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FIRST VERIFICATION OF THE DUTCH DESIGN METHOD FOR CONCRETE BLOCK ROAD PAVEMENTS

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SUMMARY

In 1988 the Working Group D3 has published the Dutch design method for concrete block road pavements. The design method is based on the analysis of falling-weight deflection measurements and rutting measurements on two test pavements in Alphen-on-Rhine (peat subgrade) and six test pavements in Rotterdam (clay/sand subgrade).
After 1988 the measurements were continued on the test pavements in Rotterdam and on five test pavements (constructed in the middle of 1987) at ECT's Delta Terminal (sand subgrade) until April 1991. The paper briefly describes the pavement structure and the traffic loading of the test pavements as well as the 1988 design method. Then a comparison is made between the results of the continued rutting measurements and the design rutting calculations which are the basis of the design method. From this comparison it is concluded that the design method tends to be conservative, especially for relative strong concrete block pavement structures.

1. INTRODUCTION

At the Third International Conference on Concrete Block Paving (Rome, 1988) 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) has presented the Dutch design method for concrete block road pavements (1). The method consists of six design charts which are the result of 'progressive stiffening' rutting calculations on the basis of an analysis of falling-weight deflection measurements and rutting measurements on two test pavements in Alphen-on-Rhine (peat subgrade) and six test pavements in Rotterdam (clay/sand subgrade).
The measurements on the test pavements in Rotterdam and on five test pavements (constructed in the middle of 1987) at ECT's Delta Terminal (sand subgrade) were continued after 1988 to serve as a first verification of the design method.

In chapter 2 the pavement structure and the traffic loading of the Working Group's 13 test pavements are shortly described. Next in Chapter 3 the Dutch design method for concrete block road pavements is briefly described. Finally in chapter 4 a comparison is made between the test pavements' life according to the continued rutting measurements (until April 1991) and those according to the design method (published in 1988).

2. TEST PAVEMENT STRUCTURES AND TRAFFIC LOADINGS

The Working Group D3 has realized concrete block test pavements in Alphen-on-Rhine (peat subgrade), in Rotterdam (sand/clay subgrade) and at ECT's Delta Terminal at the 'Maasvlakte' (sand subgrade) near Rotterdam (1,2).

The first test pavement (A1) in Alphen-on-Rhine was constructed on the work site of a precast concrete plant in the beginning of October 1982. This test pavement only had a sand sub-base. Because of extensive rutting due to ongoing shear failure the test pavement A1 only was in use until July 1, 1983 and was then excavated. Mid-July 1983 at the same location a second test pavement (A2) was constructed, which has a 250 mm crushed concrete base and a sand sub-base (table 1). In the middle of 1991 the test pavement A2 still was in use.
The cumulative number of repetitions of the several axle loading groups at the various measuring days was known until June 6, 1984 from traffic records at the work's gate. The mean annual traffic loading calculated from these records (table 1) was used for the period after June 1984.

In October 1984 six concrete block test pavements (R1 to R6) were realized on the heavily trafficked Albert Plesmanweg in Rotterdam. The test pavements R1 and R2 only have a sand sub-base, the test pavements R3 and R4 have a 300 mm crushed concrete base and a sand sub-base, and the test pavements R5 and R6 have a 300 mm crushed concrete/crushed clay bricks base and a sand sub-base (table 1). Also the test pavements R1 to R6 still were in use in the middle of 1991.
From axle load measurements during some weeks in 1984 and 1985 the mean annual traffic loading, mentioned in table 1, was found. This mean annual traffic loading was used to calculate the cumulative number of repetitions of the several axle loading groups at the various measuring days.

