BEHAVIOUR OF TWO CONCRETE BLOCK TEST PAVEMENTS ON A POOR SUBGRADE

Working Group D3 'Design of small element pavements', Study Centre for Roadconstruction, Arnhem, The Netherlands

(Working Group D3: A.A. van der Vlist, chairman, L.J.M. Houben, secretary, H.J. Dekkers, J.J. Duivenvoorden, J. van der Klooster, S.G. van der Kreeft, M. Leewis)

SUMMARY

The structural behaviour of two concrete block test pavements on a peat subgrade is described. These pavements were constructed in succession on the same location. Each consisted of two sections comprising rectangular blocks of 80 mm and 120 mm thickness respectively, laid in herringbone bond. Test pavement I was provided only with a sand sub-base, whereas test pavement II had a base consisting of concrete hardcore (0/25 mm) over a sand sub-base. The overall thickness of the pavement structure was the same for both test pavements. Fairly heavy road traffic travelled over them.
The construction of the two test pavements is described, and the results of the tests performed during their construction are presented.
In order to obtain insight into the elastic and the permanent deformation behaviour of the test pavements, falling-weight deflection measurements and level measurements were regularly carried out. A number of deflection parameters and the evolution of rutting as functions of the number of equivalent 80 kN standard axle load repetitions are indicated.
The elastic deformation behaviour of the test pavements was furthermore analysed with the aid of a finite element program in which the concrete blocks were represented as 'rigid bodies' interconnected by, and supported on, linear springs. The measured deflection curves were simulated as closely as possible by trial and error. The spring stiffnesses thus determined are presented as functions of the number of equivalent 80 kN standard axle load repetitions.
From the analysis of the measured and the calculated results it appears that the modulus of elasticity of the subgrade (which varied over the section with 120 mm thick blocks) and the quality of the base have a considerable effect on the elastic and the permanent deformation behaviour of the test pavements. On the other hand, the effect of the thickness of the rectangular concrete blocks is limited.

1. INTRODUCTION

At the beginning of 1981 the Working Group D3 'Design of small element pavements' of the Studie Centrum Wegenbouw (SCW) (Study Centre for Roadconstruction) was set up. This Working Group's task consists in establishing a simple design method for small element pavements to be constructed under conditions as encountered in the Netherlands. The present study is confined to paving elements with horizontal dimensions of approximately 200 mm × 100 mm, more particularly comprising the rectangular concrete paving blocks sizes commonly used in this country.

After carrying out a preliminary study of the literature, the Working Group prepared a flow diagram for developing the design method (figure 1). Three main activities appear in this diagram, namely, the analysis of the behaviour of test pavements under dynamic plate loading, the analysis of the behaviour of test pavements under actual traffic, and the development of a theoretical model based in part on the results of the first-mentioned two activities. This paper deals with the last-mentioned two activities for developing the design method.
First, in chapters 3 and 4, a description is given of the construction and the elastic and permanent deformation behaviour of two concrete block test pavements subjected to fairly heavy road traffic. The first test pavement, with only a sand sub-base, carried traffic from October 1982 to the end of June 1983. The second, with a sand sub-base and an unbound base (concrete hardcore), was built in July 1983 and is still in

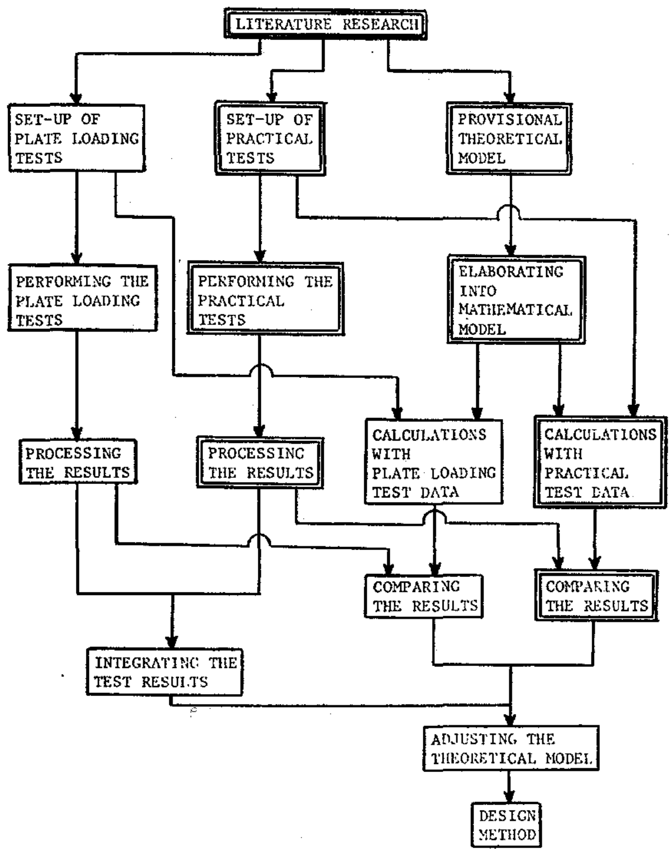


Figure 1. Main features of the flow diagram for developing a design method for small element pavements.

service at the beginning of 1984; only the initial results of measurements on this second test pavement can as yet be reported.
Next, in chapter 5 a finite element model for the elastic deformation behaviour is described, which was first tested in an experimental set-up in the laboratory and was then used in the further analysis of the test pavements.

2. OBJECTIVES AND STARTING POINTS

The purpose of the test pavements is to obtain more insight into the structural behaviour, i.e. the elastic and permanent deformations, of concrete block pavements as a function of the traffic loading and of the substructure, which in this context is understood to comprise all the courses below the bedding sand layer. The elastic deformations under load give information on the load spreading effect, while the permanent deformation (rutting) is regarded as the design criterion. With regard to the test pavements attention is more particularly focused on the effect of the thickness of the concrete blocks upon the structural behaviour.

The principal considerations forming the basis for the test pavements are:
1. the pavements should be under-designed in order to ensure that structural deterioration will occur within a few years
2. their constructional features should be characteristic of conditions encountered in the Netherlands.

Proceeding from these considerations, the following construction was chosen (figure 2):
- rectangular concrete blocks of 80 mm (section A) and 120 mm thickness (section B) laid in herringbone bond between precast concrete edge restraint units; the concrete paving blocks to be installed in accordance with the traditional craft method of road paving
- 50 mm crushed sand (bedding sand layer)
- 700 mm sand sub-base (pavement I) or 250 mm unbound base (concrete hardcore 0/25 mm) and 450 mm sand sub-base (pavement II)
- poor subgrade.

3. CONSTRUCTION OF TEST PAVEMENTS

3.1 Location

The test pavements were constructed on the works site of the precast concrete manufacturing plant of Bos Beton B.V., at Alphen-on-the-Rhine. This location was chosen for the following reasons:
- the subgrade at this site consists of a 8 to 10 m thick layer of peat
- it was practicable to route most of the heavy outgoing traffic (chiefly consisting of trucks carrying precast concrete products) over the test pavements
- records of outgoing traffic are kept at the works exit gate.

The test pavements are located at the edge of the existing works site. Each pavement has an overall length of 30 m, divided into two 15 m long sections constructed with rectangular concrete blocks of 80 mm (section A) and 120 mm thickness (section B), and is 4 m wide (figure 2). Pavement I was constructed in the period from 27 September to 4 October 1982, pavement II was constructed in the same place in the period from 11 to 19 July 1983.

