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Structural Model for Concrete Block Pavement

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ABSTRACT

A structural model for the calculation of stress, strain, and deflection in a concrete block pavement is described. This model is based on the ICES STRUDL computer program that was recently extended by the introduction of a so-called RIGID BODY element. It is shown that by means of this model excellent agreement between measured and calculated deflection profiles is obtained. Furthermore, time functions were derived from the observation of 20 concrete block pavements in service. These functions show the increase of the subgrade modulus, the stiffness of the joints and the bedding layer, and the decrease in the deflection with respect to the number of equivalent 100-kN single axles. By means of ICES STRUDL and the developed time functions tentative design charts are developed in which the number of years until a given rut depth is reached is related to the initial subgrade modulus and the average daily equivalent 100-kN single axle loads. Although concrete block pavements are common in western Europe (about one-third of the paved area in the Netherlands consists of such pavements), this pavement type is not well known in the United States. Therefore a general description of the most characteristic features of concrete block pavements is given.

Concrete block paving is the most recent development in element (segmental) paving, which is built by laying down small elements on the (improved) subgrade. Element paving has been used since the Middle Ages. Wooden setts were sometimes used as elements but, especially at first, nontooled natural stone was the only pavement material that had sufficient resistance to the traffic loading by steel wheels.

After the introduction of the rubber tire at the end of the 19th century, clay bricks were applied on a large scale in the Netherlands (1,2). Because of the absence of quarries, natural stone was more expensive than bricks.

After World War II the rectangular concrete block was developed as a substitute for the rectangular brick, which was needed for the construction of houses. Concrete blocks are now used much more than bricks because of the substantially higher cost of the bricks. Outside the Netherlands bricks are hardly used. In Germany and Belgium concrete block paving has also been used on a large scale since 1950; in a number of other countries concrete blocks have been introduced hesitatingly since 1960 (3).

The profile of a concrete block pavement is shown in Figure 1 (4). For the subbase, sand or a granular

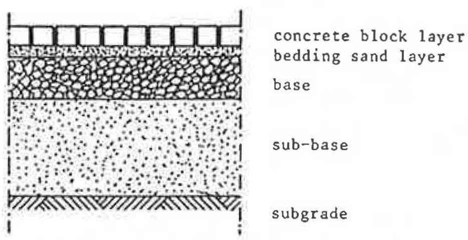

FIGURE 1 Profile of concrete block pavement.

material of higher quality is used, depending on the cost (availability) of the materials. It is important that the subbase have high permeability. The base, which is not necessary for lightly trafficked pavements (pedestrian areas, roads with hardly any trucks), may consist of granular material such as slags, natural gravels, or crushed rock (the resistance to crushing has to be high) or stabilized material, especially cement-stabilized material. A stabilized base requires special provisions for the discharge of the rainwater that percolates through the joints. The bedding sand layer, which is necessary because the subbase is too rough and often too hard, consists of stable sand (bedding sand) and sometimes fine gravel. For optimum load spreading (by friction) in the concrete block layer it is necessary not only that the joints between the blocks be narrow (2 to 3 mm) but also that they remain filled with jointing sand.

CONCRETE BLOCKS

In countries with a long tradition of concrete block paving the blocks are manufactured in plants specialized for this purpose (4). Elsewhere the blocks are often manufactured by using modified wall masonry plants (3); in general these blocks are of a lower quality.

Block Types

There are rectangular concrete blocks (with a rectangular, square, or hexagonal horizontal section) and dozens of nonrectangular (shaped) concrete blocks (3-5). A further division is made into three categories (Figure 2). Category A consists of nonrectangular blocks interlocking on all four faces; category B, nonrectangular blocks interlocking on two faces only; and category C, rectangular blocks that do not interlock.

Historically in the Netherlands rectangular blocks have been used almost exclusively. Outside

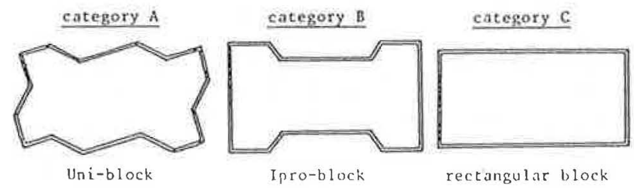

FIGURE 2 Categories of concrete blocks (with chamfer).

the Netherlands nonrectangular blocks are the most widely used, which is explained by the (presumed) better performance of such pavements, the absence of skilled paviors (nonrectangular blocks often fit together in just one way), and so forth.

In general, concrete blocks have a chamfer around the wearing face to reduce spalling, caused by blocks rotating toward one another, and to reduce differences in level between adjoining blocks in the road. Furthermore, chamfered blocks are easier to handle. The horizontal dimensions of concrete blocks are in general about 200 x 100 mm^2, and the thickness varies from 50 to 120 mm. The block type and the laying pattern determine the number of accessory blocks needed.

Specifications

In several countries there are specifications for concrete paving blocks (6-10). In general the specifications refer to materials, manufacturing, dimensions, dimensional tolerances, and quality (strength, durability, and so on). Most important for the pavement performance under traffic and the life of the blocks are the differences in size and the strength and the durability of the blocks.

Concrete blocks may have only slight differences in size in order to make laying and, if necessary, repairing of the block pavement easy and exact and to assure that there are narrow joints everywhere so that the permanent deformation, both vertical (rutting) and horizontal (in the direction of travel, or creep, and perpendicular to it), is limited. The horizontal differences in size in particular have to be small, and therefore most specifications call for a tolerance of about 2 mm; the tolerance for thickness is, in general, larger (up to 5 mm).

It has been widely assumed that strength and durability (in particular abrasion resistance) are interrelated. Therefore the strength requirements are higher than necessary to prevent failure of the blocks during manufacturing, transport, and processing and under traffic loading. In the countries of the Southern Hemisphere in general the strength requirements are lower than those in Europe and North America because resistance to damage by freezing and thawing is usually no problem. The lowest strength specifications mentioned in the literature are compressive strength of at last 40 N/mm^2 and flexural strength of at least 2.5 N/mm^2 (in the Netherlands flexural strength of at least 5.9 N/mm^2 is specified).

Properties

Because they are manufactured in steel molds, concrete blocks vary only slightly, especially in the horizontal dimensions. The strength of concrete blocks is so great that failure due to traffic loads rarely occurs; blocks with a variable width (e.g., Ipro blocks) are more susceptible to failure than blocks with a constant width. Concrete blocks are resistant to mineral oil and fuel, but they are affected by inorganic acids (hydrochloric, nitric, and so on), organic acids (lactic), and vegetable and animal oils and fats. By addition of pigments concrete blocks can be given different colors. These colored blocks have functional uses (traffic markings) or are used for aesthetic reasons. Concrete blocks are sufficiently skid and abrasion resistant.

