VALIDATION OF THE NEW DUTCH DESIGN METHOD FOR CONCRETE BLOCK ROAD PAVEMENTS

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SUMMARY

Due to the poor subgrades in the Netherlands sand is regarded as a structural material for roads. Better materials are simply not available and almost all Dutch CBPs have a sand sub-base. Also rock for base course materials is not available and thus mixtures of crushed concrete and crushed masonry are used as base material. Of these mixtures of recycled material at least 50% (m/m) should be crushed concrete.

At Pave Africa 2003 the new Dutch design method for concrete block road pavements was introduced (Huurman et al, 2003). The written paper 'The Upgraded Dutch Design Method for Concrete Block Road Pavements' discussed the behaviour of pavements with a sand sub-base only. Validation of the method was not discussed neither was the structural approach of CBPs with a base.

The new Dutch design method for concrete block road pavements has been completed since Pave Africa and can now handle the structural design of CBPs with and without a base. Furthermore the method is validated on the basis of rut development in in-service Dutch pavements as measured in the late 1980's.

This paper is a follow-up on the 2003 Pave Africa paper. The paper briefly discusses the Dutch design method with respect to pavements with a base. However, emphasis is on validation of the design method. The paper shows that the design method is capable in accurately explaining the rutting behaviour of stable pavements. The behaviour of unstable pavements is also accurately explained by the method.

Validation shows that the method is capable in recognising CBPs that are in the transition area between stable and unstable behaviour. However, differences between measured rutting behaviour and forecasted rutting behaviour are observed in such cases. The observed differences remain small and do not result in any issues of practical significance.

With the validation completed it is shown that the new Dutch design method accurately explains the rutting behaviour of Dutch segmental pavements with unbound materials only as a function of:

- **Traffic load (axle load spectrum, contact pressures, lateral wander)**
- **Element layer (block size, block thickness, block material, joint material)**
- **Design of the substructure (base thickness, sub-base thickness)**

- **Subgrade (subgrade stiffness)**
- **Base material (percentage of crushed concrete, grading, degree of compaction)**
- **Sub-base sand (grading, grain shape, degree of compaction)**

1. INTRODUCTION

Small element pavements are widely used in the Netherlands; mainly concrete blocks 80 mm thick with horizontal dimensions of 211 mm x 105 mm are applied. In industrial areas the thickness of the blocks is increased to 100 mm or 120 mm and when only minor traffic loads are expected blocks with a thickness of 70 mm are occasionally applied. Also elements that differ in size, shape and/or material (concrete, clay, and natural stone) are applied.

Due to the poor Dutch subgrades sand is regarded a structural material for roads. Almost all Dutch CBPs have a sand sub-base. Also rock for base course materials is not available in the Netherlands. If a base is required, it is most often a mixture of crushed masonry and crushed concrete. Of these recycled materials at least 50% (m/m) should be crushed concrete.

It is known from both practice and laboratory testing that the behaviour of recycled base materials and especially sands may vary strongly. The in-situ degree of compaction explains a larger part of this variation, but also the grading and the grain shape have strong effects on the behaviour of the materials used in the sub structure. For the base materials the percentage crushed concrete is an additional factor that helps to explain structural material behaviour.

On the basis of the above it is clear that any design procedure for small element pavements in the Netherlands must, apart from traffic loading and subgrade stiffness; consider the dimensions of the concrete blocks, the type of sand in the sub-base, the type of base material and the quality of construction, i.e. degree of compaction.

A design method that considers all of the mentioned factors is available in the Netherlands since 2005. The method is based on numerous finite element calculations combined with elaborate triaxial laboratory testing. The theory on which the method is based was extensively published elsewhere (Huurman 1996, 1997) also the triaxial testing is discussed elsewhere (Niekerk, A.A., 2002). An explanation of the method with respect to pavements with a sand sub-base only was published at Pave Africa in 2003 (Huurman). At the time of Pave Africa the method was not validated and was not able to handle CBPs with a base.

Since Pave Africa the method is extended so that it can also handle CBPs with a base course. Also the method is validated on the basis of measured CBP rutting behaviour. The method as a whole is made available to the Dutch market as a computer program “DELPAVE” that forms a universal design method for flexible small element pavements with unbound materials only. The method is applicable for the design of small element pavements for normal street legal traffic.
Validation of the method is discussed hereafter. The equations that from the back bone of the design of pavements with a base are given in an appendix.

2. THE NEW DUTCH DESIGN METHOD

The new Dutch design method for small element paving is a universal method for the design of flexible small element pavements. The method explains the expected rutting in a small element pavement as a function of.