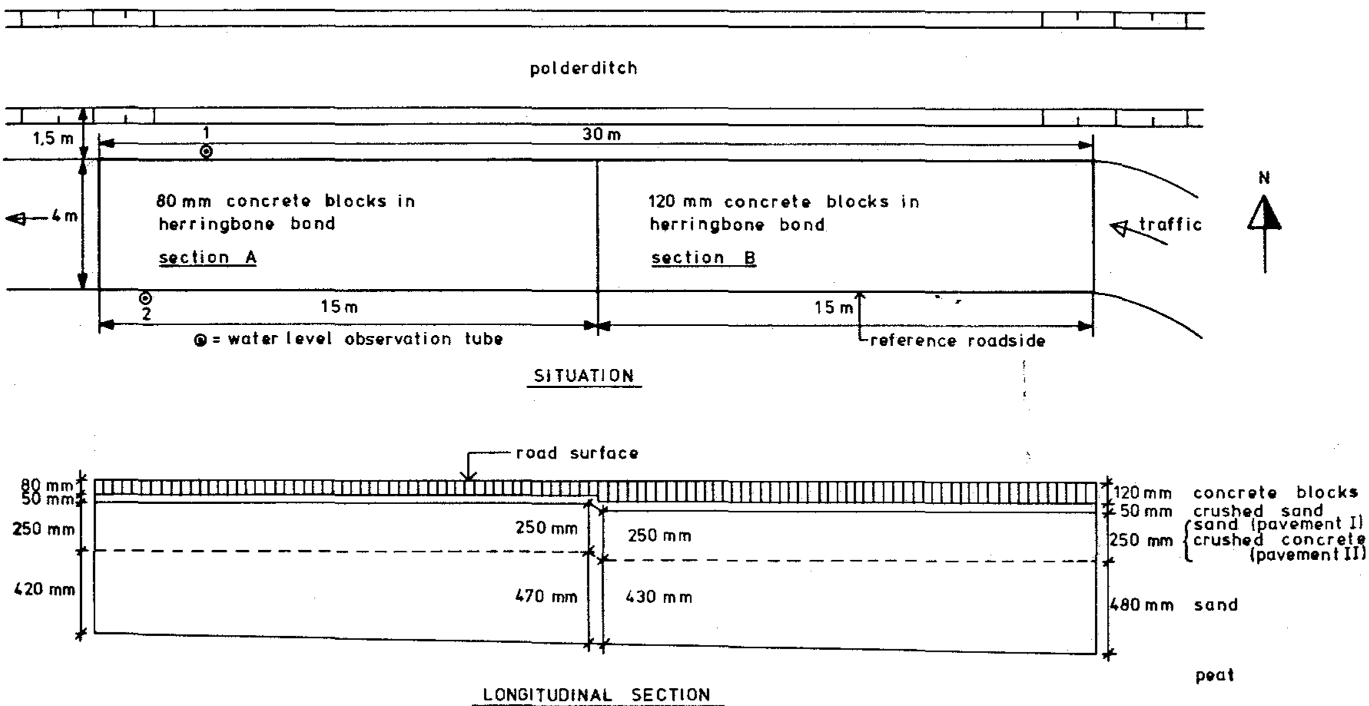


Figure 2. Planned construction of test pavements I and II.

.2 Measurements and tests during construction of pavement I

An existing pavement consisting of 120 mm thick concrete slabs on a sand sub-base occupied the location of the test pavement. After removal of the slabs, one borehole was drilled and six Dutch cone penetrometer tests to a depth 2 m were performed. The borehole showed the thickness of the existing sand sub-base to be about 400 mm, overlying a layer of peat. From four penetrometer tests at the western end and in the middle of the test pavement, as exemplified in figure 3, it emerged that the cone resistance in the peat at depths below the bottom level of the proposed excavation was only 0.2 - 0.4 N/mm^2. Two penetrometer tests at the eastern end of the test pavement (in section B) revealed a cone resistance of more than 60 N/mm^2 at a depth of about 1.2 m below ground level. This high value is attributable to the presence of concrete rubble buried in the ground.

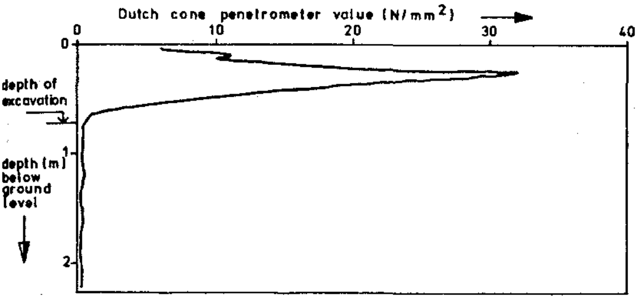


Figure 3. Example of Dutch cone penetrometer sounding.

After the excavation for the pavement substructure had been completed, two in-situ CBR measurements were performed on the bottom of the trench. These showed the CBR-value of the peat to be only 0.6 - 0.9 per cent.

The overall thickness of the sand sub-base for the test pavement was 700 mm on average (figure 2). The sand was placed in two layers, each about 350 mm thick. The bottom layer was compacted only by the trucks, in which the sand was delivered, travelling over it (with their wheel paths transversely distributed, i.e. not coinciding) and by the tyre-mounted excavator which spread the sand. Because of the peat subgrade and high groundwater level it was impracticable to apply compaction with a (very light) plate vibrator. The latter was used, however, for the final compaction of the top layer of sand.
The average grading of the sub-base sand is shown in figure 4. In respect of its grading the fine sand complies with the specification for sub-base sand as stated in 'Rijkswaterstaat Requirements for Construction Materials in Highway Engineering, 1978' (1).
Ten samples were taken with the aid of an annular shell sampler from the upper surface of the finished sand sub-base. Their moisture content and dry density were determined. The average moisture content was 13.6 per cent, with a standard deviation of 2.0 per cent by weight. The average dry density was 1701 kg/m^3, with a standard deviation

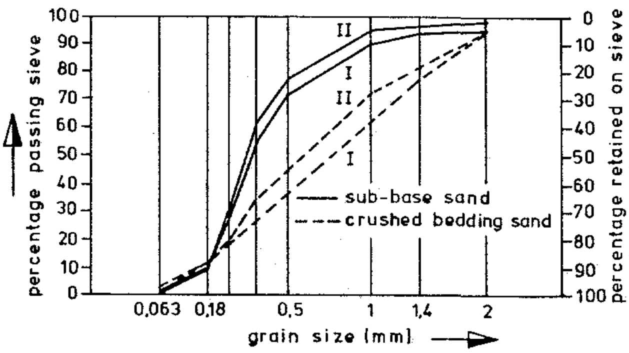


Figure 4. Grading of sub-base sand and crushed bedding sand (pavements I and II).

of 22 kg/m^3. Because of the high moisture content due to the high ground-water level the degree of compaction is lower than required in (1).
CBR tests were performed at various values of the moisture content on sub-base sand samples compacted in accordance with the standard Proctor test (1) (figure 5). From the CBR curve it appears that, for the average moisture content of 13.6 per cent by weight, the CBR-value of the sand was about 7 per cent.

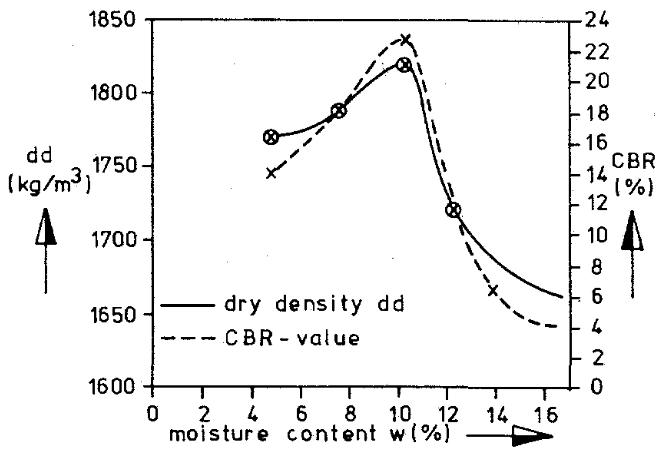


Figure 5. Dry density and CBR-value of sub-base sand as a function of moisture content (pavements I and II).

The grading of the crushed sand (bedding sand layer) is indicated in figure 4. It satisfies the requirements for bedding sand (1). The actual thickness of the bedding sand layer was determined by levelling (surveying with a levelling instrument) the surface of the finished sand subbase and the surface of the completed pavement. In section A (80 mm blocks) the average thickness was 86 mm, with a standard deviation of 15 mm, while in section B (120 mm blocks) it was 47 mm, with a standard deviation of 12 mm. In view of the manner of construction adopted (bedding sand layer directly over the sand sub-base) this difference in thickness of the bedding sand layer is considered to have hardly any effect on the behaviour of the two sections comprised in test pavement I.

Figure 6 shows the progress of road paving.
The dimensions and the flexural strength of the rectangular concrete paving blocks, of 80 mm and

120 mm nominal thickness respectively, were determined by the testing methods specified in Dutch Standard NEN 7000 (2). The blocks satisfied the requirements with regard to the dimensional tolerances and strength, as stated in abovementioned Standard.

Figure 6. Road paving in accordance with the traditional craft method.

3.3 Measurements and tests during construction of pavement II

On completion of the tests on pavement I, at the end of June 1983, the pavement structure was completely excavated down to the depth indicated in figure 3. Next, on the same location, an average thickness of 450 mm of the same sub-base sand was put back and was compacted by the passage of construction vehicles (with their wheel paths transversely distributed) (figure 2).
The average grading of the sub-base sand is represented in figure 4. It satisfies the requirements applicable to sub-base sand (1).
Ten annular shell samples were taken from the top of the finished sub-base and their moisture content and dry density were determined. The average moisture content was 16.1 per cent, with a standard deviation of 1.2 per cent by weight. The average dry density was 1665 kg/m^3, with a standard deviation of 34 kg/m^3.
From figure 5 it appears that the CBR-value of the sand with the high average moisture content of 16.1 per cent by weight was only 4 per cent. In test pavement II the moisture content of the sub-base sand was higher and its dry density and CBR-value were lower than in test pavement I, the reason being that the top surface of the sand sub-base was closer to the ground-water level.

The average grading of the unbound base (0/25 mm concrete hardcore) is indicated in figure 7. The curves for the dry density and the CBR-value^x of this base material are plotted in figure 8. From this it appears that, for the measured in-situ average moisture content of 7.2 per cent by weight, the CBR-value can be put at 75 per cent. The thickness of the unbound base, determined by a levelling survey of the surfaces of the sand sub-base and the base, had an average value of 265 mm, with a standard deviation of 20 mm.

