DESIGN METHOD FOR CONCRETE BLOCK PAVEMENTS

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Summary

Roughly half of the carriageways in Holland are paved with concrete blocks or brickstones. The experience with brickstones covers some centuries. Nevertheless design methods regarding properties of materials, traffic loads, rut dephts, etcetera were not available.
In 1980 the Road Department in Amsterdam decided to develop a design method by carrying out field-measurements on concrete block pavements followed by calculations with a finite element computer program.
The field measurements fell apart into the determination of :

1. deflection bowls, caused by a falling weight, on a new-built test section, a six years and a twenty years old road section.

2. friction forces between concrete blocks, measured with a specially built pull out device.

3. vertical soil pressures in the new test section, caused by the falling weight as well as by standing and riding trucks, and measured by means of ten soil pressure cells.

The measured data are used as input for a finite element computer program. In this program the blocks are 'rigid body' elements, connected to each other and to the underlying layer system with vertical springs. A remarkable correspondence was obtained between calculated and measured pressures and deflections.
The calculated elastic deflections were transformed to rut depths according to Veverka.

The developed design curves derived from the calculations give a possibility of determining the required E-equivalent of the underlying layers as a function of a known traffic volume, expressed in the average equivalent single 100 kN axle load repetitions per day and as a function of the designlife in combination with the maximum rutdepth.

By means of Ivanovs method, the determined E-equivalent is transformed into possible combinations of the E-modulus and thickness of the basecourse and of the sandlayer used for subbase.

Part 1

1. 0. General description and results

1. 1. Introduction

In this part the motives which led to the investigation are described, the aims of it and the results.
The investigation can be split up into an analysis of the measured behaviour of three different road sections in Amsterdam (the measurements) and the calculations with a finite element computer program, resulting in a set of design curves (the calculations).

In part 2 the execution and interpretation of deflection measurements and pull out tests, committed to H.W.Z. Consultancy Hoevelaken, are fully described.

In part 3 the soil pressure measurements and calculations, committed to Delft University, Laboratory for Road- and Railroad Research are fully described.

1. 2. Motives

In Holland carriageways covered with small elements like cobble stones and brick stones are applied since the middle ages.
From about 1955 on concrete blocks started to compete brick stones more and more, initially because brick producers could not meet the demand, later on also because of the lower costs. Besides that smaller tolerances and higher skid resistance of the concrete blocks showed some advantages.

Concrete blocks came into the market as a substitude for bricks; consequently the shape is the rectangular one. Hence the design of concrete block pavement was based on the experience with brick stones. Nevertheless the need for a reliable design method became stronger.

Firstly this was caused by the wish to built heavier loaded constructions than normal carriageways, such like the pavements of the Europe Container Terminal (E.C.T.) at Europoort paved with 120 mm thick rectangular concrete blocks on a sand cement stabilisation.

Later on, under the pressure of lower budgets, the conception of Pavement Management systems was introduced and more and more road managers wanted to know if their concrete block pavements were economical.

In the meantime outside Holland a lot of research was done, mainly in Australia, South Africa and England, resulting in design curves.

It is questionable if these design curves are applicable for Dutch circumstances because of different climatic conditions, different subsoil properties and different shape of the concreteblocks.

The Road Department of Public Works of the City of Amsterdam decided to start an investigation to set up a simple set of design curves for Dutch road managers, using experiments on test sections in the considerable road network paved with concrete blocks in Amsterdam, covering a period from the late fifties up to now.

1. 3. Objects

Goal of the investigation was the analysis of the measured performance of concrete pavements of different age but similar in construction focussed on the set up of a theoretical empirical model and to result in workable design curves for concrete block pavements.
For the theoretical model not only a linear elastic multi layer program but also a finite element program had to be considered.

At first it was thought to execute measurements on pavements of 0 year, 1 year and 10 years old respectively. Once working out the set up of the measurements and the desired situation there showed to be no road sections of these ages which were suited for the purpose, because of the traffic circumstances. So two pavements of 6 (the Donauweg) resp. 20 years old (the Ookmeerweg) were selected, having similar constructions and traffic conditions. The new test section (0 year old) was built in the 20-year old Ookmeerweg. See figure 1.



Figure 1: Test section Ookmeerweg.

1. 4. Measurements

The measurements are fully described in part 2.
The selected 20-years old and 6-years old pavements as well as the new test section are all composed of concrete blocks in herringbone bond on a bedding sand on a unbound base course, having a thickness of about 200 - 250 mm with a subgrade of sand and peat.

On all three test sections deflection measurements by falling weight deflectometer had to be executed to measure the difference in load spreading capability and to establish a possible increase of this capability in time on the new test section; after half a year the maximum deflection on the new test section was decreased considerably indeed. The deflection measurements are also used as input for the finite element program.

Furthermore the friction forces between the blocks were regarded to be of interest. Considerable differences in these forces could be expected depending on the joint widths and the ages of the pavements. To measure them a pull out device was designed and constructed to pull blocks out of the pavement, keeping the neighbouring blocks in place.

These pull out tests were executed for all test sections and repeated on the new test section after half a year.

The results of the measurements are plotted in a diagram showing pull out forces in relation to the joint widths and the ages of the pavements. Clearly is to be seen an increase in time of the friction forces between the blocks, in spite of an increase in time of the average joint widths.

A comparison between pull out forces P and spring constants k as calculated with the finite element program showed an increasing k in case of increasing P; however the correlation was rather low.

In the new test section soil pressure cells were built in, five directly under and five straight above the base course, in the bedding sand underneath the concrete blocks, in a line in the driving direction, 2.71 m out of the kerbstones. The purpose was twofold. Firstly to measure the load spreading capability not only by deflections but also by soil pressures to have a double check in the finite element programm. Secondly to compare the soil pressures caused by the falling weight and by the traffic loads. The traffic loads were performed by 2 different types of trucks loaded with sand and driving with speeds of 10, 20, 30, 40, 50, 60, 70 km/hr and also standing.

It is remarkable to note that the soil pressures are higher in case of running trucks than in case of standing trucks. Furthermore there is a relation between soil pressure and truckspeed, but not exactly the same for all wheels.

The falling weight pulses caused unreliable results for the upper soil pressure cells, probably because the structure was still very new. The lower cells gave reliable pressures.
After half a year a decrease of 14% in vertical soil pressure was measured on the same spots.

From these measurements a linear relation was found between soil pressures caused by the falling weight and the real traffic loads, although the relation was less accurate for dual wheels.

The Road Laboratory of Amsterdam investigated some properties of the base courses and the sandlayers.

H.W.Z. Consultancy also tried to set up a theoretical model by means of a linear elastic multilayer program but this appeared not to be possible.

1. 5. The calculations

The calculations are fully described in part 3.

The calculations are executed by the finite element computer program ICES STRUDL. In this program the concrete blocks are represented by means of indeformable 'rigid body' elements jointed to each other by vertical springs with spring constant c. The thin sandlayer underneath the blocks is represented by vertical springs with spring constant k, which are jointed to the base course and the subgrade. These layers are assumed to be linear elastic homogeneous and isotropic.
The relevant input data for this program are obtained from the measurements mentioned in part 1.4.
A number of calculations were executed on constructions with different moduli of subgrade and base, different base thicknesses and different characteristics, resulting in elastic deflections underneath the load.
Using the rutting model, developed by the Belgium Road Research Centre, according to Veverka [7] it was then possible to compute the plastic deformations in casu rut depths in relation to the number of passed axle loads.

1. 6. Use of the design charts

The calculations mentioned in 1.5. resulted into a set of design charts, partly for pavements with and partly for pavements without a sandbed between subgrade and base course. Figure 2 shows a design chart for pavements on a high stiffness sand subgrade without a sand subbase.