- Pavement loading: axle load spectrum with average contact pressures and lateral wander, number of repetitions per week and yearly traffic growth.
- Type of subgrade: subgrade stiffness.
- Type of sand in the sub base: particle angularity (expressed in VVS) and grading, i.e. d50 and cu=d60/d10 (50% particle size and curvature index)
- Type of recycled base: percentage of crushed concrete and grading curve.
- Small element layer: Joint width, joint stiffness, number of elements per m2 and element thickness.
- Quality of construction: Degree of compaction of both base and sub-base.
- Layer thicknesses

An example of the information required by the design method is given in the Figures 1 and 2.

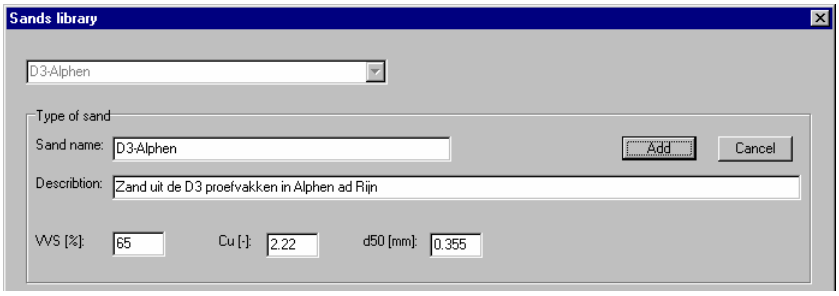


Figure 1. Information required to determine the behaviour of the sand sub-base, i.e. grain shape (VVS) and grading (Cu and d50).

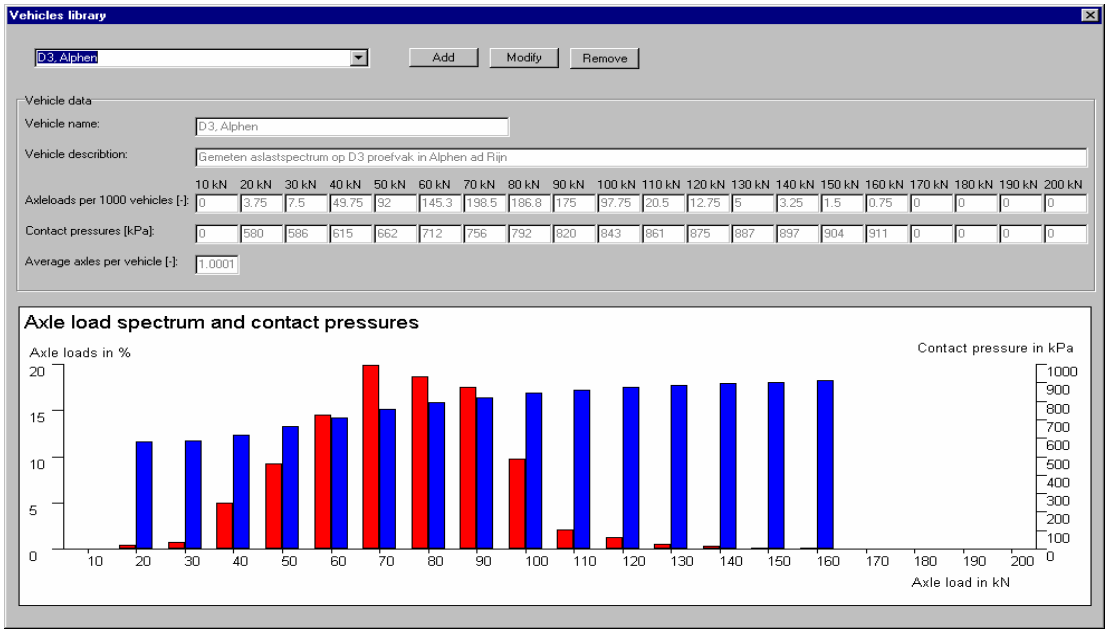


Figure 2. Some information about the traffic loading, i.e. axle load distribution and contact pressure.

3. D3 DATA SET

In 1991 the first Dutch design method for concrete block pavements became available in the Netherlands. This method is discussed elsewhere (Houben, 1988) and was developed at the Delft University of Technology by assignment from the CROW working group D3. The method is based on measurements on in-service concrete block pavements and (back) calculated deflections. The deflections under the wheel load centre were calculated on the basis of Ivanov's equivalent layer theory. The calculations give the deflection in each individual structural layer. These deflections were related to the development of permanent strain in each individual structural layer. Relations that explain the development of permanent deflection as a function of the resilient deflection were derived for various structural layers. The procedure was calibrated on the basis measured rutting in in-service concrete block pavements. For verification of the new Dutch design method for small element pavements use is made of these same D3 rut development measurements on in-service pavements.