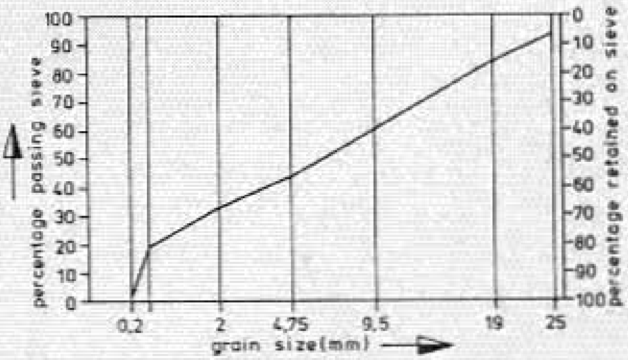


Figure 7. Grading of concrete hardcore for base (pavement II).

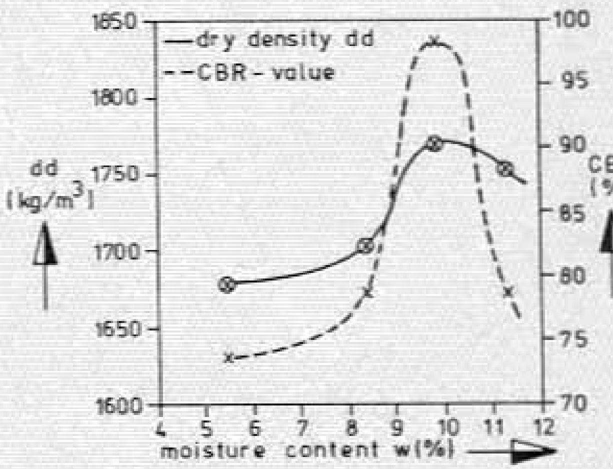


Figure 8. Dry density and CBR-value of concrete hardcore as a function of moisture content (pavement II).

Figure 4 shows the grading of the crushed bedding sand used in pavement II. The average thickness of the bedding sand layer, as determined from levelling on the completed pavement and on the base, was 82 mm with a standard deviation of 8 mm in section A (80 mm blocks) and 89 mm with a standard deviation of 22 mm in section B (120 mm blocks).

The concrete paving blocks were tested in accordance with NEN 7000 (2). These tests showed that also in pavement II the 80 mm and 120 mm blocks complied with the specified requirements as to dimensional tolerances and strength.

4. MEASURED DATA

During the periods when the test pavements were used by traffic, falling-weight deflection measurements and level measurements were regularly carried out in order to obtain insight into the behaviour of the bearing capacity and of the

x The CBR test on the concrete hardcore was performed in accordance with the AASHTO specifications (3), which require that only the material with particles in excess of 19 mm diameter must be screened out. With this procedure the material tested is in better agreement with the material actually used than in the CBR test procedure in accordance with (1), where all the material above 4 mm particle diameter has to be removed.

rutting of the pavements. The measurements were performed on 15 cross profiles (transverse survey lines), both in the wheeltrack (T) and beside the wheeltrack (M) (figure 9).
For each of the measuring days the cumulative number of equivalent 80 kN standard axle loads was determined. This was done on the basis of records of traffic passing through the works gate, where the registration mark (and thus indirectly the dead weight and the number of axles) and the loading of each vehicle were noted. The load equivalence factor $l_e = (L/80)^4$, where L denotes the axle load in kN, was applied. In this formula the 4th power, an average for flexible pavements as deduced from the AASHTO Road Test (4), was adopted because the behaviour of concrete block pavements is qualitatively comparable to that of flexible pavements.

Table 1 reviews the measuring days of the falling weight deflection and level measurements with the associated traffic loads. For test pavement II it was possible only to process the first two measuring days.

measuring day	falling-weight deflection measurements	level measurements	number of eq. 80 kN st. axle loads (n)
pavement I			
4-10-'82	x	x	0
4-11-'82	x	x	520
9-2-'83	x	x	2660
10-5-'83		x	4110
30-6-'83	x	x	5000
pavement II			
11-8-'83	x	x	0
19-9-'83	x	x	1450

Table 1. Days of falling-weight deflection measurements and level measurements and the associated cumulative number of equivalent 80 kN standard axle load repetitions (pavements I and II).

During the testing of the pavements the ground-water level was regularly measured in the standpipes 1 and 2 (see figure 2). On account of the presence of the adjacent polder drainage ditch the ground-water level was virtually constant, namely 0.55 ± 0.05 m (standpipe 1) and 0.60 ± 0.05 m (standpipe 2) below pavement surface level.

These slight fluctuations in the ground-water level were assumed to have had no effect on the structural behaviour of the pavements.

The traffic primarily travelled on the centre-line of the test pavement. In the case of pavement I (with sand sub-base only) a rut approximately 100 mm in depth had developed on the side nearest the ditch after only a few days, this being due to inadequate stability of the verge, so that the concrete edge restraint kerbs were thrust outwards. It was then decided to shift the right-hand wheeltrack transversely a distance of 1 m farther away from the ditch (see figure 9).
In the case of pavement II (with the unbound hardcore base over the sand sub-base) the traffic continued to travel on the centre-line of that pavement, in any case up to the second measuring date. Unless otherwise stated, the measurements and calculations for the wheeltrack on pavement II relate to the inner wheeltrack, i.e. the one farthest from the ditch (see figures 2 and 9).

4.1 Falling-weight deflection measurements

As the elastic deformation behaviour of a pavement is a useful aid for the evaluation of the pavement with regard to bearing capacity, falling-weight deflection measurements were performed, the measuring days of which are given in table 1. For these measurements a load of 50 kN is applied through a 300 mm diameter loading plate to the pavement; the loading time is 0.02 s. The deflections d (vertical elastic displacements at the surface of the pavement) are measured at distances of 0, 300, 500, 1000, 1500 and 2000 mm from the centre of the plate with the aid of geophones (figure 10). The deflection measurements were performed on the cross profiles 1 to 15 both in the wheeltrack (T) and beside the wheeltrack (M) (see figure 9).

Some characteristic results of the deflection measurements are represented in figures 11 and 12. For section A (80 mm blocks) the average deflection values obtained on the cross profiles 1 to 7 are given because the deflections in this section were very nearly constant. For section B (120 mm blocks) the deflections obtained on the cross profiles 9 and 13 (figure 9) are given

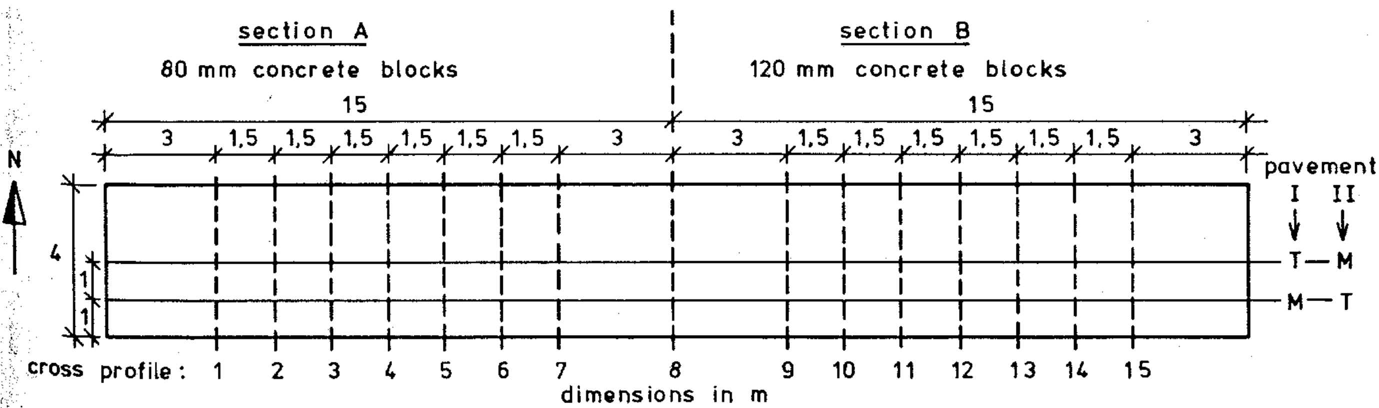


Figure 9. Cross profiles (survey lines) for the test pavements, and location of wheeltrack (T).

because the deflections vary considerably over this section, decreasing towards the east.

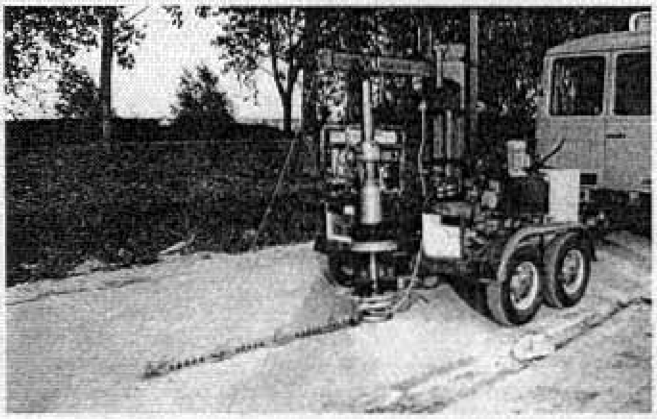


Figure 10. Falling-weight deflection measurement (pavement I, 4-10-'82).

