

A Model for Predicting Permanent Deformation of Interlocking Concrete Block Pavements on Heavy Duty Roads

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Abstract :

A rational structural design method is needed to use interlocking concrete block pavement (ICBP) on heavy duty roads. In this study, a structural model based on three dimensional finite element method (3DFEM) for the structural design of ICBP was developed. In the model, interlocking concrete block, joint and bedding layer are modeled with solid elements and interface elements. The values of spring constants in the interface element were back calculated from FWD deflection measurement conducted on a full scale test pavement. Identified spring constants increased with 14 months trafficking over the pavements. A method for predicting permanent deformation of ICBP is proposed employing the model assuming that the permanent strain is proportional to elastic strain due to traffic load. The method was validated with rut depths measured on the test pavement. It was found that the spring constants of joint significantly affects the rutting development.

Key Words : structural design; permanent deformation; joint stiffness; backcalculation; 3DFEM.

1. Introdouction

In the curent structural design of ICBP, blocks and bedding layer are treated as a surface layer and its equivalent modulus is specified [1], and the design method of asphalt pavement is applied to the block pavements. It is because there is no structural model that is able to predict mechanical behaviors of a block pavement taking into account mechanical properties of individual block, laying pattern, load transfer efficiency at joints and mechanical role of bedding layer. In this study, we develop a 3DFEM structural model that is able to take into account various structural features of ICBP [2]. The most important parameters of the model are the spring constants of interface elements for joints and bedding layer. In this study, the values of the spring constants were determined by back calculating FWD deflections measured on a full scale test pavement.

One of the major distresses of ICBP on heavy traffic roads is an excessive permanent deformation of the pavement surface [3]. A method for predicting the permanent deformation of ICBP is proposed employing the model assuming that the permanent strain is proportional to elastic strain due to traffic load. The method was validated with rut depths measured on the test pavement.

2. Test Pavement

Three sections of test ICBP were constructed on a yard of a concrete block factory. Figure 1 shows the cross section and plan view of the pavement. ICBs were placed on a 2 cm sand cushion over a 40 cm granular base course. Three types of blocks were used as shown in Figure 2. All blocks have vertical narrow strips on side faces to keep a specified joint width. Four surface edges of blocks in Sections 2 and 3 were cut off to avoid spalling.

Their surface conditions were monitored and FWD test were conducted before and 14 months after opening to the factory traffic. After the construction, trucks carrying concrete products had passed over the pavement for 20 months, which is corresponding to about 5400 of the 49 kN equivalent wheel loads. Figure 3 shows transverse surface profiles of the test pavement at the age of 20 months. Vertical distance between block surface and a 2.8 m long scale transversely put on the surface were measured at every 50 mm. Maximum amount of rutting was 6 mm in Section 1, 8 mm in Section 2, and 9 mm in Section 3.

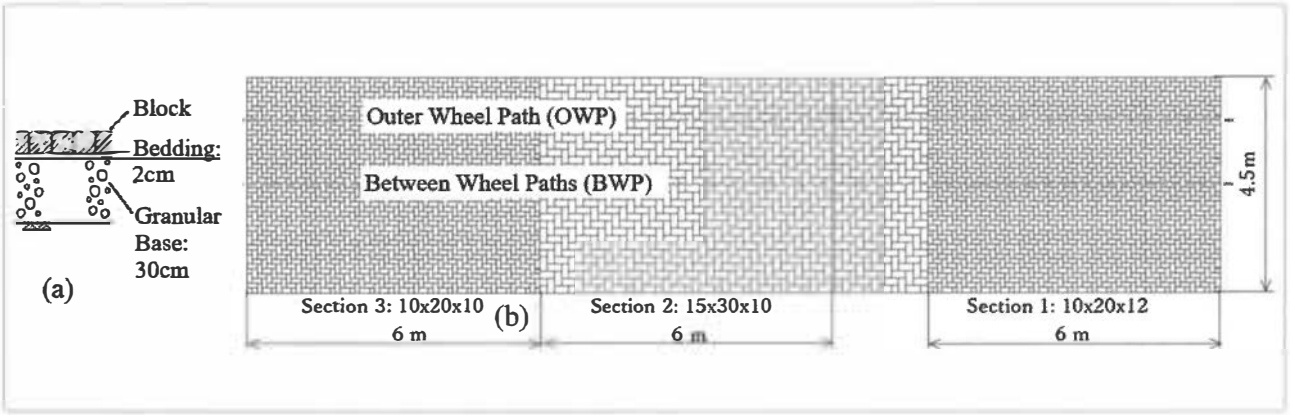

Figure 1. Test block pavement sections. (a) Cross section, and (b) plan view.