GENERAL ASPECTS OF CONCRETE BLOCK PAVING

Properties, Advantages, and Disadvantages

A concrete block pavement consists of small, precast concrete elements, which can be torn up and used again (3,4). The main advantages of concrete block paving are as follows:

1. The pavement is able to conform with the unequal settlement of the subgrade without further disintegration (cracking);
2. The subgrade remains easily accessible to underground services (cables and piping), except in the case of a stabilized subbase;
3. The blocks can be relaid (restoration of local settlement, reconstruction, and so on) easily, quickly, and with hardly any loss of material;
4. The great block strength makes a concrete block pavement (with a base) resistant to heavy and static (concentrated) loads;
5. The pavement is resistant to mineral oil and fuel;
6. The pavement can be opened to traffic immediately after construction or relaying;
7. Small and irregular surfaces can easily be paved;
8. Because concrete can be given almost any shape there are many block types, different sizes and thicknesses, and accessory blocks [half blocks, "bishop hats" for herringbone bond B (Figure 3), and so on] and therefore there are many possible applications;
9. The skid resistance remains sufficient, also because the joints tend to prevent a water film on the pavement;
10. The pavement gives diffuse light reflection, especially when uncolored or light-colored blocks are used; and
11. Application of different-colored concrete blocks, possibly laid in different patterns, offers possibilities for optical traffic-guidance markings and, from an aesthetic point of view, attractive pavements.

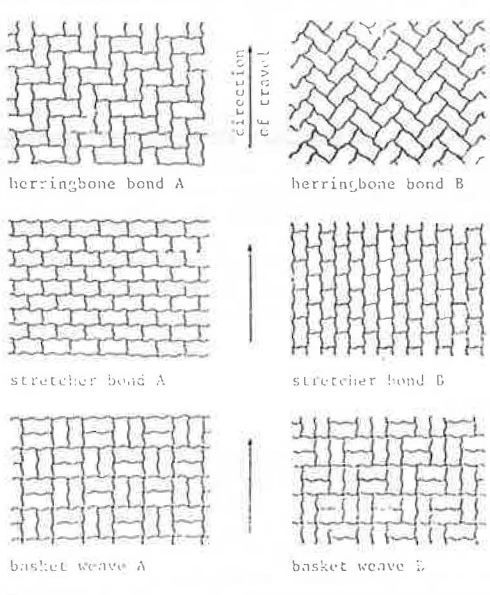

FIGURE 3 Most important laying patterns (bonds).

The most important disadvantages of concrete block paving are as follows:

1. A block pavement is not suited for vehicle speeds more than 50 to 60 km/hr because at high speed the fresh (granular) jointing sand is sucked away or, when the road surface is wet, washed away by the vehicle tires, which causes a loss of cohesion in the block layer and faster deterioration (rutting, rotating, and possibly pulling out of the blocks); furthermore, the riding quality is low.
2. The rubber of tires and the spillage of oil, soil, and so on, under traffic within some 6 to 12 months lead to a certain amount of imperviousness (luting) of the jointing sand (which leads to more load spreading in the block layer); nevertheless the joints remain more or less permeable. Therefore not only is a considerable crossfall (about 1:30) necessary, but also the drainage of the pavement requires special attention.
3. Under traffic the blocks may creep (move in the direction of travel) and they may be pressed away sideways. Because of the slight differences in the horizontal dimensions of the blocks (which means narrow joints everywhere) these movements are small, provided the joints are well filled and there is an adequate curb; the laying pattern and the block type are also important.
4. Block laying by hand, especially the traditional craft method, is rather labor intensive (which is not always a disadvantage), but the pavior has a difficult profession (injuries of the back occur frequently). The chance of injury and possibly the construction cost can be reduced by the so-called lay-down method and by mechanized block laying (in which about 1 m^2 of concrete block is laid on the prepared bedding sand layer at one time with a small machine).

Applications

Concrete block pavements are well suited to the following uses (3,4):

1. Trafficked zones in built-up regions, e.g., pedestrian walkways, residential streets, parking lots, bus stops, and fuel stations, in which frequently there are cables and piping, traffic speed is low, spillage of oil and fuel sometimes occurs, a functional division is often desired, and aesthetics can be important;
2. Trafficked zones in rural areas, especially rural roads and farmyards, in which both traffic intensity and traffic speed in general are low, but axle loads can be heavy and dirtying by such agents as soil frequently occurs (which may contribute to a fast luting of the jointing sand);
3. Industrial yards like factory grounds and container terminals, in which settlement often occurs (almost all container terminals are situated on reclaimed land in alluvial areas), the traffic loads are heavy, and the contact pressure is often high (stacked containers);
4. Small and irregular surfaces; and
5. Temporary pavements (recycling).

Laying Patterns

Concrete blocks can be laid in different patterns (bonds); the most important bonds are shown in Figure 3 (3-5). With rectangular blocks and some nonrectangular blocks (e.g., Uni blocks) all patterns can be made, but many nonrectangular blocks fit together in just one way, so these blocks can only be laid in one bond (e.g., Ipro blocks can be laid only in the stretcher bond).

The laying pattern, which can be used functionally, affects not only the horizontal movements of the blocks in the direction of travel and perpendicular to it but also the structural behavior (strength) of the block pavement under traffic. In this respect the herringbone bond is preferable to the stretcher bond and the basket weave.

AVAILABLE DESIGN METHODS

In countries with much experience in concrete block paving, the design consists of the selection of a suitable standard pavement given the traffic loads, the prevailing environmental and subgrade conditions, and the available materials. In other words design is based on the experience of the pavement engineer.

Outside western Europe a number of design methods have been developed that are partly modified for rigid and flexible pavements (11-15) or are based on the results of full-scale laboratory experiments (16-18). Until now no analytical methods were available that fully took into account the specific properties of the discontinued concrete block layer. Therefore a need was felt to develop such an analytical model so that a proper evaluation of the behavior of concrete block pavements could be made and it could be determined which factors are the key parameters that govern the behavior of such pavements. In the following sections the development of such an analytical model will be described and it will be shown how the key parameters vary with time.