3.1 Pavement structures

In total eleven sets of measured rutting behaviour are available. The data was obtained from test pavements in the municipality of Alphen "A", the municipality of Rotterdam "R" and at the European Container Terminal "ECT" in the Rotterdam harbour area. Structurally the test sections of the working group D3 differed strongly from one and other, Table 1.

Table 1. Structural data for the D3 test sections.

		Bedding	Base layer			Sand sub-base				Subgrade
Test section	Block thickness [mm]	layer thickness [mm]	Thickness [mm]	Percentage of crushed concrete [-]	Quality of grading [-]	Thickness [mm]	d50 [mm]	cu [-]	VVS [-]	stiffness E [Mpa]
A1	100	-	-	-	-	695	0.355	0	65%	25
A2	100	50	265	100%	0.89	450	0.355	2.22	65%	25
R1+2	100	-	-	-	-	950	0.325	2.75	65%	70
R3+4	100	50	300	100%	0.75	600	0.325	2.75	65%	70
R5+6	100	50	300	65%	0.89	600	0.325	2.75	65%	70
ECT1,r	80	-	-	-	-	920	0.155	1.90	65%	110
ECT1,s	80	-	-	-	-	920	0.155	1.90	65%	110
ECT2,r	80	50	150	100%	1	720	0.155	1.90	65%	130
ECT2,s	80	50	150	100%	1	720	0.155	1.90	65%	130
ECT3,r	80	50	300	100%	1	570	0.155	1.90	65%	145
ECT3,s	80	50	300	100%	1	570	0.155	1.90	65%	145

The D3 test sections were all made from standard Dutch rectangular concrete blocks (105 mm x 211 mm). The thickness of the various structural layers varied as per Table 1. No information about the grain shape of the sand particles in the various sub-bases is available. For this reason it is assumed that all sands in the D3 test sections are constructed from a sand with an average angularity (VVS=65%). All other information in Table 1 is as reported by D3.

It is stated that the quality of grading for base materials follows from the grading curve. A quality of grading of 1 indicates a grading which equals the upper Dutch limit or a Füller-curve.

3.2 Traffic loading

The contact pressure with which a load is introduced to small element pavements affects the stress levels that develop in the upper part of the sub structure and as a result affects the rutting behaviour of the pavement. In order to take this effect into account the new Dutch design method requires the contact pressure as input. The contact pressure is calculated by dividing the wheel load by the load surface, where the load surface also includes the unloaded gap between a dual tyre. In the new Dutch design method default values for the contact pressures of single and dual wheels are as indicated in Table 2.

Apart from contact pressures the Dutch design method requires the axle load spectrum, the number of repetitions per week, traffic growth. Also the standard deviation of traffic wander is required to completely describe the traffic load. From measurements on the Dutch freeways it is derived that canalised traffic will lead to a 200 mm standard deviation of wander. On wide pavements which give ample possibilities for wander the standard deviation of lateral wander may be 300 mm.

Alphen

The test sections A1 and A2 in Alphen were located at the gate of a concrete manufacturing factory. In this gate there was little room for traffic wander. It was therefore estimated that the standard deviation of lateral wander at these test sections was relatively small, 200 mm. The sections at the factory gate were loaded by 112.5 axle load repetitions per week. It was estimated that the 80% of the wheels that travelled the sections in Alphen were single wheels. The axle load spectrum as measured by D3 was as follows.

Table 2. Default contact pressures in the new Dutch design method.

Axle load [kN]	10	20	30	40	50	60	70	80	90	100
Pressure, single tyre [kPa]	600.0	600.0	607.3	642.2	694.8	747.2	791.9	827.9	856.5	879.1
Pressure, dual tyre [kPa]	500.0	500.0	500.1	505.2	529.5	569.0	610.4	646.6	676.0	699.1
Axle load [kN]	110	120	130	140	150	160	170	180	190	200
Pressure, single tyre [kPa]	897.10	911.50	923.30	932.90	940.90	947.50	953.20	957.90	962.00	965.60
Pressure, dual tyre [kPa]	717.20	731.30	742.50	751.40	758.50	764.30	769.10	773.00	776.30	779.00

Table 3. Axle load spectrum for the sections A1 and A2.

