

SMALL ELEMENT PAVEMENT STRUCTURE AND ITS DEFORMATION BEHAVIOUR

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ABSTRAK

Di Indonesia 'small element' atau paving block, telah banyak dipergunakan sebagai perkerasan jalan atau perkerasan lainnya. Akan tetapi pemakaiannya kebanyakan hanya pada jalan-jalan perumahan yang tidak mempunyai beban kendaraan yang cukup berat. Hal ini disebabkan adanya pengertian bahwa perkerasan dengan paving block tidak mempunyai nilai struktur dan oleh karenanya jalan akan mudah mengalami penurunan jika dipakai untuk jalan dengan beban yang berat.

Pada tahun 1976 dilakukan percobaan pembebanan terhadap paving block oleh J. Knapton, seorang pakar dari Cement and Concrete Association dari Inggris. Terbukti bahwa lapis perkerasan jalan dengan paving block mampu menyebarkan tegangan vertical yang timbul akibat beban lapisan lalu-lintas ke lapisan perkerasan di bawahnya dengan baik.

Pengalaman di negara-negara yang telah lama menggunakan paving block seperti Belanda, dengan menggunakan bahan lapis pondasi atas maupun bawah (base dan sub-base) serta tanah dasar yang memadai dan memenuhi syarat perkerasan, paving block dapat pula dipakai di jalan-jalan raya dengan beban kendaraan yang berat dengan tidak mengalami penurunan yang berarti.

Key word : *Small element (concrete paving block) as a pavement surface layer*

INTRODUCTION

Small element or most people name popular with Concrete Paving Block has been come into use in Indonesia in 1977/1978 as pedestrian road in jalan Thamrin and as a pavement in Pulogadung Bus Terminal, both in Jakarta. Following those projects, concrete paving block become more popular in Indonesia. Nevertheless, stills much to use for road pavement in residential area which have no heavy traffic pass it, and for pavement with static load as container terminal. This could be understood because many people assume that concrete paving block has no structural value and much deflection occurred.

J. Knapton, a civil engineer from *Cement and Concrete Association of Great Britain*, in 1976 has made some load laboratory tests, and he successfully proofs that as a surface layer of the road pavement, concrete paving block able to distribute the vertical stresses caused by traffic load to the underlying (sub-) base and sub-grade layers, and so that concrete paving block include sand bedding layer can be assumed as a surface layer in flexible pavement, replacing asphalt concrete surface layer or other surface layer material which bound by asphalt.

Since the concrete paving block layer consists of some pieces of small elements and joints, filled with sand, the (rain) water

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can easily enter to the underlying pavement. Therefore in order to use for more heavily trafficked roads, do not only use a high strength type of concrete paving block, but also have to lay over strength and proper of pavement structure. This means that (sub-) base and sub-grade materials which are used for have to meet a certain specification requirement.

This paper gives recommendations for the materials use for (sub-) base and sub-grade in the concrete paving block pavement structure in tropical climate such as in Indonesia. The recommendations may be supplemented by those given in the guides for concrete paving block pavement structure in the Netherlands [1] since the

Netherlands have long experiences with concrete paving block pavement structure, and other countries like Australia and South Africa. In addition, is also given some specifications from 'A Guide to the Structural Design of Bitumen-Surfaced Roads in Tropical and Sub-tropical Countries' Transport and Road Research Laboratory (TRRL) Road note 31.

Finally the analysis of deformation behaviour by using of 'progressive stiffening theory' proved that the elastic deflections and permanent deformation (rutting) of concrete paving block pavement structures substantially decrease with increasing number of load repetitions.

