A STUDY ON BEHAVIOR OF BLOCK PAVEMENT USING 3D FINITE ELEMENT METHOD

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SUMMARY

Three dimension finite element analyses were conducted on concrete block paving. In order to verify the calculated results, an experimental case study was analyzed. Good agreement was observed between the measured and the calculated results. Based on the finite element analysis results and available failure models, comprehensive design charts were developed for port and industrial pavement which can take into account the subgrade and pavement layers properties as well as the tire pressure and the number of repetitive loads. In addition, by using 3D finite element model, mechanisms of interlock among pavers were discussed. Parametric studies were conducted on 3D models and it was found that jointing width, shape, size and thickness of blocks have a significant influence on the behavior of block pavement.

1. INTRODUCTION

Finite element method is one of the strict ways to design of concrete block pavement which considers the discontinuous nature of block pavers. It is difficult to model block pavement by finite element for structural analysis because their layers consist of a large number of very small elements especially while using herringbone pattern. In this study, the analysis of the 3-dimensioned finite element model was carried out using the ANSYS finite element package. In order to determine the accuracy of the above analyses, a comparison was made between the vertical displacements of pavement obtained from analysis with those measured from a case study which are discussed in the following sections. In addition, the finite element analysis was incorporated in design charts for port pavement. This paper discusses finite element analysis results relating to the effect on pavement performance by changing parameters such as joint width, concrete block characters such as shape, thickness, size and compressive strength associated with concrete blocks.

2. BACKGROUND

The analysis presented by Nishazawa at al. (1984) was restricted solely to a consideration of the block surfacing but was valuable in providing theoretical confirmation of the difference in performance of pavement installed in different lying patterns. The study conducted by Molenaar et al. (1984) and Houben et al. (1984) demonstrate that finite element analysis was capable of describing pavement behavior more accurately than elastic layer theory. Two and three dimensional finite element model was made by Nejad et al. (2003) and consists of all component of concrete block pavement and uses solid elements for simulation. In this analysis in which concrete blocks are laid in a herringbone pattern, there is a good agreement between calculated results with linear and non-linear FE models and the measured result from the case study.

3. FINITE ELEMENT MODELING OF FOR BLOCK PAVEMENT

A 3-dimensional finite element model is shown in Figure 1 which the height, length and width of mesh are 755mm, 775mm and 450mm respectively. It consists of blocks 106mm wide, 212mm long, 80mm thick and laid in a herringbone pattern. The pavement structure is modeled as a combination of solid elements and contact elements. The blocks, subbase, subgrade, joints and bedding sand are divided into solid elements and the interface between block and sand joints are represented by contact elements.

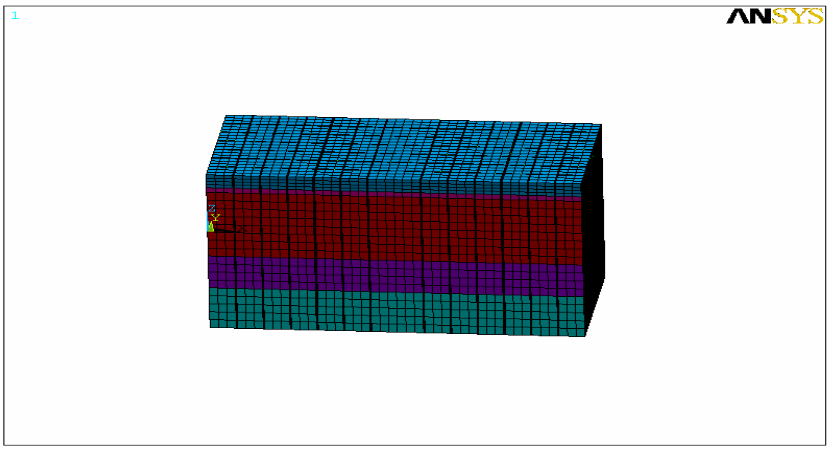

Figure1. Three – dimensioned mesh

Each layer has a finite horizontal intent and displacement is the normal direction and is fixed on all side faces of the layer. Other displacements are free. This boundary condition is not applied to the top layer. All displacements are fixed at nodes on the bottom most surface of the structure. Loads are applied on the surface as uniformly distributed circular shape.