Axle load [kN]	10	20	30	40	50	60	70	80	90	100
Repetitions per 1000 [-]	0.00	3.75	7.50	49.75	92.00	145.30	198.50	186.50	175.00	97.75
Axle load [kN]	110	120	130	140	150	160	170	180	190	200
Repetitions per 1000 [-]	20.50	12.75	5.00	3.25	1.50	0.75	0.00	0.00	0.00	0.00

Rotterdam

The test section R1+2, R3+4 and R5+6 were all located in the same urban street within an industrial area. The street had a layout that might be considered typical for concrete block pavements in Dutch urban areas. The layout offered ample room for traffic to show normal lateral wander. For this reason the standard deviation of lateral wander was estimated to be 275 mm. The sections R1+2, R3+4, R5+6 were subjected to 24038.5 axle load repetitions per week. It was estimated that the distribution of single and dual wheels was 50%-50%. The axle load spectrum as measured by D3 was as follows.

Table 4. Axle load spectrum for the sections R1+2, R3+4 and R5+6.

Axle load [kN]	10	20	30	40	50	60	70	80	90	100
Repetitions per 1000 [-]	456.00	183.90	63.80	71.30	78.80	55.40	32.00	22.90	13.50	9.90
Axle load [kN]	110	120	130	140	150	160	170	180	190	200
Repetitions per 1000 [-]	6.00	3.80	1.50	0.86	0.23	0.13	0.05	0.025	0.00	0.00

ECT

The test sections at the ECT were located within the gates of the terminal and loaded by off-road industrial vehicles. The test sections offered abundant space for lateral wander and for that reason it was estimated that the standard deviation of lateral wander would be large, i.e. 325 mm.

The sections ECT1,s, ECT2,s and ECT3,s were loaded by vehicles carrying goods from the river harbour towards the sea harbour. These sections were loaded by 885 axle load repetitions per week. Axle load measurements showed that axle loads of more than 250 kN were introduced to the pavement by the heavy off-road multi-trailer systems. Since the new Dutch design method for small element pavements is developed for the design of roads open for normal traffic axle loads up to 200 kN can be inputted (200 kN axle loads are illegal in the Netherlands, but occasionally such high axle loads are observed). To compensate for this all axle loads larger than 200 kN were translated to 200 kN axle loads on the basis of a load equivalency coefficient of 3. This equivalency coefficient is as suggested by D3. The following axle load spectrum is now obtained on the basis of D3 measurements.

The sections ECT1,r, ECT2,r and ECT3,r were initially loaded by 662 axle load repetitions per week. Again axle loads larger than 200 kN were measured. Again using the principal of load equivalency the following spectrum was obtained.

Table 5. Axle load spectrum for the sections ECT1,s, ECT2,s and ECT3,s.

Axle load [kN]	10	20	30	40	50	60	70	80	90	100
Repetitions per 1000 [-]	0.00	0.00	0.00	0.00	1.80	66.10	19.90	5.10	31.00	19.90
Axle load [kN]	110	120	130	140	150	160	170	180	190	200
Repetitions per 1000 [-]	25.10	35.10	29.30	36.00	54.80	63.40	70.00	93.20	66.40	639.80

Table 6. Axle load spectrum for the sections ECT1,r, ECT2,r and ECT3,r.

Axle load [kN]	10	20	30	40	50	60	70	80	90	100
Repetitions per 1000 [-]	0.00	0.00	0.00	0.00	3.80	143.80	133.20	8.00	15.20	39.20
Axle load [kN]	110	120	130	140	150	160	170	180	190	200
Repetitions per 1000 [-]	49.70	56.20	48.20	40.60	40.90	51.80	48.90	91.10	71.80	249.30

The sections at ECT were loaded by off-road industrial vehicles. From these vehicles almost everything was known and it was relatively easy to determine the contact pressures that develop under the tyres of these vehicles. A value of 869 kPa was determined for all axle load classes.

4. VALIDATION

4.1 Introduction

As discussed in the previous section almost all information required for objective validation of the new Dutch design method is available from the reports of D3. However, for a few issues no or no exact information was available. These are.

- Grain shape of sands
- Traffic wander
- Contact pressure (known at ECT, not known for A1, A2, R1+2, R3+4 and R5+6)
- Traffic growth
- In situ degree of compaction of the various layers in the sub structure.

For these unknowns reasonable values should be obtained for validation purposes.
For all sands in the D3 test sections the same grain shape was assumed, i.e. VVS=65%. With this all sands in the D3 test sections are assumed to have an angularity that may be considered typical for Dutch natural sands. The amount of traffic wander was estimated on the basis of the lay-out of the test sections as discussed in the previous section.

Contact pressures are assumed to be as per Table 2. The distribution of super single and dual wheels is estimated and discussed in the previous section. Contact pressures at the ECT test sections are known as discussed in the previous section.