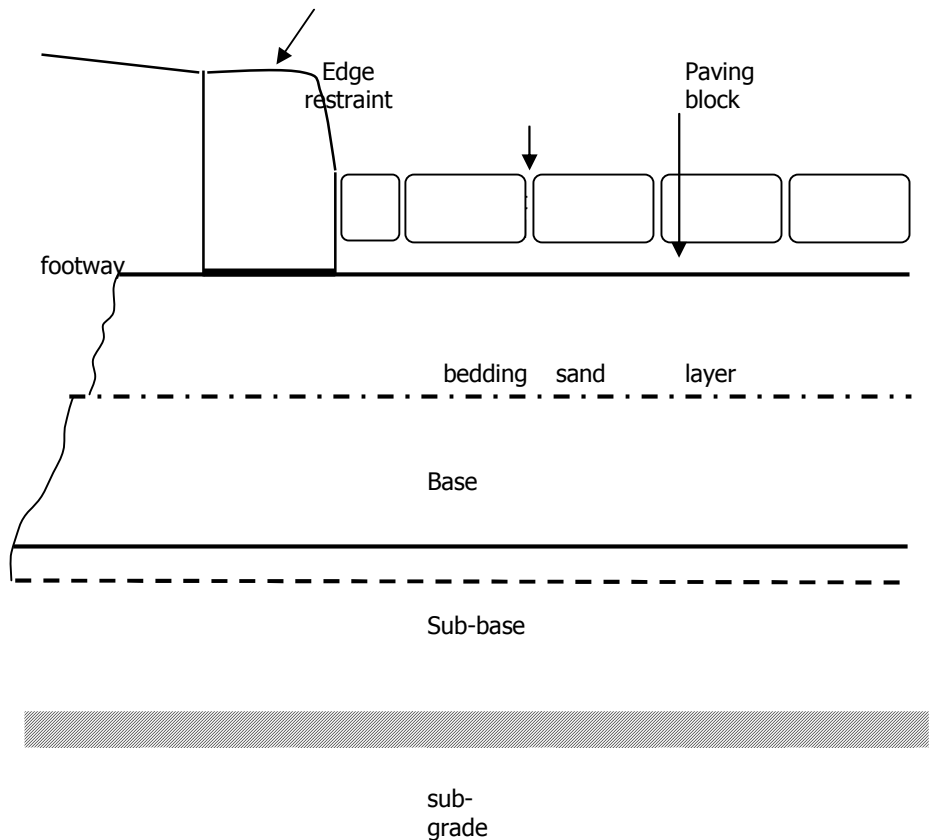


Figure 1 Layer system of Small Element Pavement Structure

FLEXIBLE PAVEMENT STRUCTURE – A LITERATURE REVIEW

Flexible pavement structure is regarded as a linear elastic multi (three)-layer system in which the materials are characterized by Young’s modulus of elasticity (E) and Poisson’s ratio (ν). The materials are assumed to be homogeneous and isotropic and the layers have horizontally infinite dimensions.

Then the primary criteria for structural design are considered to be:

1. The compressive strain in the surface of the sub-grade; if this is excessive, permanent deformation will occur at the top of the sub-grade, and this will cause the deformation at the pavement surface.
2. The horizontal tensile strain in the asphalt layer; if this is excessive, cracking of the surface layer will occur.

Considered as a semi flexible pavement, concrete paving block pavement structure also regarded as a three-layer system with the same characteristic of pavement materials, as illustrated in figure 1 above.

The different is in the criteria for structural design, there is no horizontal tensile strain in the surface layer because the crack in concrete paving block layer has already occurred in every 100 to 200 mm in the joint of elements. The only compressive strain in the surface of the sub-grade will be used as a structural design criterion.

Road Deterioration

The purpose of structural design is to limit the stresses induced in the sub-grade by traffic to a safe level at which sub-grade deformation is insignificant whilst at the same time ensuring that road pavement layers themselves do not deteriorate to any serious extent within a specified period of time. By the nature of the materials used for construction, it is impossible to design a road pavement which does not deteriorate

in some way with time and traffic, hence the aim of structural design is to limit the level of pavement distress, in the small element pavement structure measured primarily in terms rut depth or permanent deformation, to predetermined values.

To be able to limit the level of pavement distress in the small element pavement structure, sub-grade, sub-base and base must have strength to carry up

The heavy traffic load. The following articles will describe the requirement of sub-grade soil sub-base and base material as well as the material of capping layer.

SUB-GRADE

For design purpose the bearing capacity of the sub-grade usually is expressed as the CBR-value or as the dynamic modulus of elasticity. For the structural design of a small element pavement normally a relative low sub-grade CBR-value is used, for instance the value that has a 75% or 85% probability of exceeding.

The dynamic modulus of elasticity of the sub-grade can be estimated from the CBR-value by means of ‘rules of the thumb’, such as:

$$E_0 = 10CBR \dots\dots\dots\text{eq. 1}$$

$$E_0 = 24 CBR^{0.62} \dots\dots\dots\text{eq. 2}$$

where: E_0 = Dynamic modulus of elasticity
 CBR (N/mm²) of the sub-grade
 = CBR-value (%) of the sub-grade

In the tropics area such as in Indonesia, sub-grade moisture conditions under impermeable road pavements can be classified into three main categories:

Category (1). Sub-grade where the water table is sufficiently close to the ground surface to control the sub-grade moisture content.

The type of sub-grade soil governs the depth below the road surface at which a water table becomes the dominant influence on the sub-grade moisture content.