MODELING OF THE CONCRETE BLOCK PAVEMENT

Even though the top layer of a concrete block pavement consists of small elements, it is tempting to analyze the concrete block pavement by means of linear elastic theory, assuming that the layers are homogeneous and isotropic. This is because graphs, tables, and computer programs are readily available for the analysis of linear elastic structures. In most cases, however, application of linear elastic theory to concrete block pavements will result in an improper description of the behavior of this pavement. This is best illustrated by Figure 4 in which a measured deflection profile and one simulated by linear elastic theory are shown. From Figure 4 one can observe that the deflection profile is rather peaked. Such a peaked profile can only be simulated by means of linear elastic theory by assuming a low elastic modulus for the concrete block layer, but even then the decay of the deflection with respect to the distance to the loading center is more gradual than the decay that is normally observed in the field. The inability of linear elastic theory to describe the deflection behavior of concrete block pavements has led to the conclusion that a better structural model for this pavement type should be used.

Finite-Element Model

In order to be able to include the discontinuities (joints) of a concrete block pavement, a finite-element program was used. For this case the ICES STRUDL program was selected because recently a special element type called the Rigid Body has become available that could be used for a proper schematization of the concrete blocks. This element was developed at the Structural Mechanics Division of the Delft University Civil Engineering Department (19).

The main features of this element are shown in Figure 5. It consists of a rigid undeformable body that is connected to other elements or other rigid bodies by means of linear springs. How this element is used with other elements in modeling a concrete block pavement is described in the following sections.

Concrete Block Layer

For this layer three assumptions were made: the blocks do not deform, no horizontal forces are transmitted by the joints, and the blocks do not rotate.

1. Deformation: In the pavement model the blocks are represented by rigid bodies because it was assumed that the deformation of the blocks themselves is negligible. This is a reasonable assumption because the Young's modulus of the concrete blocks is about 30 000 MPa, which is about 300 times larger than the Young's modulus of the bedding layer.
2. Horizontal forces: Deflection measurements on in-service concrete block pavements (20) as well as the behavior of two prototype pavements that were subjected to repeated plate loading tests (21) indicated that the shape of the deflection bowl was much like the deflection curve of a pure-shear-layer pavement. The failure mode that was observed on the prototype concrete block pavements was shear failure, and only a limited amount of bending was observed.
3. Rotation: Assuming that the concrete block layer behaves like a pure shear layer implies that no horizontal forces are transmitted in the joints and that no rotation of the blocks occurs.

The joints of the block pavement are represented in the model by linear springs (Figure 6). The underlying assumption is that the relative displacement between the blocks is so small that a linear joint stiffness is a reasonable estimate. The stiffness of these springs is denoted by k (in newtons per millimeter).

Bedding Sand Layer

As indicated in Figure 1, a bedding sand layer is constructed just beneath the block layer. In the model this layer is represented by vertical springs. This means that this layer cannot absorb bending moments either. The stiffness of these springs is represented by the bedding constant c (in newtons per cubic millimeter). Figure 7 shows the bedding sand layer.

Base, Subbase, and Subgrade

For modeling the base, subbase, and subgrade CSTG elements were used. This means that these layers are the only continuous layers in the system and that they are capable of absorbing bending moments.

Element Mesh

The element mesh that was used in the evaluation of concrete block pavements is shown in Figure 8. The

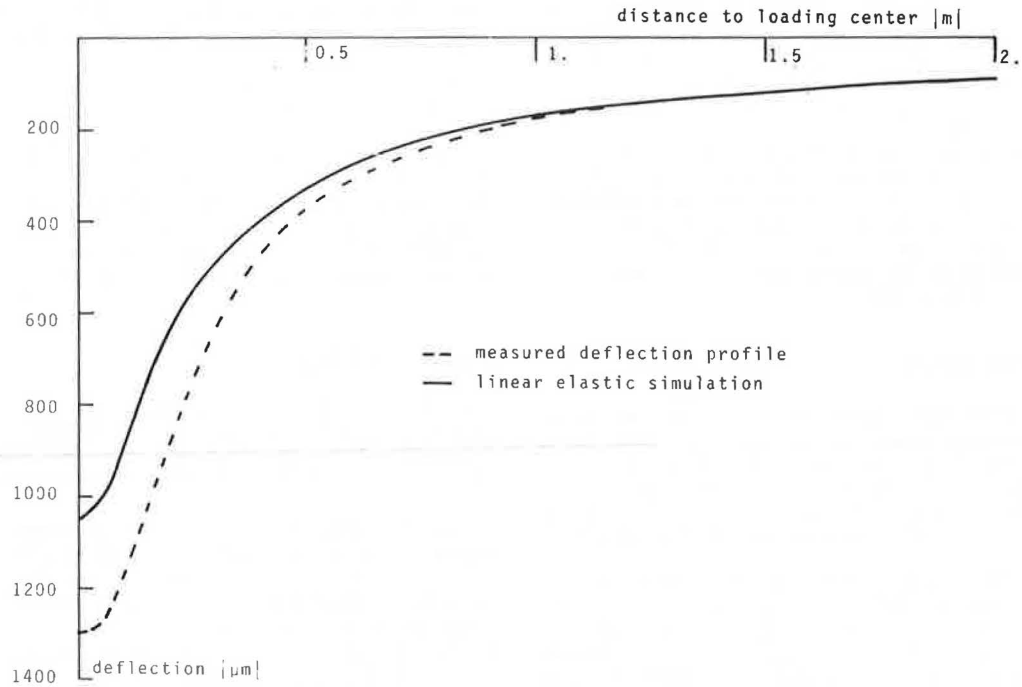

FIGURE 4 Measured deflection profile compared with profile simulated by linear elastic theory.

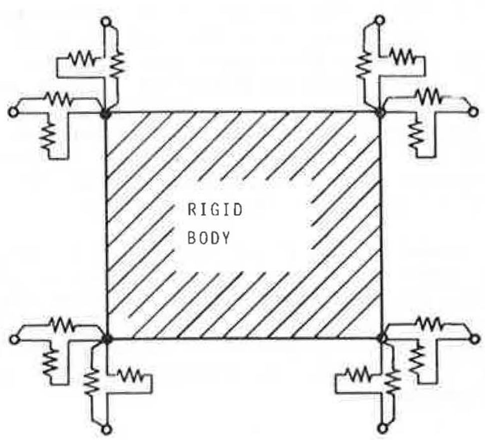

FIGURE 5 Rigid body element.

size of the rigid-body elements corresponds to a cut through herringbone bond B (see Figure 3). The calculations were made by assuming plain strain conditions. The load applied to the structure was a falling-weight-deflectometer (FWD) loading, which means a 50-kN load on a circular 0.3-m-diameter plate.

TESTING THE STRUCTURAL MODEL

The usefulness of the model was tested by simulating deflection bowls obtained from several in-service concrete block pavements. The measurements were carried out by means of the Delft University FWD (Figure 9).