Finally during May and June 1987 four concrete block test pavements (E1 to E4) were constructed at ECT's Delta Terminal. Together these four test pavements are a special by-pass on the connecting road between the seaport terminal and the inner harbour terminal. The test pavement E1 only had a sand sub-base, the test pavements E2 and E3 had a crushed concrete base (thickness 150 mm and 300 mm respectively) and a sand sub-base, while test pavement E4 had a 300 mm sand-cement base and a sand sub-base (table 1). During January and February 1989 the test pavement E1 was reconstructed (due to an unacceptable longitudinal unevenness at the boundary between the test pavements E1 and E2) to test pavement E1*, which had a 300 mm crushed concrete/crushed clay bricks base and a sand sub-base. Since March 1991 the test pavements E1*, E2, E3 and E4 no more are in use because of modified traffic operations at the Delta Terminal.
The test pavements E1, E1*, E2, E3 and E4 were very heavily trafficked by off-the-road multi-trailer systems, with axle loadings up to 250 kN. Until January 3, 1989 ECT kept records of the cumulative number of repetitions of the several axle loading groups at the various measuring days for both the traffic directions. The mean annual traffic loading calculated from these records (table 1) was used for the period after January, 1989.

	test pavement									
	A1 (s)	A2 (ccs)	R1+2 (s)	R3+4 (ccs)	R5+6 (cbs)	E1 (s)	E1* (cbs)	E2 (ccs)	E3 (ccs)	E4 (scs)
<u>pavement structure</u>										
thickness (m) rectangular concrete paving blocks in herringbone bond	0.08/ 0.12	0.08/ 0.12	0.09/ 0.12	0.09/ 0.12	0.12	0.08	0.08	0.08	0.08	0.08
thickness (m) crushed sand bedding layer	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
thickness (m) crushed concrete base	-	0.25	-	0.30	-	-	-	0.15	0.30	-
thickness (m) crushed concrete/crushed clay bricks base	-	-	-	-	0.30	-	0.30	-	-	-
thickness (m) sand-cement base	-	-	-	-	-	-	-	-	-	0.30
thickness (m) sand sub-base	0.70	0.45	0.90	0.60	0.58	0.87	0.57	0.72	0.57	0.57
mean initial subgrade modulus E0 (N/mm^2) according to equation 1	28	30	69	72	75	103	155	120	139	177
<u>traffic loading</u>										
number of axle load (>5 kN) repetitions per annum per lane (wheel track)	5850		625000			inner harbour to seaport: 23010 seaport to inner harbour: 17220				
number of equivalent 80 kN standard axle load repetitions per annum per lane (wheel track), calculated on the basis of equation 4	5730		110250			inner harbour to seaport: 324820 seaport to inner harbour: 138580				

Table 1. Summary of the (traffic loading on the) test pavement structures.

3. DESIGN METHOD

3.1. Research program

Figure 1 shows the flow-diagram of the Working Group's research (1) for the development of design charts for concrete block road pavements, consisting of:

- rectangular concrete paving blocks (cobble format, thickness ≥ 0.08 m) in herringbone bond
- 0.05 m crushed sand bedding layer
- eventually an unbound base of crushed concrete or a mixture of crushed concrete and crushed clay bricks
- a sand sub-base
- the subgrade.

The design criterion for this type of concrete block pavement structure is rutting. The rut depth standard RD_c^* is taken as the characteristic rut depth (30 per cent probability of exceeding) of 15 mm under a 1.20 m long rule.

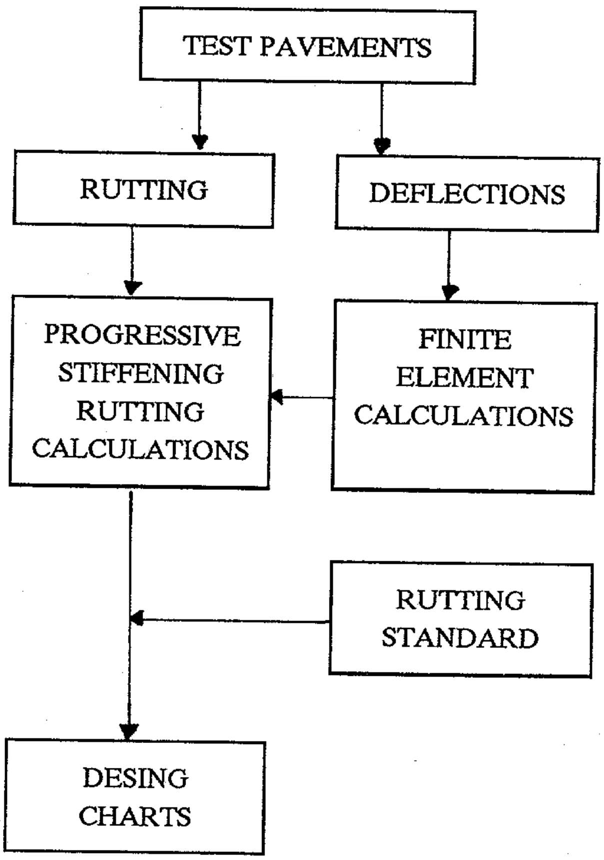

Figure 1. Flow-diagram of the Working Group's research.