Category (2). Sub-grades with deep water tables and where rainfall is sufficient to produce significant changes in moisture conditions under the road.

These conditions occur when rainfall exceeds evapotranspiration for at least two months of the year. The rainfall in such areas is usually greater than 250 mm per year and is often seasonal.

Category (3). Sub-grades in areas with no permanent water table near the ground surface and where the climate is dry throughout most of the year with an annual rainfall of 250mm or less.

Anyhow because of the very great flexibility of a small element pavement structure, unequal sub-grade settlements are not any problem at all. Of course unequal sub-grade settlements lead to irregularities at the pavement's surface, in case of roads especially longitudinal unevenness.

SUB BASE

The sub-base is an important load-spreading layer in the completed pavement. It enables traffic stresses to be reduced to acceptable levels in the sub-grade, it acts as a working platform for the construction of the upper pavement layers and it acts as a separation layer between sub-grade and road base, and to be used in the small

element pavement structure it may also should act as a filter or as a drainage layer. Generally an unbound granular material is applied for the sub-base. The selection of sub-base materials will therefore depend on the design function of the layer and the anticipated moisture regime, both in-service and at construction.

Sub-base use as a construction platform

In the small element pavement structure, sub-base are governed by its ability to support construction traffic without excessive deformation. A high quality sub-base is therefore required where loading or climatic conditions during construction are severe. Suitable material should possess properties similar to those of a good surfacing material for unpaved roads. The material should be well graded and have a plasticity index at the lower end of the appropriate range for an ideal unpaved road wearing course under the prevailing climatic conditions. These considerations from the basis of the criteria also given in tables 1 and 2. If materials to these requirements are unavailable, trafficking trials should be conducted to determine the performance of alternative materials under typical site conditions. In the construction of low volume roads like residential roads, where cost saving at construction are particularly important, local experience is often invaluable and wider range of materials may often be found to be acceptable.

Table 1. Recommended plasticity characteristics for granular sub-base [5]

climate	Liquit limit	Plasticity index	Linear shrinkage
Moist tropical and wet tropical	< 35	< 6	< 3
Seasonally wet tropical	< 45	< 12	< 6
Arid and semi-arid	< 55	< 20	< 10

Table 2. Particle size distribution for sub-base, which will meet strength requirement [5]

BS Sieve size (mm)	% by mass of total aggregate passing test sieve
50	100
37.5	80 – 100
20	60 – 100
5	30 – 100
1.18	17 – 75
0.3	9 – 50
0.075	5 - 25

Sub-base as a filter or separating layer

Sub-base in the small element pavement structure have to meet *filter laws* since the water is possible enters the pavement structure through the joints in the small element top layer. This may be required to protect a drainage layer from blockage by a finer material or to prevent migration of fines and the mixing of two layers. The two functions are similar except that for use as a filter the material needs to be capable of allowing drainage to take place therefore the amount of material passing the 0.075mm sieve must be restricted. The following criteria should be used to evaluate a sub-base as a separating or filter layer.

a) the ratio $D_{15}(\text{coarse layer})$ should be less than 5

$$D_{85}(\text{fine layer})$$

Where D_{15} is the sieve size through which 15% by weight of the material passes and D_{85} is the sieve through which 85% passes.

b) the ratio $D_{50}(\text{coarse layer})$ should be < 25

$$D_{50}(\text{fine layer})$$

For a filter to possess the required drainage characteristics a further requirement is:

c) the ratio $D_{15}(\text{coarse layer})$ should be 5 < 40

$$D_{15}(\text{fine layer})$$

These criteria may be applied to the materials at both the road base/sub-base and the sub-base/sub-grade interfaces.

The thickness

The thickness of the sub-base is dependent on:

- The designed height level of the pavement surface,
- The desired storage capacity for rain water that enters the pavement structure through joints in the small element top layer,
- The permeability and bearing capacity of the sub-grade,
- The traffic loadings, and
- The properties of the sub-base material itself.

BASE COURSE

For very lightly loaded small element pavements (such as pedestrian areas and residential streets) a base is not necessary. However in more heavily loaded small element pavement a base has to be applied in order to ensure a good traffic load spreading. Both unbound and cement bound can be used for base in the concrete paving block pavement.

Unbound base

An unbound base material has to fulfill the following requirements:

- A good permeability to remove as soon as possible (to the sub-base) the rainwater that entered the pavement structure through the joints in small element top layer.
- A high angle of internal friction to prevent shear instability due to the traffic loadings.
- A good resistance to crushing to prevent extra rutting due to the repeated traffic loadings.

