THE DUTCH DESIGN METHOD FOR CONCRETE BLOCK ROAD PAVEMENTS

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SUMMARY

The task of Working Group D3 of The Netherlands Centre for Research and Contract Standardization in Civil and Traffic Engineering consists in establishing a (simple) design method for concrete block road pavements under Dutch conditions. This paper describes the development of this design method, based on an investigation into the structural behaviour of a number of test pavements constructed by the Working Group. The design method applies to concrete block pavements (subjected to normal road traffic), consisting of rectangular concrete paving blocks (thickness 80 mm or more) in herringbone bond, 50 mm crushed sand bedding layer, eventually an unbound base of crushed concrete or a mixture of crushed concrete and crushed clay bricks, and a sand sub-base. Rutting is the design criterion for pavement structures like this.
The resilient (deflections) and permanent (rutting) deformation behaviour of the test pavements was measured by means of falling-weight deflection measurements and level measurements respectively. Next, the resilient deformation behaviour was analyzed by means of the two-dimensional finite element program ICES STRUDL 'rigid bodies' and the permanent deformation behaviour was analyzed by means of the 'progressive stiffening' theory. The measurements as well as the analyses clearly show the 'progressive stiffening' behaviour of stable concrete block pavements.
The results of these analyses are both elastic and permanent 'progressive stiffening' coefficients. Based on these coefficients, rutting calculations were carried out by means of the 'progressive stiffening' theory for a great number of concrete block pavement structures. It appeared from these calculations that the load equivalency coefficient is dependent on the total pavement structure, especially on the subgrade modulus of elasticity.
The design rutting standard is taken as 15 mm (characteristic rut depth, 30 per cent probability of exceeding). One design chart is presented for concrete block road pavements with a sand sub-base only; this chart includes a shear failure curve. For various subgrade moduli design charts were derived for concrete block road pavements with an unbound base and a sand sub-base; two charts are presented here.

1. INTRODUCTION

The Working Group D3 'Design of Small Element pavements' of The Netherlands Centre for Research and Contract Standardization in Civil and Traffic Engineering (Centre R.O.W.) was set up at the beginning of 1981. This Working Group's task consists in establishing a (simple) design method for small element road pavements to be constructed under conditions as encountered in The Netherlands. The study is confined to small element pavement structures, subjected to normal road traffic, that are common practice in this country.
This means:

- paving elements with horizontal dimensions of approximately 200 mm × 100 mm, more particularly comprising the rectangular concrete paving block sizes commonly used in The Netherlands
- pavement substructure consisting of a sand sub-base only or an unbound base and a sand sub-base.

For a pavement structure like this, with unbound materials only, rutting is the design criterion.

First, in chapter 2 a description is given of the pavement structure and the traffic loading on the Working Group's test pavements in the cities of Alphen-on-Rhine (peat subgrade) and Rotterdam (clay/sand subgrade) and on ECT's Delta Terminal on the 'Maasvlakte' near Rotterdam (sand subgrade).

In chapter 3 the results of the measurements into the resilient and permanent deformation behaviour of the test pavements are presented. This concerns the progress of the deflections, determined by means of falling-weight deflection measurements, and the progress of the rutting, determined by means of level measurements.
Next, chapter 4 gives an analysis of the behaviour of the test pavements. The resilient deformation behaviour (deflections) is analyzed by means of the two-dimensional finite element model ICES STRUDL 'rigid bodies'. The permanent deformation behaviour (rutting) is analyzed by means of the 'progressive stiffening' theory. This analyses yield elastic and permanent 'progressive stiffening' coefficients for the various layers of the test pavement structures.
Based on the test pavements' behaviour, rut depth calculations are carried out for a great number of concrete block pavement structures. On the basis of these rutting calculations and an adopted design standard (characteristic rut depth 15 mm), design charts for concrete block road pavements are derived. In chapter 5 one chart for pavements with a sand sub-base only and two charts for pavements with an unbound base and a sand sub-base are presented. Some design examples illustrate how to use the design charts.

2. TEST PAVEMENTS

2.1 Alphen 1 and 2

Working Group D3 realized two concrete block test pavements on the works site of the precast concrete manufacturing plant of Bos Beton B.V. in the city of Alphen-on-Rhine. It was practicable to route most of the heavy outgoing traffic (chiefly consisting of trucks carrying precast concrete products) over these test pavements.

The first test pavement (Alphen 1) was realized at the beginning of October 1982. This test pavement consisted of two sections (A and B), each 15 m × 4 m. The pavement structure of the test pavement Alphen 1 consisted of (figure 1):
- rectangular concrete paving blocks, thickness 0.08 m (section A) and 0.12 m (section B) respectively, in herringbone bond between concrete kerbs; the concrete blocks were paved manual according to the traditional craft method
- a bedding layer of 0.05 m crushed sand
- a sand sub-base, thickness 0.70 m
- the subgrade, consisting of about 8 m peat; CBR 0.6 - 0.9 per cent, modulus of elasticity 20 - 30 N/mm^2 (derived from falling-weight deflection measurements, see chapter 3.2).

As reported at the Second International Conference on Concrete Block Paving (1), the test pavement Alphen 1 failed completely due to ongoing shear failure of the sand sub-base under the heavy traffic loads. This test pavement was in use until July 1, 1983.

After the excavation of the test pavement Alphen 1, a second concrete block test pavement was constructed at the same location in the middle of July 1983. This test pavement (Alphen 2), that again consists of two sections (A and B) each 15 m × 4 m, has the following pavement structure (figure 1):
- rectangular concrete paving blocks, thickness 0.08 m (section A) and 0.12 m (section B) respectively, in herringbone bond between concrete kerbs; the concrete blocks were paved manual according to the traditional craft method
- a bedding layer of 0.05 m crushed sand
- an unbound base (grading 0/25 mm) of 0.25 m crushed concrete
- a sand sub-base, thickness 0.45 m
- peat subgrade; CBR 0.6 - 0.9 per cent, modulus of elasticity 20 - 30 N/mm^2.

At the end of 1987 this test pavement Alphen 2 still was in use.

From records of the outgoing traffic, kept at the works exit gate, it appeared that the test pavements Alphen 1 and 2 were subjected to about 5850 axle load (> 5 kN) repetitions per annum. The distribution of axle loads is given in table 1.

axle load (kN)	distribution (%)
5 - 20 (10)	0
20 - 40 (30)	1.5
40 - 60 (50)	18.4
60 - 80 (70)	39.7
80 - 100 (90)	35.0
100 - 120 (110)	4.1
120 - 140 (130)	1.0
> 140 (150)	0.3

Table 1. Distribution of axle loads on the test pavements Alphen 1 and 2.