The chart shows the relation between the design life of the concrete block pavement along the vertical axis and the equivalent E-módulus according to Ivanov [6] along the horizontal axis, depending on the traffic volume N/day. These design charts are set up for different values of the maximum rut depth at the end of the lifetime.

So if the road manager has chosen a design life for the pavement and a maximum rut depth at the end of this lifetime and if he has predicted the traffic volume in terms of single axle load repetitions of 100 kN per day he will find an equivalent E - modulus. Figure 3 is then used to find possible combinations for thickness and E-modulus of the base course.

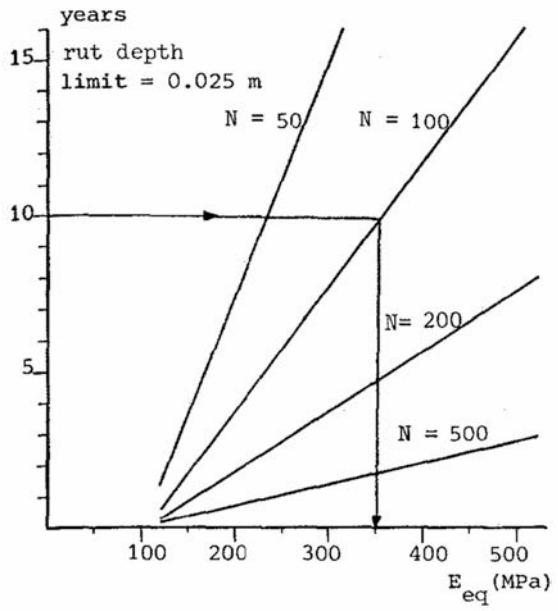


Figure 2: Design chart for a concrete block pavement on a sand subgrade (no subbase)

Out of these combinations he will choose the most optimal one for his particular circumstances.

The course of the curves is highly influenced by the rutting model according to Veverka [7]. Comparisons made by Delft University between the elastic and permanent deformations at the same road sections resulted into a refined model. For Dutch circumstances further research is necessary however.

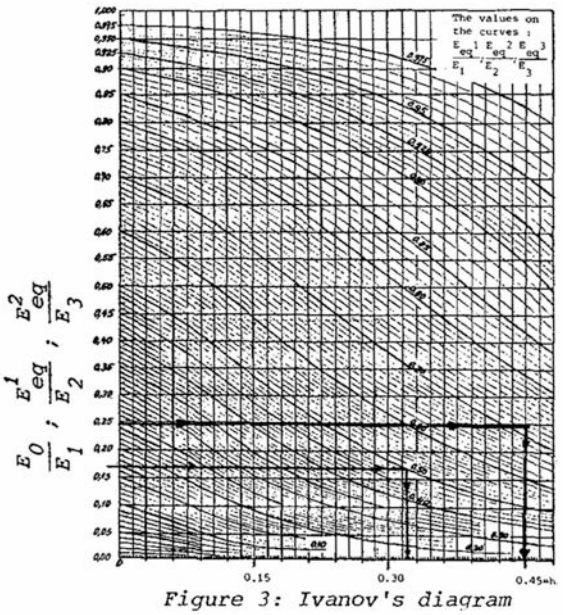


Figure 3: Ivanov's diagram

Example

Data :

- Chosen lifetime of the pavement is 10 years
- Chosen maximum rut depth at the end of this lifetime is 0.025 m
- Predicted number of equivalent single axle loads of 100 kN per day N= 100
- E-modulus of sand subgrade Eo = 120 MPa
- There are three different basecourses available with E1 = 700, 490 and 400 MPa respectivily.

Procedure to be followed :

Use figure 2 because stiffness of subgrade is high. A subbase is not necessary. Plot design life of 10 years in the vertical axis, follow a horizontal line till predicted number of traffic volume, 100 single axle loads per day, is met. From this intersection point follow a vertical line till the horizontal axis is met : E-equivalent = 350 MPa.
Now use figure 3 according to Ivanov.
First try a basecourse with E1 = 700 MPa.

$$\frac{Eo}{E1} = \frac{120}{700} = 0.17 \text{ and } \frac{Eeq}{E1} = \frac{350}{700} = 0.50$$

Plot value 0.17 into the vertical axis and follow a horizontal line till curve Eeq/E-base = 0.50 is met. From this intersection point follow a vertical line till the horizontal axis is met : thickness of base course h = 0.32 m. Now try possibility 2 : a base course with E1 = 490 MPa; follow the same procedure and find a thickness of base course h = 0.45 m. Possibility 3 with E1 = 400 MPa results into a thickness of basecourse h = 0.55 m. Now choose out of these three possibilities the most optimal one.

The entire set of charts and more information about the calculations by Delft University are to be found in part 3.

1. 7. Conclusions

The goal, the set up of design curves for concrete block pavements based on data derived from measurements on existing concrete block pavements used in a reliable theoretical model, has been realised.
The design curves are simple to work with and so road designers are able to design an economical concrete block construction.
Further investigations are necessary, especially to define a better relation between elastic and permanent deformations.

* N.B. Mentioned reports (in Dutch language) of measurements by H.W.Z. Consultancy and calculations by Delft University of Technology are available.

Part 2

The measurements

2. 1. Introduction

Three road sections of different age have been selected in order to compare them with each other and to find a relation between their bearing capacity and their age. One section (A) is a new laid concrete block pavement, as a test section, the second section (B) is a six years old concrete block paved road and the third (C) a twenty years old one. Section (B) and (C) have never been relaid. At the test section different measurements have been carried out twice, just after laying (Oct.'82) and half a year later (March '83).

Its performance will be followed in the future. All sections have more or less the same construction of rectangular concrete blocks, a bedding sand layer and a 200 - 250 mm thick base course of granular material on a subbase of sand. The concrete block size of sections (A) and (B) is : 215 x 105 x 90 mm (l x b x t) and of section C : 220 x 110 x 100 mm.

The following measurements have been carried out in the different road sections.

Section	A		B	C
Age (years)	0	0.5	6	20
Falling weight deflections	x	x	x	x
Pull out tests	x	x	x	x
Soil pressure measurements caused by lorries	x			
caused by FWD	x	x		

2. 2. Falling weight deflection measurements

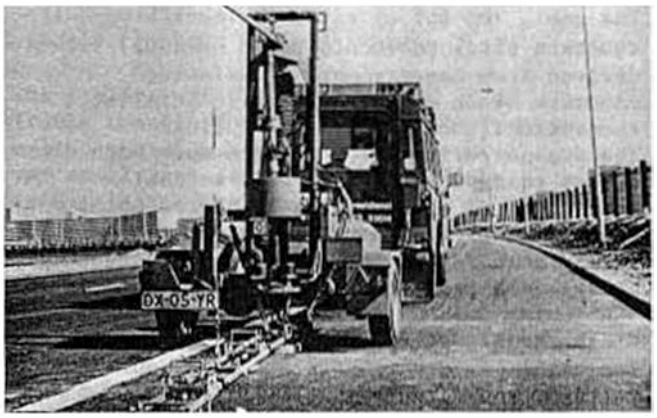


Figure 4: Falling weight deflectometer.

Deflections have been measured at seven distances from the centre of the road when a pulse load of 50 kN is applied on the road with a falling weight deflectometer (FWD). The radius of the loading plate of the FWD is 150 mm.

In each section two series of fifteen measurements were carried out. The first series were in the outer wheeltrack and the second series in the middle of the road.