A wide range of materials can be used as unbound road-bases including crushed quarried rock, crushed and screened, mechanically stabilized, modified or naturally occurring 'as dug' gravels.

Their suitability for use depends primarily on the design traffic level of the pavement and climate, but all road-base materials must have a particle size

distribution (grading) and particle shape which provide high mechanical stability. Similar to the sub-base, the grading of the base should meet the *filter laws* to the underlying sub-base material and to the overlying bedding sand. As an example table 3 gives the grading requirements from the Netherlands and Australia for unbound base materials to be applied in small element pavement structures.

The thickness of the unbound base practically is 150 to 300 mm for roads and up to 500 mm and more for very heavily loaded small element pavement structure such as container yards. Generally the thickness is dependent on:

- The traffic loadings,
- The bearing capacity of the underlying layers,
- The properties of the base material.

Cement bound base

As materials for cement bound base in a small element pavement structure, generally a granular material (sand, gravel, crusher run, blast furnace slags, etc.) stabilized by means of cement is used.

The amount of cement depends on the strength requirements and the grading of the material to be stabilized; the lower the required strength and the coarser the material, the smaller the required amount of cement.

Similar to the unbound base materials, the thickness of cement bound base generally between 150 and 300 mm, and for heavily loaded pavement the thickness goes up to 500 mm.

Table 3. Grading requirements for unbound base materials in small element pavement structure from the Netherlands and Australia [1]

% passing (by mass)	The Netherlands			Australia
	grading 0/40mm	grading 0/80mm	grading 20/80mm	
90 mm	-	90 - 100	90 - 100	-
53 mm	-	-	-	100
45 mm	90 - 100	-	50 - 80	-
37.5 mm	-	-	-	85 - 100
31.5 mm	-	60 - 90	-	-
19 mm	-	-	-	60 - 90
16 mm	60 - 90	-	0 - 10	-
8 mm	-	30 - 60	-	-
4.75 mm	-	-	-	30 - 65
4 mm	30 - 60	-	-	-
2 mm	20 - 50	15 - 45	-	20 - 50
1.18 mm	-	-	-	16 - 43
425 µm	-	-	-	10 - 30
300 µm	-	-	-	9 - 27
75 µm	-	-	-	5 - 15
63 µm	0 - 8	0 - 8	0 - 8	-

When the permeability of the cement bound base is too small for a rapid run through of the rainwater, that entered the pavement structure through the joints in the small element top layer, one has to take special measures to prevent soaking of the overlying bedding sand layer. A possible measure is to make every square meter a hole (diameter about 100mm) over the total cement bound base thickness, and fill it with coarse sand or fine gravel.

BEDDING SAND LAYER AND JOINTING SAND

Over the base (or over the sub-base when no base is applied) a thin layer of fine material is necessary to eliminate the unevenness of the base surface and the variation of the thickness of the small elements. This special layer is called the bedding sand layer.

This layer is directly subjected to the rainwater penetration through the joint of small element top layer. Therefore the material for the bedding sand layer has to

be a well-graded fine granular material with sharp particles and not containing clay. As an example table 4 gives the grading requirements for the bedding sand material from the Netherlands, Australia and Great Britain.

Usually the material for the bedding sand layer also is applied to fill the 2 to 3mm wide joints between the small elements of the top layer. Table 4 also gives a supplementary grading requirement for this jointing sand from Australia/South Africa

The thickness

In case the small elements are placed one by one according to the traditional craft method, the thickness (after compaction) of the bedding sand layer should be 50 to 70mm. However, when the small elements are laid down (manually by paviours or mechanically by means of special equipment) on the prepared (leveled) bedding sand layer, the thickness (after compaction) of this layer can be restricted to 30 to 50mm.

Table 4. grading requirements for bedding sand and jointing sand in small element pavement structure from several countries [1]

% passing (by mass)	Bedding sand				Jointing sand	
	The Netherlands			Australia	Gr. Britain	Australia / South Africa
	'bedding sand'	Blast furnace slag	Crusher sand			
9.52mm	-	-	-	100	100	-
4.75mm	-	-	-	95 – 100	90 – 100	-
4.00mm	-	≥ 90	-	-	-	-
2.36mm	-	-	-	80 – 100	75 – 100	100
2.00mm	≥ 90	-	≥ 80	-	-	-
1.18mm	-	-	-	50 – 85	55 – 90	90 – 100
1.00mm	-	-	≥ 40	-	-	-
600µm	-	-	-	25 – 60	35 – 70	60 – 90
300µm	-	-	-	10 – 30	8 – 35	30 – 60
150µm	-	-	-	5 – 15	0 – 10	15 – 30
75µm	-	-	-	-	0 – 3	5 – 10
63µm	≤ 5	≤ 10	≤ 10	-	-	-

Another recommended grading for bedding sand gives by Hodgkinson and Morrish (1982) is shown in table 5.