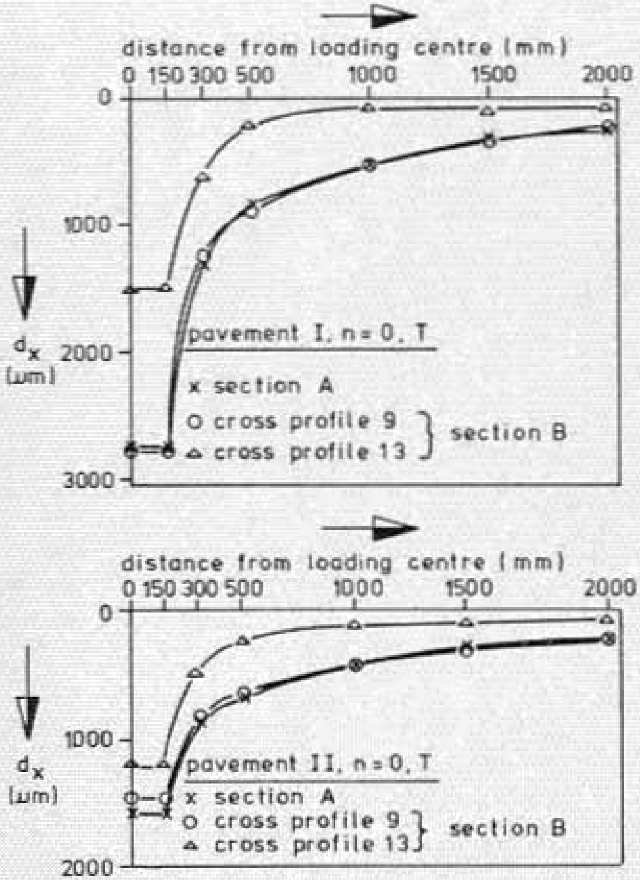


Figure 11. Some examples of measured deflection curves on the test pavements I and II.

The modulus of elasticity E_0 (N/mm^2) of the subgrade can be calculated from the following formula (5):

$$\log E_0 = 3.869 - 1.009 \log d_{2000} \quad (1)$$

where: d_{2000} = deflection (µm) at a distance of 2000 mm from the centre of load application (50 kN load)

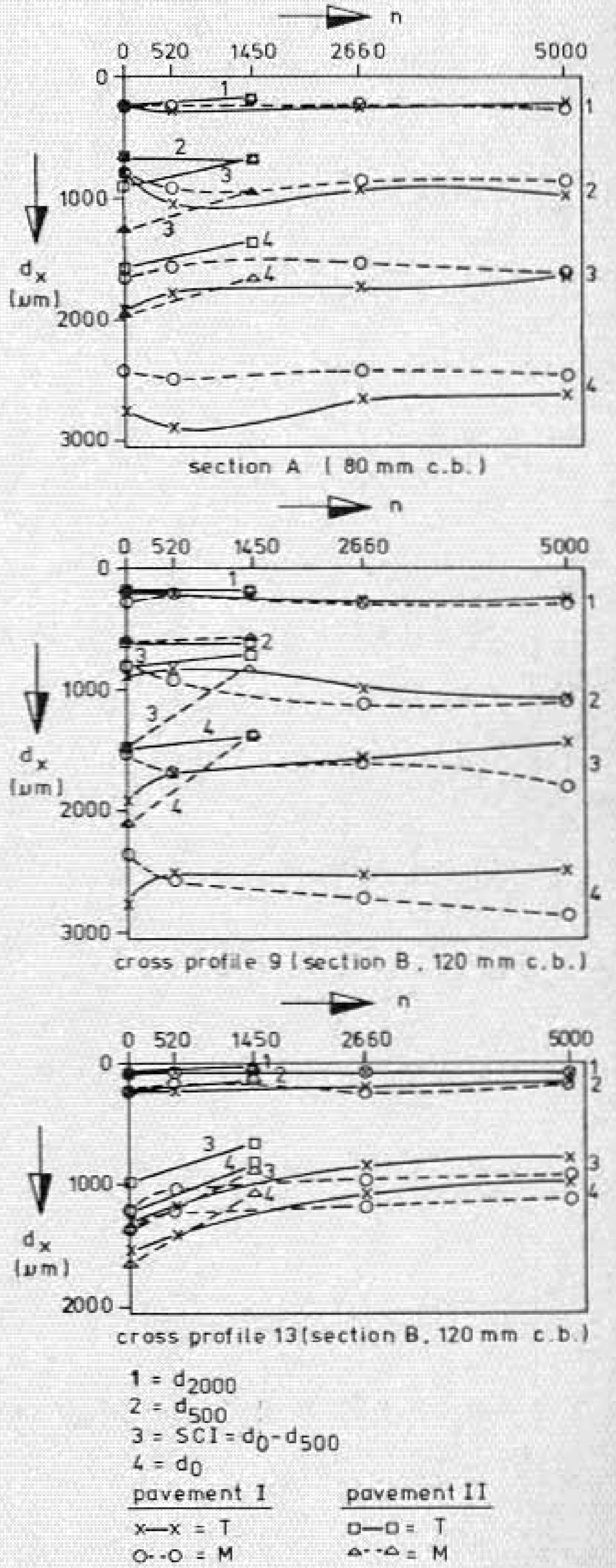


Figure 12. Some characteristic deflection parameters as a function of the number of equivalent 80 kN standard axle load repetitions (pavements I and II).

With the aid of formula 1 it has been calculated that the subgrade modulus - in both test pavements - had an average value of 25 N/mm^2 in section A and on cross profile 9 (section B). On the other hand, on cross profile 13 (section B) the subgrade modulus was 75 N/mm^2 on average.

From figures 11 and 12 it is apparent that, for the same poor subgrade (E_0 = 25 N/mm^2), the thickness of the concrete paving blocks in test pavement I (sand sub-base only) has a negligible effect on the magnitude of the deflections; in the case of pavement II (unbound base on sand subbase) there is some slight effect. It also emerges that on a better subgrade (compare cross profiles 9 and 13 with E_0 = 25 N/mm^2 and 75 N/mm^2 respectively) and with a concrete hardcore base (compare pavements I and II) the deflections show a marked decrease.
From figure 12 it furthermore appears that in pavement I on the poor subgrade with E_0 = 25 N/mm^2 (section A and cross profile 9 of section B) the pavement is unable to develop a load-spreading capacity as a function of the number of equivalent 80 kN standard axle load repetitions. On the other hand, on cross profile 13 of test pavement I (E_0 = 75 N/mm^2) and on the entire test pavement II (with unbound base) the deflections decrease in magnitude as a function of the number of equivalent 80 kN standard axle load repetitions; in these cases there is considerable progressive stiffening of the pavement.
It also appears from figure 12 that in all the cases considered, except section A of pavement I, the deflections in the wheeltrack are smaller than beside the wheeltrack.

4.2 Level measurements

The level (height) measurements listed in table 1 were performed with the aid of a levelling instrument with a view to determining the rutting behaviour as a function of the number of equivalent 80 kN standard axle load repetitions (figure 13). These measurements were obtained on the cross profiles 1 to 15 (figure 9). The results for the profiles 2, 6, 9 and 13 are represented graphically in figures 14 and 15, while for pavement I the rut depth is given as a function of the number of equivalent 80 kN standard axle load repetitions in figure 16. The rut depth RD and

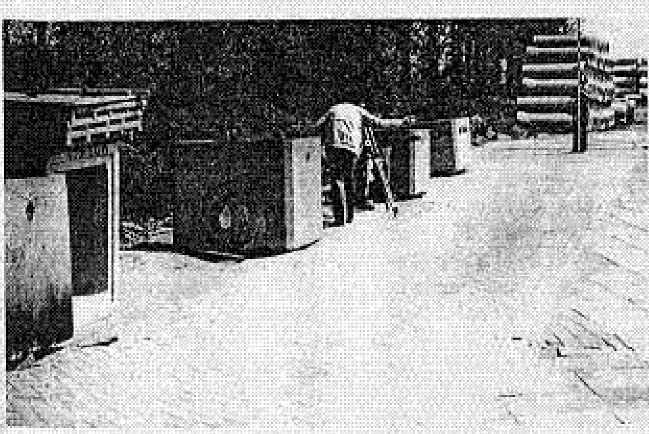


Figure 13. Level measurement (pavement I, 10-5-'83).