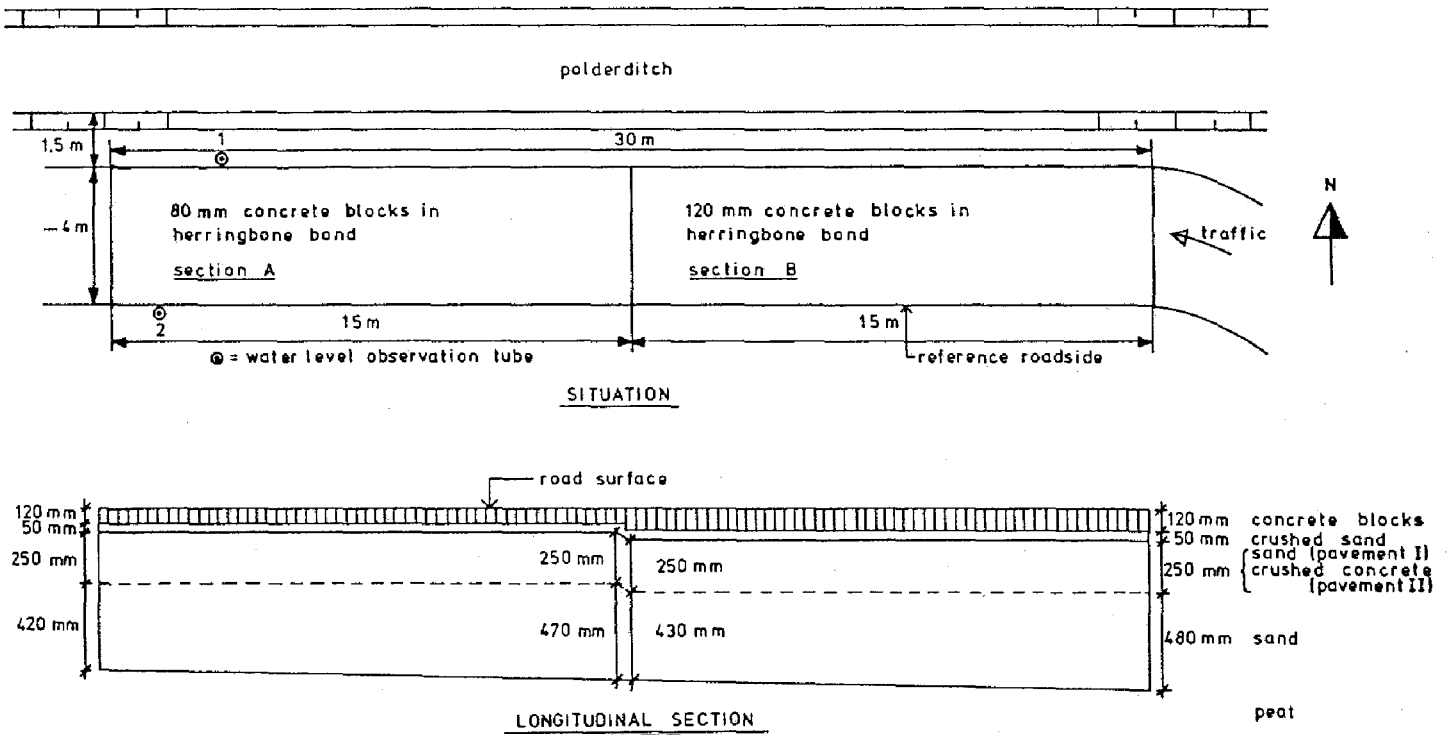


Figure 1. Plan and pavement structure of the test pavements Alphen 1 and 2.

2.2. Rotterdam 1 to 6

In October 1984 the Working Group D3 had the opportunity to realize four concrete block test pavements (numbers 1, 2, 3 and 4) on the heavily loaded Albert Plesmanweg in the Rotterdam port area. Next to these test pavements, the Public Works Department of the Municipality of Rotterdam constructed another two test pavements (numbers 5 and 6).
Each test pavement has dimensions 25 m × 6.8 m. Adjacent to the road there are parking places or concrete kerbs and a footway (figure 2).

After excavation until a depth of 1.05 m below the road surface level, the following pavement structures were built on the test pavements Rotterdam 1 to 6:
- rectangular concrete paving blocks, thickness 0.09 m (pavements 1 and 3) and 0.12 m (pavements 2, 4, 5 and 6) respectively, in herringbone bond; the concrete blocks were laid mechanically by means of a Delta S block-laying machine
- a bedding layer of 0.05 m crushed sand
- an unbound base (grading 0/40 mm) of 0.30 m crushed concrete (pavements 3 and 4) or 0.30 m mixture of crushed concrete (about 65 per cent mass) and crushed clay bricks (about 35 per cent mass) (pavements 5 and 6)
- a sand sub-base, thickness ranging from 0.91 m (pavement 1) to 0.58 m (pavements 4, 5 and 6) clay/sand subgrade; modulus of elasticity 65 - 70 N/mm^2.

Also the test pavements Rotterdam 1 to 6 still were in use at the end of 1987.

During some weeks in 1984 and 1985 axle load measurements were carried out by means of a small axle load weigh-device, temporary glued at the load surface. It appeared from these measurements that the test pavements Rotterdam 1 to 6 are subjected to about 1,250,000 axle load (> 5 kN) repetitions per annum per lane. The distribution of axle loads is given in table 2.

axle load (kN)	distribution (%)
5 - 20 (10)	60.80
20 - 40 (30)	12.75
40 - 60 (50)	15.75
60 - 80 (70)	6.40
80 - 100 (90)	2.75
100 - 120 (110)	1.20
120 - 140 (130)	0.30
140 - 160 (150)	0.045
> 160 (170)	0.01

Table 2. Distribution of axle loads on the test pavements Rotterdam 1 to 6.

2.3. ECT 1 to 4

Finally during May and June 1987 the Working Group D3 constructed three concrete block test pavements (numbers 1, 2 and 3) on Europe Container Terminus' (ECT's) Delta Terminal on the 'Maasvlakte' near Rotterdam. Next to these test pavements, ECT constructed another test pavement (number 4). Together these four test pavements are a special by-pass on the connecting road between the seaport terminal and the inner harbour terminal. Each test pavement has dimensions 25 m × 8 m.

After excavation until a depth of 1.0 m below the road surface level, the following pavement structures were built on the test pavements ECT 1 to 4:
- rectangular concrete paving blocks (with reduced top surface because of the heavy axle loads), thickness 0.08 m, in herringbone bond between concrete kerbs; the concrete blocks were laid mechanically by means of a Delta S block-laying machine
- a bedding layer of 0.05 m crushed sand
- on the pavements 2 and 3 an unbound base (grading 0/40 mm) of crushed concrete (thickness 0.15 m on pavement 2 and 0.30 m on pavement 3) and on pavement 4 a 0.30 m thick sand-cement base (140 kg cement per m^3 = 8 per cent mass; 7-days compressive strength = 3.2 N/mm^2)
- a sand sub-base, thickness 0.87 m (pavement 1), 0.72 m (pavement 2) and 0.57 m (pavements 3 and 4) respectively
- (silty-)sand subgrade; modulus of elasticity 100 - 110 N/mm^2 (pavement 1), 120 - 130 N/mm^2 (pavement 2), 140 - 150 N/mm^2 (pavement 3) and 160 - 180 N/mm^2 (pavement 4) respectively.

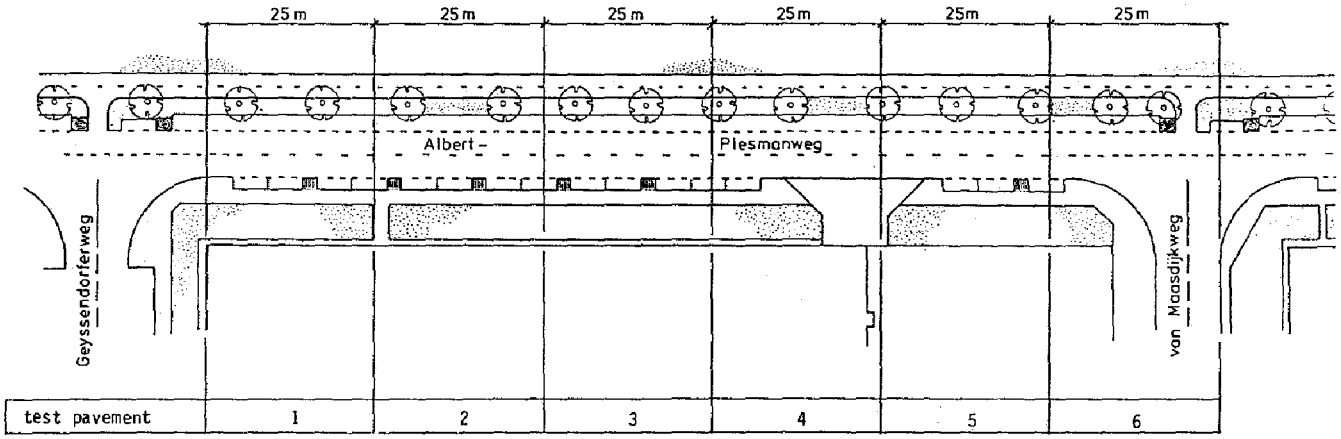


Figure 2. Plan of the test pavements Rotterdam 1 to 6.