Table 5. Recommended grading for bedding sand layer by Hodgkinson and Morrish [3]

Seive Size	9.52 mm	4.75 mm	2.36 mm	1.18 mm	600 μm	300 μm	150 μm	75 μm
% passing	0	95 - 100	80 - 100	50 - 85	25 - 60	10 - 30	5 - 15	0 - 10

SMALL ELEMENT SURFACE LAYER

The top layer of a small element pavement structure consists of concrete paving blocks that can be lifted up and used again. In order to achieve a maximum load spreading (by means of shear force, see figure 2) in the top layer, the joints between the

concrete paving blocks have to be narrow (preferably 2 to 3mm) and they have to be continuously filled with jointing sand. In this way also the permanent deformations of a small element, relative to adjacent elements, are limited.

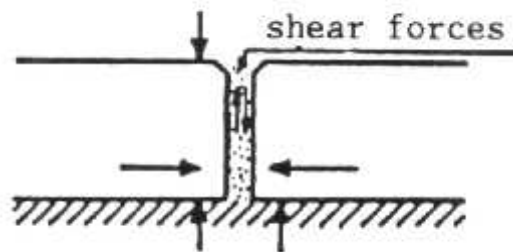


Figure 2. Load spreading in the small element top layer by means of shear forces in the joints.

There are several hundreds shapes of concrete paving blocks. At least 40 blocks shapes are in common use around the world, however not all of these are suitable for trafficked small element pavement structure.

The principle blocks used in roads and industrial hard standings are shown in figure 3, where three categories of blocks shapes are distinguished:

- *Category A*: dentate blocks which key into each other on all four faces and which by their plan geometry, when keyed together, resist the spread of joints parallel to both the longitudinal and transverse axes of the joints.

- *Category B*: dentate blocks which key into one another on two faces only and which, when keyed together, resist the spread of joints parallel to the longitudinal axes of the blocks but which rely on their dimensional accuracy of laying to interlock on the other faces.
- *Category C*: non-dentate blocks which do not key together and which rely on their dimensional accuracy and accuracy of laying to develop interlock.

Generally the block dimensions are such that there are between 40 and 50 blocks in 1 square meter.

Worldwide concrete paving blocks can be defined with respect to their dimensions as pre-cast concrete paving element with:

- A top surface between 50000 and 60000 mm²

- Horizontal dimensions not greater than 280mm
- A ratio of mean length and mean width between 1 and 3
- A thickness between 60 and 140mm.























CATEGORY A						
	A (1)	B (1)	C (1)	D (1)	E (1)	F (1)
CATEGORY B						
						
	G (2)	H (2)	I (2)	J (2)	K (2)	L (2)
	M (2)	N (2)	O (2)	P (2)	Q (2)	R (1)
CATEGORY C						
	S (2)	T (2)	U (1)	V (2)		
NOTES	(1) Suitable for a variety of bonds including hemingbone		(2) Suitable only for stretcher bond		Blocks known to have had load-distribution studies or traffic tests	

Figure 3. Categories of Concrete Block shapes

The most important properties of concrete paving blocks are:

- The small shape and dimensional tolerances, which make it possible to realize concrete block layers with narrow joints
- A high strength, which makes it possible to use them for very heavily loaded pavements (such as container terminal)
- A high resistance against physical affection
- A good resistance against mineral oil and fuel; however, (an) organic acids, sulphates, vegetable and animal oils and fats do affect the concrete
- A good skidding resistance, and rather good abrasion resistance
- A good light reflection, especially the non-colored blocks and the blocks having a light color.

DEFORMATION BEHAVIOUR

There are two types of deformations in the concrete paving block pavements which will be analyzed in this paper. Those are resilient deformation or elastic deflection and permanent deformation or rutting.

1. Resilient deformation (elastic deflections)

The resilient deformation behaviour of concrete block pavements usually is analyzed by means of falling weight deflection measurements. In such a measurement a 50kN dynamic load is applied on the pavement structure by means of a circular plate diameter 300mm, so the contact pressure equals 0.707N/mm²; the loading time is 0.02 second. The deflections (d) are measured at distance of 0, 0.3, 0.5, 1.0, 1.5 and 2.0 meter from the centre of the loading plate (figure 4).