Traffic growth is set to be 2% per year for all test sections. Traffic growth will only effect the calculations over a longer period of time. As will be shown later available data does not exceed a period of almost 5 years. Errors in the estimate of traffic growth are thus not expected to have a strong effect on the validation calculations.

The above indicates that it is expected that most of the unknowns either have limited effects on calculation results or can be estimated with reasonable accuracy. However, the degree of compaction of the materials in the sub structure will have a strong effect on the initial rutting behaviour of small element pavements. Only slight differences in compaction may lead to stronger differences in calculated rutting. To tackle this problem the default values of the new Dutch design method are applied. The default values consider compaction of the sand sub-base to a degree of compaction of 101.5% in ideal circumstances. In ideal circumstances a degree of compaction of 107% is assumed for the base layer. With respect to compaction of both the sand sub-base and the base the method considers the stiffness of the subgrade and the thickness of the structural layers. When a structural layer is compacted over a soft or non compacted underlying layer; the program accounts for this by reducing the degree of compaction of that particular structural layer. For all validation calculations the default compaction values have been applied.

The Dutch design method requires the level of confidence to be inputted. At a level of confidence of 50% the method gives the most realistic output. All validation calculations are therefore performed at a 50% level of confidence.

4.1 Results

Figures 3 through 6 give the results of the validation calculations.

The figures indicate that rutting in CBPs with unbound materials develops relatively fast over a short initial phase. After this initial phase further rutting in stable CBPs occurs at a much lower rate. This particular behaviour is reflected in both measured and forecasted behaviour.

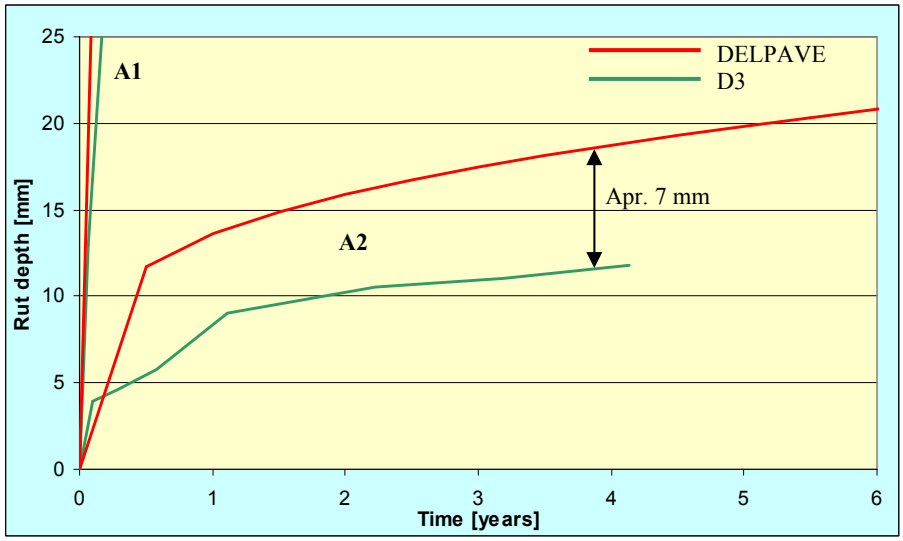


Figure 3. Validation on the basis of D3 sections in Alphen.

The calculations indicate that the new Dutch design method gives a good estimate of the rate of rutting after the initial phase. However, off-set differences between measured and forecasted rutting are observed. Of the 11 validation calculations that were made the design method forecasted a smaller rut depth than measured in 3 cases (R3+4, R5+6, ECT2s), in 2 cases the correct rut depth was forecasted (A1, R1+2) and in 6 cases the forecasted rut depth was larger than measured (A2, ECT1s, ECT3s, ECT1r, ECT2r, ECT3r). From these observations it is concluded that the method is neither conservative nor progressive at a confidence level of 50%.