In the test section, deflections also have been measured just after laying the blocks, but only at three distances from the centre of the load. The mean deflection curves as measured in the different sections are drawn in figure 5.

Remarkable is the decrease of the maximum deflection in the test section after half a year.

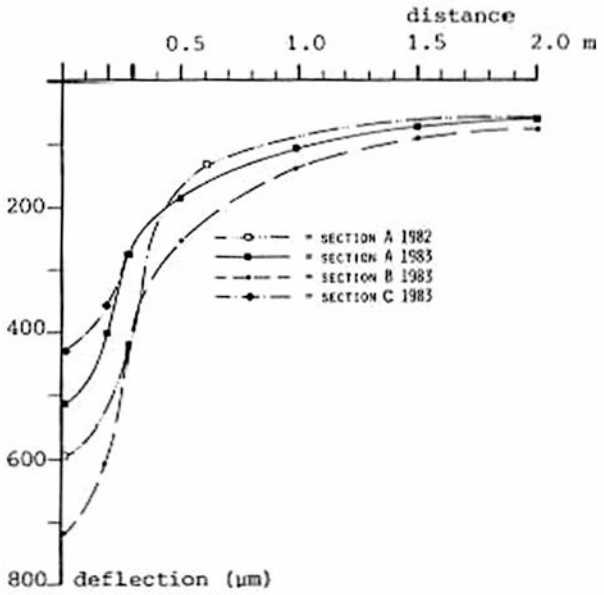


Figure 5: The mean deflection curves in different sections.

The measured deflection curves have been used as input in the finite element program, as described below. Furthermore the curves have been used to select the concrete blocks to be pulled out. For this purpose the joint widths between the concrete blocks were also measured (mean value of the width at six points each block).

2. 3. Pull out tests

In order to get more information of the way of transducing forces between the concrete blocks, a pull out device has been designed and built.

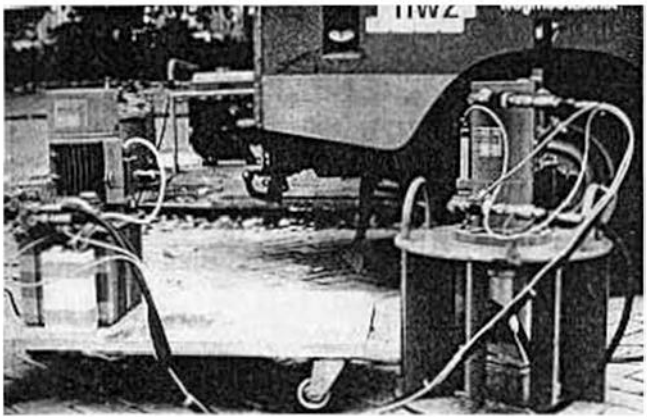


Figure 6: Pull out device.

The pull out device consists of a rigid metal frame that is placed upon the road surface. At this frame a cylinder with a piston has been attached, that can be fastened to a plate. The plate is glued on the stone which is to be pulled out.

The metal plate on the road surface has a rectangular opening, through which the concrete block can be pulled. Between piston and frame a linear variable displacement transducer L.V.D.T. has been mounted. The piston can be moved hydraulically by an electric pump. An oil pressure transducer measures the pull-out force. Both transducers are connected to a x-y-recorder, thus registrating the force to pull out the blocks and the displacement of the blocks.
Figure 7 shows a copy of the registrationform from the x-y-recorder.

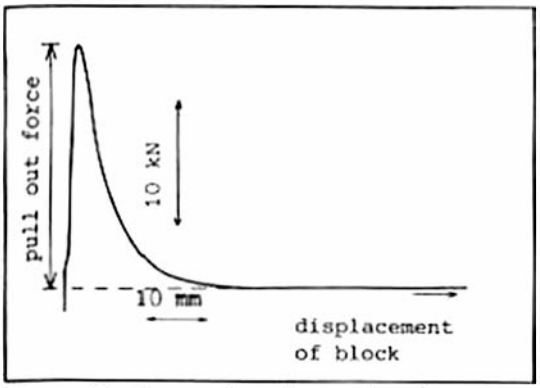


Figure 7: Copy of registration form from pull out test.

In each road section two series of 15 concrete blocks have been pulled out. One serie in the outer wheeltrack and the other serie in the middle of the road. The blocks that were under the centre of the loading during the deflection measurements have been marked; so those blocks have been pulled out, that correspond with a measured deflection curve.

Test results.
The measured maximum pull out forces (P) are related to the average joint width between the pulled block and the surrounding blocks. In the oldest road section only blocks have been found with more than 5 mm average joint width.
In the test section the average joint width did not exceed 5 mm.

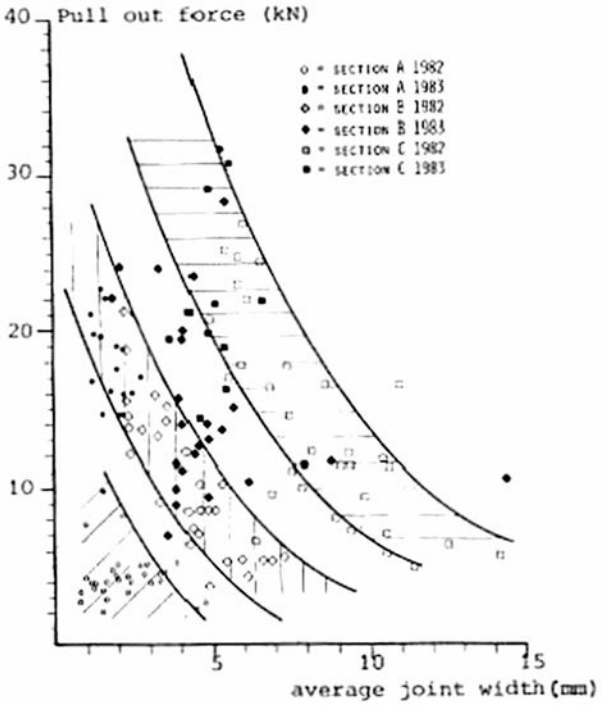


Figure 8: Pull out test results.

From figure 8 can be seen that pull out force increases with pavement age and that in old roads with wide joints, a high pull out force has been measured as well. For a road of a certain age the pull out force increases with decreasing joint width. The needed pull out force in the test section (A) increased from about 4 kN just after laying the concrete blocks till about 18 kN half a year later.

The test results have also been used to compare the pull out force with the spring constant factor k between the concrete blocks as calculated with the finite element program. Different relations have been found for the various measuring series in the road sections.

Figure 9 shows the pull out forces compared with the calculated spring constant factor k for the blocks pulled out in the right wheel track of the sections (A), (B) and (C) in March 1983. An increase in the pull out force gives also an increasing k-value as calculated by the finite element program with the deflection curve as input.

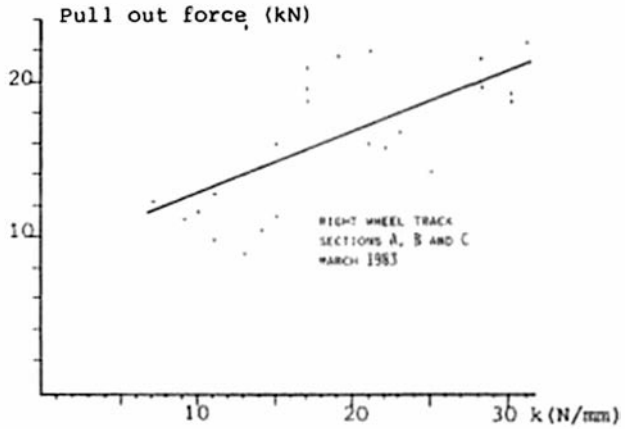


Figure 9: Pull out forces compared with calculated spring constant factor k.