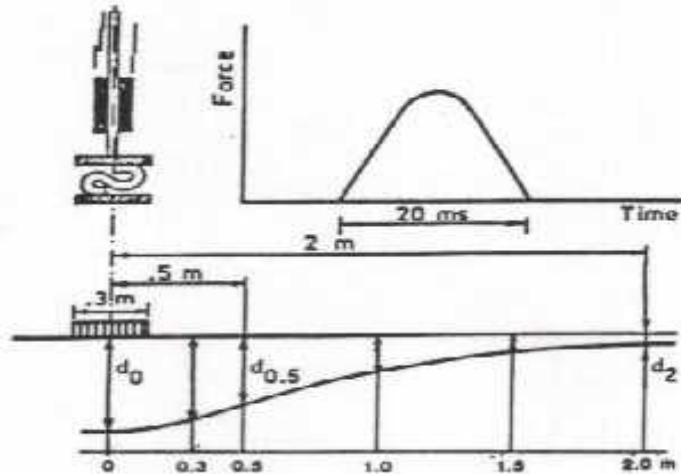


Figure 4. Outline of a falling-weight deflection measurement [1]

It appeared from the falling-weight deflection measurements that the deflections of concrete paving block

pavement structures substantially decrease with increasing number of load repetitions, as can be seen in figure 5.

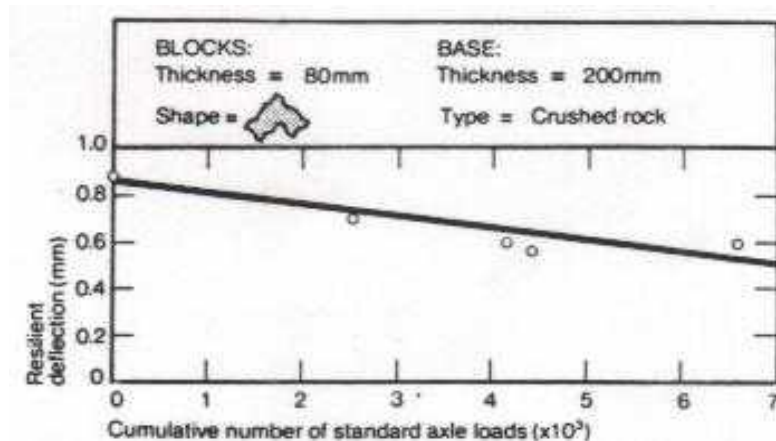
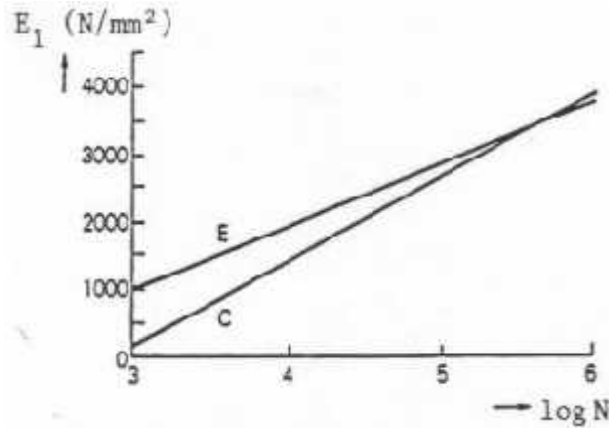


Figure 5. Progress of mean maximum deflection d_0 for Australian concrete block pavements carrying controlled truck traffic. [1]

The decrease of deflections means that the concrete paving block pavement structure is becoming stiffer with increasing number of load repetitions. This phenomenon, which is unique for stable concrete paving block

pavement is called '*progressive stiffening*'. A deflection level which more or less remains constant indicates a structural (shear) force of the small element pavement.



Note: C = sand sub-base thickness 1.0 – 1.2 meters
 E = sand sub-base thickness > 1.4 meters

Figure 6. Progress of the equivalent modulus of elasticity E_1 of the concrete block top layer with increasing number of equivalent 80kN s.a.l repetitions.

Figure 6 above shows that the progressive stiffening of concrete paving block pavement structures is partly caused by a substantial increase of the equivalent modulus of the concrete block top layer (back calculated from falling-weight deflection measurements by means of a linear-elastic multi-layer analysis) with increasing number of load repetitions. The figure was derived for concrete block pavement structures (in the city of Delft the Netherlands) consisting of 80 mm rectangular concrete paving blocks in herringbone bond and a sand sub-base over the clay sub-grade.