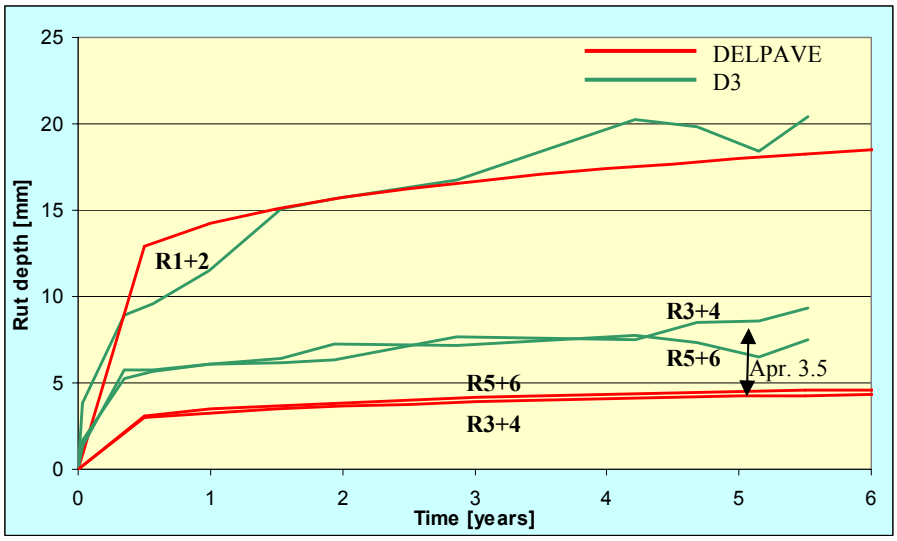


Figure 4. Validation on the basis of D3 sections in Rotterdam.

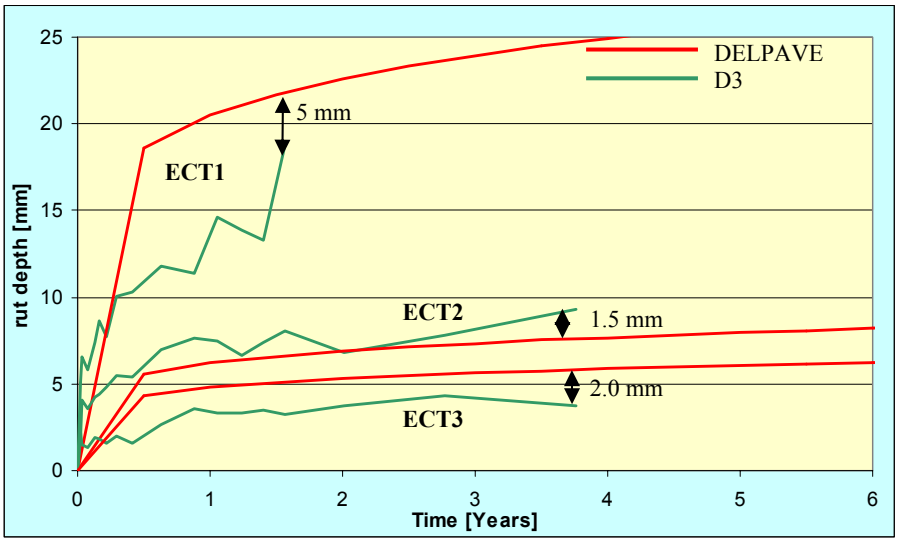


Figure 5. Validation on the basis of ECT to sea D3 sections.

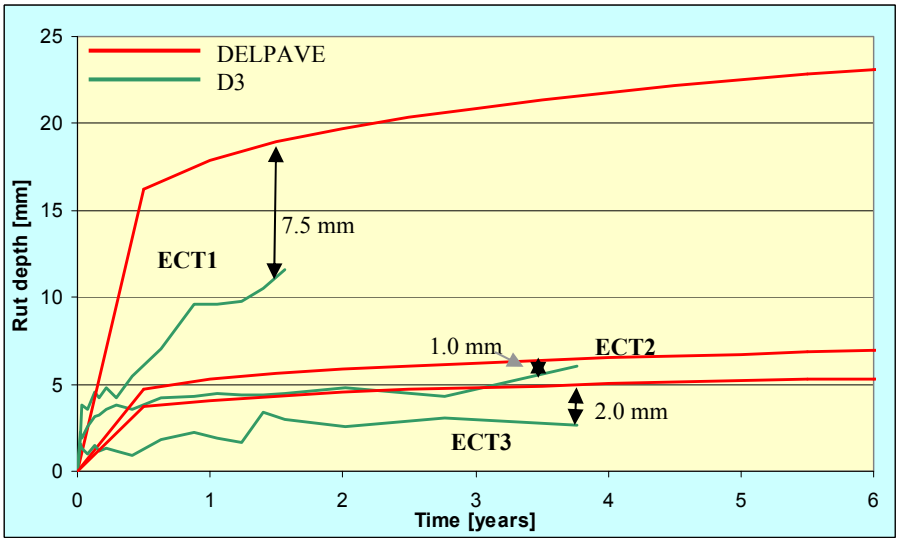


Figure 6. Validation on the basis of ECT to river D3 sections.