date	axle load (kN)																				
	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250
	From seaport to inner harbour																				
10-06-87	0	8	18	26	28	64	26	44	32	24	14	12	20	10	2	0	0	0	0	0	0
25-06-87	0	84	18	26	28	64	26	62	32	24	14	46	20	10	2	0	0	0	0	0	0
02-07-87	0	84	18	26	28	64	26	62	32	24	14	46	20	10	2	0	0	0	0	0	0
07-07-87	0	142	36	26	28	64	28	64	32	24	14	46	20	10	2	0	2	0	2	4	8
22-07-87	2	324	126	26	28	64	32	74	34	26	16	84	24	10	2	2	2	2	2	4	18
11-08-87	8	418	263	38	53	134	126	154	68	72	66	150	50	70	40	42	8	4	8	6	34
03-09-87	18	466	565	42	57	178	184	204	122	106	112	200	114	122	82	70	20	16	16	12	64
24-09-87	24	480	631	44	57	188	238	254	150	136	132	206	132	134	94	96	26	20	16	14	72
01-10-87	26	490	641	44	57	190	240	260	158	144	144	212	142	154	108	106	28	30	16	18	72
11-11-87	38	804	949	48	91	314	496	438	286	278	244	420	264	332	296	196	58	82	32	54	262
	From inner harbour to seaport																				
10-06-87	24	30	8	0	14	16	2	20	64	44	134	34	36	36	10	0	0	0	0	0	0
25-06-87	30	52	8	2	16	18	6	32	70	56	160	42	48	68	24	8	2	0	0	6	10
02-07-87	30	52	8	2	20	18	6	42	78	68	172	52	68	110	40	10	4	2	2	14	58
07-07-87	30	102	8	10	20	18	8	44	78	70	186	68	72	122	40	30	8	4	14	18	84
22-07-87	32	182	8	14	24	34	14	78	98	96	210	104	88	166	64	62	36	24	22	34	182
11-08-87	34	262	122	16	60	74	48	114	156	146	286	184	204	354	154	132	100	74	80	94	550
03-09-87	36	414	150	24	134	118	94	156	214	184	358	302	306	582	246	298	158	114	126	184	1082
24-09-87	36	694	154	26	158	148	114	202	248	240	412	382	392	820	358	362	214	140	192	264	1470
01-10-87	36	698	154	30	158	150	124	222	260	246	420	418	400	842	368	374	224	152	198	336	1526
11-11-87	40	858	252	44	230	242	238	378	428	390	572	654	658	1180	564	550	318	260	318	486	2082

Table 3. Cumulative number of axle loads on the test pavements ECT 1 to 4.

The test pavements ECT 1 to 4 (opened to traffic in June 12, 1987) are subjected to very heavy 'off-the-road' multitrailer containerterminal systems. Because the traffic loading varies substantially, ECT keeps records of the traffic for both the traffic directions. The cumulative number of axle load repetitions on the test pavements ECT 1 to 4 is given in table 3 for all the measuring days until now.

3. MEASUREMENTS

3.1. Introduction

For the determination of the resilient deformation (deflections) behaviour and the permanent deformation (rutting) behaviour of the concrete block test pavements, regularly falling-weight deflection measurements and level measurements were carried out. The measuring days for the test pavements Alphen 1 and 2, Rotterdam 1 to 6 and ECT 1 to 4 are summarized in table 4.

As already mentioned in chapter 2.1, the measurements on the test pavement Alphen 1 were completed in June 1983. The measurements on the test pavements Alphen 2 and Rotterdam 1 to 6 were completed in September 1987. However, on the test pavements ECT 1 to 4 the measurements are continued.

3.2. Falling-weight deflection measurements

In a falling-weight deflection measurement a 50 kN dynamic load is applied on the pavement structure by means of a circular plate diameter 300 mm, so the contact pressure equals 0.707 N/mm^2; the loading time is 0.02 s. The deflections (d) are measured at distances of 0, 0.3, 0.5, 1.0, 1.5 and 2.0 m from the centre of the loading plate (figure 3).

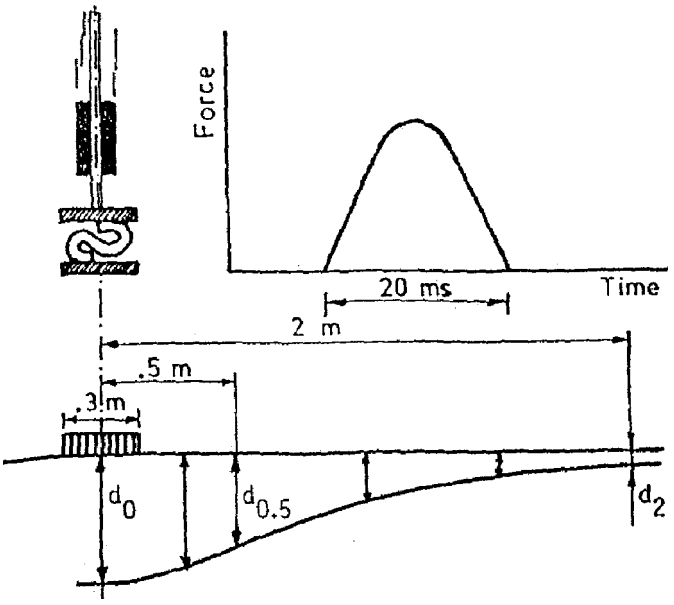


Figure 3. Outline of a falling-weight deflection measurement.

The modulus of elasticity E_0 (N/mm^2) of the subgrade is calculated by means of the formula (1):

$$\log E_0 = 3.869 - 1.009 \log d_2 \qquad (1)$$

where: d_2 = deflection (µm) at a distance of 2 m from the centre of the loading plate (50 kN load)

date	test pavement							
	A 1		A 2		R 1-6		E 1-4	
	F	L	F	L	F	L	F	L
04-10-82	x	x						
04-11-82	x	x						
09-02-83	x	x						
10-05-83		x						
30-06-83	x	x						
11-08-83			x	x				
19-09-83			x	x				
28-11-83			x	x				
07-03-84			x	x				
27-09-84			x	x				
25-10-84					x	x		
05-11-84					x			
19-11-84					x	x		
19-03-85					x	x		
04-06-85					x	x		
28-10-85			x	x				
29-10-85					x	x		
03-06-86					x	x		
21-10-86					x	x		
22-10-86			x	x				
10-06-87							x	x
18-06-87								x
25-06-87								x
02-07-87							x	
07-07-87								x
22-07-87								x
11-08-87								x
03-09-87								x
22-09-87			x	x				
24-09-87							x	
29-09-87					x	x		
01-10-87								x
11-11-87								x

1 = test pavement Alphen 1
2 = test pavement Alphen 2
1-6 = test pavements Rotterdam 1 to 6
1-4 = test pavements ECT 1 to 4
= falling-weight deflection measurements
= level measurements

Table 4. Measuring days on the test pavements.

Figure 4 shows the progress of the mean maximum deflection d_0 (in the loading centre) on the test pavements. In this figure corresponding test sections or test pavements, that are only different with respect to the concrete paving block thickness, are taken together because the block thickness had not a significant influence on the measured maximum deflection. For the test pavements ECT 1 to 4 the progress of the mean maximum deflection is given separately for each traffic direction because of the very different traffic loading (table 3).

Figure 4 shows a substantial decrease of the maximum deflection with increasing time (number of axle load repetitions) on the test pavements Alphen 2, Rotterdam 1 to 6, ECT 1 to 4 in the less heavily loaded direction (from seaport to inner harbour) and ECT 2 and 3 in the very heavily loaded direction (from inner harbour to seaport).

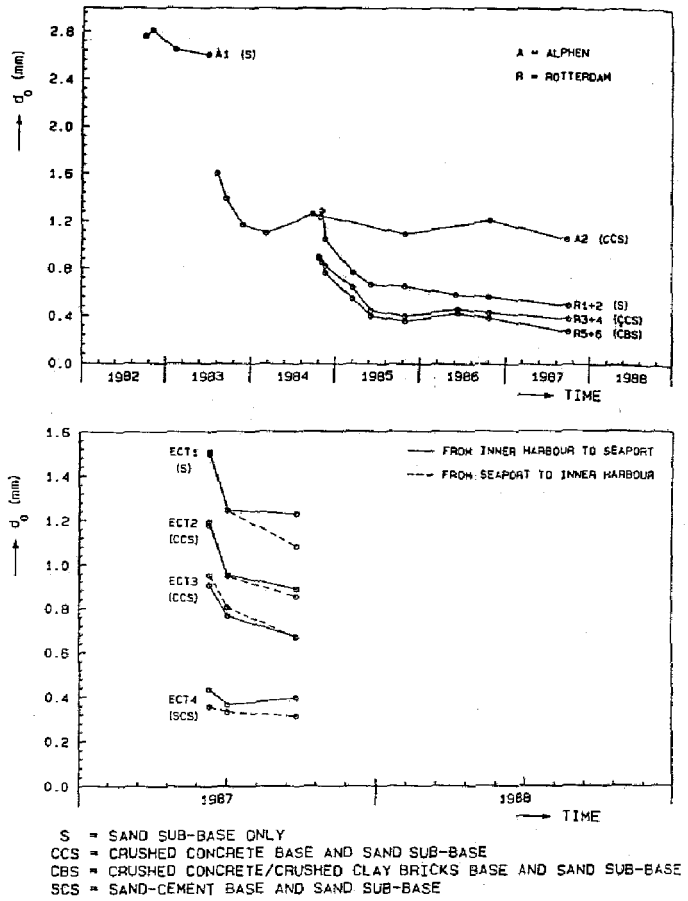


Figure 4. Progress of mean maximum deflection d_0 (due to 50 kN load) on the test pavements Alphen and Rotterdam (above) and ECT (below).

