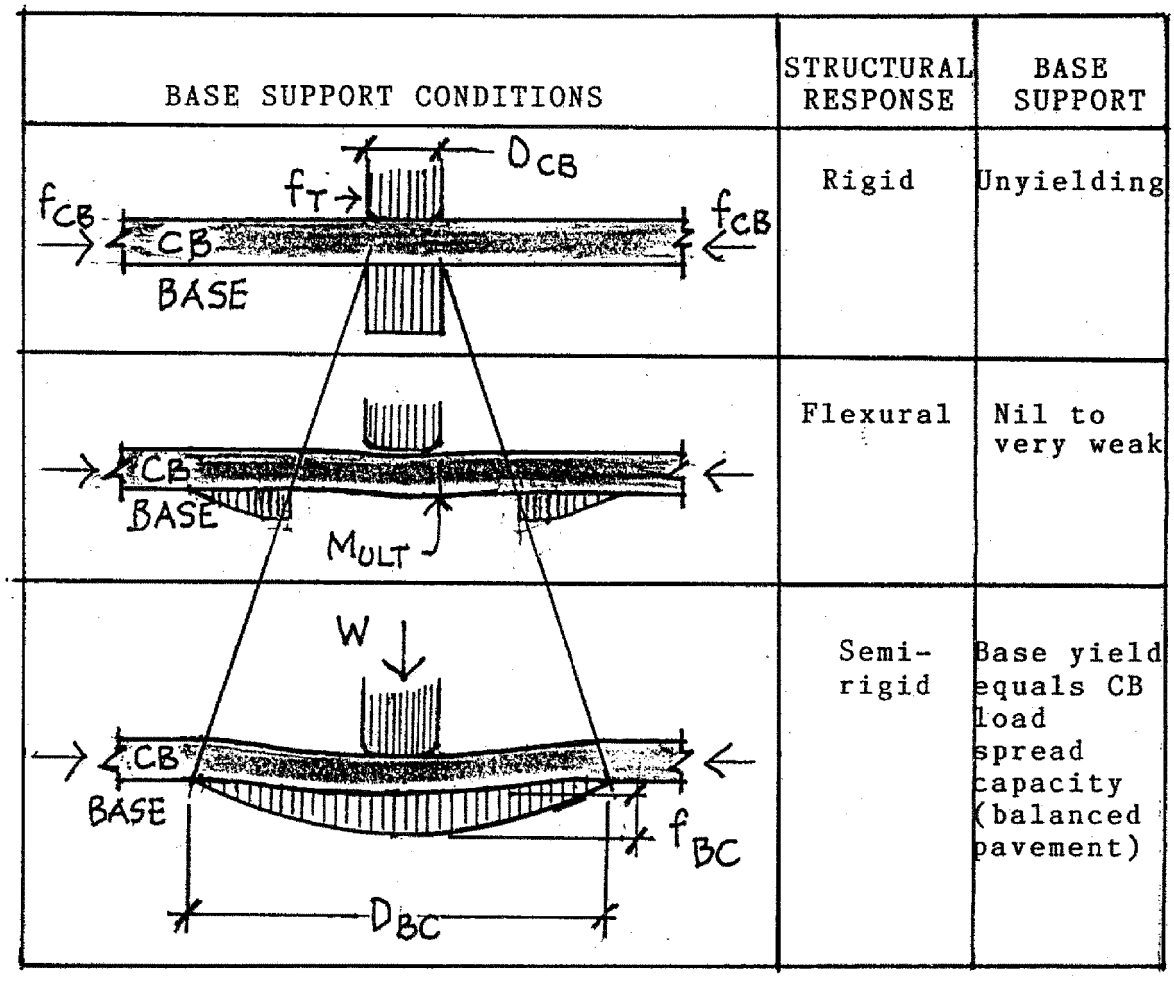


FIGURE 1

The following assumptions are made for the balanced pavement condition:

2.1 The base supports the surface load over a more or less circular area with a diameter of vgo Base stresses diminish from the centre outward with a maximum level of f_{BC}.