3.2. Measurements

For the determination of the resilient deformation (deflections) behaviour and the permanent deformation (rutting) behaviour of the test pavements, regularly falling-weight deflection measurements and level measurements were carried out.

The modulus of elasticity E_0 (N/mm²) of the subgrade is calculated from the falling-weight deflection measurements by means of the equation:

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

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

The mean initial subgrade modulus E_0, calculated from the first falling-weight deflection measurement at every test pavement before opening to traffic, is given in table 1.

The progress of rutting on the test pavements could be described by the equation:

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

where: RD_c = characteristic rut depth (mm), 30% probability of exceeding
N = cumulative number of equivalent 80 kN standard axle load repetitions per lane in the wheel track (channelized traffic)
a_p,b_p = rutting coefficients with respect to the total pavement structure.

The development of the design charts, published in 1988, was only based on the measurements at the test pavements A2 and R1 to R6 until November 11, 1987. The test pavement A1 was not taken into account because it failed completely (shear failure), while the test pavements E1 to E4 were constructed only a few months before (May and June 1987).
The results of the falling-weight deflection measurements and the rutting measurements will be presented in chapter 4, especially figures 4 and 5 and table 2.

3.3. Analysis of test results

The measured resilient deformation behaviour (deflection curves) of the test pavements A2 and R1 to R6 was analyzed by the two-dimensional finite element programme ICES STRUDL 'Rigid Bodies'. In this the concrete block layer was modelled as a pure shear layer, consisting of indeformable 'rigid body' elements interconnected by means of linear vertical springs. The elements are supported by linear vertical springs, which represent the connection of the concrete blocks to the bedding layer. The bedding layer, the unbound base (if any), the sand sub-base and the subgrade were schematized to a system of continuous elements, characterised by the modulus of elasticity and Poisson's ratio.

By means of this two-dimensional finite element model the measured deflection curves could be backcalculated with great accuracy. The finite element calculations also confirmed the measured 'progressive stiffening' behaviour of the stable test pavements A2 and R1 to R6.

3.4. Design rutting calculations

On the basis of the finite element calculations and the measured rutting behaviour of the test pavements A2 and R1 to R6 rutting calculations by means of the 'progressive stiffening' theory (1,3) were done for the following 84 concrete block pavement structures:

- rectangular concrete paving blocks (cobble format, thickness ≥ 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% mass) crushed concrete and (35% mass) crushed clay bricks
- sand sub-base
- subgrade, modulus 40, 60, 100 or 140 N/mm².

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

The result of these 'progressive stiffening' calculations, i.e. the progress of rutting, was then described by a formula according to equation 2 for all 84 pavement structures. From this equation it follows for the life N^* of the concrete block pavement:

$$N^* = (RD_c^*/a_p)^{1/b_p} \qquad (3)$$

where: N^* = allowable number of equivalent 80 kN standard axle load repetitions per lane in the wheel track (channelized traffic)

RD_c^* = rut depth standard, taken as the characteristic rut depth (30% probability of exceeding) of 15 mm under a 1.20 long rule

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

3.5. Design charts

The N^*-values, calculated by means of equation 3, were the basis for six design charts (1).

Figure 2 shows the design chart for concrete block pavements with a sand sub-base only. In order to cover (almost) all Dutch subgrades, the subgrade modulus E_0 ranges from 30 (peat) to 140 N/mm² (sand). As can be observed in figure 2, the pavement life mainly depends on the subgrade modulus E_0 and, in case of a low E_0-value, also on the sand sub-base thickness. The design chart contains a shear failure curve.