It should be noted that the deflections were measured at six points that are located 0, 0.2, 0.3, 0.5, 1, and 2 m from the center of the loading plate. The deflections were measured close to the loading plate because in that region the largest de-

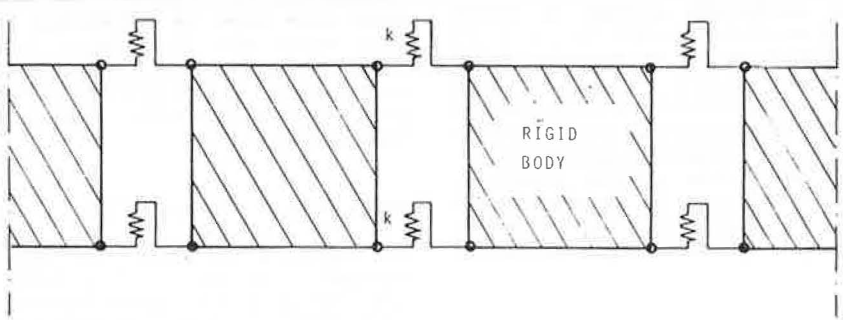

FIGURE 6 Modeling of the concrete block layer.

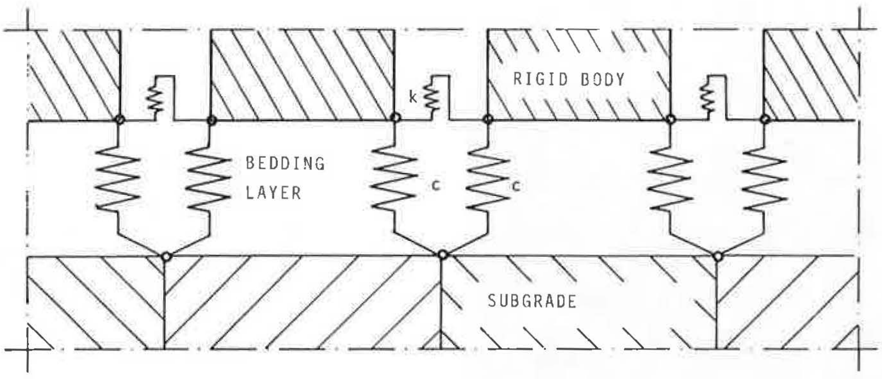

FIGURE 7 Modeling of the bedding sand layer.

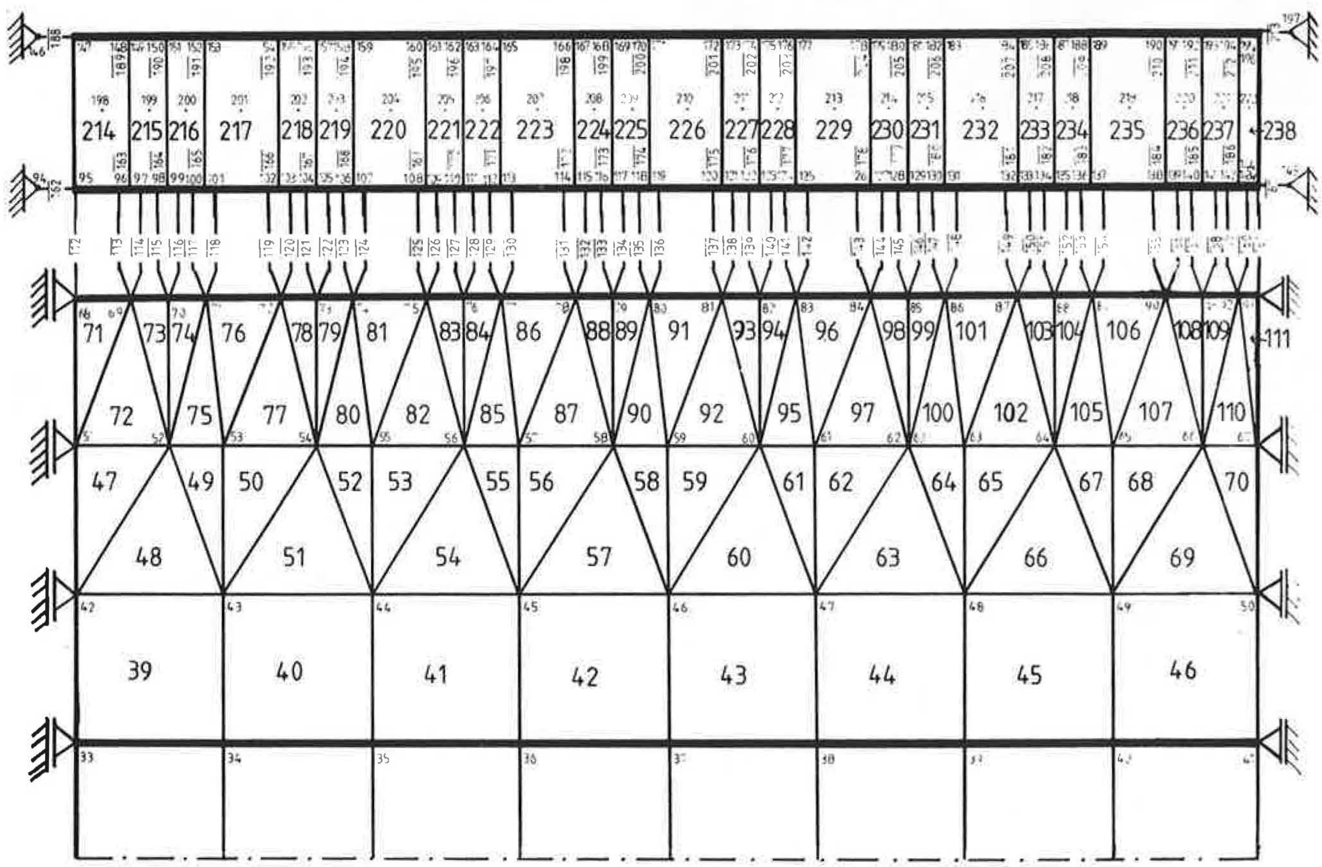

FIGURE 8 Finite-element mesh.

flection decay takes place. This decay needs to be measured accurately in order to be able to make precise estimates for k and c from the measured deflection profile.