3.1 Material Properties

Material properties used in this analysis are selected from case study reports and in the absence of specifications; properties recommended by Shackel (1990) were used. The layers properties are presented in Table 1.

Table1. Material Properties (Shackel, 1990)

	Geotechnical Parameters				
Material	E MPa	ρ ton/m^3	μ	C kN/m^2	ϕ Deg.
Conc. block	2500	2	0.3	---	---
Sand	350	1.8	0.33	---	41.08
Base	225	1.8	0.35	10	30
Subgrade	5.10	---	0.40	10	30

For this analysis, concrete block is considered to be elastic, bedding sand, base, subbase and subgrade layers were assumed to have perfectly plastic behavior and Drucker-Prager model (Drucker & Prager, 1952) was utilized as their failure criteria.

4. CASE STUDY

In order to evaluate the analysis results, a laboratory-scale test on block pavements was selected as a case study (Bikasha & Ashok, 2002). Figure 2 illustrates the vertical deflection of pavement against load which increased from 10kN up to 51kN.

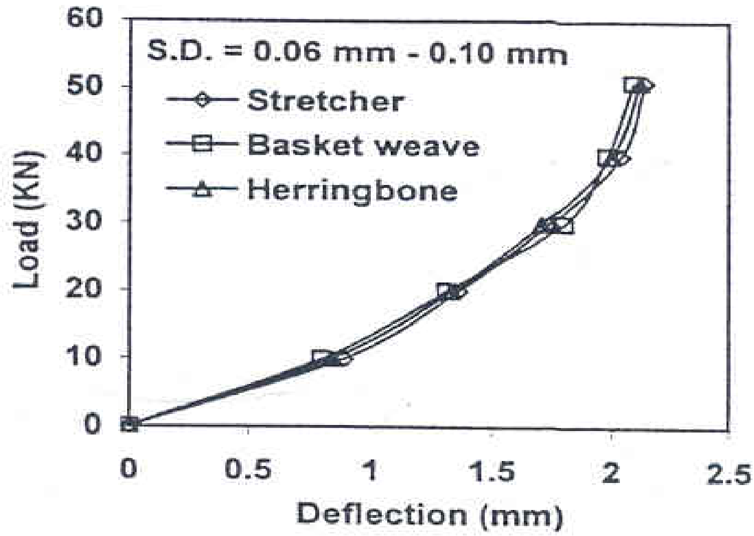

Figure 2. Deflection of block pavement against increasing load (Bikasha & Ashok 2002)

Figure 3 shows the vertical deflection of pavement under vertical load, for non-linear 3-dimensioned analysis. There is reasonable agreement between numerical and the laboratory-scale test results as has shown in Figure 4.