Five design charts were developed for concrete block pavements with an unbound base and a sand sub-base, on a subgrade with a modulus E_0 of 30, 40, 60, 100 and 140 N/mm² respectively, again in order to cover (almost) all Dutch subgrades. Each design chart applies to both a crushed concrete base material and a crushed concrete/crushed clay bricks base material. In figure 3 one design chart is shown as an example.

To be able to use the design charts one needs to know:

- the mean initial dynamic subgrade modulus E_0 (N/mm²)
- the predicted cumulative number of equivalent 80 kN standard axle load repetitions N per lane in the wheel track (channelized traffic), which has to be calculated by means of the following load equivalency factor l_e:

$$l_e = (L/80)^3 \qquad (4)$$

where: L = axle load (kN)

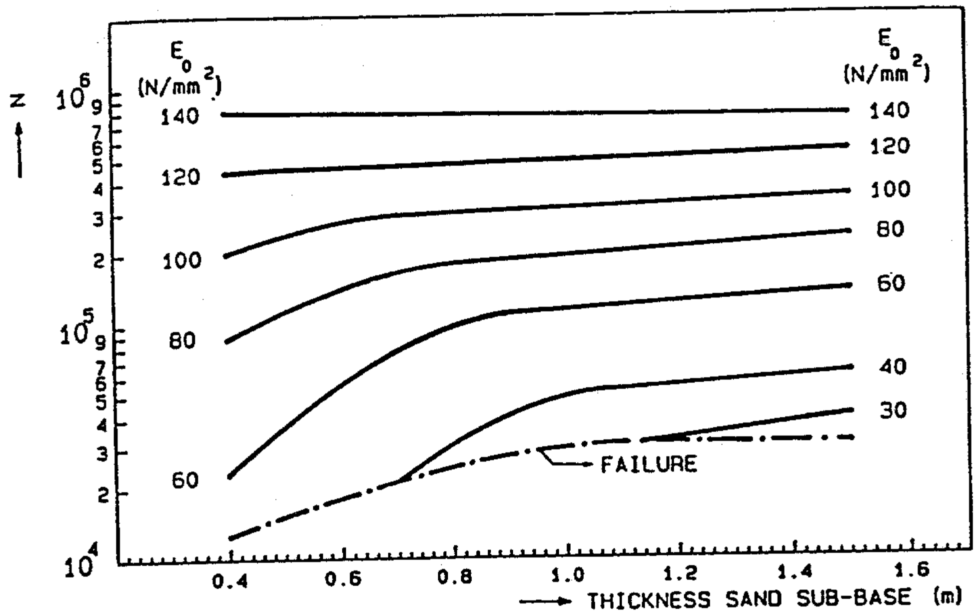

Figure 2. Design chart for concrete block road pavements consisting of rectangular concrete paving blocks (cobble format, thickness ≥ 0.08 m) in herringbone bond, 0.05 m crushed sand bedding layer and a sand sub-base.