The measured deflection profiles were simulated by means of the ICES STRUDL program in the following manner. First the subgrade modulus was calculated from the deflection measured at 2 m from the loading center by means of the following formula (22):

$$\log E = 3.868 - 1.009 \log d_2 \qquad (1)$$

where E is the subgrade modulus in megapascals and d_2 is the deflection at 2 m from the loading center in micrometers (P = 50 kN). Next the joint stiffness (k) and bedding layer stiffness (c) were calculated from the measured deflection profile by means of trial and error. The resulting calculated deflection profile fitted well to the measured profiles. A typical example is shown in Figure 10 (23). Because in almost each case good correspondence between the measured and the simulated profiles could be obtained, it was concluded that the finite-ele-

FIGURE 9 Falling-weight deflectometer.

ment model adopted is indeed a proper schematization of the real pavement behavior, and it can therefore be used with confidence for design purposes. This will be discussed in a later section.

RELATION BETWEEN SURFACE CURVATURE INDEX AND STIFFNESS OF CONCRETE BLOCK JOINTS AND BEDDING LAYER

Because it is quite expensive to run the ICES STRUDL computer program, it is desirable to have a method for the selection of reasonably accurate starting values for k and c. It was therefore determined whether a first estimate of k and c could be obtained from the surface curvature index (SCI) of the measured deflection profile, because SCI is normally a good indicator of the stiffness of the pavement layers. SCI is defined here as follows:

$$SCI = d_0 - d_{0.5} \qquad (2)$$

where d_0 is the deflection at the loading center of the falling weight in micrometers (P = 50 kN) and $d_{0.5}$ is the deflection at a distance of 0.5 m from the loading center in micrometers. From the results of the simulations it appeared that such relations could indeed be derived. They are given in Figures 11 and 12.

With these relations a first estimate of k and c can easily be made. If these starting values are used for k and c, normally only two or three computer runs are needed to match the calculated profile with the measured one. It is obvious that these graphs are especially useful in the evaluation of existing pavements.

STRUCTURAL PERFORMANCE OF CONCRETE BLOCK PAVEMENTS

As might be expected, rutting is the most important defect that can be observed in concrete block pavements. There is usually a considerable amount of

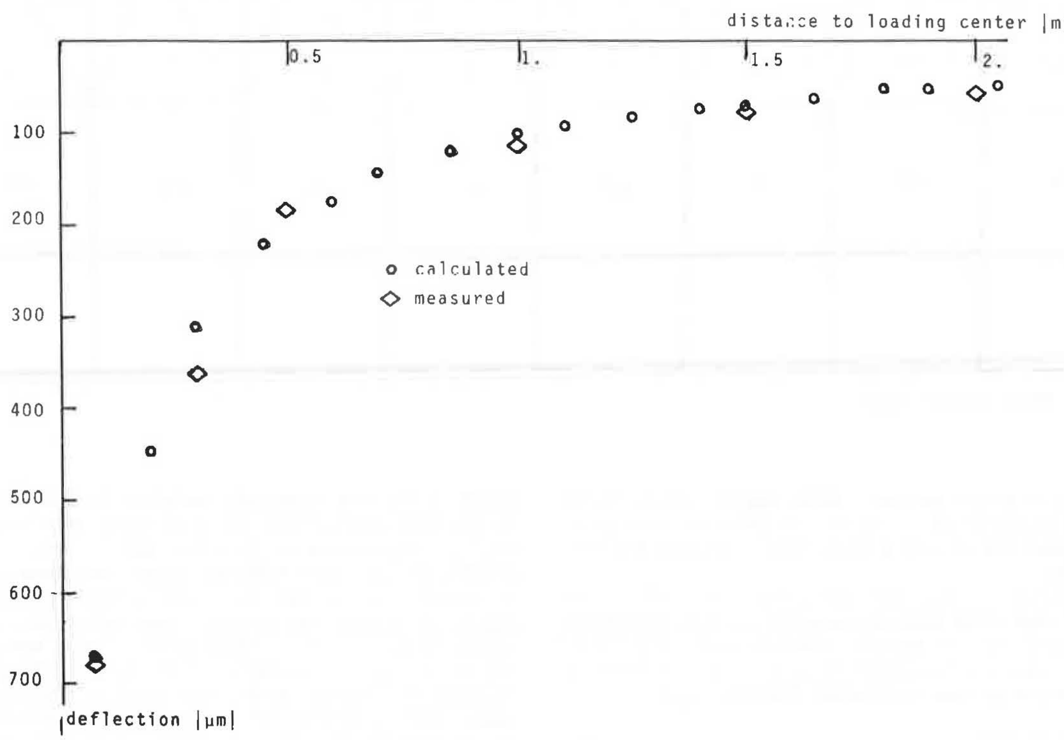

FIGURE 10 Agreement between measured and calculated deflection profiles for an in-service concrete block pavement.

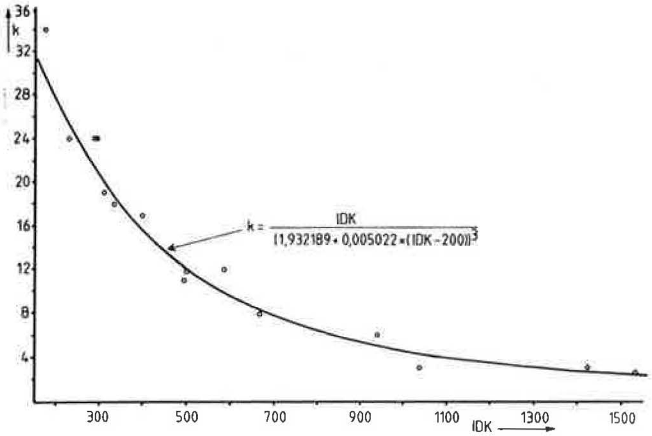

FIGURE 11 Relation between SCI and joint stiffness (k).

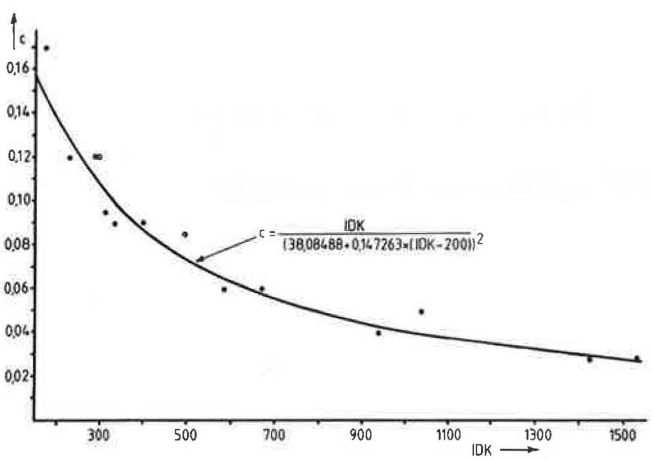

FIGURE 12 Relation between SCI and bedding layer stiffness (c).

initial rutting, which is mainly caused by postcompaction of the bedding layer, base, and subgrade. There is, however, a rapid decrease of the rutting rate with increasing number of load repetitions.

