MODELING AND STRUCTURAL DESIGN OF A CONCRETE BLOCK PAVEMENT SYSTEM

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SUMMARY

The application of concrete block pavements is developing very fast due to their resistance to deformation, their durability, easy and rapid construction, their ability to carry traffic immediately after construction, the possibility of reusing the concrete blocks, and their compatibility with the environment and aesthetic features. The application of mechanistic methods of design and finite element theory to concrete block pavements is therefore suggested as a good alternative to experimental methods. In this research the behavior of concrete block pavements was studied by using the finite element method. First, the components of the concrete block pavement system were modeled using slab analysis finite element software called SAFE. The results were compared against those from an existing valid model and after the reliability of the developed model had been confirmed, the structural behavior of this pavement system in different block-laying patterns was studied. As a result of this research, a base thickness design chart has been developed which is in accordance with the ICPI's design chart.

1. INTRODUCTION

Various methods are available for designing concrete block pavements, all of which are based on different analysis software. The advent of high-speed digital computers has made it possible to develop software with high processing speeds and user-friendly interfaces. One software package that can be used for analyzing a concrete block pavement system is SAFE (Slab Analysis Finite Element). In this program, each of the components of different concrete block-laying patterns, as well as the other pavement layers, is modeled to study the slab performance. The structural behavior of this pavement system was studied by specifying the parameters and using them as inputs into the software. Based on the results of the models analyzed, an aggregate base thickness design chart has been developed which is in accordance with the design chart published by the ICPI (Interlocking Concrete Pavement Institute).

2. BACKGROUND

Several approaches to the analysis of block pavements have been described:

a) Modified slab analysis (Potter and Donald 1984; Braker et al.1982).
b) Layered elastic analysis (Shackel 1982; Houben et al. 1982).
c) Finite element analysis (Houben et al. 1982; Nishizawa et al.1984).

With layered elastic theory, the pavement is modeled as a succession of layers, each having linear elastic properties. Prior to the advent of high-speed digital computers in the 1960s, little progress was made with the analysis of layered systems. Since that time a variety of elastic solutions has been published, including such widely known programs as CHEVRON, ELSYM, BISTRO and CIRCLY (Shackel 1988). Most of these programs require mainframe computers and are relatively cumbersome. After the advent of high-speed digital personal computers with high data-processing ability, many useful packages were developed for analyzing and designing concrete block pavements. The best known of these are LOCKPAVE (Shackel 2000), BLPPAVE 3D (Nishizawa 2003) and DELPAVE (Huurman et al. 2003). By using the SAFE finite element software and inputting the dynamic properties of slabs, the authors modeled concrete block pavements in different block-laying patterns, i.e. herringbone, stretcher and parquet.

SAFE software has strong graphic tools for drawing different paver shapes and laying patterns, a mesh-generator system, the capability of creating different load combinations for each layer, the capability of modeling various wheel load configurations and output contours, and the capability of showing the pavement's response to loading by 3D animation.

3. MODELING THE CONCRETE BLOCK PAVEMENT STRUCTURE

3.1 Modeling the Concrete Block Layer

In contrast to cement concrete and asphalt pavements, the surface course of concrete block pavements consists of two different materials, namely concrete blocks and joint sand. In this research, each concrete block was modeled as a small concrete slab using a shell element in the software. The joint sand was modeled as a sand slab with a width of 2 to 4 mm and a thickness equal to the thickness of the block, using the shell model. SAFE software has the ability to assign many nodes within the interface of the two materials automatically. This means that sufficient adherence and full contact are established between all the materials. A non-homogenous, but adhesive and steady, layer is formed between all the elements of the block layer. The bedding sand layer is defined as a set of springs beneath the concrete block layer. A schematic representation of the modeled concrete block layer and bedding sand is shown in Figure 1.