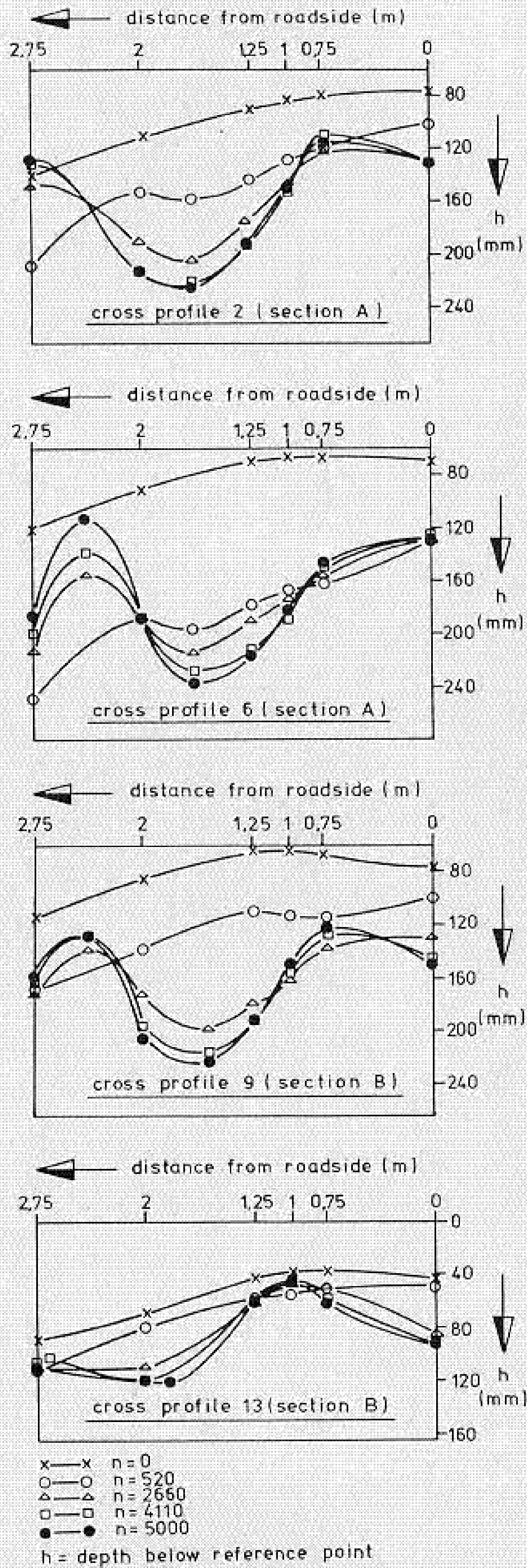


Figure 14. Evolution of rutting in pavement I.

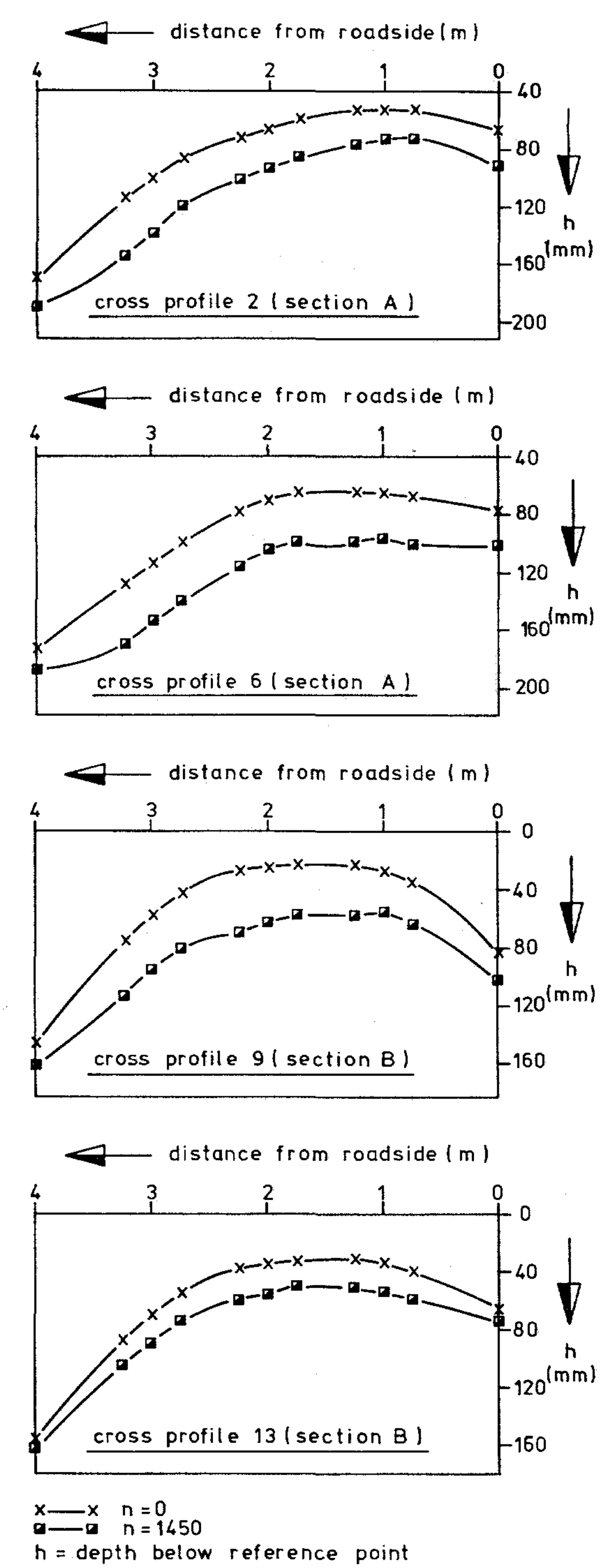


Figure 15. Evolution of rutting in pavement II.

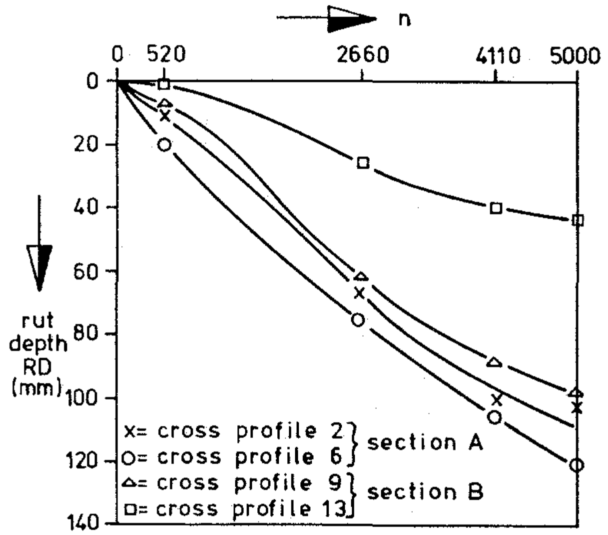
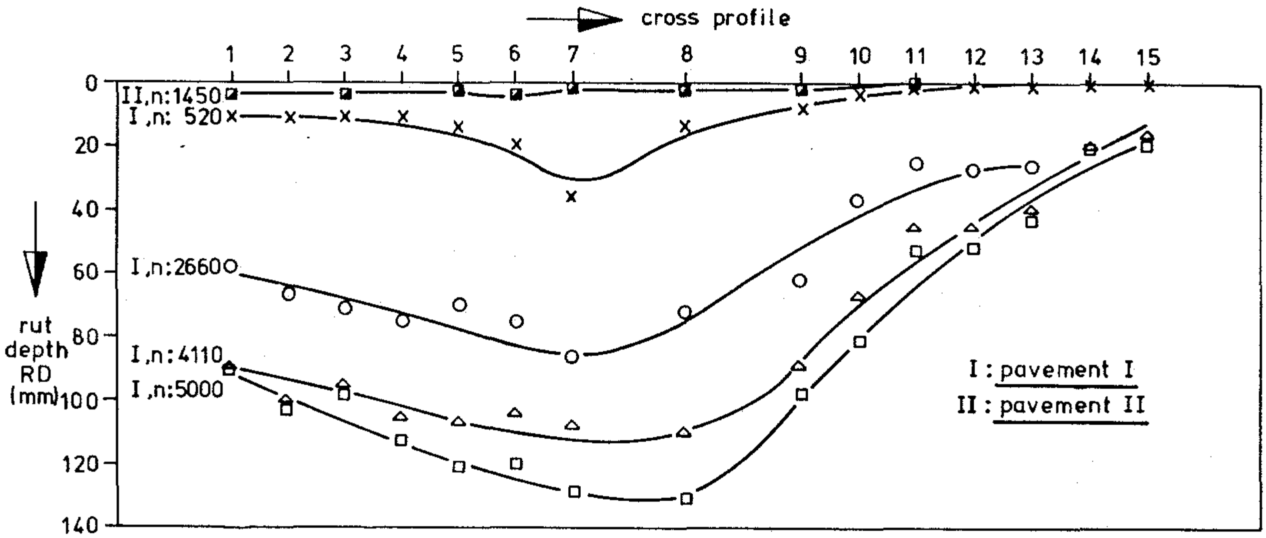


Figure 16. Evolution of rut depth RD as a function of the number of equivalent 80 kN standard axle load repetitions (pavement I).