An interesting aspect of concrete block pavements is that the deflections decrease in time rather than increase, which is the case with flexible and rigid pavements. The decrease in deflection is caused by stiffening of the subgrade, base, bedding layer, and joints between the concrete blocks and is caused mainly by traffic and pollution or intrusion of fine material into the joints.

In order to be able to make a realistic design of a concrete block pavement one needs to have a proper insight into the stiffening of the construction with time. By means of a careful analysis of 20 different roads having a concrete block top layer it was possible to derive some of the most important time functions (Figures 13-16) (20,24). Figure 13 shows the increase of the subgrade modulus with respect to the number of 100-kN equivalent single axles. Figure 14 shows the decrease of the falling-weight SCI with respect to the number of 100-kN equivalent axles. It should be noted that the number of axles was not determined by means of axle-load surveys but is the best possible estimate. For instance, on most pavements the main part of the loading was caused by bus traffic; from the bus time schedule and the axle loads of the buses the total number of axle loads could be assessed. Figures 15 and 16 were obtained by combining the relations given in Figures 11, 12, and 14.

It is obvious that these time functions together with the number of equivalent axle loads are the most important parameters in the design of concrete block pavements. How they are used to develop tentative design charts is shown in the next section.

TENTATIVE DESIGN CHARTS FOR CONCRETE BLOCK PAVEMENTS

Based on the time functions for the subgrade modulus, bedding layer stiffness, and joint stiffness a number of computer runs were made with the ICES STRUDL program and subgrade E, k, and c values that are representative for different pavement ages or that occur after given numbers of load repetitions. From the calculated maximum deflection, the associated rut depth was derived by means of the following:

$$U_{pl_N} = \sum_{n=1}^{N} U_{el_n} \left(a n^{b}_{n+\Delta n} - a n^{b}_{n-\Delta n}\right) \quad (3)$$

where

U_{pl_N} = pavement deformation of a concrete block pavement after the design number of load applications (N),
U_{el_n} = maximum deflection occurring at the nth load repetition, and
a,b = constants.

For $n_{n+\Delta n}$, $n_{n-\Delta n}$, see Figure 17, which is a schematic representation of the above-mentioned rut-depth equation.

The rut-depth equation used is in fact the same as that developed by the Belgian Road Research Laboratory for use in the design of flexible pavements (25,26). It is modified in the sense that it takes into account the variation of the maximum deflection during the pavement life. It is obvious that the amount of rutting is dependent not only on the maximum deflection but also on the magnitude of the constants a and b. From the analysis of the 20 in-service and the two prototype concrete block pavements that were subjected to repeated plate loading tests, no accurate values for a and b could be derived. Nevertheless, it was concluded that a = 2 and b = 0.2 are reasonable estimates to be used in tentative design charts.

By using the results of the ICES STRUDL runs together with the rut-depth equation and the proposed values for a and b, charts were derived in which the number of years to a given rut depth can be determined from the average daily number of 100-kN single axle loads and the elastic modulus of the subgrade as constructed. An example of these charts is given in Figure 18, which is based on a final rut depth of 25 mm, a reasonable functional rut-depth limit. The structural rut-depth limit can be seen as 35 mm.

It should be noted that Figure 18 is not really a design chart. It is in fact a performance expectation chart; i.e., the pavement engineer is able to determine how well the concrete block pavement will perform given the prevailing subgrade conditions. If the expected pavement life is considered too low, the subgrade modulus can be improved by applying heavier compaction or by applying a base.

Efforts are now being made to determine the effect of including a base on the life of a concrete

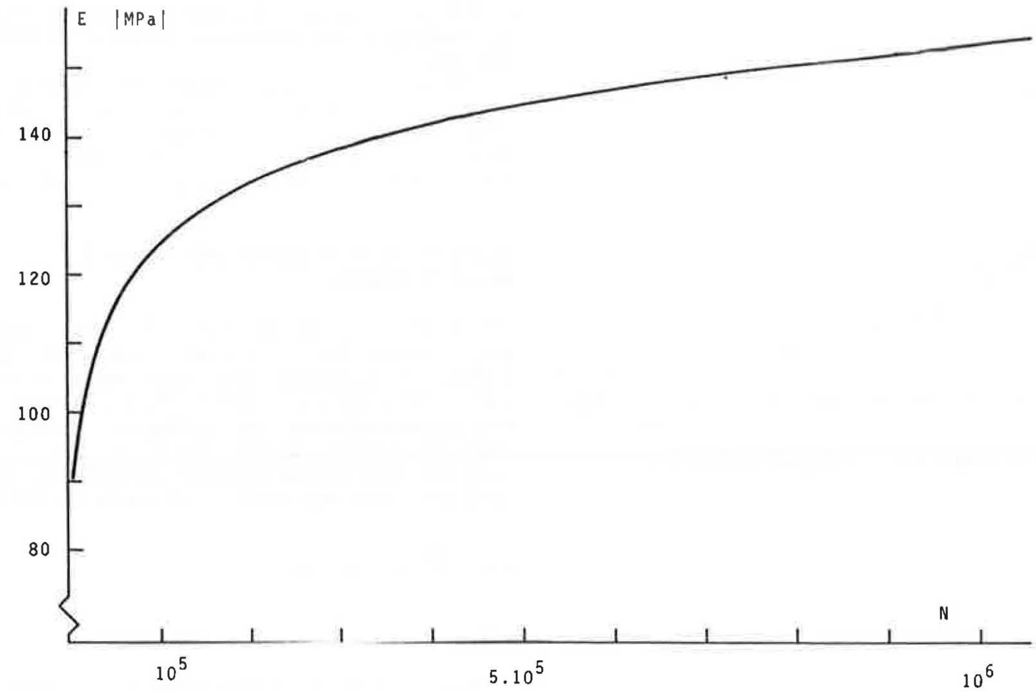

FIGURE 13 Relation between number of equivalent 100-kN single axles (N) and increase in subgrade modulus (E).