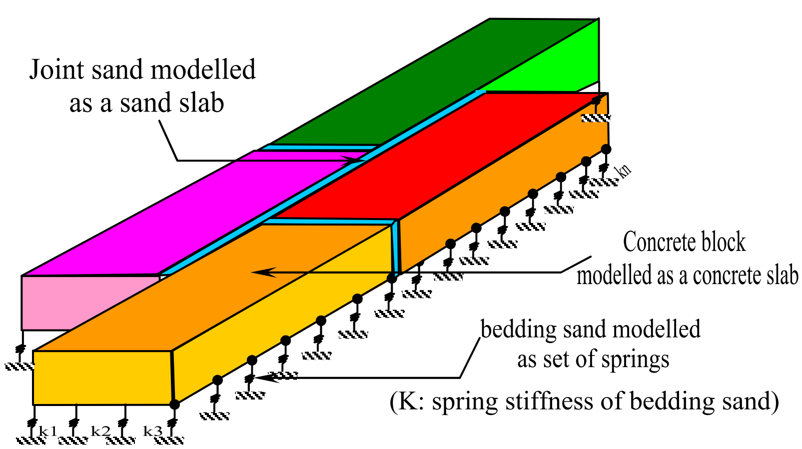


Figure 1. Schematic representation of the concrete block layer and bedding sand layer as modeled using SAFE software

3.2 Modeling the Base Layer

The base layer of the block pavement system was modeled as a homogenous slab placed on set of springs. The stiffness of the springs is equal to the reaction modulus of the base layer below.
A schematic representation of the base layer modeled by the software is shown in Figure 2.

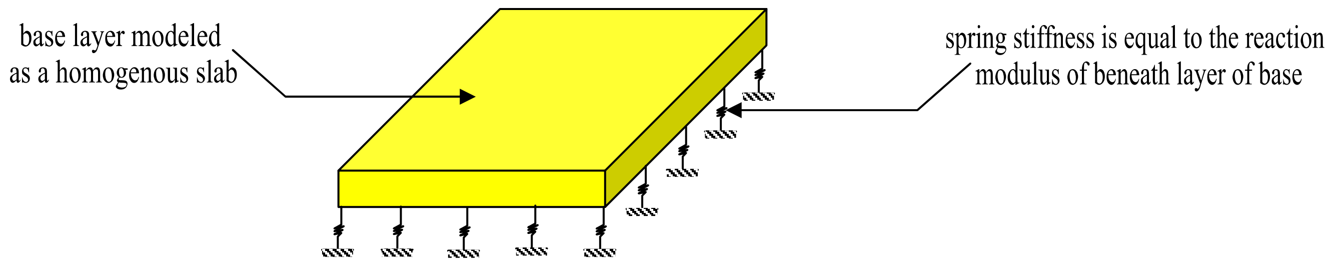


Figure 2. Schematic drawing of the base layer on the spring supports

4. GEOMETRIC DRAWING OF MODELS

The first step in modeling is drawing the components. As the blocks can have different laying patterns and shapes for the geometric description of the model, coordination of the different meshes used in the horizontal and vertical directions is introduced into the software for describing the blocks and joint sand. In this research, rectangular blocks of 200 x 100 x 100 mm were modeled, with sand-filled joints having 3 mm widths. The block-laying patterns used were herringbone, stretcher, parquet and square block. The square blocks had the same area as the rectangular blocks that were modeled in order to study the effect of the block shape on the pavement's structural behavior. Figure 3 shows the different block-laying patterns in a 2 x 2m panel modeled by SAFE software.

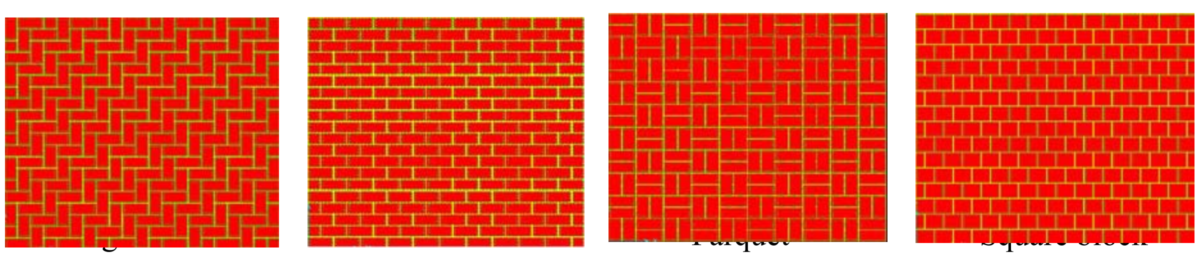


Figure 3. Different block-laying patterns in a 2× 2 m panel

5. INPUT DATA

The input data for each of the components are:

- Elasticity modulus
- Poisson's ratio
- Unit weight
- Bending thickness in the X and Y directions
- Twisting thickness.