2. 4. Soil Pressures

In the test section the soil pressure cells have been built in at two different depths. One series of five pressure cells was situated in the middle of the sandlayer between base course and concrete blocks, ca. 120 mm below road surface. The second series of pressure cells was situated just under the base course, 350 mm below road surface. The outside diameter of the soil pressure cells is 30 mm and their thickness is 6.5 mm.



Figure 10: Soil pressure cell.

The measuring capacity of the upper cells is max. 1.0 MPa, of the lower cells max. 0.5 MPa. All cells were connected to carrier wave amplifiers and recorders in a van.

The cells are positioned in a line in driving direction, at a distance of 2.71 m from the curbstone. The line is marked on the road. The distance between the cells is 150 mm. Figures 11 and 12 show the position of the cells on the road.

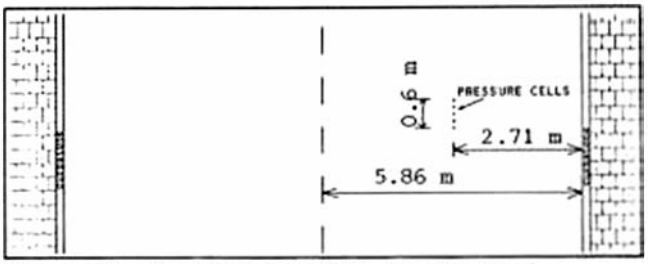


Figure 11: Position of cells in the road.

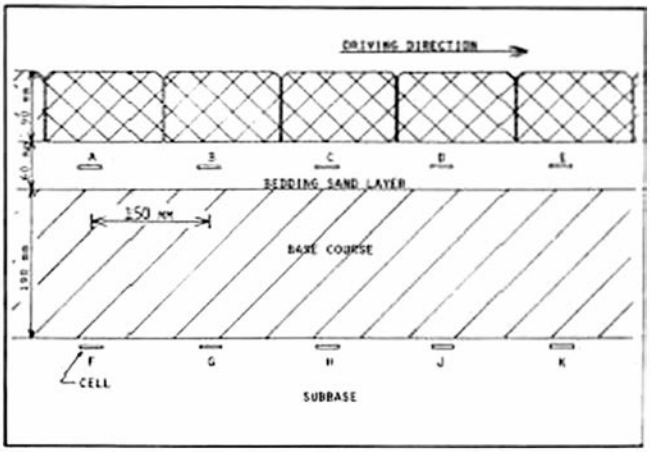


Figure 12: Position of cells in pavement.

Measuring procedure

The first series of tests have been carried out just after finishing the test section in October 1982, on a new laid pavement. These soil pressure tests consisted of

a. static measurements as a result of the loads of standing trucks
b. dynamic measurements as a result of the loads of riding trucks
c. dynamic measurements as a result of the pulse load of a falling weight deflectometer

The second series have been carried out half a year later, in March 1983 and consisted of

d. dynamic measurements as a result of the pulse load of a falling weight deflectometer.

The two trucks, used at the test, were a two-axle and a three-axle truck, loaded with sand. The axle loads of the trucks have been measured with a static weigh-bridge and they range between 55 to 128 kN. The distribution over right and left has been calculated with aid of the contact areas of the tires on the road. The pulse load from a falling weight is measured by a load cell above the loading plate. The load ranges from 50 to 53 kN. All measured soil pressures have been corrected to a standard load of 50 kN. As the loading plate has a radius of 150 mm, the applied load corresponds with a uniformly distributed contact stress of 0.707 MPa.

sub.a. Measurements with standing trucks.
Soil pressures have been registrated from all cells when each wheel (and also the centre of a dual wheel) was right above the middle cell. The soil pressure measured under the base course, caused by the load of a dual wheel, is in the centre of one of the wheels equal to the pressure between the two wheels. The soil pressure measured in the bedding sand layer caused by the load of a dual wheel, is in the centre of one of the wheels higher than the pressure between the two wheels.

sub.b. Measurements with riding trucks.
The trucks have driven three till five times, both with their right wheel and their left wheel over the marked line, at speeds of 10, 20, 30, 40, 50, 60 and 70 km/hr.



Figure 13: Trucks on test section.

It appeared to be difficult to drive with high speed exactly over the marked line, so some test results could not be used. The mean value given by the cells under the base course is given in figure 14 for both of the trucks at different speeds. The mean value of the cells just under the concrete blocks in the bedding sand is also given in figure 14.

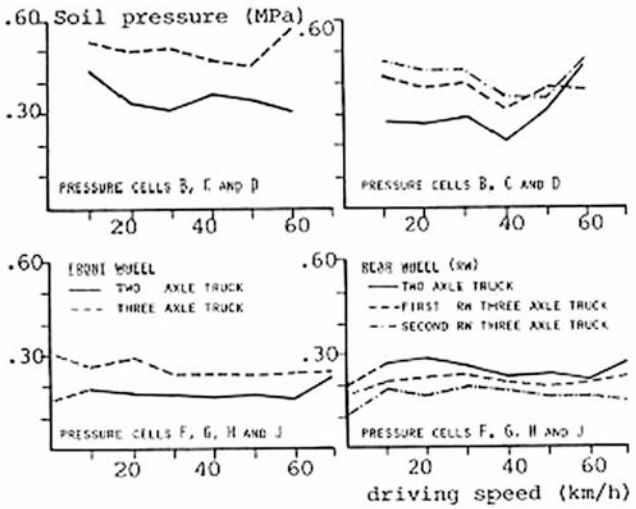


Figure 14: The mean soil pressure at different driving speeds.

The static wheelload of the right front-wheel of the two axle truck is 28 kN and of the right rearwheel 69 kN. The wheelload of the right frontwheel of the three axle truck is 46 kN, the first right rearwheel 58 kN and the second right rearwheel 56 kN. Some relation between soil pressure and speed is evident, but it is stated that the relations are not the same for all wheels. The pressures caused by a dynamic load is higher than caused by a static load of the same weight.

sub.c. Measurements as a result of the pulse load of a falling weight deflectometer.
Five series of measurements have been carried out in October 1982. One just over the cells (in the centre line), two at 150 mm distance and two at 300 mm distance from the centre line. Each series consisted of 10 - 20 loads at different distances between them. The pulse load ranged from 50 - 53 kN and the loading plate had a radius of 150 mm. All measured values have been corrected to a load of 50 kN. Probably due to the fact that the pavement was very new, the upper cells have not given reliable values. The cells under the base course have given similar curves for the series of loads in the centre line and for the series of loads at distance of 150 mm. The series at 300 mm distance have given few information. Examples of the curves measured from loadings in the centre line and at 150 mm distance are given in figures 15 and 16.

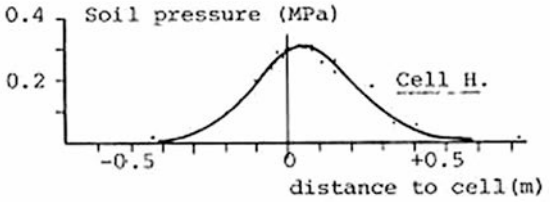


Figure 15: Example of soil pressure curve from loadings in the centre line (1982)

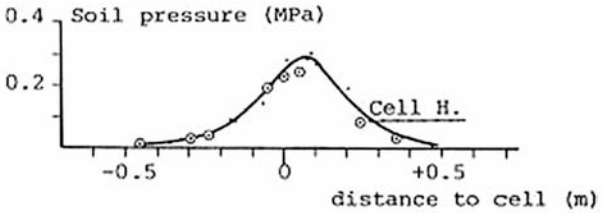


Figure 16: Example of soil pressure curve from loadings at 150 mm distance (1982).