All these (lanes of) test pavements show the characteristic 'progressive stiffening' behaviour of stable concrete block pavements.
The maximum deflection on the test pavement Alphen 1 only slightly decreased with increasing time. As already stated in chapter 2.1, this test pavement (without a base) failed completely because of ongoing shear failure in the sand subbase.
In the very heavily loaded direction from inner harbour to seaport the recently constructed test pavements ECT 1 and 4 show only a slight decrease, or even increase, of the maximum deflection with increasing time. This might indicate that, because of the great number of heavy 250 kN axle loads, these lanes of the test pavements ECT 1 and 4 are going to fail: ECT 1 (with a sand subbase only) due to shear failure and ECT 4 (with a sand-cement base) due to cracking.

3.3. Level measurements (rutting)

The progress of rutting, determined on the basis of level measurements, on the test pavements is shown in figure 5. Considering the adopted design standard with respect to rutting (see chapter 5.1), in figure 5 the characteristic rut depth RD_C (30 per cent probability of exceeding), below a 1.20 m long rule, is given.
Similar to figure 4, in figure 5 corresponding test sections or test pavements again are taken together, because the concrete paving block

thickness also had not a significant influence in the test pavements' rutting behaviour.

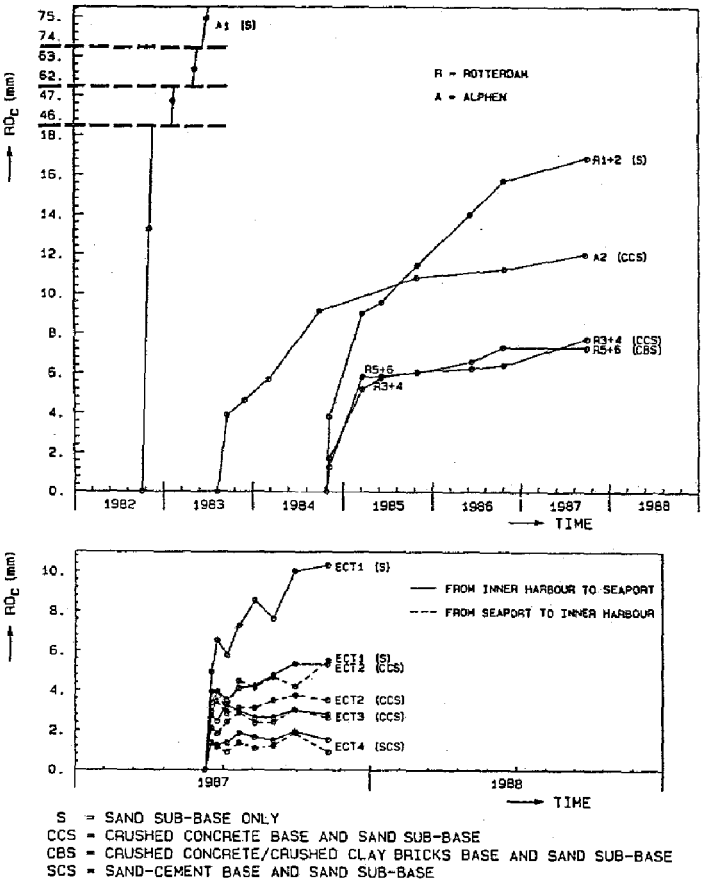


Figure 5. Progress of characteristic rut depth RD_c (30 per cent probability of exceeding) on the test pavements Alphen and Rotterdam (above) and ECT (below).

A comparison of the rutting behaviour of the test pavements Alphen 1 and 2 clearly shows the very beneficial effect of a 0.25 m crushed concrete unbound base on a weak subgrade. This base not only prevented the test pavement Alphen 2 from instability (shear failure), but also it keeps the rut depth within reasonable limits, in spite of the very weak peat subgrade.
The rutting behaviour of the test pavements Rotterdam 3 + 4 (0.30 m crushed concrete) and Rotterdam 5 + 6 (0.30 m mixture of crushed concrete and crushed clay bricks) more or less is the same.
The rutting behaviour of the test pavements Rotterdam 1 + 2 (with a sand sub-base only) is substantially worse, although no shear failure occurred (because of the greater bearing capacity of the clay/sand subgrade, compared with the peat subgrade in Alphen).
With respect to the recently constructed test pavements ECT 1 to 4, the level measurements indicate that the rut depth increases with decreasing bearing capacity of the test pavement structure and with increasing traffic loading (considering both traffic directions, table 3). The possible failure, as indicated by the falling-weight deflection measurements (see chapter 3.2), of the pavements ECT 1 (shear failure) and ECT 4 (cracking) in the most heavily loaded direction (from inner harbour to seaport) has not been confirmed until now by means of the rut depth measurements.

With the exception of the completely failed test pavement Alphen 1 and the recently constructed test pavements ECT 1 to 4, the progress of rutting on the test pavements is described by means of the equation:

$$RD_c = a_p \cdot N^{b_p} \qquad (2)$$

where: RD_c = characteristic rut depth (mm), 30 per cent probability of exceeding
N = cumulative number of equivalent 80 kN standard axle loads per lane, making allowance for the lateral load distribution (reduction factor 1.0 and 0.5 for the test pavements Alphen 2 and Rotterdam respectively)
a_p, b_p = rutting coefficients with respect to the total pavement structure

The cumulative number of equivalent 80 kN standard axle loads N is obtained by addition of the relative damage, done to the pavement structure by each axle load repetition. The most widely used model for this relative pavement damage is the AASHTO-type load equivalency factor l_e according to:

$$l_e = \left(\frac{L}{L_{st}}\right)^m \qquad (3)$$

where: L = axle load (kN)
L_{st} = standard axle load (= 80 kN)
m = load equivalency coefficient

From equation 2 it follows for the load equivalency coefficient m (with respect to rutting), for concrete block pavements:

$$m = \frac{1}{b_p} \qquad (4)$$

where: b_p = rutting coefficient (see equation 2)

For the test pavements Alphen 2 and Rotterdam 1 to 6 the rutting coefficients a_p and b_p and the load equivalency coefficient m were calculated on the basis of:
- the measured characteristic rut depth (figure 5)
- the measured or estimated number of load repetitions and the distribution of axle loads (chapter 2, especially the tables 1 and 2)
- the equations 2, 3 and 4.

The result is given in table 5.

Table 5 makes it very clear that the rutting behaviour (i.e. the rutting coefficients a_p and b_p) of concrete block pavements is highly dependent on the total pavement structure, or more specific:
- the modulus of elasticity (bearing capacity) of the subgrade
- the thickness of the sand sub-base
- both the base thickness and the base material
- the total pavement thickness.

It appears further from table 5: the greater the bearing capacity of the total pavement structure, the greater the rutting-related load equivalency coefficient m of concrete block pavements.

test pavement	a_p	b_p	m
test pavement Alphen 2			
0.45 m sand sub-base + 0.25 m crushed concrete base + 0.05 m crushed sand bedding layer	1.379	0.211	4.7
test pavements Rotterdam			
1+2: 0.90 m sand sub-base + 0.05 m crushed sand bedding layer	0.133	0.381	2.6
3+4: 0.60 m sand sub-base + 0.30 m crushed concrete base + 0.05 m crushed sand bedding layer	0.930	0.162	6.2
5+6: 0.58 m sand sub-base + 0.30 m crushed concrete/crushed clay bricks base + 0.05 m crushed sand bedding layer	0.666	0.190	5.3

Table 5. Rutting coefficients a_p and b_p and load equivalency coefficient m for the test pavements Alphen 2 and Rotterdam 1 to 6.

4. ANALYSIS OF TEST RESULTS

4.1. Resilient deformation behaviour (deflections)

The measured resilient deformation behaviour (deflection curves) of the test pavements Alphen 1 and 2, Rotterdam 1 to 6 and ECT 1 to 4 was analyzed by means of the two-dimensional finite element program ICES STRUDL 'rigid bodies', as already reported at the Second International Conference on Concrete Block Paving (1,2,3,4).
In the two-dimensional finite element representation the concrete block layer is modelled as a pure shear layer: the concrete paving blocks, represented as indeformable 'rigid body' elements that are interconnected by means of linear vertical springs with stiffness k, only can move in the vertical direction (figure 6). Considering herringbone bond and the measured block dimensions, the width of the paving blocks was taken as 0.1494 m (block thickness 0.08 m and 0.09 m) and 0.1529 m (block thickness 0.12 m) respectively, including a joint width of 2 mm and 3 mm respectively.
The 'rigid body' elements are supported by linear vertical springs with stiffness k', that represent the connection of the concrete blocks to the underlying bedding layer.