In this research the bending thickness in the X and Y directions and the twisting thickness are equal to the thickness of the block.

6. LOADING PATTERNS

In the load definition, the type of the load, and the different loading combinations and their coefficients can be specified. In this paper, an 8.2 ton single axle load has been modeled by using a 41 kN single wheel load at the center of the pavement. This load was uniformly distributed over a square area with sides of 270 mm, which makes the contact pressure 600 kPa.

7. OUTPUT DATA

The outputs of the software after the analysis of each layer are as follows:

- Vertical stress
- Displacement
- Bending moment and shear forces in both directions.

In order to compare the results of the model with the case study (Nejad 2003), the material properties listed in Table 1 were used.

Table 1. Material properties as input data (Shackel 1979)]

Layer	*Elasticity Modulus (MPa)*	*Unit Weight (kN/m^3)*	*Poisson's Ratio*	*C (kN/m^3)*	*Φ (Deg)*
Concrete block	2500	20	0.3	-	**-**
Bedding and joint sand	350	18	0.35	10	**30**
Base	225	18	0.35	10	**30**
Subgrade	225	18	0.35	10	**30**

The results obtained from the analysis of the models and from the case study (Nejad 2003) are compared in Figure 4.

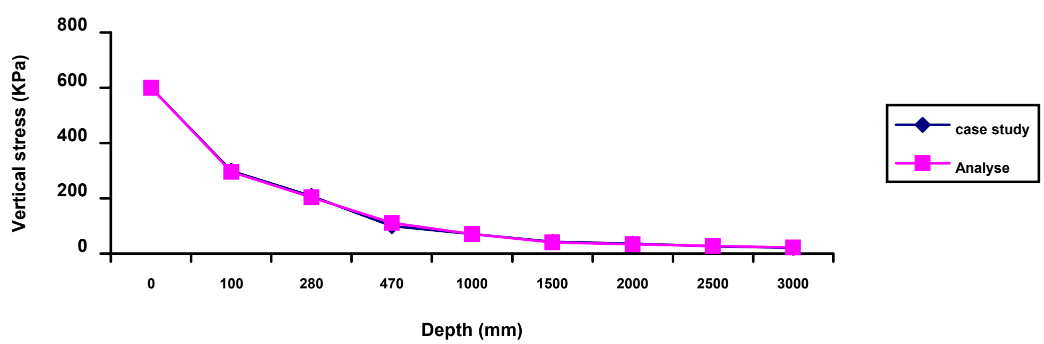


Figure 4. Comparison of the results obtained from the analysis with those from the case study (Nejad 2003)

8. STUDY OF THE BEHAVIOR OF CONCRETE BLOCK PAVEMENTS

Before the design methods are developed, it is necessary to understand the behavior of this pavement system correctly. For this, the factors affecting the performance of concrete block pavements must be determined. Table 2 shows these factors.

Table 2. Factors affecting the performance of concrete block pavements (Shackel 2003)

Pavement Component	Factors Affecting Performance under Traffic
Pavers	▪ Paver shape ▪ Paver thickness ▪ Paver size ▪ Laying pattern ▪ Joint width
Bedding and jointing sands	▪ Sand thickness ▪ Grading ▪ Angularity ▪ Moisture ▪ Mineralogy
Basecourse and subbase	▪ Material type ▪ Grading ▪ Plasticity ▪ Strength and durability
Subgrade	▪ Soil type ▪ Stiffness and strength ▪ Moisture regime

Using the parameters shown in Table 2, the effect of both the block and joint sand thicknesses on the structural behavior of the block layer in different block-laying patterns was investigated.