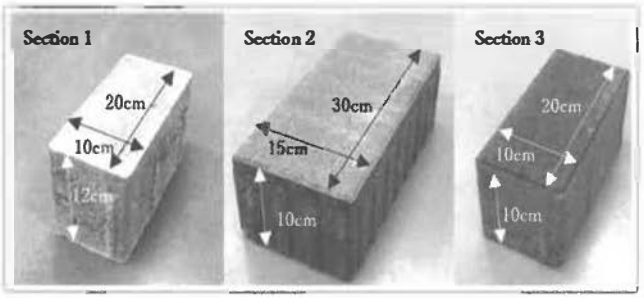

Figure 2. Concrete blocks used in test pavements.

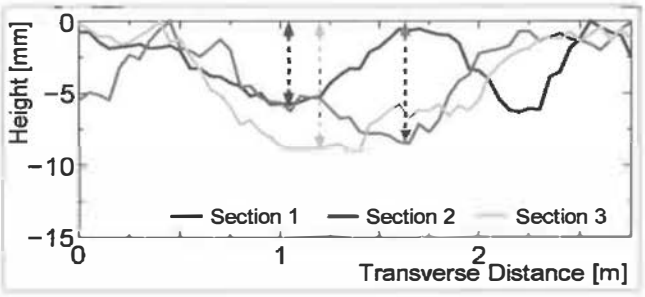

Figure 3. Transverse profiles at the age of 20 months.

3. Backcalculation of FWD Measurement

FWD measurements were conducted before opening to traffic (0 month) and at the age of 14 months. Elastic moduli of the ICB layer that includes joint and bedding sand layer, the base course and the subgrade were back calculated with a software BALM [4] from the FWD deflections. The blocks, joints and bedding sand layer were treated as one uniform surface layer with a thickness of 120 mm in Sections 1 and 3, 140 mm in Section 2. Poisson's ratio was assumed 0.35 for all layers. Identified moduli were summarized in Table 1. The moduli of the surface layer and the base course increased after 14 months service.



Table 1. Elastic modulus of block layer (E1), base course (E2) and subgrade (E3).

		Section 1		Section 2		Section 3	
Age (Month)		0	14	0	14	0	14
E1 (MPa)	BWP	1292	2422	2150	3628	2477	3045
	OWP	1067	2294	1716	3853	2250	4654
E2 (MPa)	BWP	71.6	52.1	39.1	171.3	42.2	131.1
	OWP	72.7	357.6	42.6	317.3	56.8	149.7
E3 (MPa)	BWP	85.0	145.2	95.8	62.8	80.0	59.4
	OWP	80.5	80.5	84.8	71.9	87.3	75.6

4. Identification of Stifness of Joint and Bedding Sand Layer

Figure 4 shows an example of 3DFEM modeling of the test pavement, where a block is divided with solid elements and a joint between adjoining blocks is modeled with interface elements. A bedding sand layer is also modeled with the interface element because the layer is too thin to be divided with the solid elements. The interface element transfers loads between two planes of adjoining solid elements with three linear springs: two springs parallel to the plane (ks and kt) and a spring perpendicular to the plane (kn). The spring constants are important parameters and an appropriate estimation of their values is crucial in this model. Individual block was divided into two elements in the short edge, four elements in the long edge and three elements in the thickness.

The thickness of the bedding layer was 2 cm and joint width was 5 mm. The width and length of the entire structure were 3 m and 4 m, respectively. The thickness of base course was 0.3 m and that of the subgrade was 5 m. The FWD load was applied at the center with a 30 cm by 30 cm squire area. The deflections at FWD sensor locations were calculated using the structural model with a number of combinations of spring constants of bedding layer and joint, Kb and Kj. The elastic moduli of base course and subgrade presented in Table 1 were used. Elastic modulus and Poisson's ratio of block were assumed 30,000 MPa and 0.2, respectively. Since the effects of spring constants are logarithmic, those values were generated as:

$$\log_{10}K_j = 4 \times RND + 1,\ \log_{10}K_b = 3 \times RND + 1$$

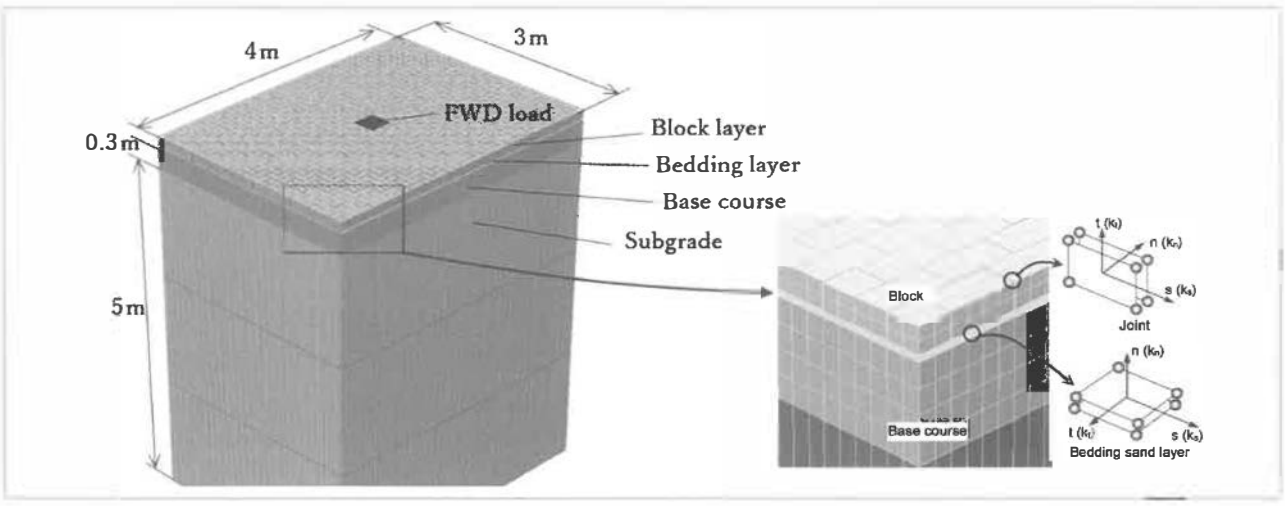

Figure 4. 3DFEM model of Section 1.

where, RND is the random variable in the range from 0 to 1. Using these spring constants in the structural model, 200 sets of FWD deflections were calculated. The squared error that is the sum of the squared differences between calculated and measured deflections were estimated. The values of Kb and Kj were selected from the calculated FWD deflections by minimizing the squared error.

Comparisons of calculated and measured deflections for Section 1 are shown in Figure 5. The fitted deflections agree well with measured ones. Identified values of Kb and Kj are summarized in Table 2. It can be seen that Kj significantly increased after 14 months, while Kb did not change consistently; some increased and others decreased.

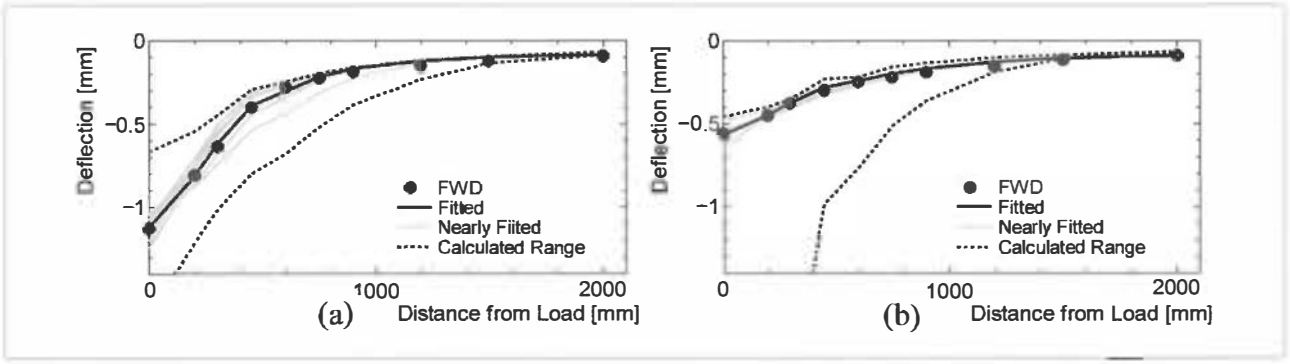

Figure 5. Measured and calculated deflection basins for Section 1. (a) Before open to traffic and (b) at the age of 14 months.

Table 2. Kb and Kj identified from FWD deflections.