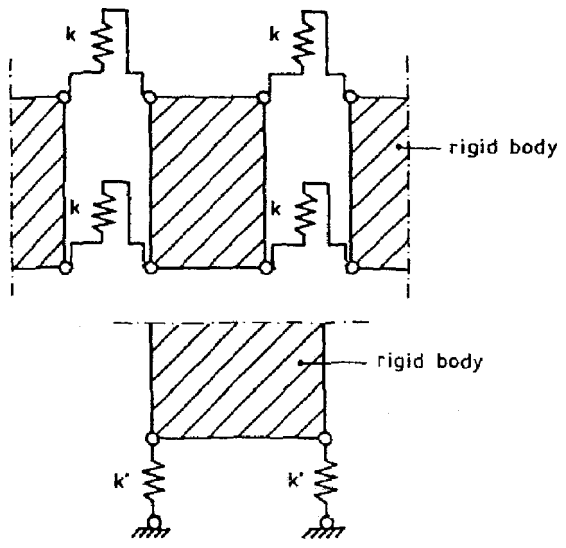


Figure 6. Model concept for the blocks and the joints (above) and the block support (below) in the ICES STRUDL calculations.

The layers below the concrete paving blocks, i.e. the bedding layer, the (un)bound base (if any), the sand sub-base and the subgrade, are schematized to a system of continuous elements, characterized by the modulus of elasticity and Poisson's ratio.

The modulus of elasticity of the subgrade E_o (N/mm^2) was calculated from equation 1.

The modulus of elasticity E_i (N/mm^2) of the sand sub-base and the unbound base was calculated from the following empirical equation (5):

$$E_i = l \cdot E_{i+1} \quad \text{with } l = 0.206\, h_i^{0.45} \quad (2 \leq l \leq 4) \qquad (5)$$

where: h_i = 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 and the crushed concrete/crushed clay bricks unbound base-material was taken as 150 N/mm^2 and 250 N/mm^2 respectively. No maximum value was set for the crushed concrete base-material.

The modulus of elasticity of the bound sand-cement base of test pavement ECT 4 was taken as 4000 N/mm^2.

The modulus of elasticity of the crushed bedding sand was arbitrary taken as 1.5 times the modulus of elasticity of the sand sub-base.

Poisson's ratio was taken as:
- 0.45 for the peat subgrade of the test pavements Alphen 1 and 2
- 0.35 for the clay/sand subgrade of the test pavements Rotterdam 1 to 6 and for the (silty-) sand subgrade of the test pavements ECT 1 to 4 as well as for all sub-base, unbound base and bedding layers
- 0.20 for the bound sand-cement base of test pavement ECT 4.

Based on the results of preliminary calculations with the linear-elastic multilayer computerprogram BISAR (6), the non-deformable base of the

finite element model was taken at a depth of 10 m below the pavement surface; at this depth the vertical displacements are reduced to only a few per cent of the maximum deflection of the road surface in the centre of the load (figure 7). The width of the finite element model is 2 m on the top and 10 m at the bottom because of the load spreading within the pavement structure. The thickness of the finite element model is taken as 1 mm.

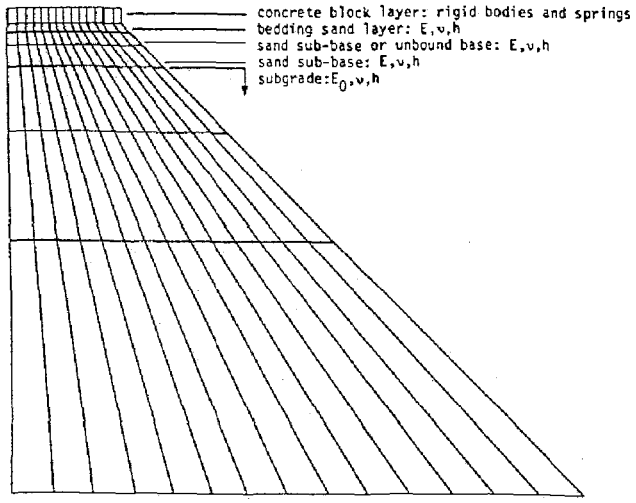


Figure 7. Schematic representation of the distribution of elements in the ICES STRUDL finite element calculations.

The two-dimensional finite element model is 'loaded' by a displacement equal to the measured maximum deflection d_0 in the centre of the load.

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 structure. It was therefore attempted to calculate by means of the ICES STRUDL finite element program the following three parameters of each deflection curve as accurately as possible:

$SCI_0 = d_0 - d_{0.3}$

$SCI_1 = d_0 - d_{0.5}$

Σd_x where x = 0, 0.3, 0.5, 1.0, 1.5 and 2.0 m (see also figure 3)

142 mean deflection curves, measured on the test pavements Alphen 1 and 2, Rotterdam 1 to 6 and ECT 1 to 4, were fully analyzed and in 73 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 progress of the spring stiffnesses k and k', found for the test pavements' wheel track by means of trial and error, is shown in the figures 8 and 9 respectively.

From figure 8 it appears that the joint stiffness k (the load transfer from the loaded block to adjacent blocks) substantially increases with time

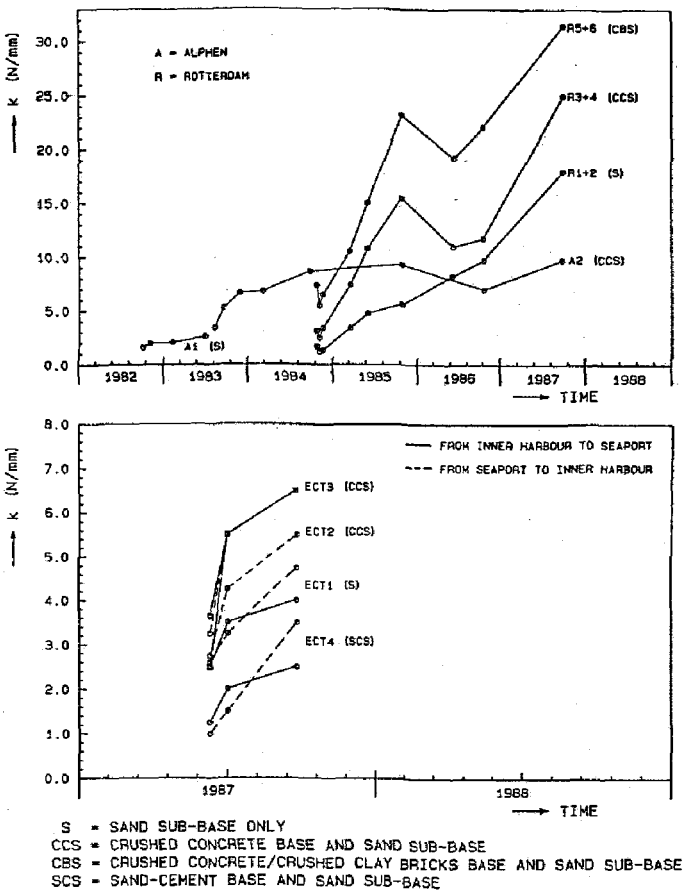


Figure 8. Progress of mean joint stiffness k on the test pavements Alphen and Rotterdam (above) and ECT (below).