8.1 Effect of block thickness

Figure 5 shows the results for the different block-laying patterns. By increasing the thickness of the block layer, the stress generated below this layer decreases. There is a greater decrease in stress with the herringbone pattern than with the other patterns and the herringbone pattern performs better than the other patterns.

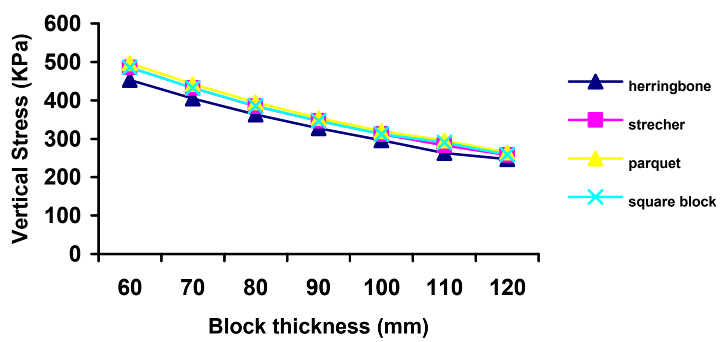


Figure 5. Stresses caused below the block layer by changes in the block thickness

8.2 Effect of bedding sand thickness

Figure 6 shows the effect of bedding sand thickness on vertical stress.

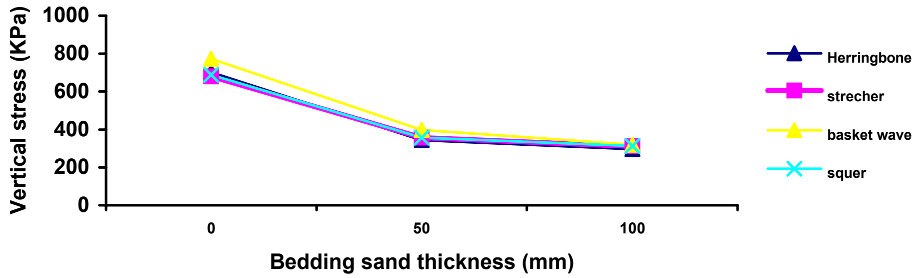
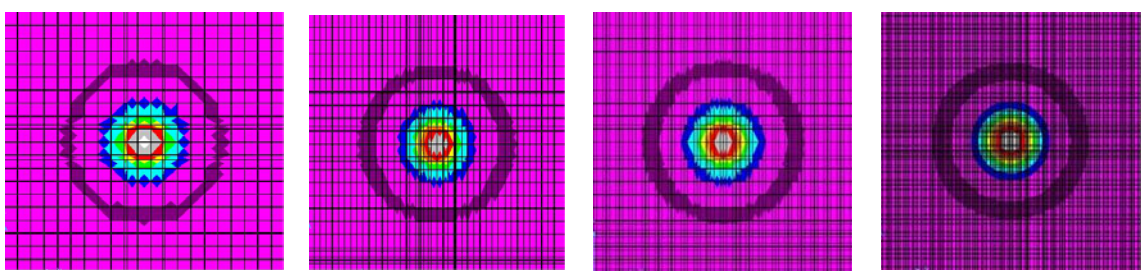


Figure 6. Vertical stress caused by changes in the thickness of the bedding sand below the block layer

As the contact pressure is 600 kPa, the results of the analysis (Figure 6) show that when the bedding sand thickness is zero, the block layer is not able to reduce the stresses caused by the imposed load. The stress below the block layer is also increased by the absence of joint sand because there is no contact between the blocks and the stress created by loading therefore cannot be distributed over the whole of the block layer. The imposed load will be distributed over just the few blocks located immediately under the contact area. When the thickness of the joint sand is equal to half that of the block layer (50 mm), the stress generated is considerably reduced. When the bedding sand thickness and the block layer thickness are equal (100 mm), the amount of stress is minimized.

9. STRESS DISTRIBUTION PATTERNS

Figure 7 shows the horizontal distribution of vertical stress under the block layer in each laying pattern.