It is remarkable that the maximum value in the curve at 150 mm distance is higher than the value at 150 mm distance in the centre curve. The maximum values of the cells caused by loadings in the centre line range between 0.22 and 0.32 MPa.

sub.d. Measurements as a result of the pulse load of a FWD, half a year after construction.
In the centre line of the cells 38 loadings have been applied at a distance of 40 mm between them and the measured soil pressures have been corrected to a load of 50 kN.

Four out of five upper cells gave a similar curve with two maxima, at a distance of about 160 - 200 mm. The maximum stress measured is 1.0 MPa whereas the average stress applied by the loading plate is 0.7 MPa.
Four out of five lower cells also gave similar curves, with maximum values between 0.19 and 0.28 MPa. The average decrease of these maximum values in half a year is 14%.
Examples of the measured curves are given in figures 17 and 18.

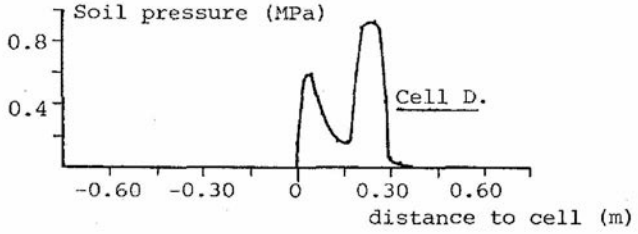


Figure 17: Example of the soil pressure curve in the bedding sand layer (1983).

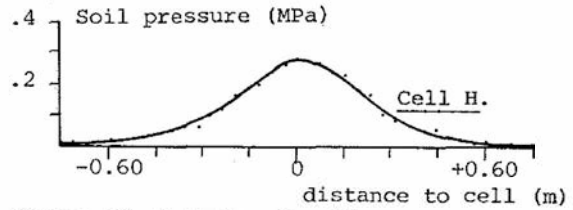


Figure 18: Example of soil pressure curve from loadings in the centre line (1983)

Comparing test results.
For each cell the soil pressure measured under the base course caused by the truck wheels and by the falling weight deflectometer have been compared with the loads applied.

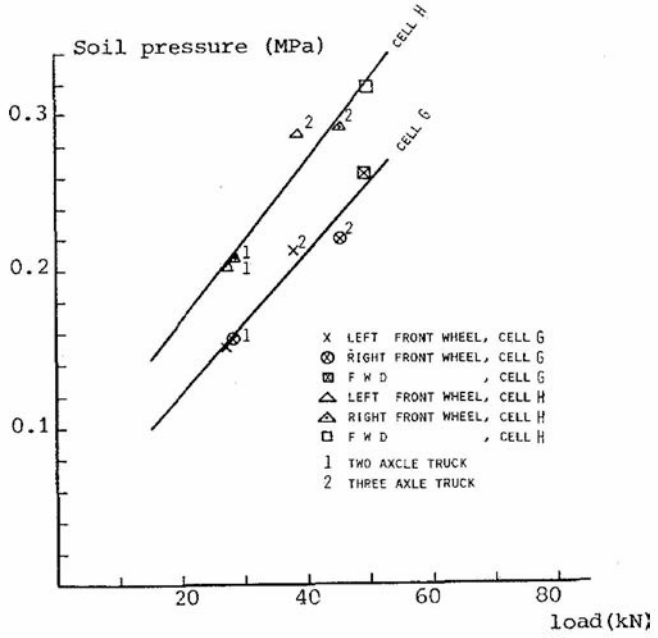


Figure 19: Linear relation between soil pressure and single wheel + FWD

It is found that there are linear relations between the different loadings of single (front) wheels and the FWD. Figure 19 gives the relation for two cells.

Dual wheels also have a linear relationship but less accurate. Figure 20 gives the relations for the same cells.

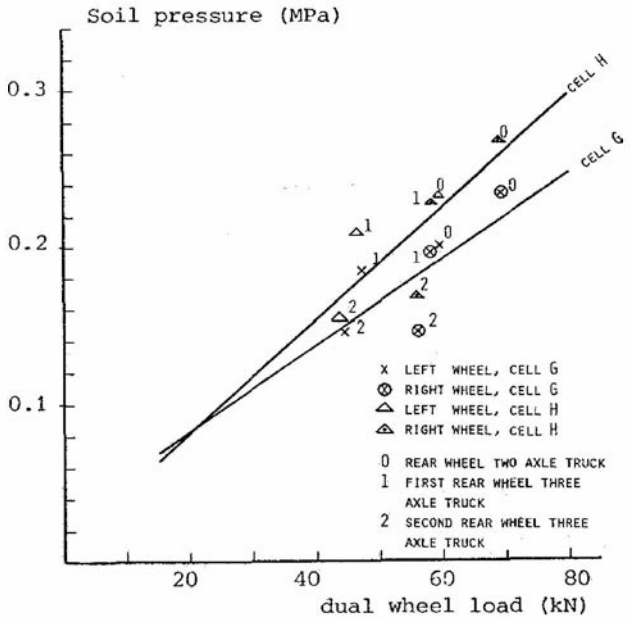


Figure 20: Linear relation between soil pressure and dual wheel load.

When the relations of single and dual wheels are compared, it appears that the soil pressure caused by a dual wheel of about 50 kN is about 0.6 times the soil pressure caused by a single wheel or FWD of about 50 kN.

2. 5. Measurements compared with calculations.

Calculations have been made by using the aid of a linear elastic multi layer program (Chevron) to simulate the measured deflections and soil pressures caused by a pulse load of 50 kN from a falling weight deflectometer. It appeared to be possible to calculate the measured stresses if the thickness of the concrete block is neglected and the load is applied directly on the bedding sand layer. The deflections calculated in this case are much lower than the measured deflections.

Furthermore the measured deflections are calculated with aid of the Chevron-program. It appeared to be possible to simulate the measured deflection-curve but in that case the stresses calculated under the base course are about half the measured values.

Part 3.

The Calculations

3. 1. Introduction

As has been indicated in the previous part, linear elastic multi layer computer programs cannot be used to simulate both the deflections measured at the surface of a concrete block pavement as well as the vertical pressures measured within the structure. Therefore use has been made of the ICES STRUDL finite element program since recently a so-called RIGID BODY element has come available [1] by which a proper schematization of the concrete block layer can be obtained. This program has especially been used for the evaluation of the pavement sections considered and for the construction of design charts for concrete block pavements. In the following sections first of all the schematization of a concrete block pavement by means of the RIGID BODY and other elements will be given. Next examples will be shown of the excellent correspondence that could be obtained between the measured and calculated deflection profiles and soil pressures. Finally the development of design charts by means of the ICES STRUDL program will be described and typical examples of the charts will be given.

Schematization of the Concrete Block Pavement

Figure 21 shows the schematization as adapted in this study of a concrete block pavement.

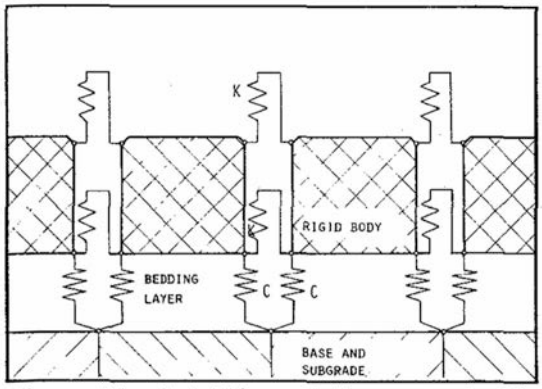


Figure 21: Modelling of the concrete block pavement.