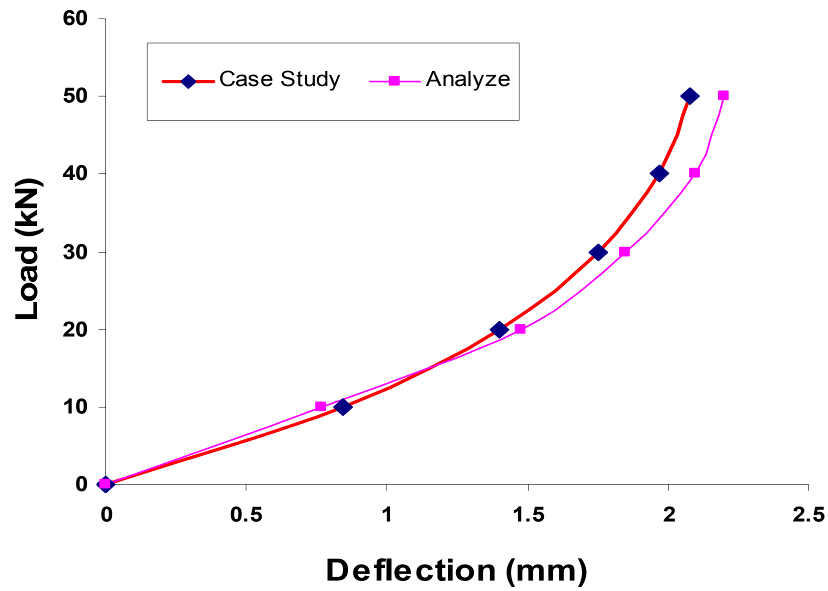

Figure 3. Deflection of pavement against increasing load for the finite element model and cues study

5. PARAMETRIC STUDY

The following results were obtained from parametric study using 3D finite element analysis:

5.1 Joint Width

Figure 4 shows the response of pavement for joint widths of 1.5~9mm. As the joint width decreases, the deflection of the pavement also decreases. Up to a certain point and then slightly increases with decrease in joint width. The optimum joint width is 2.3mm. An increase of joint width caused lower normal stiffness of the joints. More rotation and translations would occur in concrete blocks and there would be more deflections under the same load for joints of more width.

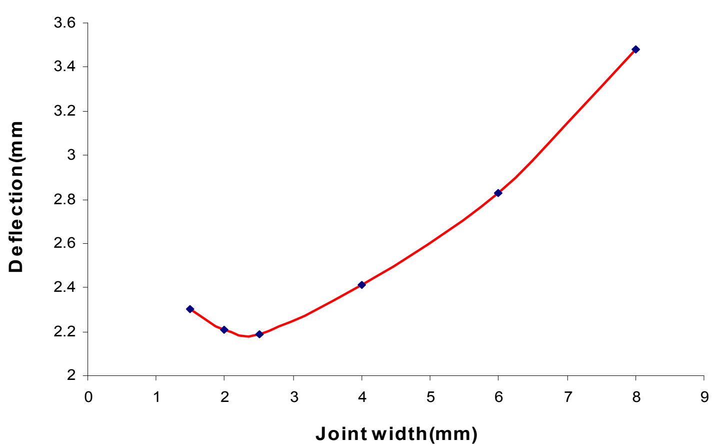

Figure4. Pavement deflections with varying joint width

5.2 Block Size
Three sizes of block were analysed having the same thickness. The blocks were laid in a herringbone bond pattern for each test. Figure 5 shows the response of pavement against block size. Lesser deflections of pavement have been obtained with increasing block size. Increasing block size would realize better pavement performance.

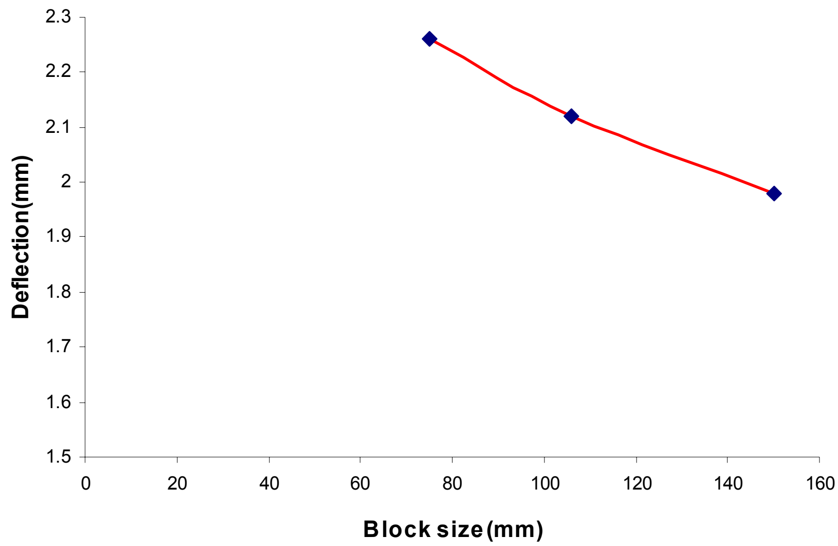

Figure 5. Effect of block size (consistent 80 mm thickness) on deflection behavior of block pavement