Herringbone Stretcher Parquet Square block

Figure 7. Stress distribution beneath the block layer in the patterns studied

Figure 7 indicates that the vertical stress distribution in the herringbone block-laying pattern has an X, Y axis symmetry in comparison with the other patterns. The herringbone distribution pattern tends to be hexagonal, whereas with the other patterns the distribution is circular.

10. DESIGNING THE BASE THICKNESS

For pavement design, the overall response of a pavement to traffic needs to be assessed. To achieve this, a single wheel load of 41 kN for the number of repetitions (N) or a single axle load of 8.2 tons was used. In order to predict N, a failure mechanism must be postulated. Where unbound materials such as gravel or crushed rock are used, the pavement failure mode is assumed to be the gradual accumulation of permanent rutting deformation. Failure is commonly defined as being the result of excessive vertical compressive strain at the top of the subgrade. The failure criterion most widely used in block pavement design is deformation, developed by Claassen et al. (1977) as the basis of the Shell design procedure for flexible asphalt pavements. This can be written as:

$$\xi_z = \frac{2800}{N^{0.25}} \qquad (1)$$

where ξ_z = the permissible subgrade compressive strain (micro-strain)

The material properties of the different layers used in the design procedure are shown in Table 3.

Table 3. Properties of the pavement materials (Nishizawa 2003; Shackel 1979 and 1988)

Layers	*Elasticity Modulus (MPa)*	*Unit Weight (kN/m³)*	*Poisson's Ratio*
Concrete block	30,000	20	0.2
Joint sand	350	18	0.35
Base	980	18	0.35
Subgrade	10 × CBR	18	0.35

In this research, using the results obtained from the SAFE model, the compressive strains at the top of the subgrade were calculated and, by using the relationship obtained by Claassen (1977), the base thicknesses required for different CBR values and the number of allowable repetitions of a single axle load of 8.2 tons were determined using the procedure developed in this study. As an example, the required base thickness (h), the vertical strain and the number of allowable repetitions (N) for CBR = 10 are given in Table 4.

Table 4. Required base thicknesses (h), vertical strain and number of allowable repetitions (N) of a 41 kN wheel load for CBR = 10

h (mm)	ξ_z (micro)	N
5	224.77	24,081
10	117.45	323,013
15	74.925	1,950,406
20	56.7	5,947,027
25	46.5	13,146,807
30	40.5	22,846,098
35	36.6	34,630,652
40	34.4	43,893,312

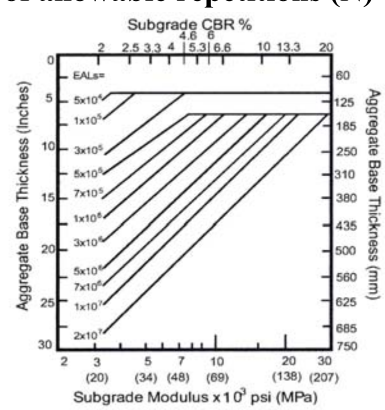


Figure 8. Base thickness design chart for granular materials (ICPI Tech. Spec. 4, 2003)

The thickness obtained for the base in this study, as shown in Table 4, corresponds closely to the thickness of the base at CBR = 10 as shown in Figure 8. Figure 9 shows the required base thicknesses for subgrades having different CBRs, for 2,000,000 wheel load repetitions of 41 kN. Figure 10 is a design chart for different CBRs.