2.2 The subgrade deflection under the load is within the limit set empirically to reflect the long-term damaging effect of load intensity and frequency.

2.3 At this limit, the block joints remain in compression when the surface load is applied (refer to Section 5).

Such a balanced condition will seldom be attained; generally the CBP will be under-utilised. If the balance is exceeded, the CBP will fail.

What are the parameters that determine a balanced pavement condition?

3. PRE-COMPRESSION AND LOCK-UP

A unreinforced concrete slab with a compressive strength of 60 N/mm^2 has a modulus of approximately 35,000 N/mm^2. The slab spreads surface loads by beam action until it fails when flexural tensile stresses cause cracking.

To overcome this type of failure and, at the same time, increase its load-bearing capacity, the slab is reinforced. The added steel reinforcement takes care of,the tensile stresses, increases the slab's bending moment capacity and reduces rotations and therefore deflections. Reinforcement can be unstressed mild steel or high strength prestressed cables. In the latter case, a pre-compression is set up in the slab to balance the flexural tensile stresses generated by surface loads. Failure occurs when these stresses exceed the pre-compression.

A CBP consists of small high strength elements with a material modulus of 35,000 N/mm^2, and sanded joints with a modulus ranging from less than 10 N/mm^2 at initial construction to the stage when, due to repeated stress cycles and cementation, the modulus could well exceed 100 N/mm^2. Composite moduli for the block course can now be estimated for a range of joint conditions. As the joints tighten up, the pavement strains under lateral loads, such as braking and accelerating, reduce and the composite modulus Egg increases from an initial low value less than 500 N/mm^2 to possible levels in excess of 5000 N/mm^2. This E value is the pavement modulus and is a quantifiable measure of lock-up.

4. PAVEMENT MODULUS OF ELASTICITY

Moduli for the base and subgrade layers relate to vertical stresses and strains. The block course modulus E_{CB} proposed in this paper relates to horizontal stresses and strains and should therefore not be confused with its apparent E-value in a vertical direction.

E_{CB}, the measure of the block layer's lock-up, is an important parameter as will be demonstrated later.

During the pavement's service life, compression in the joints progressively increases due to:

4.1 Lateral traffic forces

4.2 Block rotations due to deflections induced by rolling traffic

4.3 Climatic conditions

This last event is worth considering, as well-maintained pavements show a tendency to lock up even with little or no traffic on them. Consider the case of a dry and cold pavement. When the surface temperature rises from 10°C to 30°C and a rain storm saturates the blocks, the expansion will be in the order of one millimetre per metre of pavement width. Provided that the pavement is restrained from expanding by an adequate confinement system, this climate-generated strain will induce a compressive stress f qgin the order of 0.5 N/mm^2.

Thus, the pavement modulus increases gradually as time goes on.

The relationship between E_{CB} and f_{cb} is estimated to average out at: E_{CB} - 5000 f_{CB} (both in N/mm^2) for a good quality, 2.5mm wide joint.

If this progressive stiffening phenomenon is to be achieved, it is of the greatest importance that the block joints be main tained in a full condition by occasional topping up, especially at the early stages of the pavement's design life. The build-up of precompression can be verified by single block pull-out tests at selected stages during the pavement's design life.

The effect of progressive stiffening on a balanced pavement structure is illustrated in Figure 2. For the criteria that determine a balanced structure refer to Section 2.