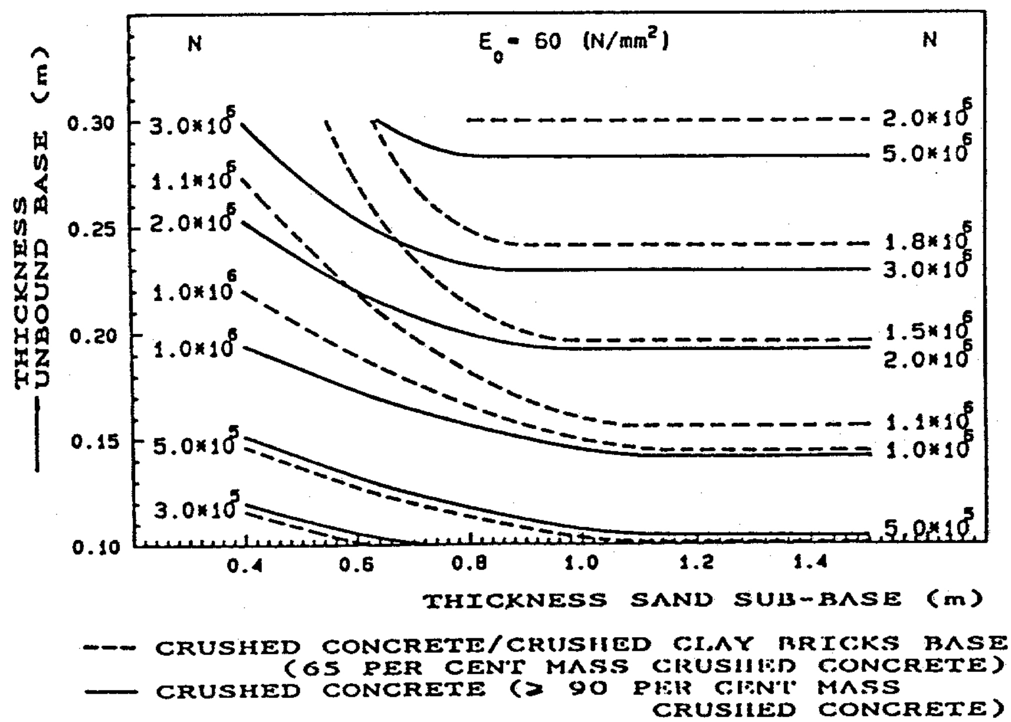

Figure 3. Design chart for concrete block road pavements consisting of rectangular concrete paving blocks (cobble format, thickness ≥ 0.08 m) in herringbone bond, 0.05 m crushed sand bedding layer, an unbound base and a sand sub-base on a subgrade with a modulus E_0 = 60 N/mm².

4. CONTINUED MEASUREMENTS

After the publication of the design method for concrete block road pavements in 1988, the Working Group D3 has continued the falling-weight deflection measurements and the level measurements on the test pavements R1 to R6 in Rotterdam and E1 ($E1^*$) to E4 at ECT's Delta Terminal for a first verification of the design charts.

4.1. Measurement results

Figure 4 shows the progress of the mean maximum deflection d_0 (in the loading centre) on all the Working Group's test pavements until April 10, 1991.
Figure 4 shows a substantial decrease of the maximum deflection with increasing time (number of load repetitions) on the test pavements A2, R1 to R6 and E1, $E1^*$, E2 and E3. All these test pavements show the characteristic 'progressive stiffening' behaviour of stable concrete block pavements with an unbound base and sub-base.
As already stated in chapter 2, the test pavement A1 (without a base) failed completely due to ongoing shear failure in the sand sub-base. The maximum deflection remained more or less constant during the short time that this test pavement was in service.
In the first instance the maximum deflection on the test pavement E4 decreased a little bit. But then the deflection increased during about 1 year, which indicates an ongoing cracking of the 300 mm sand-cement base. After this the deflection decreased again (and remains some 12% smaller than the deflection on the adjacent test pavement E3 with a 300 mm crushed concrete unbound base), which indicates that the cracked sand-cement behaves like an unbound base material.

Figure 5 shows the progress of the characteristic rut depth RD_c (30 per cent probability of exceeding) on all the Working Group's test pavements until April 10, 1991.

For each of the three test locations (Alphen-on-Rhine, Rotterdam, ECT's Delta Terminal) figure 5 clearly shows the beneficial effect of applying a base in a concrete block pavement.
In section 4.2 these rutting measurements will be discussed.

4.2. Verification of the design method

As already mentioned in section 3.1 the design criterion in the Dutch design method for concrete block road pavements is rutting, where the rut depth standard is taken as the characteristic rut depth RD_c (30 per cent probability of exceeding) of 15 mm.
Therefore the verification of the design method has to be based on rutting, which is described by means of equation 2, resulting in a pavement life N^* according to equation 3.