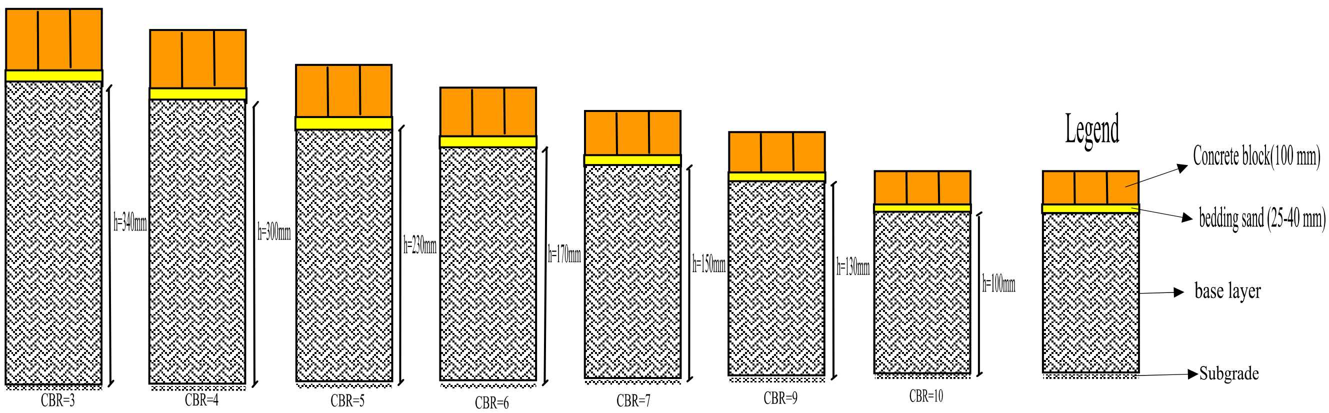


Figure 9. Required base thickness for various subgrades CBRs, for 2,000,000 wheel load repetitions of 41 kN or a single axle load of 8.2 tons

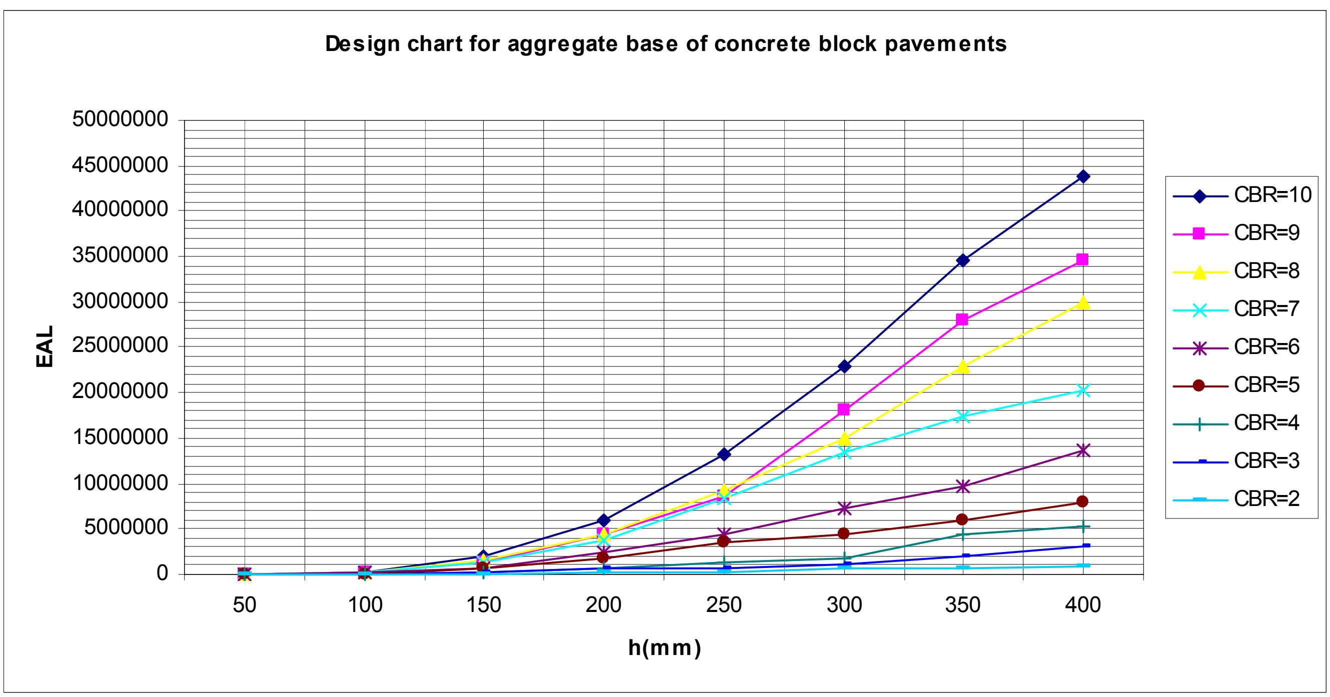


Figure 10. Aggregate base design chart compiled from this research for different subgrade CBRs