5.3 Block Strength
Finite element analysis was conducted on three different block strengths having average compressive strengths of 25, 30 and 42 MPa. The blocks were laid in a herringbone pattern. Deflection of pavements is almost the same for all analysis (see Figure 7). The discontinuous nature of block paving and their small size means bending stress would be negligible.

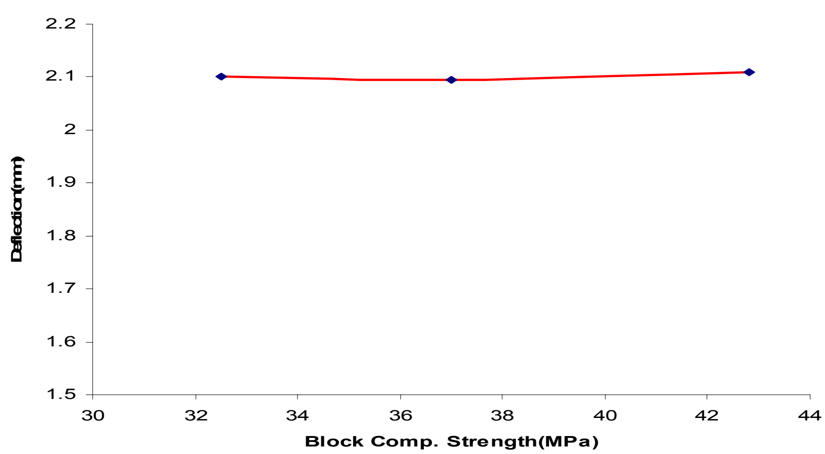

Figure 6. Effect of block compressive strengths on behavior of block pavement

5.4 Block Thickness

Three different thicknesses were selected for testing. The thicknesses were 100, 80 and 60mm. Blocks were laid in a herringbone pattern for each analysis. A change in thickness from 60 to 100mm significantly reduces the vertical deflection of pavement (Figure 7). Thicker blocks provide a higher friction area. Thus load transfer will be high for thicker blocks.

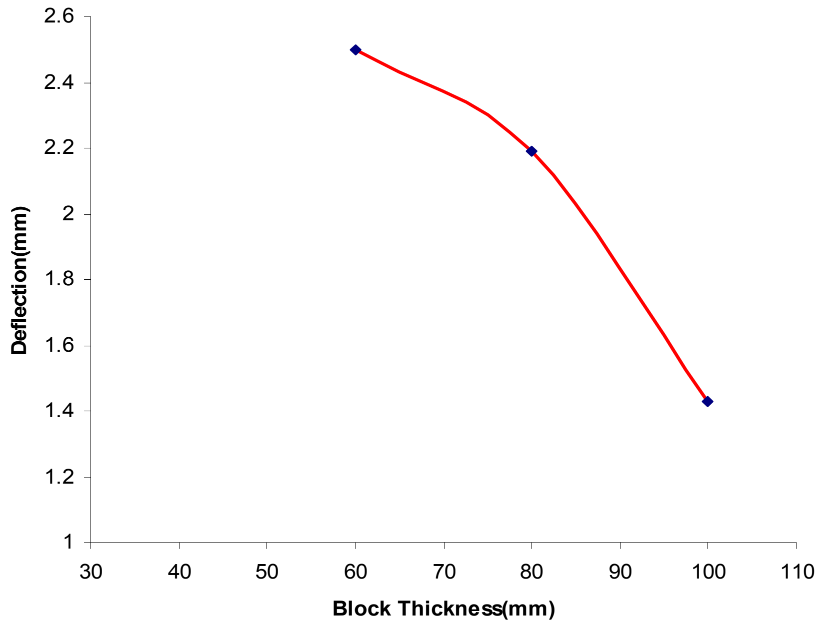

Figure 7. Effects of block thickness on behavior of block pavement

Similar findings for effects of this main component of block pavement behavior were observed by Bikasha and Ashok (2002) from laboratory-scale test.