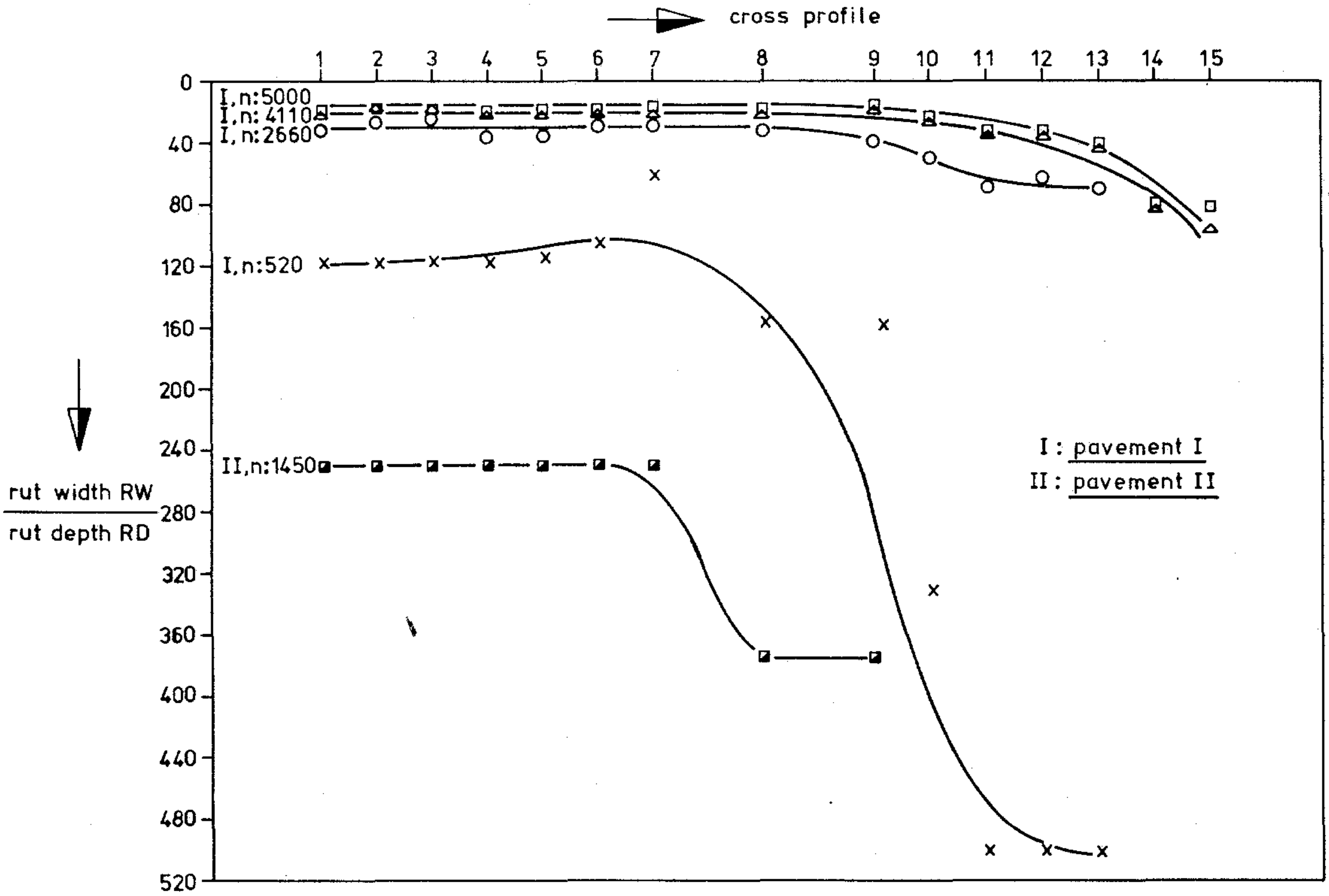
the quotient of rut width RW and rut depth RD occurring along the length of the test pavements are respectively shown in figures 17 and 18.

With reference to figures 14 to 18 the following can be commented in respect of rutting in test pavement I (sand sub-base only):
On cross profile 6 (section A, 80 mm blocks) shearing occurred directly after traffic was allowed on the test pavement and it continued to occur up to the end of testing. For the cross profiles 2 (section A, 80 mm blocks) and 9 and 13 (section B, 120 mm blocks) the development of rut depth as a function of the number of equivalent 80 kN standard axle load repetitions shows an S-shaped curve, whence it can be inferred that shearing occurred only after an initial stiffening period. On comparing the cross profiles 2 (80 mm blocks) and 9 (120 mm blocks) it emerges that, for the same poor subgrade ($E_0 = 25$ N/mm^2) in both cases, the thickness of the concrete blocks has hardly any effect on rutting, both as regards rut depth RD and as regards the 'shape factor' RW/RD (rut width/rut depth). Comparison of the cross profiles 9 and 13 (120 mm blocks in both cases) indicates that the better subgrade at profile 13 ($E_0 = 75$ N/mm^2) has a distinctly favourable effect on rutting.
The immediate shearing that occurred in the region around cross profile 7 was caused, so far as could be ascertained, by the locally poor condition of the verge, so that the concrete edge restraint kerbs were thrust sideways.

From the first level measurements available for test pavement II (unbound base and sand sub-base) it appears that after 1450 equivalent 80 kN standard axle load repetitions the rut depth on the inner wheeltrack was 4 mm maximum, while the shape factor RW/RD had a minimum value of 250. The rutting behaviour was very much better than in the case of pavement I after an equal number of load repetitions, a fact that shows how great an effect



'igure 17. Evolution of rut depth RD along the length of pavements I and II as a function of the number of equivalent 80 kN standard axle load repetitions.



'igure 18. Evolution of the quotient of rut width RW and rut depth RD along the length of pavements I and II as a function of the number of equivalent 80 kN standard axle load repetitions.

:he quality of the base has upon the permanent leformation behaviour of a concrete block pavement. On the basis of the available measured re-ults it is not yet possible to draw inferences is to the effect of the paving block thickness. lowever, the favourable effect of better subgrade .s manifest in test pavement II as well.
ỳy way of illustration of the effect of (inadeuate) lateral support from the verge upon the rutting behaviour of the pavement, table 2 presents a summary of the rutting on the two wheeltracks of pavement II. It appears that more particularly in the region between the cross profiles 2 and 9 the stability of the verge is inadequate.

cross profile	inner wheeltrack (T)		outer wheeltrack (along polder ditch)	
	rut depth RD (mm)	rut width RW (mm)	rut depth RD (mm)	rut width RW (mm)
1	4	1000	5	1300
2	4	1000	3	1200
3	3	750	12	1300
4	3	750	10	1200
5	2	500	6	1200
6	3	750	13	1700
7	2	500	10	1250
8	2	750	20	1300
9	2	750	0	-
10 to 15	no rutting could be measured			

Table 2. Rutting in pavement II after 1450 equivalent 80 kN standard axle load repetitions.

5. ANALYSIS BY THE FINITE ELEMENT METHOD

For the further analysis of the elastic deformation behaviour of the concrete block test pavements, calculations were carried out with the ICES STRUDL finite element program, in which the concrete paving blocks were introduced as non-deformable 'rigid bodies' (6,7,8). Before the calculations for the pavements were performed, the finite element method was tested by means of a laboratory experiment, which will now first be described.

5.1 Calculations for a laboratory set-up

For testing the finite element method an experimental set-up was built in the Eastern Highway Engineering Laboratory at Twello. It comprises (figure 19):

- a row of 15 sharp-edged hardwood-blocks with dimensions of 80.3 mm × 28.4 mm × 38.5 mm; the joints between the blocks are filled with rubber, 5 mm thick (type Alpac Soft, hardness 55 Shore); the faces in contact with the rubber (i.e. longitudinal sides and undersurfaces) have abrasive paper (Klingspor PL 41-180, 0.4 mm thick) stuck to them; the roughness of this paper (Leroux value) is equal to that of an average concrete paving block
- the row of 15 blocks is supported on four layers of rubber with a total thickness of 20 mm
- this whole assembly is mounted on the back of a rolled steel channel section (UNP 14), machined to a flat surface, to which are fixed strips for restraining the blocks in the transverse direction.

A variable load P (measured in N) is applied through a ball (32 mm diameter) and a metal bearing plate (30 mm × 80 mm) to the centre block B_1.

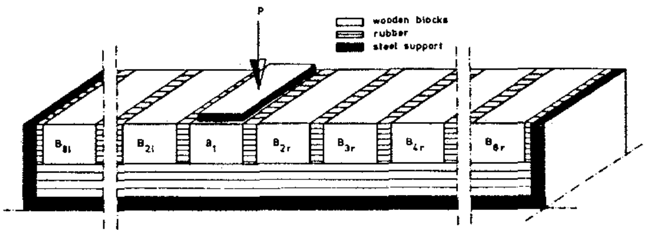


Figure 19. Experimental set-up in the laboratory (schematic).