2. Permanent deformation (rutting)

Some typical results with respect to the development of rutting in concrete paving block pavement structures are shown in the figure 7 and 8. In these figures it can be seen that after an initial stage (where a substantial rutting occurs) the rate of accumulation of permanent deformation decreases due to the progressive stiffening of the concrete block pavement structure.

The progress of rutting on the pavements was described by means of the equations:

$$RD_c = a_p N^{b_p} \dots\dots\dots \text{eq. 3}$$

Where:

- RD_c = characteristic rut depth (mm)
- N = cumulative number of equivalent 80 kN standard axle load per lane,
- a_p, b_p = rutting coefficients with respect to the total pavement structure.

N was 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 damage is the AASHTO-type load equivalency factor l_e according to:

$$l_e = (L/L_{st})^m \dots\dots\dots \text{eq. 4}$$

- Where: l_e = load equivalency factor
- L = axle load (kN)
- L_{st} = standard axle load (taken as 80kN)
- m = load equivalency exponent

from equation 4 it follows for the load equivalency exponent m (with respect to rutting) for concrete block pavements:

$$m = 1 / b_p \dots\dots\dots \text{eq. 5}$$

where: b_p = rutting coefficient (see eq. 3)

some of the calculation results based on the above equations 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. The greater the bearing capacity of the total pavement structure, the greater the rutting-related load equivalency exponent m of concrete block pavements.

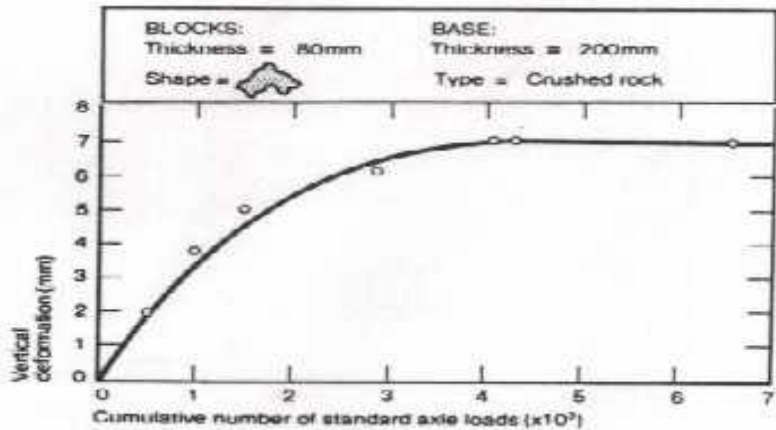


Figure 7. Progress of mean rut depth for Australian concrete paving block pavements carrying controlled truck traffic.

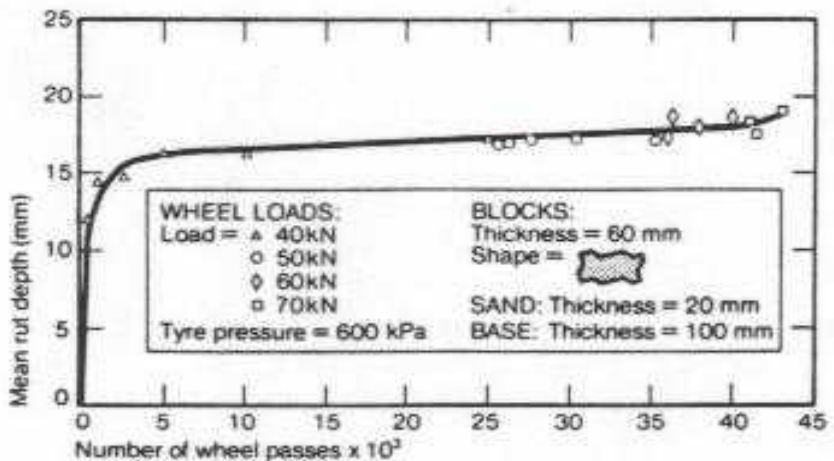


Figure 8. Progress of mean rut depth of a concrete block pavement in a Heavy Vehicle Simulator test in South Africa.

Analysis of the deformation behaviour by 'Progressive stiffening' theory

Progressive stiffening theory which had been developed by The Delft University of Technology in the Netherlands is used to analyze the permanent deformation (rutting) behaviour and the deflections of concrete paving block pavement. The basic equation of the progressive stiffening theory is (figure 9):

$$\frac{du_p}{dN} = u_e \frac{df}{dN} \dots\dots\dots \text{eq. 6}$$

where:

- u_p = permanent deformation in a layer of unbound material.
- u_e = elastic compression of the layer due to an equivalent 80kN standard axle load.
- f = permanent deformation relationship of the unbound material.
- N = cumulative number of equivalent 80kN standard axle load repetitions per lane.