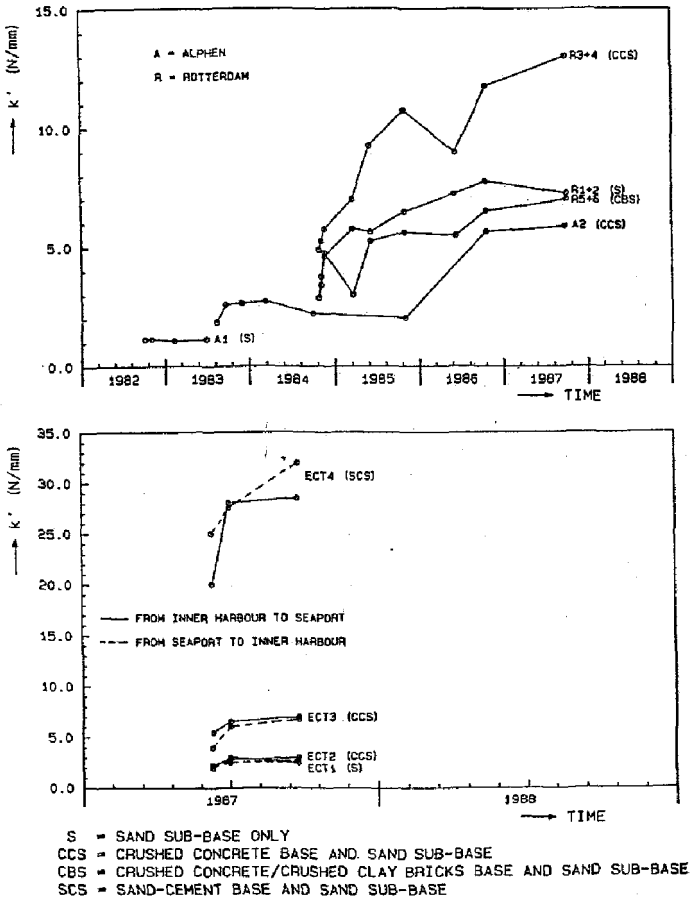


Figure 9. Progress of mean support stiffness k' on the test pavements Alphen and Rotterdam (above) and ECT (below).

(number of load repetitions) on the test pavements Alphen 2, Rotterdam 1 to 6 and ECT 1 to 4. In the totally failed test pavement Alphen 1 only a slight increase of k can be observed. the initial decrease of k on the pavements Rotterdam 1 to 6 most probably is caused by the rather bad mechanical laying of the paving blocks; the manual paved test pavements Alphen 1 and 2 as well as the good mechanical paved test pavements ECT 1 to 4 do not show this phenomenon.

In figure 9 it can be observed that the support stiffness k' (slightly) increases with time on the test pavements Alphen 2, Rotterdam 1 to 6, ECT 1 to 4 in the less heavily loaded direction (from seaport to inner harbour) and ECT 2 and 3 in the most heavily loaded direction (from inner harbour to seaport).
In the test pavement Alphen 1 (shear failure within the sand sub-base) k' remains more or less constant.
In the test pavements ECT 1 and 4 in the most heavily loaded direction, k' increases in the first instance but later on k' tends to remain constant or even decrease. This preliminary result confirms the possible failure of the most heavily loaded lane of the pavements ECT 1 and 4 (see chapter 3.2).

From the figures 8 and 9 it appears that on concrete block pavements with unbound materials only, both the joint stiffness k and the support stiffness k' tend to increase with increasing total bearing capacity of the test pavements' substructure (= bedding layer + unbound base (if any) + sand sub-base + subgrade).
The high modulus of elasticity (bearing capacity) of the bound sand-cement base of the test pavement ECT 4 yields a very high support stiffness k', but a rather low joint stiffness k due to the very small relative displacements of the paving blocks.

It can be concluded that the two-dimensional ICES STRUDL finite element calculations confirm the 'progressive stiffening' behaviour of the Working Group's test pavements, with the exception of the completely failed test pavement Alphen 1 and possibly the test pavements ECT 1 and 4 in the very heavily loaded direction from inner harbour to seaport.

It is a clear disadvantage of the two-dimensional finite element representation of the figures 6 and 7 that the supporting springs k' 'absorb' a great part of the load. Only the calculated deflections at the pavement surface and those within the subgrade are reliable. Therefore, for each measured (mean) deflection curve the deflections within the bedding layer, the base (if any) and the sub-base were calculated on the basis of the finite element calculations by means of Ivanov's equivalency theory (7) (see chapter 4.2).

4.2. Permanent deformation behaviour (rutting)

As already mentioned, the test pavements Alphen 1 and Rotterdam 1 to 6 clearly show the characteristic 'progressive stiffening' behaviour of concrete block pavements. Therefore the Working Group adopted the 'progressive stiffening' theory (2,4), developed by the Delft University of Technology, for the analysis of the test pavements' permanent deformation behaviour. Until now the rutting behaviour of the recently constructed test pavements ECT 1 to 4 is not yet analyzed in this way.
The 'progressive stiffening' theory is not applicable to the test pavement Alphen 1 because of the shear failure within this pavement structure.

The basic equation of the 'progressive stiffening' theory is (figure 10):

$$\frac{d(\Delta h_p)}{dN} = f_1 \cdot \frac{df_2}{dN} \qquad (6)$$

where: Δh_p = permanent deformation in a layer of unbound material
f_1 = elastic compression of the layer (= the deflection at the top of the layer minus the deflection at the bottom of the layer) due to an equivalent 40 kN standard wheel load (80 kN standard axle load)
f_2 = permanent deformation relationship of the unbound material

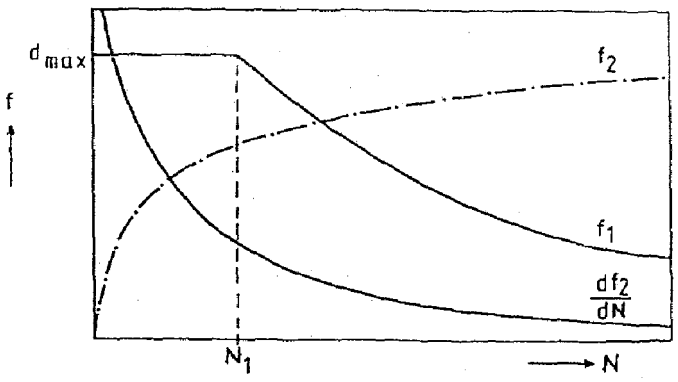


Figure 10. Schematical representation of permanent deformation functions.

For a granular material the 'compaction' relation f_2 is:

$$f_2 = a_m \cdot N^{b_m} \qquad (7)$$

where: N = number of equivalent 80 kN standard axle load repetitions per lane (in the wheel track)
a_m, b_m = permanent deformation coefficients of the granular material

The elastic compression f_1 of a granular layer can be described as:

$$\text{if } N \leq N_1: \; f_1 = d_{max} = \text{constant} \qquad (8a)$$

$$\text{if } N > N_1: \; f_1 = p + q \cdot e^{-\log N} \qquad (8b)$$

where: N_1 = initial number of equivalent 80 kN standard axle load repetitions per

lane (in the wheel track) until 'progressive stiffening' occurs

d_{max}, $_{p,q}$ = elastic deformation coefficients of the granular layer

permanent deformation Δh_p in a layer of grar material in a concrete block pavement is ained by combining the equations 6, 7 and 8:

$$N \leq N_1: \Delta h_p = d_{max} \cdot a_m \cdot N^{b_m} \quad (9a)$$

$$N > N_1: \Delta h_p = d_{max} \cdot a_m \cdot N_1^{b_m} + \quad (9b)$$

$$a_m \cdot p \cdot (N^{b_m} - N_1^{b_m}) +$$

$$\frac{a_m \cdot b_m \cdot q}{b_m - 0.4343} \cdot (N^{b_m - 0.4343} - N_1^{b_m - 0.4343})$$

The 'progressive stiffening' coefficients N_1, d_{max}, p, q, a_m and b_m for the various granular layers of the test pavements Alphen 2 and Rotterdam 1 to 6 were calculated by means of the equations 8 and 9 on the basis of:

- the estimated number of equivalent 80 kN standard axle load repetitions on the various days of rutting measurements (see chapter 3.3 and the tables 1 and 2)
- the measured characteristic rut depth (figure 5)
- the progress of the elastic compression in the bedding layer, the unbound base (if any) and the sub-base, calculated by means of Ivanov's equivalency theory on the basis of the two-dimensional ICES STRUDL finite element calculations (see chapter 4.1)
- the assumption that no permanent deformation occurred within the subgrade.

The result of the calculations is given in table

Starting with the test pavement Rotterdam 1 + 2, for the sand sub-base a b_m-value of 0.53 was found; this value was also taken for the sand sub-base in the other test pavements.
For the crushed concrete base (including 0.05 m crushed sand bedding layer) of the test pavements Rotterdam 3 + 4 a b_m-value of 0.21 was calculated; this value was also taken for the crushed concrete base of the test pavement Alphen 2.
For the crushed concrete/crushed clay bricks base (including 0.05 m crushed sand bedding layer) of the test pavements Rotterdam 5 + 6 a b_m-value of 0.285 was found.
As concerns the coefficient a_m, its value is not only dependent on the material (the lower b_m, the higher a_m) but also on the total pavement structure (similar to the rutting coefficients a_p and b_p, see chapter 3.3).