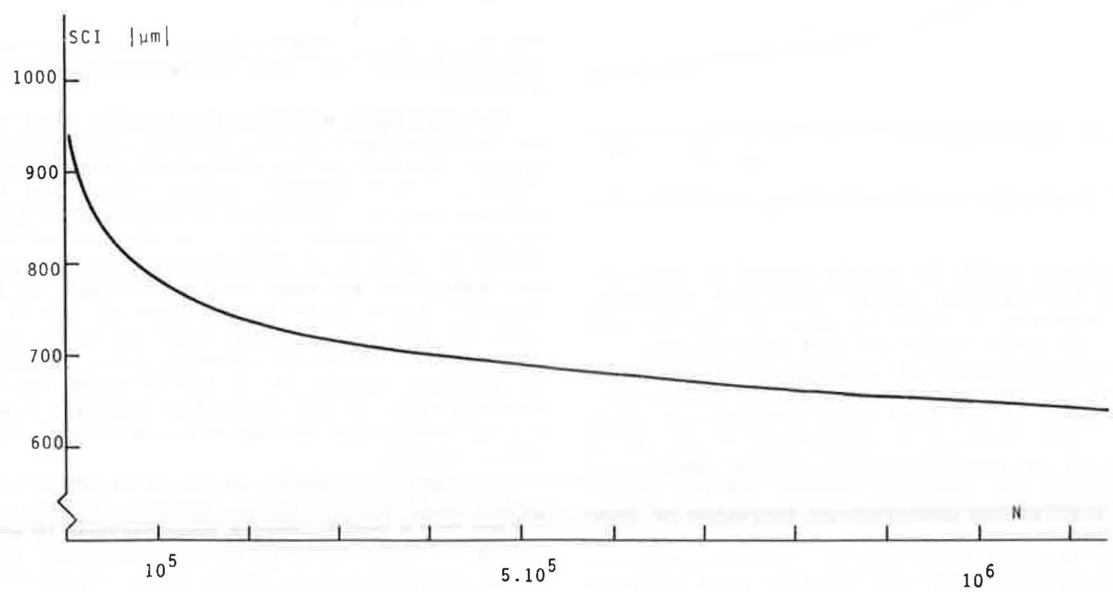

FIGURE 14 Relation between the number of equivalent 100-kN single axles (N) and decrease in SCI.

block pavement. With this determination the method presented can be used as a real design method, because then it will be possible to select base thickness and base stiffness in relation to the subgrade stiffness, number of load repetitions, and allowable rut depth.

CONCLUSIONS

Based on the results of the analysis of concrete block pavements presented here, the following main conclusions can be drawn:

1. Concrete block pavements can be modeled by means of a finite-element model consisting of rigid body elements representing the undeformable concrete blocks;

2. By means of the finite-element model an excellent correspondence between the calculated and measured deflection profiles is obtained;

3. The maximum deflection as well as SCI as measured on concrete block pavements decrease with increasing number of load repetitions, and the subgrade modulus as well as the joint stiffness and

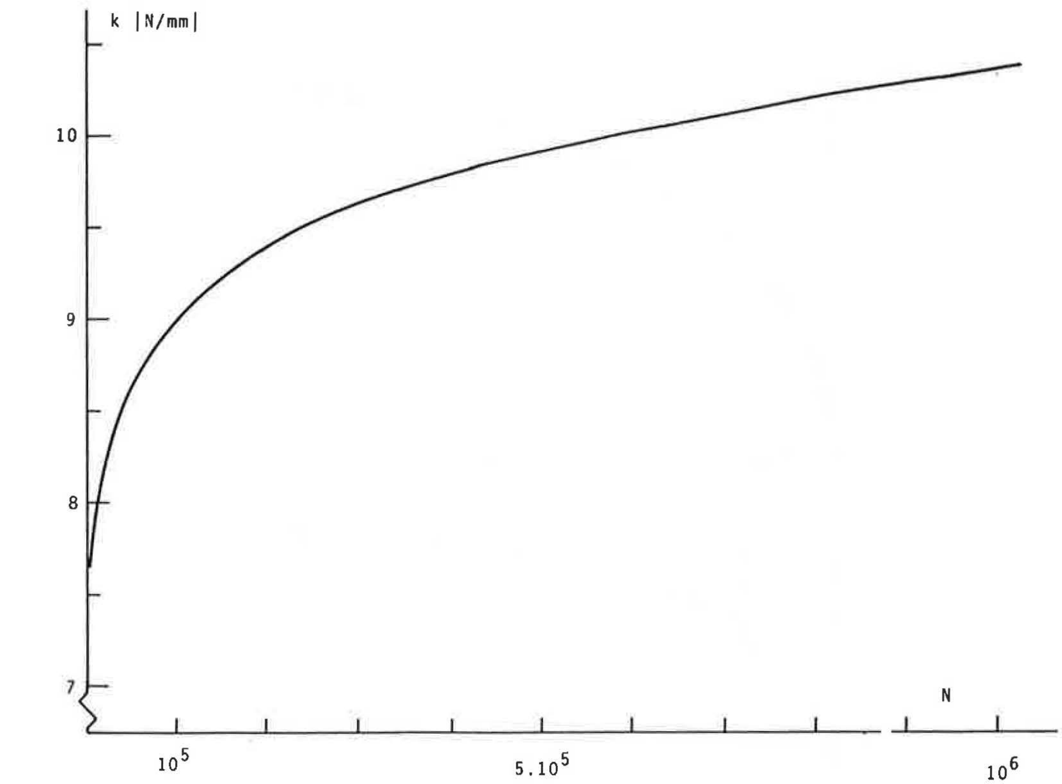

FIGURE 15 Relation between number of equivalent 100-kN single axles (N) and increase in joint stiffness (k).