The deflections measured for various magnitudes of the load are given in table 3. Because of symmetry, only half the deflection curve is given, δ_x being the average displacements of two symmetrically located blocks (B_{xl} and B_{xr}) in relation to the loaded block (B_1). The displacement is reckoned as positive in the direction of loading.
From table 3 it appears that for P ≈ 50 N the directly loaded block (B_1) begins to slide (shear) in relation to the adjacent block (B_2). It furthermore emerges that the blocks B_3 to B_8 undergo negative deflection, i.e. they rise in relation to the initial (zero) condition.

Next, by means of calculations with the ICES STRUDL finite element program, the deflection curves stated in table 3 were simulated as closely as possible in order thereby to obtain insight into the magnitude and behaviour pattern of characteristic parameters for the joints and the support.
The calculations were performed two-dimensionally (the construction depth is equal to the unit length of 1 mm). For reasons of symmetry only half the set-up was considered.
The experimental set-up was schematized to a system of rigid elements and springs. The hardwood blocks were schematically conceived as rigid bodies because their stiffness far exceeds that of the rubber in the joints. The latter were each schematized to two horizontal springs with spring

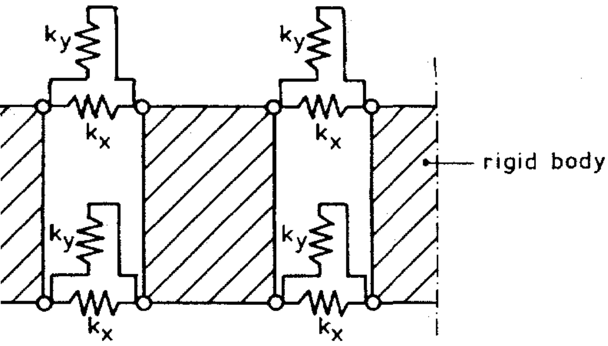
load P (N)	deflection (μm)							
	δ_1	δ_2	δ_3	δ_4	δ_5	δ_6	δ_7	δ_8
30	105	20	-1	-3	-2	-2	-1	0
60	162	27	0	-5	-3	-2	-2	-1
190	317	28	-8	-11	-8	-5	-5	-2
350	473	15	-17	-17	-14	-6	-5	-2

Table 3. Measured deflections in the experimental set-up for various values of the load.

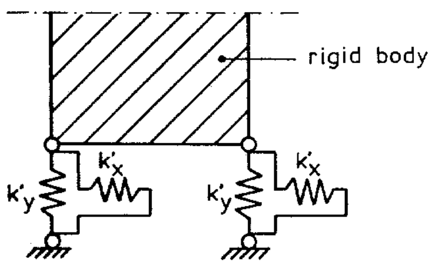
load P (N)	deflection (μm)								spring stiffness (N/mm)			
	δ_1	δ_2	δ_3	δ_4	δ_5	δ_6	δ_7	δ_8	k_x	k_y	k'_x	k'_y
30	106	21	5	0	-2	-2	-1	0	2.95	0.74	0.32	1.26
60	162	27	6	0	-3	-3	-2	-1	3.11	0.78	0.44	1.74
190	316	28	4	-2	-4	-4	-2	-1	2.70	0.68	0.79	3.17
350	473	15	1	-1	-2	-1	-1	0	1.15	0.29	1.08	4.33

Table 4. Calculated deflections in the experimental set-up for various values of the load, with associated spring stiffnesses.

ffness k_x and two vertical springs with spring
ffness k_y (figure 20), while the support was
ematized to two horizontal springs with spring
ffness k'_x and two vertical springs with spring
ffness k'_y (figure 21). The steel channel sect-
was conceived as a non-deformable base.



ure 20. Model concept for the joints and hardwood blocks in the ICES STRUDL finite element analysis.



ure 21. Model concept for the support in the ICES STRUDL finite element analysis.

this model concept the rigid bodies can under-
both horizontal and vertical displacements
can moreover rotate. In the calculations for
various loads (table 3) the combination of
k_y, k'_x and k'_y for which the calculated and
measured deflection curves are in closest
sible agreement was determined by trial and
or. The results of these calculations are
en in table 4.

comparing tables 3 and 4 it is apparent that
actual (as-measured) deflections of the di-
tly loaded block (B_1) and of the adjacent
ck (B_2) can be calculated very accurately with
S STRUDL. On the other hand, the calculated
lections of the blocks B_3 to B_8 deviate to a
ater or less extent from the measured deflect-
s, the probable reason for this being that
h the model concept shown in figure 21 the be-
iour of the four layers of rubber forming the
port cannot be properly simulated at greater
tances from the point of load application.
m table 4 it furthermore appears that for in-
asing magnitude of the load and shearing be-
en the directly loaded block (B_1) and the ad-
ent block (B_2), i.e. for $P > 50$ N, the stiff-
s of the joints (k) decreases; on the other
d, the stiffness of the supporting rubber (k')
omes greater with increasing load because of
compression of the rubber.

5.2 Calculations for the test pavements

Since the problem is characterized by axial symmetry (assuming the bond, i.e. the laying pattern, of the blocks to be of no effect on the elastic deformation behaviour of the surfacing), the pavement structure of the test pavements is reduced to two dimensions, the depth being equal to the unit length of 1 mm. The concrete paving blocks are laid in herringbone bond, and for this reason a slice at 45° to the longitudinal direction of the blocks is chosen, because the deflection measurements on the test pavements were also performed in that direction. In consequence of this slice the width dimensions of the blocks are 149.4 mm in section A and 152.9 mm in section B. These dimensions comprise a joint width of 2 mm and 3 mm in sections A and B respectively. In connection with symmetry only half the structure is considered. The structure is schematized to a system of continuous elements (layers under the concrete blocks), springs and rigid bodies.
The model concept for the blocks and the joints between them is identical with that represented in figure 20, while the coupling of the blocks to the underlayer (bedding sand layer) is as already shown in figure 21. The distribution for the elements of the substructure of the pavement is represented in figure 22.

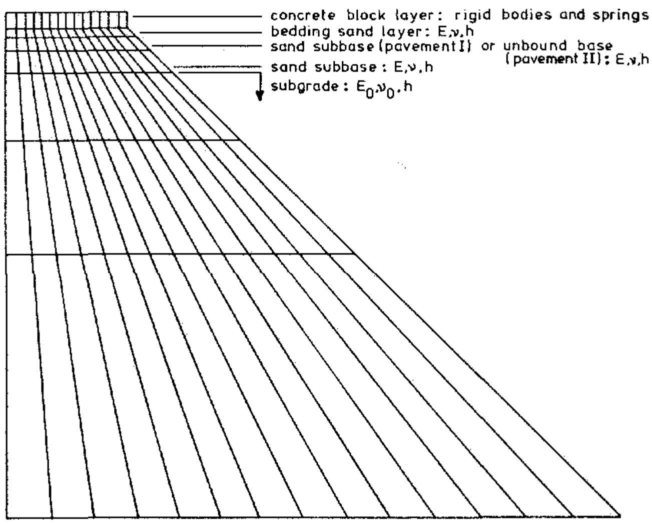


Figure 22. Schematic representation of the distribution of elements in pavements I and II as adopted in the ICES STRUDL finite element analysis.

The modulus of elasticity of the subgrade E_0 (N/mm^2) was calculated from formula 1. The modulus of elasticity of the sand sub-base and (for pavement II) the unbound hardcore base E_i (N/mm^2) was calculated from the following empirical formula (9):

$$E_i = 1 \,.\, E_{i+1} \quad \text{with } 1 = 0.206\, h_i^{0.45} \quad (2 \leqslant 1 \leqslant 4) \qquad (2)$$

where: h = thickness (mm) of the course considered
E_{i+1} = modulus of elasticity (N/mm^2) of the underlying course

The maximum value of the modulus of elasticity of the sand sub-base was taken as 150 N/mm^2.
In test pavement I (sand sub-base only) the bedding sand layer was not introduced as a separate course, but was reckoned as forming part of the sand sub-base. On the other hand, in test pavement II (with unbound hardcore base) the bedding sand layer was introduced as a separate course; the modulus of elasticity of the bedding sand layer was arbitrarily taken as 1.5 times that of the sand sub-base.
Poisson's ratio for the peat subgrade was taken as $\nu = 0.45$, and for the sand sub-base, the unbound base and the bedding sand layer it was taken as $\nu = 0.35$.

The structure as a whole was conceived as supported by a non-deformable base at 10 m below the undersurface of the concrete paving blocks. This assumption was based on the results of preliminary calculations with the linear elastic multilayer computer program BISAR (10) which showed that the stresses and displacements at a depth of 10 m in a semi-infinite medium are reduced to not more than a few per cent of the applied stresses and displacements.