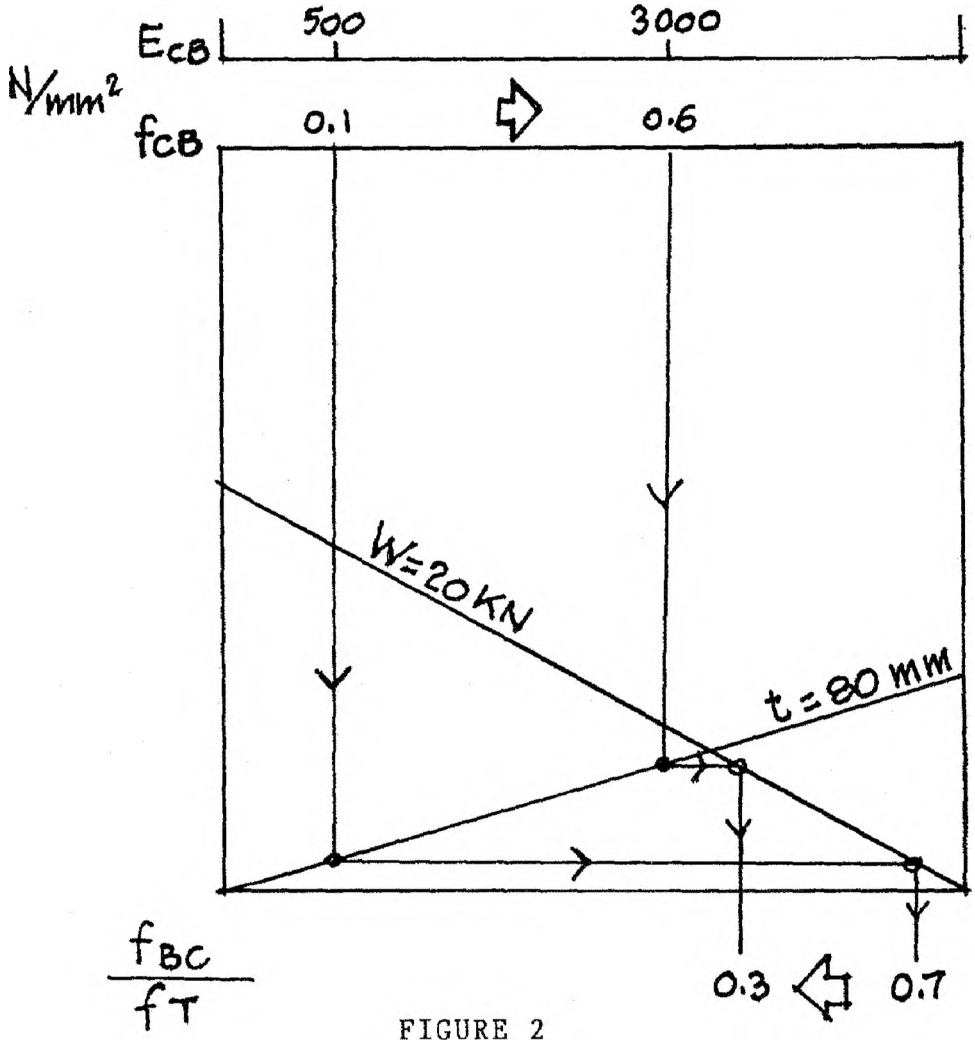


FIGURE 2

THE INFLUENCE OF LOCK-UP ON BASECOURSE STRESSES

Example:

A partially locked-up CBP with a pre-stress f_{CB} of 0.1 N/mm² in 80mm blocks subjected to a wheel load of 20 KN with a tyre pressure f_T of 0.5 N/mm² will result in a peak basecourse stress of 0.7 x 0.5 = 0.35 N/mm² while a high degree of lock-up (f_{CB} - 0.6 N/mm²) will reduce this stress to 0.3 x 0.5 = 0.15 N/mm².

5. LOAD SPREAD CAPACITY

In order to ensure load sharing between the blocks, the joints must be utilised over their entire depth. This can only happen when the block interface is in compression. My definition of a CBP failure is the event of the load-induced joint tension exceeding the pre-compression in the block layer. When this happens, the joint opens up and becomes a hinge with virtually no capacity to transfer vertical loads. This hinge formation also leads to substantially increased rotations and deflections (rutting) .