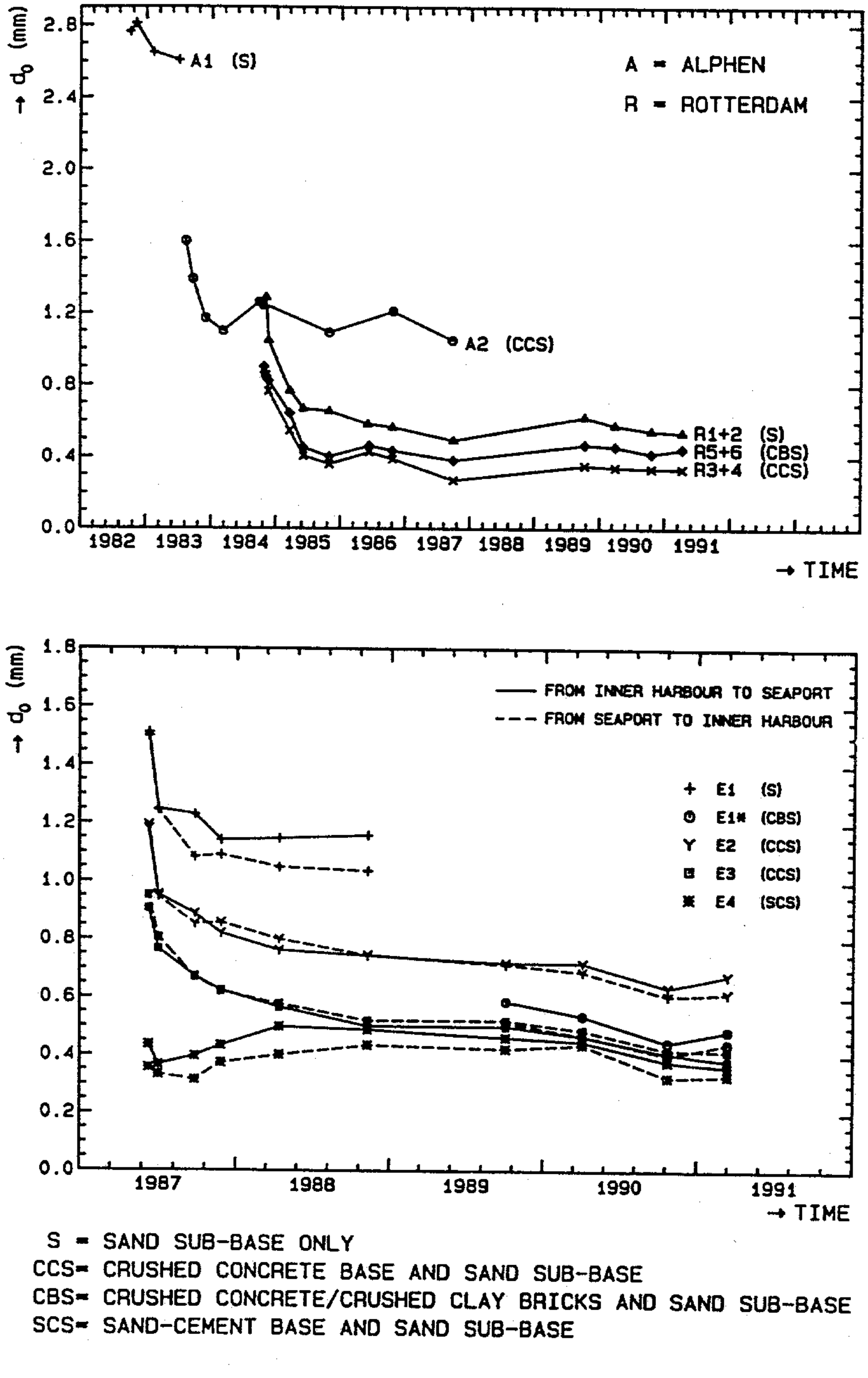

Figure 4. Progress of mean maximum deflection d_0 (due to a 50 kN load) on the test pavements A1 and A2 and R1 to R6 (above) and E1 (E1*) to E4 (below).