5. THE DUTCH DESIGN METHOD FOR CONCRETE BLOCK ROAD PAVEMENTS

5.1. Design criterion and standard

The design criterion for concrete block pavements with solely unbound materials is rutting.
With respect to the degree of rutting (rut depth under a 1.20 m long rule) and the extent of rutting (percentage of the area affected) on concrete block pavements, the Working Group R1 'Pavement Management' of The Netherlands Centre for Research and Contract Standardization in Civil and Traffic Engineering distinguishes five classes, that are briefly described in table 7 (8,9). The minimum rutting of class 5 is taken as the rutting standard.

Working Group D3 has adopted the description of the degree and the extent of rutting according to table 7 and the rutting standard.
From the Working Group's rutting measurements it appeared that on all test pavements rutting class 5a is reached earlier than rutting class 5b. Therefore rutting is described as the characteristic rut depth RD_C (30 per cent probability of exceeding) under a 1.20 m long rule (see chapter 3.3), while the rut depth standard $\overline{RD}_C$ is taken as 15 mm.

test pavement	layer	N_1	d_{max} (mm)	p (mm)	q (mm)	a_m	b_m
Alphen 2	0.05 m crushed sand bedding layer + 0.25 m crushed concrete base	314	0.492	0.283	2.533	2.786	0.210
	0.45 m sand sub-base	314	0.277	0.184	1.134	0.043	0.530
Rotterdam 1 + 2	0.05 m crushed sand bedding layer + 0.90 m sand sub-base	3,438	0.777	0.262	17.669	0.045	0.530
Rotterdam 3 + 4	0.05 m crushed sand bedding layer + 0.30 m crushed concrete base	19,047	0.285	0.034	18.125	1.700	0.210
	0.60 m sand sub-base	19,047	0.204	0.083	8.739	0.012	0.530
Rotterdam 5 + 6	0.05 m crushed sand bedding layer + 0.30 m crushed concrete/crushed clay bricks base	5,022	0.338	0.079	10.488	0.749	0.285
	0.58 m sand sub-base	5,022	0.187	0.079	4.366	0.011	0.530

Table 6. Elastic and permanent 'progressive stiffening' coefficients (with respect to the characteristic rut depth RD_C, 30 per cent probability of exceeding) of the various granular layers of the test pavements Alphen 2 and Rotterdam 1 to 6 for equivalent 80 kN standard axle loads.

class		rutting degree (mm)	rutting extent (%)
1 = good:	1a	-	-
	1b	5 - 15	< 1
2 = fair:		5 - 15	1 - 15
3 = moderate:	3a	5 - 15	16 - 30
	3b	15 - 30	< 15
4 = poor:	4a	5 - 15	> 30
	4b	15 - 30	16 - 30
5 = very poor:	5a	15 - 30	> 30
	5b	> 30	> 1

Table 7. Classes of rutting on concrete block pavements.

5.2. Rutting calculations

With the objective to deduct design charts for concrete block pavements, subjected to normal road traffic, a number of rutting calculations was carried out. These calculations were done for the following 84 concrete block pavement structures:
- rectangular concrete paving blocks, thickness (at least) 0.08 m, in herringbone bond
- 0.05 m crushed sand bedding layer
- unbound base (thickness 0, 0.1, 0.2 or 0.3 m) of crushed concrete or a mixture of (65 per cent mass) crushed concrete and (35 per cent mass) crushed clay bricks
- sand sub-base
- subgrade, modulus of elasticity 40, 60, 100 or 140 N/mm^2.

The total thickness of base and sub-base was taken as 0.7, 1.1 and 1.5 m.

The permanent deformation (rutting) calculations were carried out according to the 'progressive stiffening' theory, described in chapter 4.2 (equation 9). After a critical review of the test pavements' resilient and permanent deformation behaviour (table 6), the values of table 8 sive stiffening' coefficients a_m and b_m.

As can be observed in table 8, with respect to the coefficient a_m a 'compaction factor' CF was introduced because of the impossibility of a good initial compaction (during construction) of a thin sand sub-base, and in a less extent of the unbound base (if any), on a poor subgrade. Table 9 summarizes the estimated CF-values.

The initial number of equivalent 80 kN standard axle load repetitions before 'progressive stiffening' occurs (N_1, see figure 10 and equation 8) was more or less arbitrary taken as:

$$N_1 = 5700\ (2.7544 - CF) \qquad (10)$$

For each of the 84 pavement structures the progress of the elastic compression (i.e. the 'progressive stiffening' coefficients d_{max}, p and q) was determined by means of calculations according to Ivanov's equivalency theory (see chapter 4.2).

First, for different numbers of equivalent 80 kN standard axle load repetitions the permanent deformation Δh_p of each layer (sub-base and unbound base, if any) of all 84 distinguished pavement structures was calculated by means of equation 9. Next, the rutting was found by addition of the permanent deformation of the subsequent unbound layers of the pavement structure.
Finally, for all 84 pavement structures the progress of rutting was described by a formula according to equation 2. From this equation it follows for the life $\bar{N}$ of the concrete block pavement:

$$\bar{N} = \left(\frac{\overline{RD}_c}{a_p}\right)^{\frac{1}{b_p}} \qquad (11)$$

where: $\bar{N}$ = acceptable number of equivalent 80 kN standard axle load repetitions per lane in the wheel track (making allowance for the lateral load distribution)

layer		a_m	b_m
sand sub-base (+ 0.05 m crushed sand bedding layer)		0.058 CF d^*_{max}	0.530
0.05 m crushed sand bedding layer + x m crushed concrete base:	x = 0.1	1.00 (0.467 CF + 0.533)	0.210
	x = 0.2	1.40 (0.467 CF + 0.533)	0.210
	x = 0.3	1.70 (0.467 CF + 0.533)	0.210
0.05 m crushed sand bedding layer + x m crushed concrete/crushed clay bricks base:	x = 0.1	0.44 (0.467 CF + 0.533)	0.285
	x = 0.2	0.62 (0.467 CF + 0.533)	0.285
	x = 0.3	0.75 (0.467 CF + 0.533)	0.285

* d_{max} = maximum elastic compression (mm) of the sand sub-base, due to an equivalent 40 kN standard wheel load, before 'progressive stiffening' occurs, so if $N < N_1$ (see figure 10 and equation 8)

Table 8. Values of the 'progressive stiffening' coefficients a_m and b_m in the rutting calculations.

grade modulus E_o (N/mm²) \ base (m)	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	≥ 1.2
40	2.10	1.90	1.70	1.525	1.35	1.20	1.10	1.02	1.00
60	1.225	1.14	1.09	1.04	1.00	1.00	1.00	1.00	1.00
≥ 100	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 9. Compaction factor CF as a function of the sand sub-base thickness and the subgrade modulus of elasticity.

$\overline{RD}_c$ = characteristic rut depth (30 per cent probability of exceeding) standard: $\overline{RD}_c$ = 15 mm (see chapter 5.1)

a_p, b_p = rutting coefficients with respect to the total pavement structure

The $\overline{N}$-values, calculated in this way, are the basis for the design charts described in the next chapter.

5.3. Design charts

5.3.1. Pavements with a sand sub-base only

Figure 11 shows the design chart for concrete block pavements with a sand sub-base only. In order to cover (almost) all Dutch subgrades, the modulus of elasticity of the subgrade (E_o) ranges from 30 N/mm² (peat) to 140 N/mm² (sand).
As can be observed in figure 11, the pavement life mainly depends on the subgrade modulus E_o and, in case of a low E_o-value, also on the sand sub-base thickness.

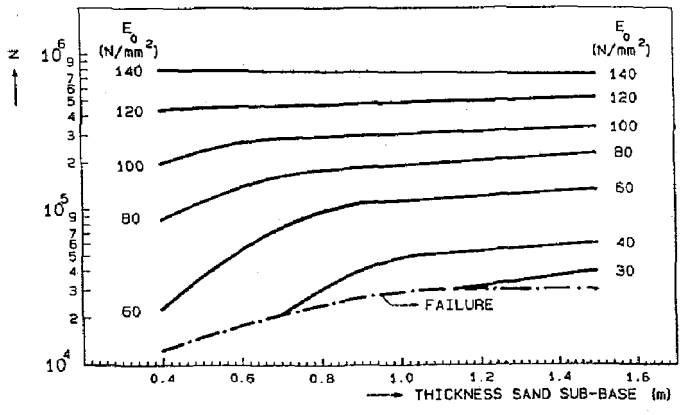


Figure 11. Design chart for concrete block road pavements, consisting of rectangular concrete paving blocks (thickness ≥ 0.08 m) in herringbone bond, 0.05 m crushed sand bedding layer and a sand sub-base.