		Section 1		Section 2		Section 3	
Age (Month)		0	14	0	14	0	14
Kj (MPa/m)	BWP	1851	5520	4255	14137	4846	17010
	OWP	2016	12260	2697	12849	4211	14137
Kb (MPa/m)	BWP	253	212	58	99	128	94
	OWP	275	236	82	246	177	99

5. Prediction of Permanent Deformation

The prediction method of the permanent deformation employs the similar concept to the rutting prediction of asphalt pavement, which assumes the following relationship between the permanent strain and elastic strain (or resilient strain) for base course and subgrade materials [5]:

$$\varepsilon_p = \beta_1 N^{\beta_2} \varepsilon_e \tag{1}$$

where, N is the number of load repetitions and β_1 and β_2 are material constants, whose values were proposed by Takeuchi et al; β_1 = 0.581 and β_2 = 0.248 for base course; β_1 = 2.35 and β_2 = 0.17 for subgrade [6]. In this study, the relationship is expanded to three dimensional strains. Assuming that the total strains consist of permanent component and elastic component, the stiffness equation of 3DFEM can be formulated as

$$\left(\sum_i \frac{1}{1+\beta_1 N^{\beta_2}} [K_i] \right) \{d\} = \{f\} \tag{2}$$



where, $[K_i]$ is the stiffness matrix of the element i, $\{d\}$ is the displacement vector and $\{f\}$ is the external force (traffic load) vector. The total deformation including the permanent deformation can be calculated by solving Eq. (2) considering the proper boundary conditions. The permanent deformation is estimated as $\{d_p\} = \{d\} - \{d_e\}$, where$\{d_e\}$ is the elastic deformation due to a traffic load. In this study, this relationship is applied to the permanent deformations of joint and bedding layer.

Figure 6 shows calculated profile of the permanent deformations of the surface, the top of base course and the top of subgrade in Section 2 when N = 5400 that corresponds to the traffic for 20 months. In this case, the values of structural parameters were assumed to be those identified from FWD measurement for before open to traffic (0 month) and for 14 months age.

Table 3 summarizes measured and calculated rut depths. The measured rut depths fall between the calculated ones with the structural parameters for 0 month and 14 months. This means that structural parameters corresponding to the ones after being exposed to some traffic should be employed to provide a realistic prediction of long term rutting.

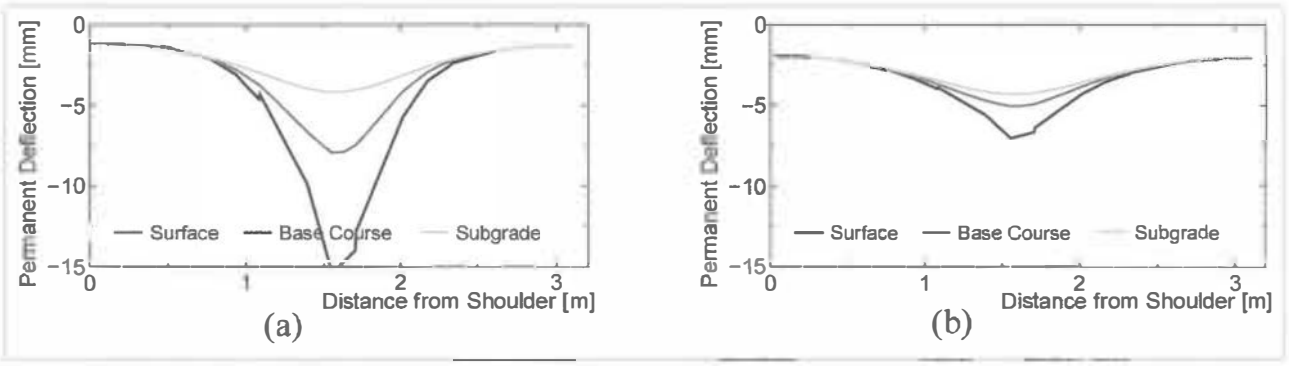

Figure 6. Profiles of permanent deformation at top of each layer in Section 2, which were calculated with structural parameters for (a) 0 month age and (b) 14 months age:

Table 3. Comparisons of measured and calculated rutting depth (mm).

Section	1	2	3
Measured	6	8	9
0 month parameters	10	14	10
14 months parameters	4	5	6.5

4. Conclusion

In this study, a structural model of ICBP for heavy traffic was developed based on 3DFEM. In this model, it is crucial to properly estimate the spring constants of interface element that represents the stiffness of joint and bedding layer. The value of the constants were backcalculated from FWD data acquired on the test pavement. A prediction method of rutting of ICBP was developed employing the concept of VESYS plastic strain model, which assumes that the plastic strain is a function of the elastic strain due to traffic load and the number of load repetitions. The model was validated with rutting depth measured on the test pavement. From the validation, it was found that spring constant of joint and bedding layer significantly affects the rutting development.

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