The 'compaction' relation f of a granular and cohesive material is:

Granular material: $f = a_m N^{b_m} \dots\dots\dots \text{eq. 7a}$

Cohesive material: $f = a_m + b_m \log N \text{ eq. 7b}$

Where:

a_m, b_m = permanent deformation coefficients of the unbound material.

The elastic compression u_e of the unbound material can be described as:

If $N \leq N_1$: $u_e = d_{max} = \text{constant} \dots\dots\dots \text{eq. 8a}$

If $N > N_1$: $u_e = p + q \cdot e^{-\log N} \dots\dots\dots \text{eq. 8b}$

Where:

N_1 = initial number of equivalent 80kN s.a.l repetitions per lane until progressive stiffening occurs.

d_{max}, p, q = elastic deformation coefficients.

The permanent deformation u_p in a layer of unbound material in a concrete block pavement structure is obtained by combining the equations 6, 7 and 8.

Granular material:

If $N \leq N_1$; $u_p = d_{max} a_m N^{b_m} \dots\dots\dots \text{eq. 9a}$

If $N > N_1$; $u_p = d_{max} a_m N_1 + a_m p (N - N_1)$

$$+ \frac{a_m b_m q}{b_m - 0.4343} (N^{b_m - 0.4343} - N_1^{b_m - 0.4343}) \dots\dots\dots \text{eq. 9b}$$

cohesive material :

If $N \leq N_1$; $u_p = d_{max} (a_m + b_m \log N) \dots\dots \text{eq.10a}$

If $N > N_1$; $u_p = d_{max} (a_m + b_m \log N_1) +$

$$b_m p \log (N/N_1) - b_m q (N^{0.4343} - N_1^{0.4343}) \dots\dots \text{eq.10b}$$

The equation 8b (resilient deformation), equations 9b and 10b (permanent deformation) respectively are the mathematical description of the phenomenon 'progressive stiffening' of concrete paving block pavement structures.

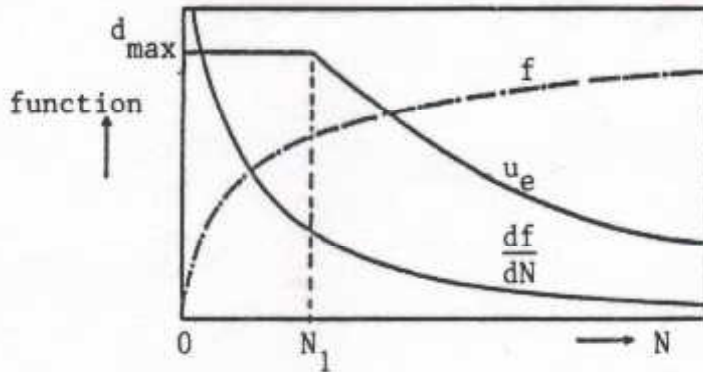


Figure 9. Schematically representation of permanent deformation functions.

The rutting within the concrete block pavement structure is the sum of the permanent deformation in the subsequent unbound layers, and calculated by the equation:

$$RD = \sum_{i=1}^j u_{pi} \dots\dots\dots \text{eq. 11}$$

where: RD = rut depth
 u_{pi} = permanent deformation of unbound layer i.
 j = total number of unbound layers.

It appeared that the progress of rutting, calculated by means of equation 8 on the basis of the progressive stiffening theory, can be described very well by means of the equations 3:

$$RD = a_p N^{bp} \dots\dots\dots \text{(eq. 3)}$$

The 'progressive stiffening' theory has been applied to the pavements in some city in the Netherlands.

CONCLUSION

The results of this study have led to the following conclusions:

1. the concrete paving block pavement structure can be used over a weak sub-grade with high (unequal) settlements, or the structural behaviour is not affected by unequal sub-grade settlements.
2. Concrete paving block pavements having an adequate (sub-) base are resistant to very heavy dynamic and static (for instance stacked containers) loadings, also due to the high concrete paving block strength.
3. The structural design criterion is rutting, with an acceptable characteristic (30% probability of exceeding) rut depth of 15mm below a 1.20 meter long rule.
4. Resilient deformation (elastic deflections) decrease and permanent deformation or rutting will remains constant with increasing of number load repetitions.

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