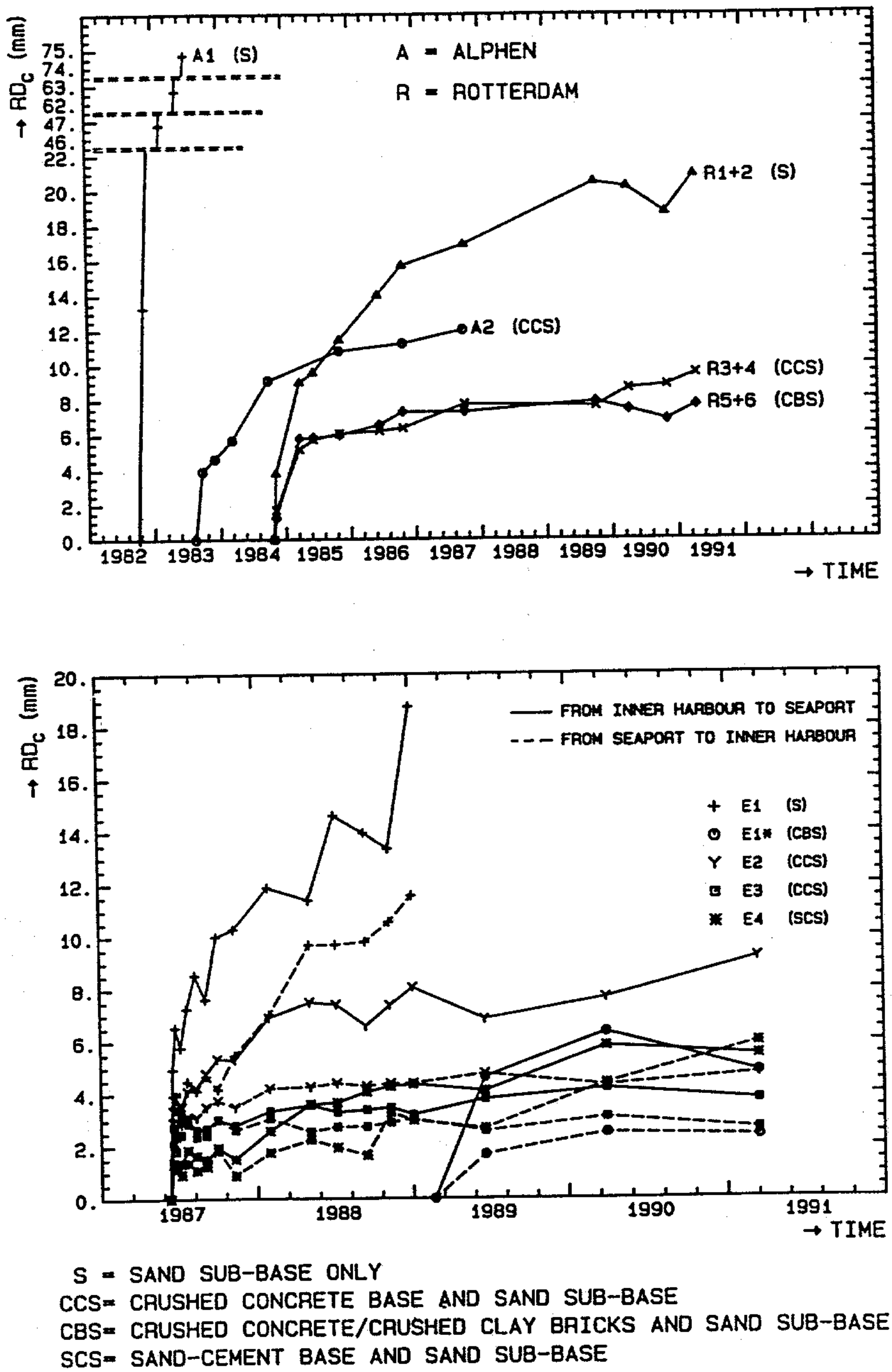

Figure 5. Progress of characteristic rut depth RD_c (30 per cent probability of exceeding) on the test pavements A1 and A2 and R1 to R6 (above) and E1 ($E1^*$) to E4 (below).

In table 2 a comparison is made between:

- the rutting coefficients a_p and b_p (equation 2) of the test pavements A2 and R1 to R6, determined on the basis of the rutting measurements until November 11, 1987 and the predicted pavement life N^* (equation 3) of these test pavements (section 3.2)
- the rutting coefficients a_p and b_p and the pavement life N_c^* of the test pavements A2, R1 to R6 and E1 (E1*) to E3 from the design rutting calculations, which were the basis for the design charts published in 1988 (section 3.4)
- the rutting coefficients a_p and b_p and the predicted pavement life N_m^* of the test pavements R1 to R6 and E1 (E1*) to E3, based on the continued rutting measurements until April 10, 1991 (section 4.1).