Figure 3 illustrates the structural model of a block joint at the point of failure.

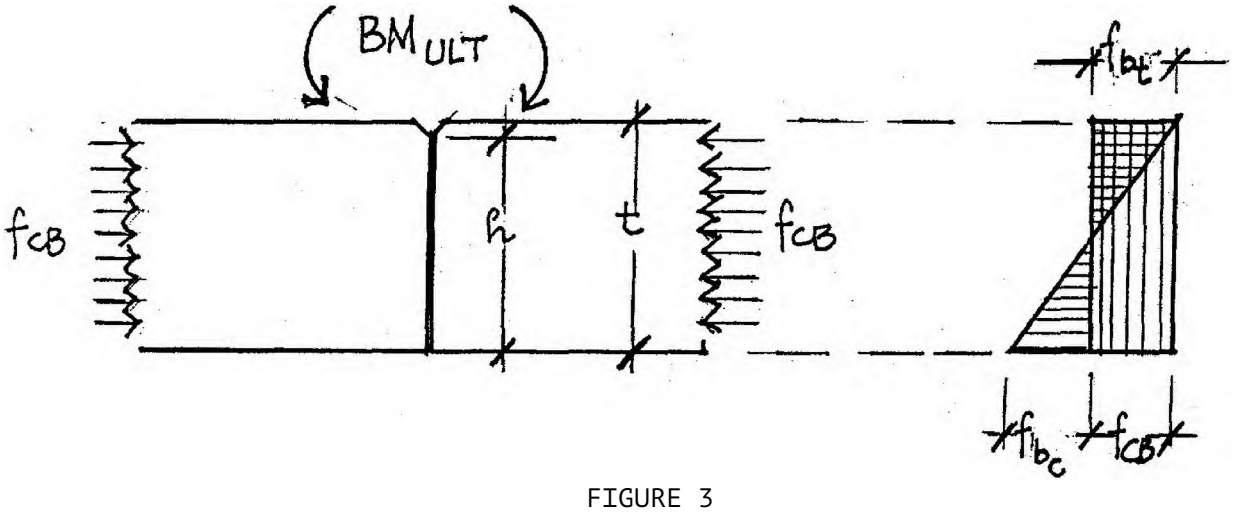


FIGURE 3

BLOCK JOINT STRESSES AT BALANCED CONDITION

f_{CB} = block layer precompression - N/mm²

$$f_{bt} = f_{bc} = \frac{6BM_{ULT}}{b\ h^2} \quad \text{- N/mm}^2$$

$$BM_{ULT} = f_{BC} \times \frac{(D_{BC} - D_{CB})^3}{80\ D_{BC}} \quad \text{- Nmm/unit width}$$

$b = 0.79\ D_{CB}$ - mm

$h = t - 7$ - mm

D_{CB} = diameter of surface load contact area - mm

D_{BC} = diameter of load sharing area at top of base - mm

The load spread capacity of a block layer is not only dependent on its pre-compression, but also on the thickness of the blocks. This will be apparent from the structural model shown in Figure 3

Figure 4 is drawn on the same basis as Figure 2, but highlights the change in base response when the block thickness is varied under balanced design conditions. As for Figure 2, the graph shows trends in base response which may be used in pavement assessments and analyses. The values should not be accepted for final design until verified by full scale testing results have been obtained.