The load equivalency coefficient m (equations 3 and 4) of concrete block pavements with solely a sand sub-base appeared to be:

$$m = 1.87 + 183\ E_o^{-1.5} \qquad (12)$$

where: E_o = modulus of elasticity (N/mm²) of the subgrade, according to equation 1

Based on the behaviour of the Working Group's test pavement Alphen 1 and observations on other in service concrete block pavements (2), it was deducted that a concrete block pavement with solely a sand sub-base has to fulfil the following equation to prevent shear failure under normal road traffic:

$$E_o \cdot (h_{sand})^{0.6} \geq 33 \qquad (13)$$

where: E_o = modulus of elasticity (N/mm²) of the subgrade, according to equation 1

h_{sand} = sand sub-base thickness (m)

This failure curve is drawn in figure 11.

5.3.2. Pavements with an unbound base and a sand sub-base

Five design charts were developed for concrete block pavements with an unbound base and a sand sub-base, for subgrade moduli of 30, 40, 60, 100 and 140 N/mm² (again in order to cover (almost) all Dutch subgrade conditions). Each design chart applies to both a crushed concrete base material and a crushed concrete/crushed clay bricks base material. Two design charts are shown in figure 12.
As can be observed in figure 12, in the case of a high E_o-value (for example 140 N/mm²) the pavement life depends on the base material and the base thickness, and in the case of a low E_o-value (for example 40 N/mm²) also on the sand sub-base thickness.

The load equivalency coefficient m appeared to be dependent on the base material and the base thickness, the sand sub-base thickness and the subgrade modulus.
For a certain subgrade modulus E_o the maximum m-value was found in the case of a thick base (0.3 m) on a thin sub-base (0.4 m) and the minimum m-value in the case of a thin base (0.1 m) on a thick sub-base (1.5 m).

For concrete block pavements with a crushed concrete base were calculated:

maximum m-value: $m = 3.81 + 242\ E_o^{-1.5}$ (14a)

mean m-value: $m = 2.97 + 95\ E_o^{-1.5}$ (14b)

minimum m-value: $m = 2.30 + 70\ E_o^{-1.5}$ (14c)

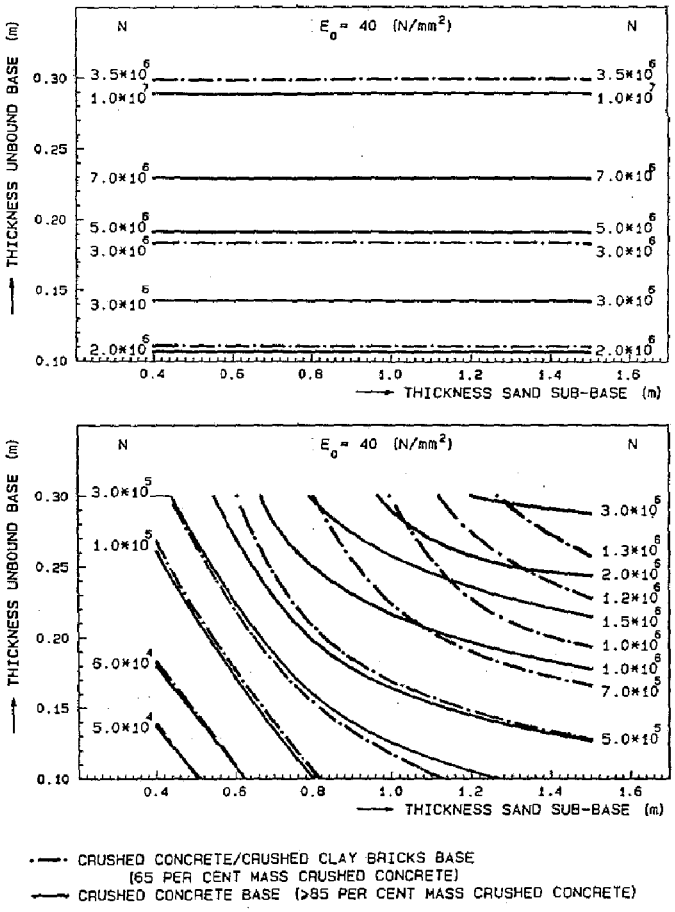


Figure 12. Design charts for concrete block road pavements, consisting of rectangular concrete paving blocks (thickness ≥ 0.08 m) in herringbone bond, 0.05 m crushed sand bedding layer, an unbound base and a sand sub-base.

For concrete block pavements with a crushed concrete/crushed clay bricks base were calculated:

maximum m-value: $m = 3.33 + 177\ E_o^{-1.5}$ (15a)

mean m-value: $m = 2.72 + 95\ E_o^{-1.5}$ (15b)

minimum m-value: $m = 2.30 + 70\ E_o^{-1.5}$ (15c)

It is assumed that under normal road traffic sh failure of a concrete block pavement with an ur bound base is most unlikely.

5.4. Design examples

In order to illustrate the design method, prese ed in the previous chapter, table 10 gives some design examples for two traffic loadings:

- case 1: residential street:
  total number of axle load repetitions per lan in the wheel track during design life: 2.10^6; axle load distribution: 5 kN: 85%, 10 kN: 5%, 40 kN: 5%, 50 kN: 5%
- case 2: industrial road:
  total number of axle load repetitions per lan in the wheel track during design life: 15.10^6 axle load distribution: 5 kN: 50%, 10 kN: 10% 30 kN: 15%, 50 kN: 15%, 70 kN: 6%, 90 kN: 2.5 110 kN: 1.2%, 130 kN: 0.3%.

It is assumed in the design examples of table 1(that (e.g. for reason of minimization of construction costs) the total thickness of unbound base and sand sub-base has to be minimum.

6. CONCLUDING REMARKS

The design method, developed by Working Group D3 applies to concrete block pavements with unbound sub-base and base materials, which nowadays are

subgrade modulus of elasticity E_o (N/mm²)	40						140					
traffic	case 1			case 2			case 1			case 2		
pavement structure[1)]	S	CCS	CBS	S*	CCS	CBS*	S	CCS	CBS	S*	CCS	CBS
load equivalency coefficient m (equation 12, 14b and 15b resp.)	2.6	3.3	3.1	2.6	3.3	3.1	2.0	3.0	2.8	2.0	3.0	2.8
total number (N) of equivalent 80 kN standard axle load repetitions per lane in the wheel track during design life ($.10^6$)	0.048	0.032	0.035	2.57	2.44	2.46	0.072	0.038	0.042	2.87	2.47	2.51
concrete paving block thickness (m): minimum	0.08	0.08	0.08	-	0.08	-	0.08	0.08	0.08	-	0.08	0.08
crushed sand bedding layer (m)	0.05	0.05	0.05	-	0.05	-	0.05	0.05	0.05	-	0.05	0.05
crushed concrete base (m)	-	0.10	-	-	0.30	-	-	0.10**	-	-	0.13	-
crushed concrete/ crushed clay bricks base (m)	-	-	0.10	-	-	-	-	-	0.10**	-	-	0.15
sand sub-base (m)	0.90	0.40	0.40	-	1.10	-	0.00	0.00	0.00	-	0.00	0.00

S = sand sub-base only
CCS = crushed concrete base and sand sub-base
CBS = crushed concrete/crushed clay bricks base and sand sub-base

pavement structure impossible for the present combination of traffic loading N and subgrade modulus E_o
overdesigned because a base and a sub-base are not necessary, as concerns the bearing capacity of the concrete block pavement structure

Table 10. Some design examples for concrete block road pavements.

mostly recycled materials, consisiting of crushed concrete and mixtures of crushed concrete and crushed clay bricks. However, the design approach is applicable in general.

The design method is a rather simple one, that allows the design and comparison of alternative concrete block pavement structures for the present traffic and subgrade conditions.

The Working Group D3 is about to end the research activities into concrete block pavements. The final report will be published during 1988.

7. ACKNOWLEDGEMENTS

Working Group D3 is indebted to Bos Beton B.V., Alphen-on-Rhine (mr. J.A. Kemmeren), the Public Works Department of the Municipality of Rotterdam (mr. W.J. van der Ende) and Europe Container Terminus B.V., Rotterdam (mr. H. van Leeuwen and mr. J.G. van Hees) for the very willing co-operation received in the construction and investigation of the test pavements.
Furthermore, the Working Group is indebted to mr. A.M.A.M. van Pelt and mr. M.M.J. Jacobs, who carried out the calculations with the finite element program ICES STRUDL.

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