6. MECHANISMS OF PAVER INTERLOCK

Even block pavement which are judged to be well laid typically exhibit small rotations of the pavers relative to one another (Shackel, 2003). As shown in Figure 8 schematically in the cross-section, the wedging action caused by rotation of paver B around a horizontal axis leads to the development of horizontal forces within the paving. The wedging action explains why pavers act as structural surfacing rather than merely providing a wearing course (Shackel, 2003).

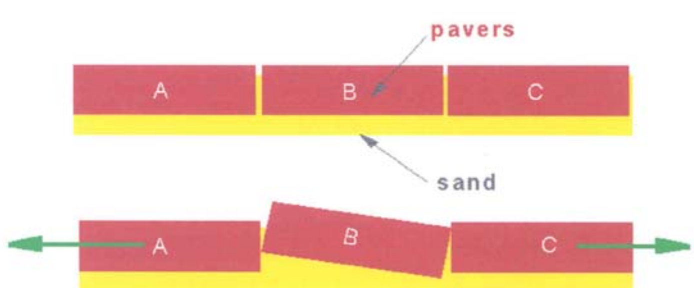

Figure 8. Rotation of Paver B causing outward wedging of Pavers A and B (Shackel, 2003)

Figures 9 and 10 show deflections of block pavement against vertical loads obtained from 3D finite element analysis. As shown in these figures, wedging action is caused by rotation of pavers and develops horizontal forces within the paving.

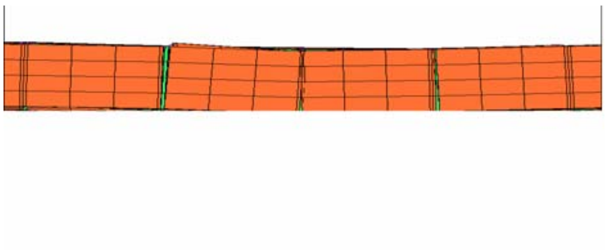

Figure 9. Mechanism of interlocking in block pavement

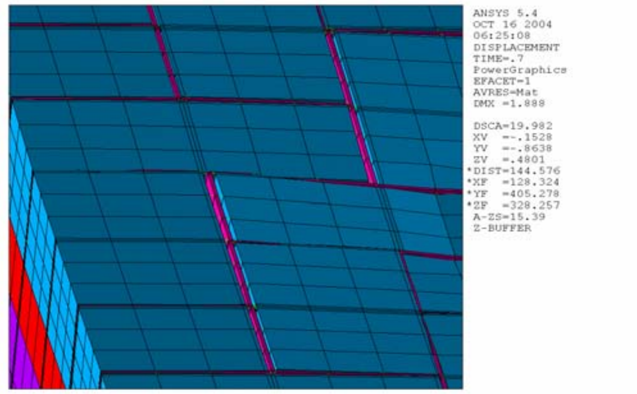

Figure 10. Rotation of blocks for development of interlocking in herringbone patterns

7. PORT PAVEMENT DESIGN WITH CONCRETE PAVERS

Based on the finite element analyses results, a series of design charts were developed for common axle loads in ports area such as front lift trucks, straddle carriers, trailers and mobile cranes.

7.1 Subgrade Characteristics

Subgrade material is characterized in terms of California Bearing Ratio (CBR). Hence, the elastic modulus of subgrade most be evaluated from a CBR value. Among a variety of correlations, the following widely accepted relation was selected:

$$E = 10 \text{ x CBR} \quad (1)$$

Where the modulus, E, is in MPa and CBR is in percent.