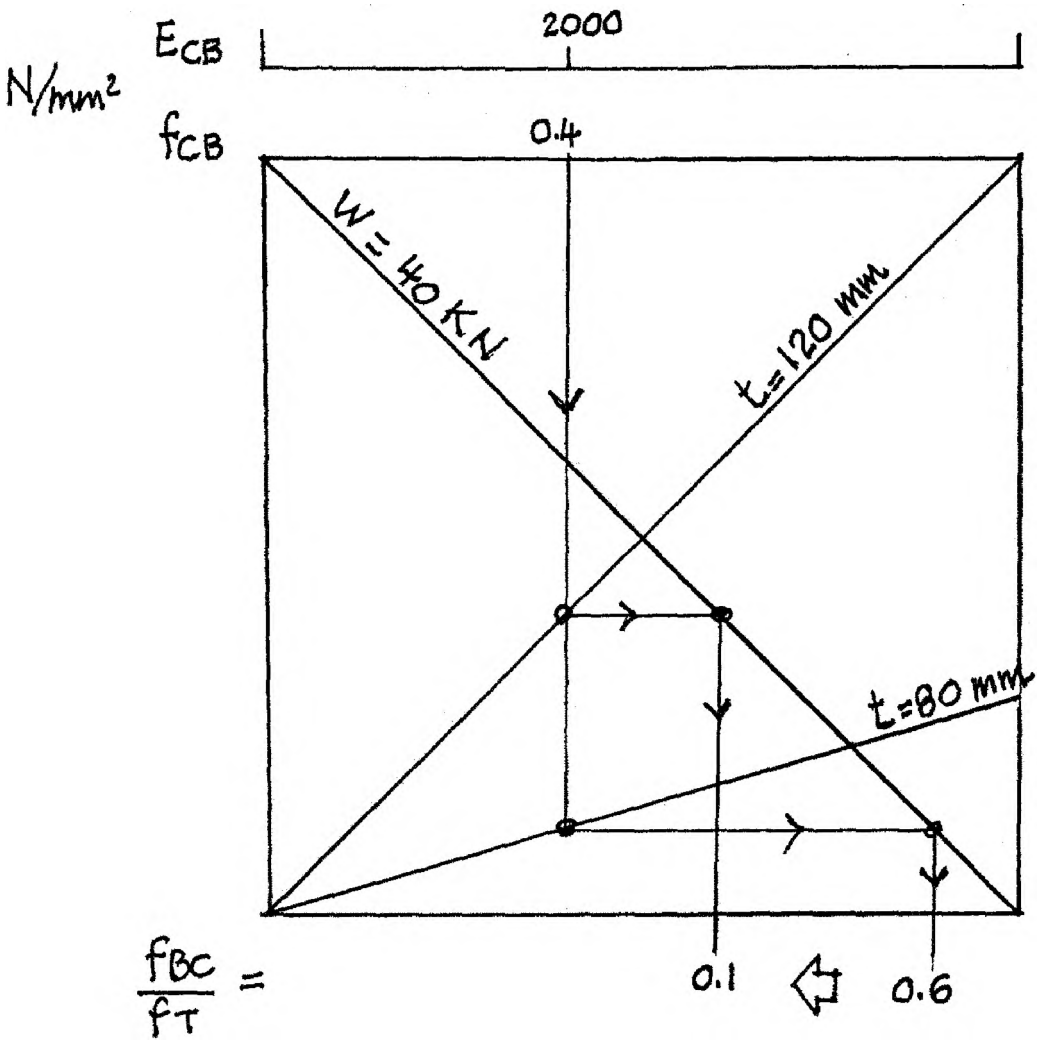


FIGURE 4

THE INFLUENCE OF BLOCK THICKNESS ON BASECOURSE STRESSES

Example:

A reasonably well locked-up CBP with a prestress of 0.4 N/mm² produces peak basecourse stresses, of 0.42 N/mm² for 80mm. blocks and 0.07 N/mm² for 120mm. blocks, given the following equal parameters:

- o Wheel load of 40KN
- o Tyre pressure 0.7 N/mm²
- o Ultimate stress conditions for both 80 and 120 CBP

6. BLOCK COURSE DESIGN BASED ON A BALANCED PAVEMENT SYSTEM

As discussed previously, the pavement will perform most efficiently when a design close to the balanced condition has been achieved. From a design predetermined by the usual criteria, one can estimate the ultimate load spread in the block course by analysing the trends shown in Figure 5. This graph combines the data depicted in Figures 2 and 4.