The concrete block layer is represented by a set of indeformable RIGID BODY elements, representing the concrete blocks that are connected to each other with a set of springs that are acting in the vertical direction only. These springs represent the joints. The rigid bodies are supported by a set of springs acting in the vertical direction that are representing the bedding sand layer. The joint stiffness is characterised by means of the magnitude k, the bedding layer stiffnes by means of the constant c.

The base and subgrade are characterised by means of the elastic modulus and Poisson's ratio. For these layers CSTG elements were used. Furthermore it was assumed that the concrete block layer is more or less acting like a pure shear layer which means that no bending moments are transmitted in the block layer and that only vertical displacements of the blocks will occur. This assumption is based on the fact that the deflection profile of such a shear layer is very much alike a concrete block pavement. Also the bedding sand layer was assumed to be incapable of transmitting bending moments.

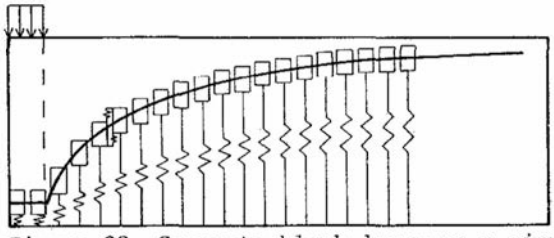


Figure 22: Concrete block layer as a simply supported pure shear layer.

3. 3. Correspondence between measured and calculated behaviour

The schematization of the concrete block pavement as described in the previous section was used to analyse the structural characteristics (k, c and E-values) of the Donauweg, Ookmeerweg and the test section of the Ookmeerweg. The structural characteristics have mainly been assessed from the deflection bowls measured on those sections. However an in-depth-evaluation of the test section of the Ookmeerweg was possible since there soil pressure cells were built in, so not only the deflections measured on this section could be simulated but also the measured soil pressure.

The simulation of the measured deflection profiles was carried out in the following way. First of all the subgrade modulus was estimated by means of the relation [2]

$$\log E_s = 3.869 - 1.009 \log d_2$$

where E_s = elastic modulus of the subgrade (MPa)

d_2 = deflection measured at a distance of 2 m from the loading centre of a falling weight deflectometer (F = 50 kN)(μm).

Then the k, c and elastic modulus of the base were assessed by means of trial and error. It should be noted that starting values for k and c were assessed from a relation between the surface curvature index (SCI) and the k, c resp. that was taken from literature [3]. We recall

that the SCI is defined here as :
$SCI = d_0 - d_{0.5}$

where d_0 = maximum falling weight deflection (F = 50 kN)(μm)
$d_{0.5}$ = deflection measured at a distance 0.5 m from the loading centre (μm).

Typical examples of the simulation of the measured deflection profiles are given in figure 23. As can be observed an excellent corespondence between the measured and calculated profiles was obtained.

Considering the soil pressure measured at the Ookmeerweg test section it should be noted that the soil pressures as measured just beneath the base could be simulate with a rather high degree of accuracy.
This is illustrated in figure 24.

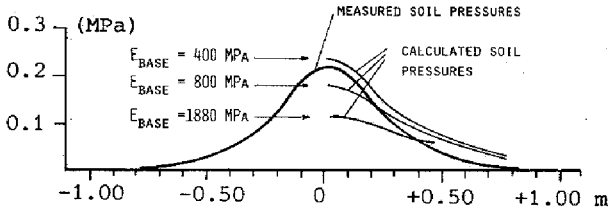


Figure 24: Soil pressures under the base course.

As can be observed the stresses are considerably influenced by the stiffness of the base. It was impossible to simulate the stresses as measured in the bedding sand layer. The measured maximum stresses were much higher that the calculated stresses. Figure 25 shows the stress distribution as calculated for the bedding sand layer. As can be observed these stresses are hardly influenced by the stiffness of the base.

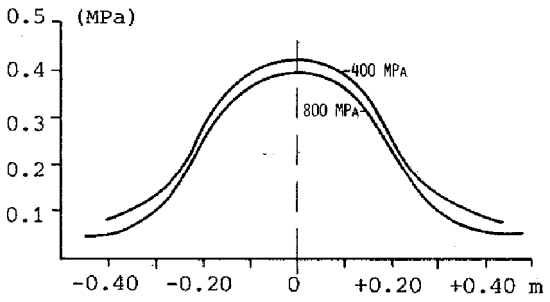


Figure 25: Calculated soil pressures in the bedding sand layer.

Since deflection and soil pressure measurements were taken at the test section of the Ookmeerweg directly and half a year after construction was completed, it was possible to determine the so-called stiffening of the construction.

Table 1 shows the observed increase in k, c, E-base and E-subgrade. As can be observed especially the stiffness of the bedding sand layer and the base show a marked increase in stiffness which is mainly due to post compaction of the material.

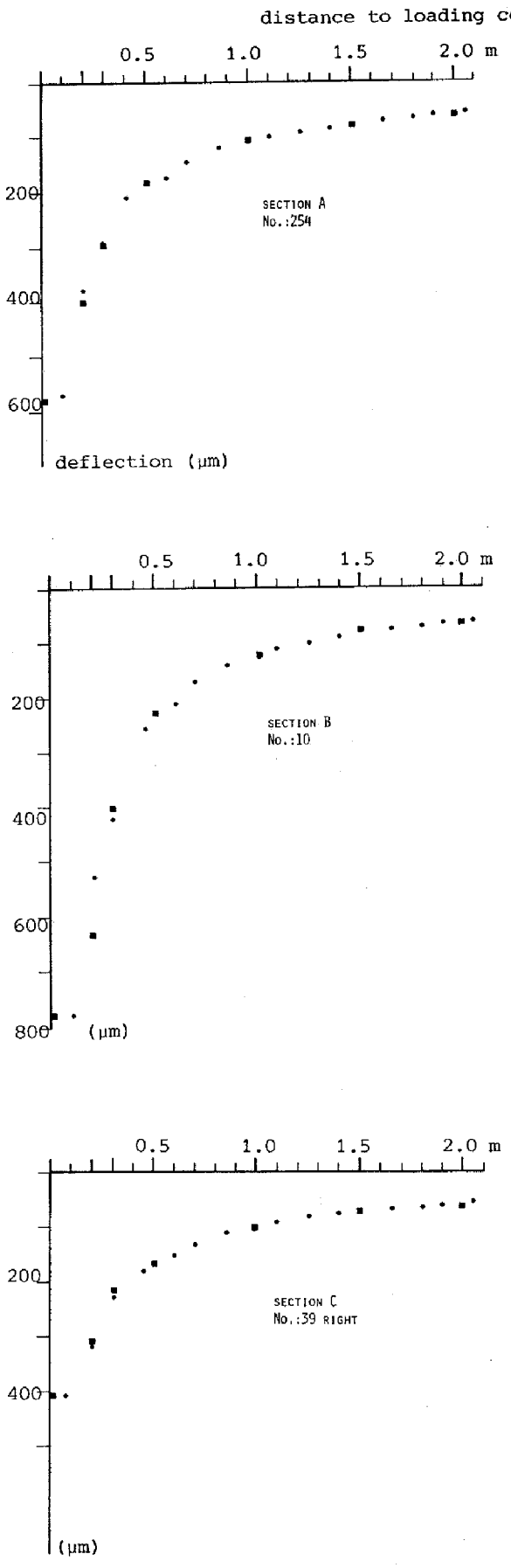


Figure 23: Typical examples of the simulation

	Months after construction	
	0	6
k (N/mm)	13.4	15
c (N/mm3)	0.079	0.12
E (MPa)	180 - 200	400
E (MPa)	127	140

Table 1. Increase of the Load Spreading Capacity in Time of the Test Section of the Ookmeerweg.