7.2 Characteristic of Pavement Response

For pavement design, the overall response of pavement to traffic needs to be assessed. To accomplish this task, Miner's linear cumulative damage hypothesis was adopted. The Miner hypothesis states that irrespective of the magnitude of the stress repetition is responsible for a certain amount of fatigue damage. It is assumed that there is a linear rate of fatigue damage irrespective of the order of load application and that fatigue accurse when the sum of the damage increment at each level of stress accumulates to unity. The law can be expressed in the form:

$$\sum_{N=1}^{n} \frac{n_i}{N_i} = 1 \quad (2)$$

Where N_i is the number of cycles to failure level i and n_i is the number of cycles actually applied at stress level i.

In order to predict N_i in above equation, a failure mechanism must be postulated. Where unbound materials such as crushed rocks and gravel are used, the pavement is assumed to be failed by gradual accumulation of permanent rutting deformation. For bound material such as cement stabilized base the pavement in assumed to be failed by gradual accumulation of cracks in bound base layer. It is commonly accepted that rutting deformation is related to the vertical compression strain at the top of the subgrade and cracks in bound base layer is related to the horizontal tensile strain at the bottom of the base layer. The criteria used in this study are stated below (Shackel, 1999).

$$S_V = \frac{2800}{N^{0.25}} \qquad (3)$$

Where S_V is the permissible subgrade compression strain (micro strain) and N is the number of strain repetition.

$$S_t = \frac{993500\, f'c}{E_b^{1.022}\, N^{0.0502}} \qquad (4)$$

Where St is the tensile strain at the bottom of the bound layer, f'c is the characteristic compressive strength of the base material, Eb is the modulus of the base and N is the number of load repetitions.
Figure 11 illustrates a typical design chart for various and load categories (wheel load for ports see Table 2).

Table 2. Wheel contact pressure used in design charts

Graph Label	Wheel Load (kN)
A	210
B	65
C	45
D	225

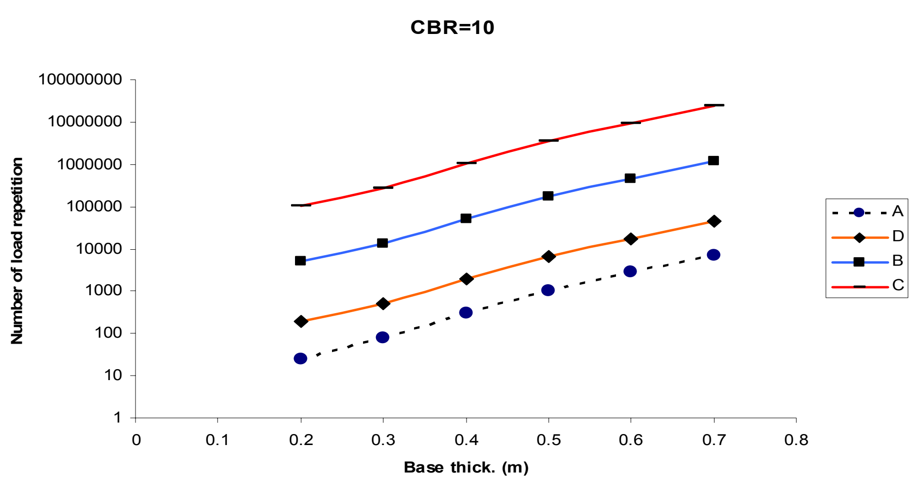

Figure11. Typical design chart; E Block = 4,200MPa, E bound base = 35,000 MPa, Block Thickness = 80 mm

8. CONCLUSIONS

Using the 3D finite element model:

- Joint widths should be limited from 2mm to 4mm for the better performance of the pavement.
- With increasing block size, better pavement performance is obtained.
- The performance of block pavement is independent from block compressive strength.
- The vertical deflection of the pavement is highly influenced by block thickness. An increase in block thickness decreases pavement deflection.
- Interlocking in block pavers is caused by rotation and wedging action between blocks.

9. REFRENCES

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