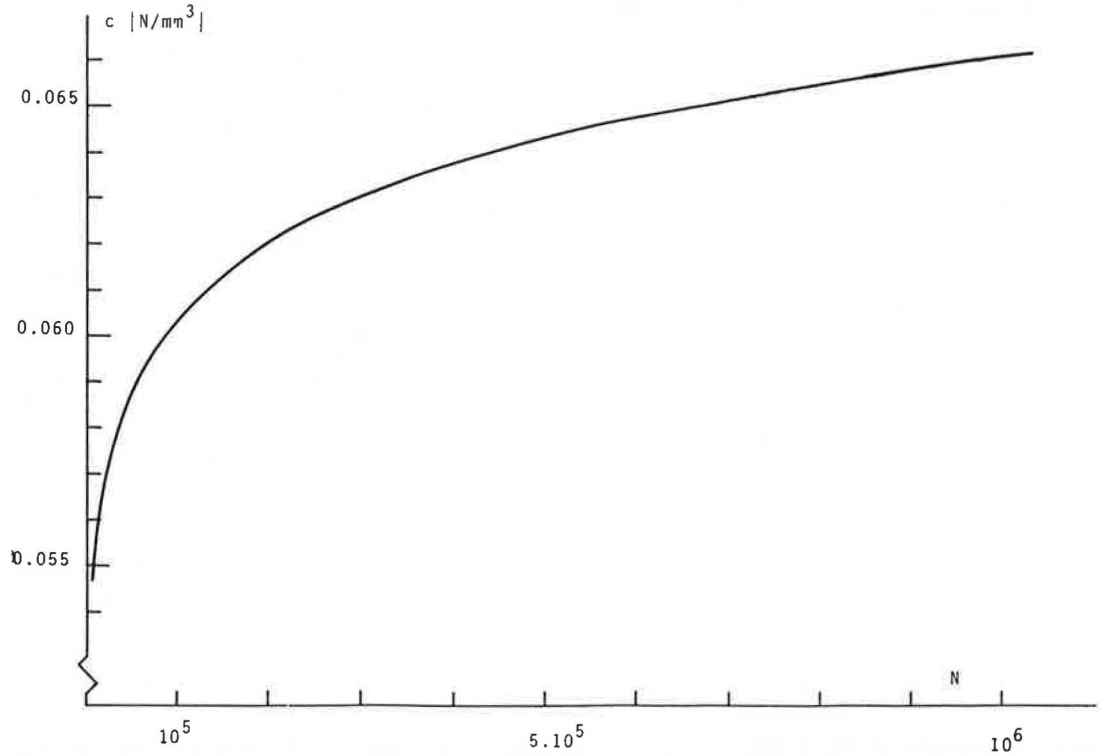

FIGURE 16 Relation between number of equivalent 100-kN single axles (N) and increase in bedding sand layer stiffness (c).

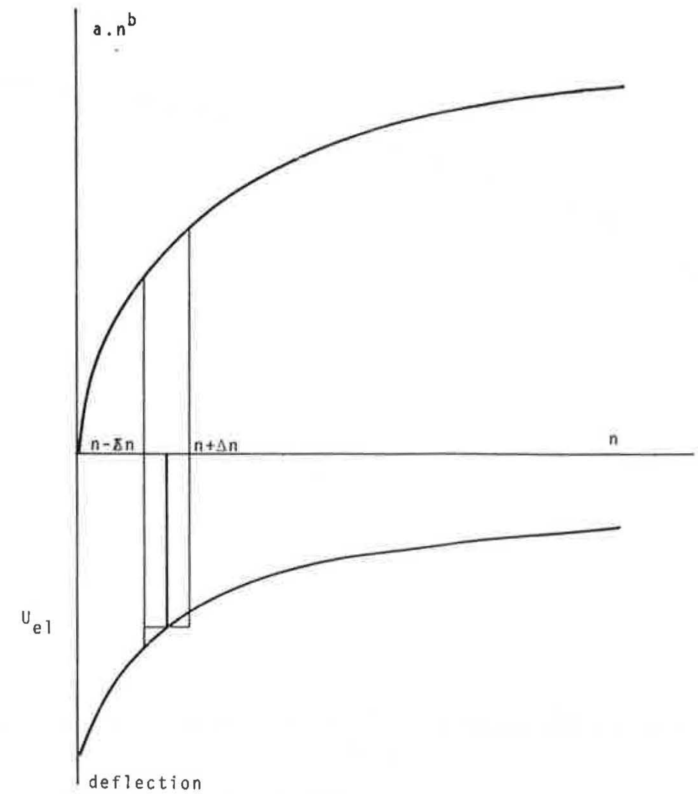

FIGURE 17 Schematic representation of the rut-depth equation.

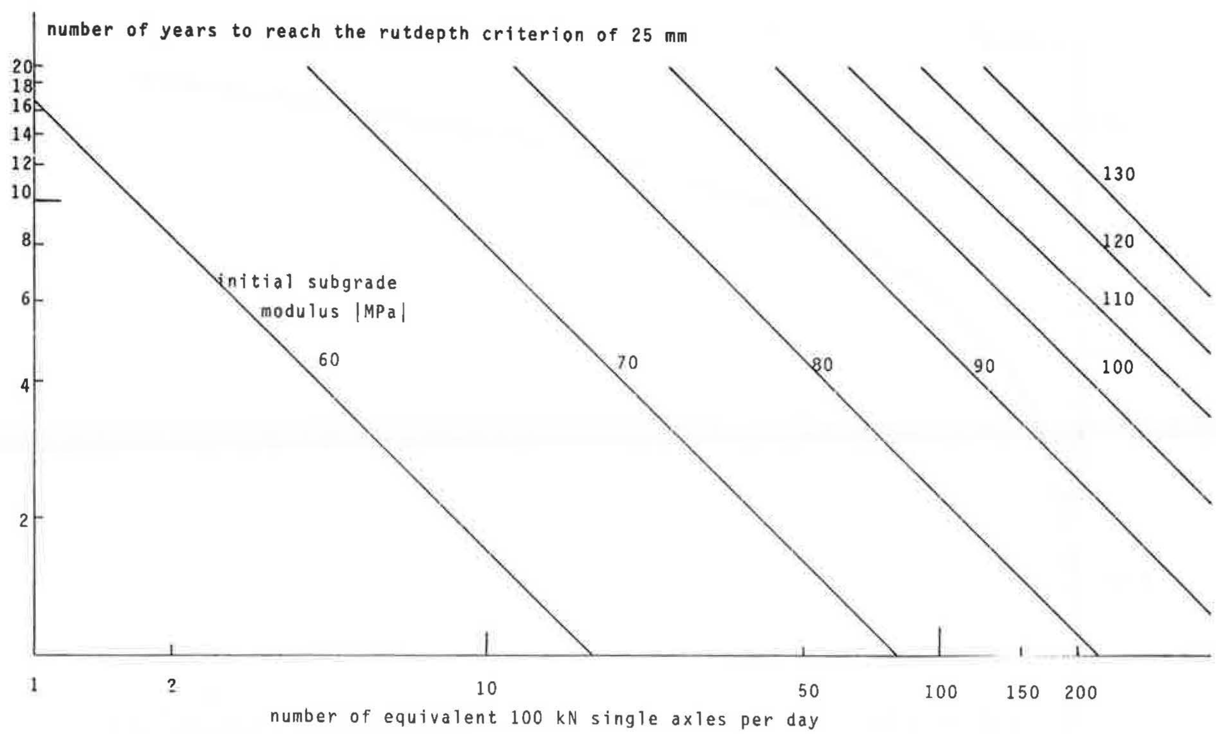

FIGURE 18 Pavement life in relation to average daily equivalent 100-kN single axle loads, initial subgrade modulus, and rut-depth criterion of 25 mm.

bedding-layer stiffness increase with increasing number of load repetitions; and

4. Based on these time functions, tentative design charts for concrete block pavements have been derived.

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