It is stated that unstable structures (design life < 1 year) are well recognized (A1). Stable structures (design life > 15 years) are also well recognized (R3+4, R 5+6, ETC2r, ECT2s, ECT3r and ECT3s). CBPs that are not really stable but also not unstable (1 year < design life < 15 years) are also recognized by the design method (A2, R1+2, ECT1r, ECT1s). The largest differences between measured and forecasted rutting are however found in this particular group of pavements. Indications are that the design method is conservative (and thus safe) for this particular pavement behaviour.

4.3 Compaction

In the previous sections it was shown that the new Dutch design method for segmental pavements for road going traffic is highly accurate in forecasting the rate of rut development after the initial rutting phase. However minor differences between measured and forecasted levels of rut depth are found. These differences, which find their cause in the initial rutting phase, can be explained by differences in levels of compaction. When the sub structure of a CBP with unbound materials is not properly compacted traffic will compact the sub structure in the initial phase. This will of course lead to rutting. After compaction by traffic, further rutting will develop at a much slower rate. This indicates that rut depth at the end of the initial phase is highly dependent on the level of compaction directly after construction (quality of construction). The degree of compaction after construction was not measured by the working group D3. Because of this it is not possible to further validate the method with respect to rutting in the early stage directly after construction.

However, the D3 test sections were constructed over subgrades varying from 25 MPa to 145 MPa. Depending on the circumstances, amongst others the subgrade stiffness, the design method adjusts the in-situ compaction. Furthermore, compaction has strong effects on rutting. This combined with the results of the validation calculations allows concluding that the method is properly adjusting levels of compaction in relation to the circumstances. For individual constructions however no conclusions with respect to compaction can be drawn.

5. CONCLUSIONS

The following conclusions are drawn:

- There is a Dutch universal design method for segmental paving. The method may be used to design segmental pavements for street going traffic in which only unbound materials are used. The method results in a rutting forecast and considers:
  - Traffic load (axle load spectrum, contact pressures, lateral wander)
  - Element layer (block size, block thickness, block material, joint material)
  - Design of the substructure (base thickness, sub-base thickness)
  - Subgrade (stiffness)
  - Base material (percentage of crushed concrete, grading, degree of compaction)
  - Sub-base sand (grading, grain shape, degree of compaction)
- The method is objective, i.e. neither pessimistic nor optimistic
- The method is validated and accurate, i.e. it gives a proper forecast of rutting rate
- The method is validated, but it was not fully possible to check the method accuracy with respect to the effects of compaction. However, since the method performs well over a range of subgrades it is concluded that compaction default values are correct.

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Appendix, equations applied in the method

At Pave Africa 2003 the new Dutch design method for concrete block road pavements was introduced in the written paper 'The Upgraded Dutch Design Method for Concrete Block Road Pavements'. That paper describes the equations that form the basis of the methodology applied for the design of pavements without a base. For reasons of continuity the equations that are the back bone in the design of pavements with a base are discussed hereafter. Because of limited space the explanation of the equations remains very limited. Determination of the parameters marked by * may be found in the paper published at Pave Africa 2003.

Rutting in CBPs with a base course is described by

$$RD = a \cdot \left(\frac{N}{1000}\right)^{b} + c \cdot \left(\exp\left(\frac{d \cdot N}{1000}\right) - 1\right) \quad (1)$$

with

$$a = a_c \cdot \left(\frac{L}{100}\right)^{pla} \cdot \left(\frac{150}{R}\right)^{pra} \text{ and } b = b_c \cdot \left(\frac{L}{100}\right)^{plb} \cdot \left(\frac{150}{R}\right)^{prb} \text{ and}$$
$$c = c_c \cdot \left(\frac{L}{100}\right)^{plc} \cdot \left(\frac{150}{R}\right)^{prc} \text{ and } d = d_c \cdot \left(\frac{L}{100}\right)^{pld} \cdot \left(\frac{150}{R}\right)^{prd} \quad (2)$$

Where:

a_c, c_c: model parameters, dependent on pavement design as described hereafter [mm]
b_c, d_c: model parameters, dependent on pavement design as described hereafter [-]
L: axle load [kN]
R: wheel load radius [mm]
pla=1.5959 / pra=0.1384 / plb=0.5685 / prb=0.1971 / plc=2.6405 / prc=0.6604 / pld=4.3774 / plr=3.4271