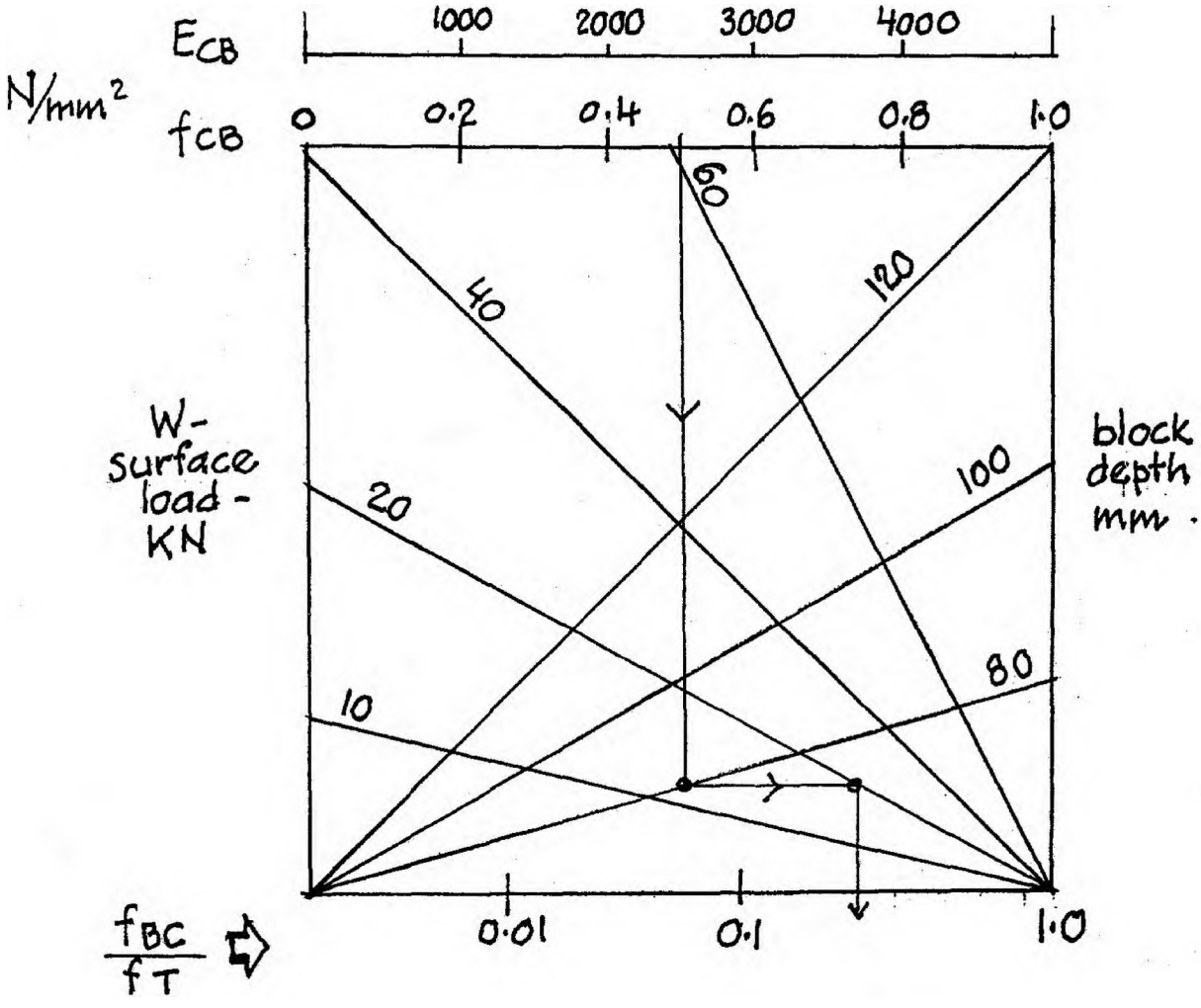


FIGURE 5

LOAD SPREAD THROUGH BLOCK COURSE FOR BALANCED PAVEMENT CONDITIONS

The sequence of design steps for any given combination of load and subgrade conditions is as follows:

6.1 Find the permissible subgrade strain ε_{SG}

6.2 Determine the allowable subgrade stress f_{SG} $E_{SG} \times \varepsilon_{SG}$

6.3 Select a block course modulus E_{CB} = 5000 f_{CB} on the basis of the anticipated block course quality and maintenance. (This value could vary between 100 and 5000 N/mm²)

6.4 Select a block thickness.

6.5 From Figure 5, determine the corresponding load spread through the block course for a balanced condition. This load spread is represented by $\frac{f_{BC}}{f_T}$ the ratio of basecourse stress over tyre pressure, Assign a value for $\frac{f_{BC}}{f_T}$

somewhat higher than found from the graph to ensure some reserve, strength.

6.6 Having obtained vertical stress levels at the top and the bottom of the base layer, the required thickness of this layer can be determined in the usual manner.

The values for E_{CB}, f_{CB} and $\frac{f_{BC}}{f_T}$ given in Figure 5 are the result of a structural analysis only and are, at this stage, not backed up by full-scale test results. This must therefore be regarded with caution and could change considerably after appropriate tests have been conducted and analysed. The graph is purely presented here to show the effect of interaction between lock-up and block thickness on load spread in the block course to explain the divergence of results reported by other researchers.

7 PRACTICAL IMPLICATIONS

Lock-up - or precompression - in the block course is greatly enhanced by the following construction practices:

7.1 A confinement system capable of withstanding the pre-compression forces without yielding.

7.2 Even joints, wide enough to allow the joint sand to flow down and the bedding sand to push up, yet narrow enough to avoid excessive creep. The generally accepted optimum joint width is 2.5mm. Precompression values will increase more rapidly when the joints are kept narrow.

7.3 The joints must be kept full at all times. This can be achieved by specifying a maintenance programme at the tender stage.

7.4 Block orientation at 45 degrees to the confinement system reduces the likelihood of creep.

7.5 Plate compactors should be of a dynamic force appropriate to the block thickness, and of a frequency high enough to vibrate the fine joint sand particles into the joints. Heavy rolling, prior to the admittance of traffic, initiates block movements and joint stresses under controlled conditions, resulting in partial lock-up at the very start of the pavement's design life.

8 VERIFICATION OF ASSUMPTIONS

The degree of pre-compression in the block course can be most readily assessed by block pull-out tests.

If the pull-out force is P, the block interface area A and the coefficient of friction in the compacted joint sand f_S, then:

Joint pre-compression

The coefficient of friction f_s is likely to be in the vicinity of 0.7, which value equates to an angle of shear resistance of 35°.

Another method of verification of lock-up development is by taking a series of load deflection measurements using deflectometers such as the Benkelman beam, or more recently in New Zealand and South-East Asia, the more sophisticated Geobeam. The shape of the deflection bowl produced by these measurements can be used to analyse the degree of beam action in the inter-locking blocks and the stiffness characteristics of the under-lying layers.

A note of warning however: results are valid, as far as progressive stiffening in the block course is concerned, if base conditions remain constant throughout the series of measurements. This applies to all underlying layers, from the bedding course down to the subgrade.

9 CONCLUSIONS

The structural analyses discussed in this paper indicate that the performance of a concrete block pavement varies considerably with lock-up,expressed in pre-compression stress, and with block thickness.

The contribution that the block course makes to the load capacity of the total pavement is found to be dependent on how close the system is to a balanced pavement design, in which the stiffness characteristics of the block layer match those of the underlying base.

The assumptions made in this paper can (and should) be verified by full-scale testing.