The test pavement A1 is not included in this comparison due to the instability of this test pavement structure (in this case the 'progressive stiffening' theory does not apply). The test pavement E4 is excluded from the comparison because cracking of the sand-cement base is the primary design criterion and rutting is only a secondary criterion (the equations 2 and 3 do not apply to this case).

test pavement	rutting measurements until 11-11-1987			design rutting calculations/ design charts (1988)			rutting measurements until 10-4-1991			Nm*/Nc*
	a_p (mm)	b_p	N* (10^6)	a_p (mm)	b_p	Nc* (10^6)	a_p (mm)	b_p	Nm* (10^6)	
A2 (ccs)	1.379	0.211	0.0817	2.867	0.156	0.0404	-	-	-	-
R1+2 (s)	0.133	0.381	0.243	0.068	0.454	0.145	0.176	0.358	0.247	1.70
R3+4 (ccs)	0.930	0.162	28.5	0.223	0.265	7.89	0.140	0.314	2.92	0.37
R5+6 (cbs)	0.666	0.190	13.2	0.182	0.302	2.21	0.132	0.314	3.52	1.59
E1 (s): i→s	-	-	-	0.031	0.485	0.343	1.376	0.181	0.539	1.57
s→i	-	-	-				0.913	0.196	1.59	4.64
E1* (cbs): i→s	-	-	-	0.163	0.299	3.70	2.646	0.054	>100	>100
s→i	-	-	-				0.195	0.205	>100	>100
E2 (ccs): i→s	-	-	-	0.052	0.385	2.45	1.162	0.142	66.5	27.1
s→i	-	-	-				1.913	0.069	>100	>100
E3 (ccs): i→s	-	-	-	0.211	0.263	11.0	1.762	0.052	>100	>100
s→i	-	-	-				1.805	0.037	>100	>100

s = sand sub-base only
ccs = crushed concrete base and sand sub-base
cbs = crushed concrete/crushed clay bricks base and sand sub-base
i→s = from inner harbour to seaport
s→i = from seaport to inner harbour

Table 2. Comparison of the design rutting calculations and the continued rutting measurements on the concrete block test pavements.

It first can be seen in table 2 that the pavement life N^*, predicted on the basis of the rutting measurements until November 11, 1987 was considerably reduced in the design charts for the test pavements R3+4 and R5+6 (both with a 300 mm unbound base). The continued rutting measurements until April 10, 1991 confirm that this was a correct thing to do.
The (predicted) pavement life N_m^* according to the continued rutting measurements until April 10, 1991 is always (substantially) greater than the pavement life N_c^* according to the design charts for the test pavements with a sand sub-base only (R1+2 and E1) and for the test pavement R5+6 with a crushed concrete/crushed clay bricks base and a sand sub-base.
On the contrary the pavement life N_m^* of the test pavement R3+4 with a crushed concrete base is far smaller than the pavement life N_c^* according to the design charts. By strong contrast, the test pavements E2 and E3 (with a crushed concrete base too) as well as the test pavement E1* (with a crushed concrete/crushed clay bricks base) behave extremely well and far better than according to the design charts.

5. CONCLUSION

From the comparison of the measured rutting behaviour of the Working Group's test pavements until April 1991 and the design rutting calculations (presented as design charts in 1988) it can be concluded that the Dutch design method for concrete block road pavements with an unbound base (if any) and a sand sub-base:

- tends to be (slightly) conservative for (relative) weak concrete block pavement structures, which are:
  - pavements with a sand sub-base only on a subgrade with a modulus E_0 between 30 and 140 N/mm²
  - pavements with an unbound base and a sand sub-base on a subgrade with a modulus E_0 between 30 and about 100 N/mm²
- seems to be very conservative for relative strong concrete block pavement structures, having an unbound base and a sand sub-base on a subgrade with a modulus E_0 between about 100 and 140 N/mm².

Therefore it is clear that further research is needed (4,5), especially for a proper design of this last category of strong concrete block pavement structures.

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