3. 4. Development of Design Charts for Concrete Block Pavements

Based on the achievements described in the previous sections, design charts for concrete block pavements were developed. In this section the procedure that was followed to construct the charts will be outlined and typical examples will be given.

Table 2 shows the 21 different construction types that were analysed by means of the ICES STRUDL computer program. The load configuration that was used in the analysis was a 50 kN load applied on a circular flexible plate with a diameter of 0.3 m. This means that in fact a 100 kN equivalent single axle load was applied to the pavement. As can be observed two different subgrades were analysed. It was assumed that on the weak subgrade (E = 50 MPa) a sand layer needs to be constructed having a thickness of 0.5 m and 1.00 m resp.

Furthermore it was assumed that the stiffer subgrade (E = 120 MPa) was a sand subgrade. The effect of different base stiffnesses on the behaviour of a concrete block pavement was also analysed. For the unbound base the stiffness (240, 350 MPa) was set dependent on its thickness and the stiffness of the sand layer using the relation developed by Shell [4] which is :

$$E_b = 0.206 h_b^{0.45} E_s \qquad 2E_s \leq E_b \leq 4E_s$$

where E_b = elastic modulus of the base (MPa)
h_b = thickness of the base (mm)
E_s = elastic modulus of the sand layer (MPa)

Furthermore a semi bound (E_b = 800 MPa) and a bound base (E_b = 2000 MPa) were analysed.

As can be observed the calculations were carried out for two combinations of k and c. The low k and c values were thought to be representative for the first year after construction. It is assumed that after one year all post compaction and stiffening has taken place and that both k and c have increased with a certain amount. In order to determine the magnitude of this increase use has been made of a relation, taken from literature [5] that describes the dependency of k and c on the the equivalent stiffness of the sub-structure (subgrade + sand layer + base).

These relations are shown in figures 26 and 27. In figures 26 and 27 also the 70% confidence interval is shown. It was assumed in the calculations that during the first year when the post compaction and stiffening takes place, the k and c values can be determined from the equivalent substructure modulus using the lower confidence level. After the first year the k and c values were determined using the upper confidence level. It should be noted that no field data were available to confirm these assumptions. Further it should be noted that the above mentioned equivalent substructure modulus was calculated by means of Ivanov's [6] theory.

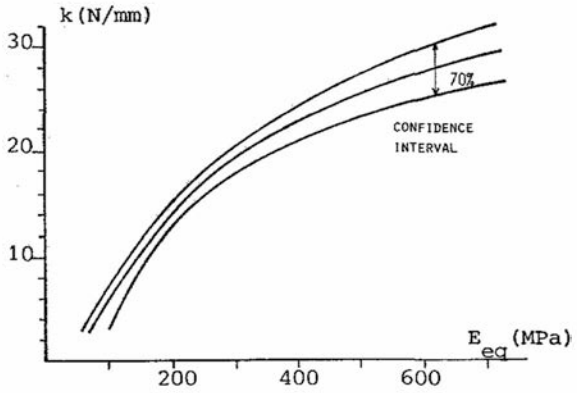


Figure 26: Relation between E_{eq} of the substructure and k.

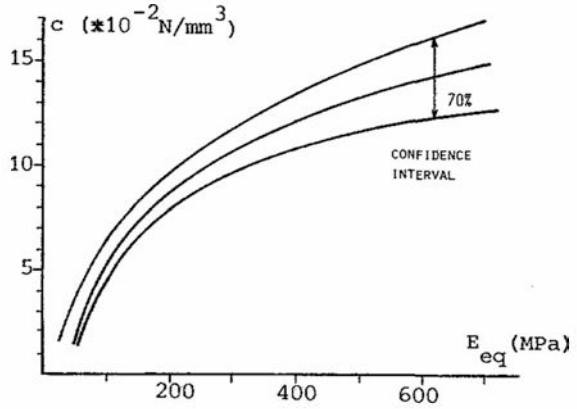


Figure 27: Relation between E_{eq} of the substructure and c.

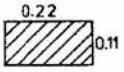
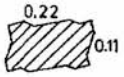
Table 2 also shows the maximum surface deflection as calculated for the different structures and low and high k and c values. These maximum deflections were used in rut depth calculations that were the basis for the design charts. This will be described hereafter.

Permanent deformation (rutting) is considered to be an important structural defect of concrete block pavements.

Tabel 2. Constructions analyzed in the Development of Design Charts

No.	Subgrade	Subbase		Base		Eeq	k/c		u_{el} /mm/	
	E[MPa]	h[m]	E[MPa]	h[m]	E[MPa]	[MPa]	low	high	k/c low	k/c high
1	50	0.50	120	0.15	240	142	8.5/0.065	11.5/0.08	1.055	0.918
2	50	0.50	120	0.15	800	208	13.5/0.085	16.0/0.095	0.861	0.804
3	50	0.50	120	0.15	2000	280	16.5/0.095	19.5/0.110	0.789	0.732
4	50	0.50	120	0.30	350	219	14.0/0.085	16.5/0.10	0.836	0.769
5	50	0.50	120	0.30	800	336	18.5/0.1	22.0/0.12	0.735	0.675
6	50	0.50	120	0.30	2000	480	22.0/0.115	26.5/0.145	0.666	0.604
7	50	0.50	120	0.		104	4.5/0.045	8.5/0.065	1.458	1.100
8	50	1.00	120	0.15	240	155	10.0/0.07	12.5/0.085	0.964	0.861
9	50	1.00	120	0.15	800	232	14.5/0.09	17.0/0.10	0.810	0.760
10	50	1.00	120	0.15	2000	300	17.5/0.10	20.5/0.115	0.772	0.698
11	50	1.00	120	0.30	350	231	14.5/0.09	17.0/0.10	0.799	6.749
12	50	1.00	120	0.30	800	356	19.0/0.105	22.5/0.125	0.708	0.653
13	50	1.00	120	0.30	2000	500	22.5/0.115	27.0/0.145	0.655	0.595
14	50	1.00	120	0.		120	6.0/0.055	10.0/0.070	1.219	0.998
15	120	0.		0.15	240	155	10.0/0.07	12.5/0.085	0.776	0.674
16	120	0.		0.15	800	232	14.5/0.09	17.0/0.10	0.625	0.576
17	120	0.		0.15	2000	300	17.5/0.10	20.5/0.115	0.565	0.515
18	120	0.		0.30	350	231	14.5/0.09	17.0/0.10	0.621	0.572
19	120	0.		0.30	800	356	19.0/0.105	22.5/0.125	0.533	0.479
20	120	0.		0.30	2000	500	22.5/0.115	27.0/0.145	0.482	0.424
21	120	0.		0.		120	6.0/0.055	10.0/0.070	1.007	0.790

Table 3 : Values for a and b in relation to Material and Construction Type

Material / Construction Type Type of Loading	Ref.	Bond Type	Block Type	Thickness [m]		Stiffnes	a	b
				Block	Base	Subgrade [MPa]		
Sand subbase dynamic triaxial	7						2	0.3
Granular Base dynamic triaxial	7						2	0.2
Conc.Block Pav. Rep.plate loading	8	Herring bone 45°		0.08	-	137	0.48	0.38
Conc.Block Pav. Rep.plate loading	8	id.	id.	0.12	-	144	1.73	0.22
Conc.Block Pav. Load simulator	9	id.		0.10	0.16	CBR = 66%	0.22	0.22
Conc.Block Pav. Load simulator	9	id.	id.	0.08	0.10	id.	0.26	0.23
Conc.Block Pav. Load simulator	9	id.	id.	0.06	0.06	id.	0.24	0.34