The parameters a_c, b_c and d_c are determined by

$$Fs = (1 - Fts \cdot Fss) \cdot s7 \text{ with} \quad (3)$$

$$Fts = \exp\left(-\left(\frac{s1}{ts}\right)^{s2}\right) \text{ and } Fss = s6 + (1 - s6)\cdot\exp\left(-\left(\frac{s3}{c_s + s4\cdot\tan\phi_s}\right)^{s5}\right)$$

$$Ftb = \exp\left(-\left(\frac{b1}{tb}\right)^{b2}\right) \text{ and } Fsb = b6\cdot\exp\left(-\left(\frac{b3}{c_b + b4\cdot\tan\phi_b}\right)^{b5}\right) \quad (4)$$

$$Fkw = \left(\frac{5500}{kn}\right)^{pk}\cdot\left(\frac{100}{stdev}\right)^{pw} \quad (5)$$

$$a_c, b_c, c_c \text{ or } d_c = Fs\cdot Fsb\cdot(1 - Ftb)\cdot Fkw \quad (6)$$

Where:

c_s*, c_b: cohesion of sand sub base and base respectively [kPa]
$Ø_s$*, $Ø_b$: angle of internal friction of sand sub base and base respectively [degr]
ts, tb: thickness of sand sub base and base respectively [mm]
kn*: equivalent joint stiffness [N/mm]
stdev: standard deviation of traffic wander [mm]

	a_c [mm]	b_c [-]	d_c [-]		a_c [mm]	b_c [-]	d_c [-]
s1	191.21	699.98	223.89	b1	296.57	61.03065	73.0769
s2	1	0.5	0.69244	b2	1.8269	0.2575	1.815501
s3	6.7328	7.4016	1.71489	b3	150	249.138	24.46049
s4	0	0	0	b4	0	0	0
s5	4.9966	5	3.92086	b5	-1	-3.80226	-1.15571
s6	0.23846	0.1	0.45102	b6	1.6472	1.45172	1.191432
s7	15	0.319772	0.287244				
pk	0.1127	0.086259	1.082353	pw	0.2004	0	0

The parameter c_c is described by

$$Ftb = b1\cdot\exp\left(-\left(\frac{Fss}{tb}\right)^{b2}\right) \text{ with } Fss = s1\cdot\exp\left(-\left(\frac{c_s + s2\cdot\tan\phi_s}{s3}\right)^{s4}\right) \quad (7)$$

$$Fkw = \left(\frac{5500}{kn}\right)^{pk}\cdot\left(\frac{100}{stdev}\right)^{pw} \quad (8)$$

$$c_c = Ftb\cdot Fkw \quad (9)$$

Where:

s1: model parameter = 734.9195 [MPa]
s2: model parameter = 0 [-]
s3: model parameter = 7.97876 [-]
s4: model parameter = 2.28589 [MPa]
b1: model parameter = 4.57602 [-]
b2: model parameter = 1.01846 [-]
pk: model parameter = 0.180425 [-]
pw: model parameter = 1.214989 [-]

c_b and $Ø_b$ follow from

$$c_b = c1 \cdot qg \cdot qs \cdot qc^{c2} \quad \text{and} \quad \phi_b = \phi 1 + \phi 2 \cdot qg \cdot qc \tag{10}$$

$$qc = qc1 \cdot \exp\left(\left(-\left(\frac{rot}{DOC_b}\right)^{qc2}\right)\right) \quad \text{with} \quad rot = 101\% \cdot \ln(qc1)^{\left(\frac{1}{qc2}\right)} \text{ and} \tag{11}$$

$$DOC_b = DOC_{b,\min} + \frac{DOC_s - DOC_{s,\min}}{DOC_{s,\max} - DOC_{s,nim}} \cdot \left(DOC_{b,\max} - DOC_{b,nim}\right)$$

$$qs = \left(pc \cdot qs_1 + (100 - pc) \cdot qs_2\right) \Big/ 100 \tag{12}$$

where

DOC_s*: in-situ degree of compaction of the sand sub base in % [-]
DOC_b: in-situ degree of compaction of the base base in % [-]
$DOC_{s,min}$: parameter = 85 % [-]
$DOC_{s,max}$: parameter = 101.5% [-]
$DOC_{,b,min}$: parameter = 82.5 % [-]
$DOC_{b,max}$: input dependent on base compaction effort, default = 107 % [-]
qc: quality of compaction [-]
qc1: model parameter = 1.5 [-]
qc2: model parameter = 8 [-]
qs: quality of stone [-]
pc: percentage of crushed concrete in base material [-]
qs1: model parameter = 1 [-]
qs2: model parameter = 0.4 [-]
qg: input parameter, quality of grading retrieved from grading curve [-]
c1: model parameter = 134.5057 [kPa]
c2: model parameter = 2.24955 [-]
Φ1: model parameter = 30.2727 [degr]
Φ2: model parameter = 13.8595 [degr]