11. CONCLUSIONS

- The advent of high-speed computers has allowed the development of design and analysis software for concrete block pavements. SAFE finite element software can be used for this purpose. The software is user-friendly and the parameters that can be specified include the elasticity modulus, Poisson's ratio, thickness and unit weight. This software has a variety of outputs that can be used to study the structural behavior of concrete block layers, bedding sand and other layers.
- By using the SAFE software, different block-laying patterns with desirable block sizes can be modeled. Various loading combinations and different wheel configurations can also be assessed with this software. These capabilities make it possible to model concrete flag pavements as well.
- By studying the models obtained with the software, it can be seen that joint sand is one of the vital components of concrete block pavement systems. If joint sand is not used, the stresses from loading will not be distributed over the block layer and the pavement system will not be able to perform well.
- After analyzing the models of different block-laying patterns in this research, it is concluded that the herringbone block-laying pattern yields better performance than the other patterns.
- Using the results of this analysis, an aggregate base thickness design chart has been developed which can be compared with the ICPI base thickness design chart.

12. REFERENCES

Braker, W.R. Branston, W.N. and Chou, Y.I., 1982. A general system for the structural design of flexible pavements. Proc. 5th Int. Conf. on Structural Design of Asphalt Pavements.

Claassen, A.I.M., Edwards, J.M., Sommer, P. and Uge, P, 1977. Asphalt pavement design –The Shell method. Proc. 4th Int. Conf. on Structural Design of Asphalt Pavements, Ann Arbor, Michigan, USA.

Houben, L.J.M., Molenaar, A.A.A., Fuchs, G.H.A.M. and Moll, H.O., 1982. Analysis and design of concrete block pavements. Proc. 2nd Int. Conf. on Concrete Block Paving, Delft, the Netherlands, pp. 86-99.

Huurman, M., Houben, L.J.M., Geense, C.W.A. and Van der Vring, J.J.M., 2003. The upgraded Dutch design method for concrete block road pavements. Proc. 7th Int. Conf. on Concrete Block Paving, Sun City, South Africa, pp 1-22.

ICPI, 2003. Structural design of interlocking concrete pavements for roads and parking lots. Tech. Spec. 4, Interlocking Concrete Pavement Institute, Washington, DC, U.S.A.

Nejad, F.M., 2003. Finite element analysis of concrete block paving. Proc. 7th Int. Conf. on Concrete Block Paving, Sun City, South Africa, p 41.

Nishizawa, T., Matsono, S. and Komura, M., 1984. Analysis of interlocking block pavements by finite element method. Proc. 2nd Int. Conf. on Concrete Block Paving, Delft, the Netherlands, pp 80-85.

Nishizawa, T., 2003. A tool for structural analysis of block pavements based on 3DFEM. Proc. 7th Int. Conf. on Concrete Block Paving, Sun City, South Africa, p 1-4.

Potter, D.W. and Donald, G.S., 1984. Revision of NAASRA Interim Guide to Pavement Thickness Design. Paper presented at the 12th ARRB Conf., Hobart, Australia, *Aust. Rd Res*. **15**(2), pp 106-08.

Shackel, B., 1979. An experimental investigation of the response of interlocking block pavements to simulated traffic loading. Australian Road Research Board, Research Report ARR 90, pp 11-44.

Shackel, B., 1982. The systematic design and construction of heavy-duty industrial interlocking concrete block pavements. Proc. Biennial Conf. of the Concrete Masonry Association of Australia, Perth, Australia.

Shackel, B., 1988. Computer-aided design and analysis of concrete segmental pavement. Proc. Workshop on Interlocking Concrete Pavements, p 61.

Shackel, B., 2000. The development and application of mechanistic design procedures for concrete block pavements. Proc 6th Int. Conf. on Concrete Block Paving, Tokyo, Japan, p 11.

Shackel, B., 2003. The challenges of concrete block paving as a mature technology. Proc. 7th Int. Conf. on Concrete Block Paving, Sun City, South Africa, p 52.