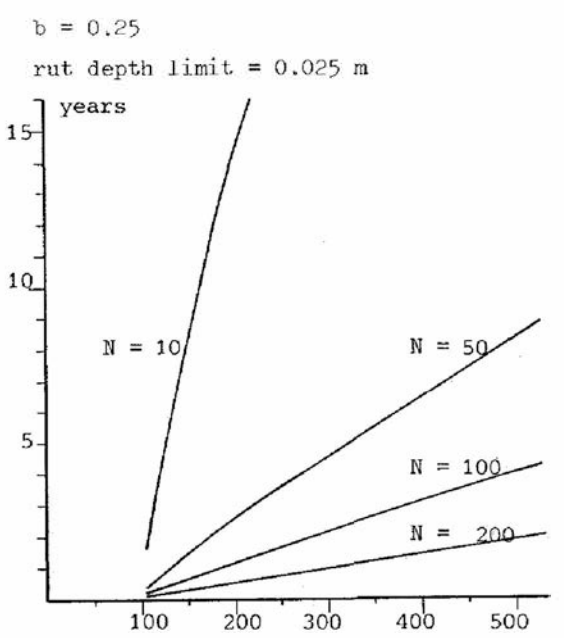


Figure 28: Design chart for concrete block pavement with a sand subbase on a weak subgrade.

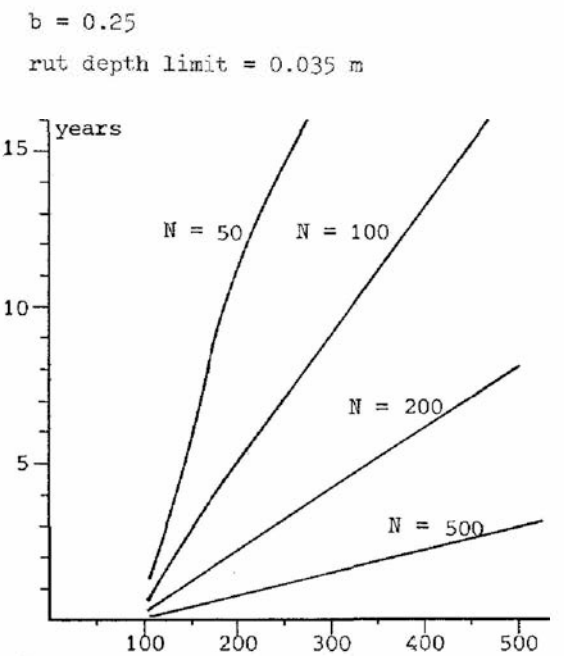


Figure 29: Design chart for concrete block pavement with a sand subbase on a weak subgrade.

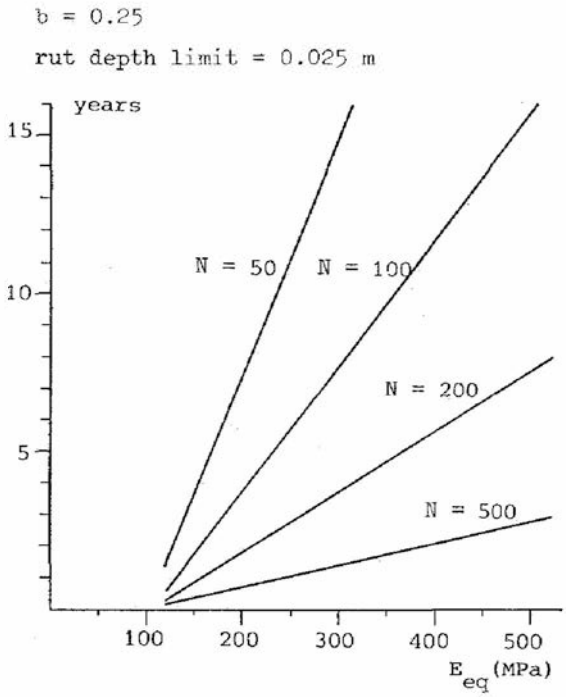


Figure 30: Design chart for a concrete block pavement on a sand subgrade (no subbase).

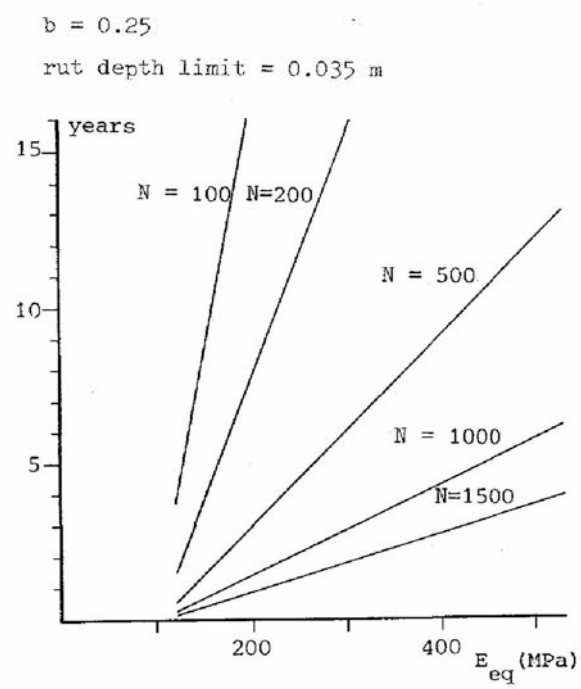


Figure 31: Design chart for a concrete block pavement on a sand subgrade (no subbase)

Therefore the design of these pavements should be such that the maximum alowable rut depth is not exceeded before the predefined design number of load repetitions is reached. In this study the rut depth development has been calculated using the equation

$u_p = u_{el} .a.n^b$

where u_p = permanent deformation (mm)

u_{el} = elastic deformation (mm)

n = number of load repetitions

a, b = constants

This rut depth equation has been developed by researchers of the Belgium Road Research Centre [7].

The original equation has been developed for different types of material. In this particular case however the permanent deformation of the overall construction is calculated directly from the elastic deformation of the overall construction (maximum deflection) and not from the permanent deformation of the individual layers. This means that the constants a and b should be related to the behaviour of the overall construction. It will be understood that the selection of proper values for a and b is rather critical since especially b is governing the permanent deformation behaviour to a considerable extent.
Since no information was available on the rutting behaviour of concrete block pavements like those considered in this study, reasonable estimates were made for a and b that were based on information taken from literature.
Table 3 shows typical values for a and b as reported in different studies.
Based on this information it was decided that a = 2 and b = 0.25 are reasonable first estimates to be used in the calculation of the permanent deformation of the concrete block pavement type as considered in this study.

Using the calculation results given in table 2 and taking into account the above mentioned assumptions on the stiffening of a concrete block pavement in time, the number of years was calculated until a predefined rut depth was reached given the number of equivalent 100 kN single loads per day [10].
The results are presented in the shape of design charts that are given in figures 28 to 31. Figures 28 and 29 are applicable for pavements on a low stiffness subgrade on which a sand subbase is constructed. Figures 30 and 31 are applicable for pavements on a sand subgrade. Figures 29 and 31 are based on a rut depth limit of 0.035 mm which can be considered as a structural limit (failure). Figures 28 and 30 are based on a rut depth limit of 0.025 m which can be considered as a funtional limit (safety, driving comfort).
An example of how the design charts have to be used is given in part 1 of this paper.

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