In the ICES STRUDL calculations, primarily the deflections at 0 mm and at 2000 mm from the centre of the loading plate were imposed, and again the combination of k_x, k_y, k'_x and k'_y was sought for which the measured and the calculated deflection curve were in closest possible agreement. For the reasons already stated, the simulations of the elastic deformation behaviour of the pavement surface were performed only for the average deflection curve of section A (cross profiles 1 to 7) and for the cross profiles 9 and 13 in section B.
Starting from this model concept and these boundary conditions, it was found not to be possible to obtain a reasonably good approximation of the measured deflection curves. This was due to the rotational capacity in the joints and to the imposed deflection d_{2000}. It was therefore decided to adopt a purely shear model, in which the springs with spring stiffness k_x (figure 20) were omitted and moreover the deflection d_{2000} was not imposed.
In simulating the measured deflection curves it was more particularly endeavoured to approximate as closely as possible the deflection curve in the vicinity of the load because these deflections are characteristic for the top part of the pavement. It was therefore attempted, with the aid of the ICES STRUDL finite element program, to calculate the following three parameters of each deflection curve as accurately as possible:

$$SCI_0 = d_0 - d_{300}$$

$$SCI_1 = d_0 - d_{500}$$

$$\sum_{x=1}^{6} d_x$$

36 deflection curves were fully analysed, and in 77 per cent of the cases the calculated values of these deflection parameters agreed with the measured values thereof to within 3 per cent accuracy. The values of k and k' found for the two test pavements by trial and error are shown graphically in figures 23 and 24.

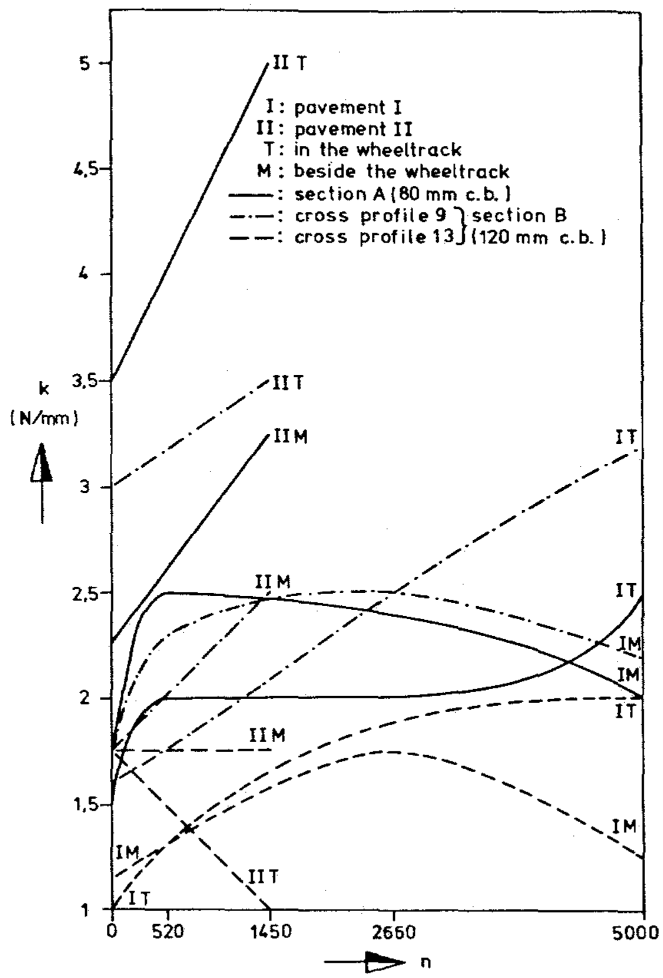


Figure 23. Joint stiffness k as a function of the number of equivalent 80 kN standard axle load repetitions (pavements I and II)

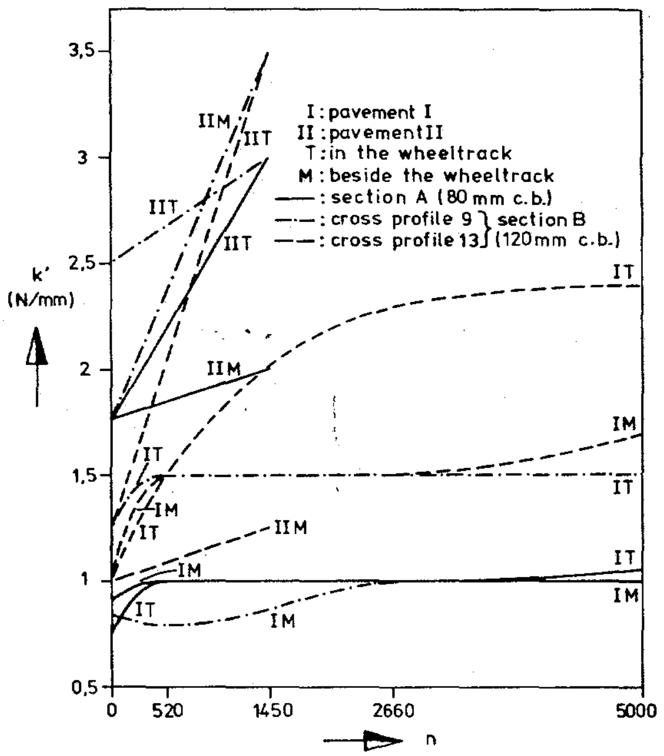


Figure 24. Support stiffness k' as a function of the number of equivalent 80 kN standard axle load repetitions (pavements I and II

From figures 23 and 24 the following can be inferred:

Test pavement I (sand sub-base only)
In the wheeltrack both the joint stiffness k and the support stiffness k' increase to a greater or less extent with the number of equivalent 80 kN standard axle load repetitions. With regard to the joint stiffness k this effect is more pronounced according as the subgrade modulus is lower (compare the cross profiles 9 and 13) and according as the thickness of the concrete blocks is greater (compare section A with 80 mm blocks and cross profile 9 of section B with 120 mm blocks). The joint stiffness k is higher according as the blocks are thicker and the subgrade modulus is lower. With regard to the support stiffness k' it can be stated that a higher subgrade modulus and greater concrete block thickness both result in a higher value of k'.
Beside the wheeltrack the joint stiffness k primarily increases in every case, but decreases after a certain number of standard axle load repetitions, which indicates the occurrence of shearing (cf. table 4); the decrease of k commences earlier according as the concrete block thickness is less. The support stiffness k' in every case undergoes only a slight increase. On comparing cross profile 9 of section B (120 mm blocks) with section A (80 mm blocks) it emerges that beside the wheeltrack both k and k' are virtually independent of the block thickness. On the other hand, a higher subgrade modulus produces a reduction of k and an increase of k'.
From figures 23 and 24 it can further be seen that initially both the k and the k' values beside the wheeltrack are larger than in the wheeltrack, but that in the longer term the load spread in the wheeltrack is distinctly better than next to it.

Test pavement II (unbound hardcore base and sand sub-base)
Both in and beside the wheeltrack the joint stiffness k and the support stiffness k' in general undergo an increase with the number of equivalent 80 kN standard axle load repetitions, the only exception being the behaviour of the k value in the wheeltrack (T) of cross profile 13. Apart from this, in all cases the joint stiffness k is greater according as the concrete block thickness is less and the subgrade modulus is lower, whereas a greater thickness of the blocks results in a higher k' value.
In the wheeltrack the value of k' is higher according as the subgrade modulus is higher, but beside the wheeltrack k' is lower according as the subgrade modulus is higher. It further appears that, with the exception of cross profile 13, the values of k and k' in the wheeltrack are higher than those beside the wheeltrack.

On comparing the calculated k and k' values of the test pavements I and II it can be inferred that in pavement II the hardcore base (as yet) prevents shearing in the upper part of the pavement structure, so that progressive stiffening of the pavement is much more marked than in the case of pavement I with the sand sub-base only.

6. CONCLUDING REMARKS

First of all it is to be noted that falling-weight deflection measurements can be performed successfully even on very light pavement structures such as the concrete block test pavement I constructed merely on a sand sub-base.
Also, it proved possible with the ICES STRUDL finite element program, using the model concept outlined in this paper, to describe with reasonable accuracy even the extreme deflection curves obtained more particularly in test pavement I.

Allowing for the fact that as yet only the initial behaviour of test pavement II has been analysed, the following can be stated with regard to the effect of the concrete block thickness, the quality of the base and the modulus of elasticity of the subgrade upon the elastic and the permanent deformation behaviour of the two test pavements constructed with rectangular concrete paving blocks:
Thickness of the blocks: On poor subgrade (E_0 = 25 N/mm^2) the thickness of the concrete blocks has hardly any effect on the deflections and on rutting. In the wheeltrack the support stiffness k' increases with greater block thickness. The effect of block thickness on the joint stiffness k depends on the rigidity of the substructure (comprising the subgrade, the sub-base and the base, if any).
Quality of the base: Better quality of the base (more particularly the concrete hardcore base as compared with sand) results in a considerable reduction of the deflections and of rutting. The hardcore base prevents shearing, so that k and k' are greater and moreover increase more markedly than when only a sub-base consisting of sand is installed.
Subgrade: According as the modulus of elasticity of the subgrade is higher (E_0 = 75 N/mm^2 as against 25 N/mm^2) the deflections that occur are smaller and rutting behaviour is better. In the wheeltrack k' increases if the modulus of the subgrade increases, whereas k decreases.

The results so far available are insufficient for establishing the design method for concrete block pavements which it is aimed to develop. For that purpose at least the complete results of test pavement II will have to be available.

7. ACKNOWLEDGEMENTS

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