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ANALYSIS OF SPALLING OF CONCRETE BLOCKS BY PHOTO-ELASTIC EXPERIMENT AND FEM

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ABSTRACT

Spalling is one of major distress modes in concrete block pavements. The aim of this study is to make clear the mechanism of spalling by stress analysis considering the movement of each block and support of bedding sand. In order to analyze the stress state in concrete block, we carried out the photoelastic experiment where concrete blocks were modeled by epoxy resin specimens and a load was applied at the edge of the specimen to simulate the tire to block and block to block interactions. From the results, it was found that the high stress concentration occurs at the contact area in the concrete block and that the intensity of the concentration depends on where and how the blocks contact with each other. Furthermore, the effects of the support of bedding sand and block thickness were investigated by FEM which is able to compute stress and deformation of blocks varying stiffness of bedding sand as well as block configurations.

1. INTRODUCTION

Spalling of block edge is one of major distress modes in concrete block pavements [1]. It was often observed that if block has joint keep on each side to prevent direct contact of adjacent blocks, spalling rarely occurs. Therefore, contact of blocks at edge or corner in narrow joint produced by traffic load actions is considered to be a cause of spalling of block. Also, when small stones go into joint or joint keep is worn out, adjacent blocks are strongly pushed each other at the edge by wheel loads, generating large stress there. If the stress exceeds the strength of concrete, small potion at the edge of the block would break away. However, these explanations on block spalling have not been confirmed experimentally nor theoretically so far.

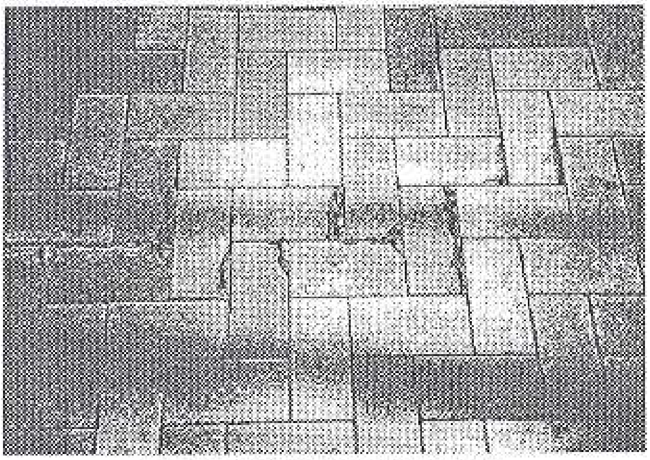


Photo 1 Spalling of Blocks

The aim of this study is to make clear the mechanism of spalling by stress analysis considering the movement of each block and support of bedding sand. In order to analyze the stress state in concrete block, we carried out the photoelastic experiment where concrete blocks were modeled by epoxy resin specimens and a load was applied at the edge of the specimen to simulate the tire to block and block to block interactions. Furthermore, the effects of stiffness of bedding sand and block thickness were investigated by FEM.

2. PHOTOELASTIC ANALYSIS

In order to investigate stress state at block edge produced by horizontal force of a wheel tire, a photo-elastic experiment was conducted [2]. Figure 1 shows an overview of specimen, support and loading conditions. Specimens which represent concrete blocks were made of epoxy resin. Its height, length and thickness were 40 mm, 80 mm, and 10 mm, respectively. Two specimens were put on a metal frame and a horizontal load was applied by a loading equipment. The contact position between the loading plate and the specimen was varied as at top corner, at 1mm down from the top, and at 2mm down from the top as shown Figure 2. To prevent buckling of the specimens, they were sandwiched between transparent acryl plates.

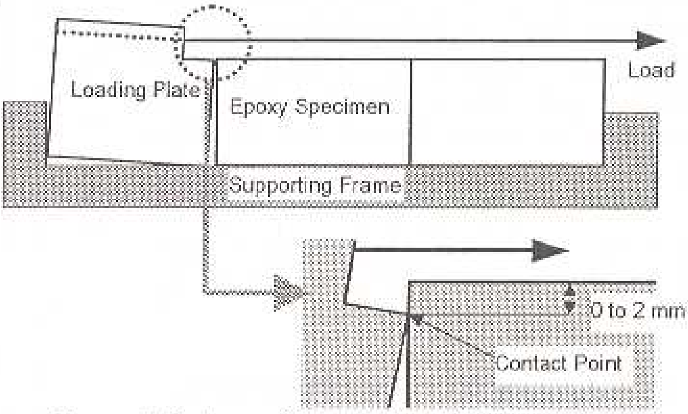
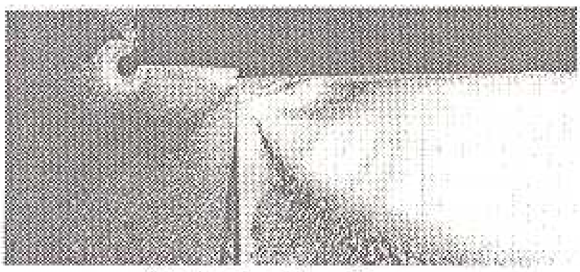
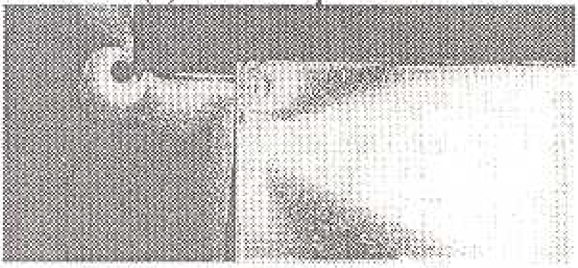


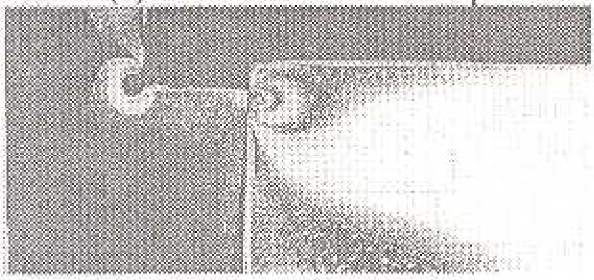
Figure 1 Set-up of Photo-Elastic Experiment



(a) At the Top Corner



(b) 1mm down from the Top



(c) 2mm down from the Top

Photo 2 Shear Stress Contours

Photo 2 shows isochromatic fringe around the contact area. Each fringe order is proportional to the absolute value of the principal stress differential which equals to a half of the maximum shear stress. Therefore, by counting the number of the fringe, the shear stress can be computed. From this photo, stress concentration at contact area is clearly observed.

Figure 2 shows the stress distribution along the horizontal line in the specimen. The maximum stress is observed in the case of the top corner loading. The stress distributes in the widest range in this case. When the contact point moves down 1 mm from the top, the stress decreases from 3.0 N/mm^2 to 2.5 N/mm^2. If it goes down 2mm, the stress becomes 2.25 N/mm^2. The range of stress distribution becomes narrow, when the contact point goes down.

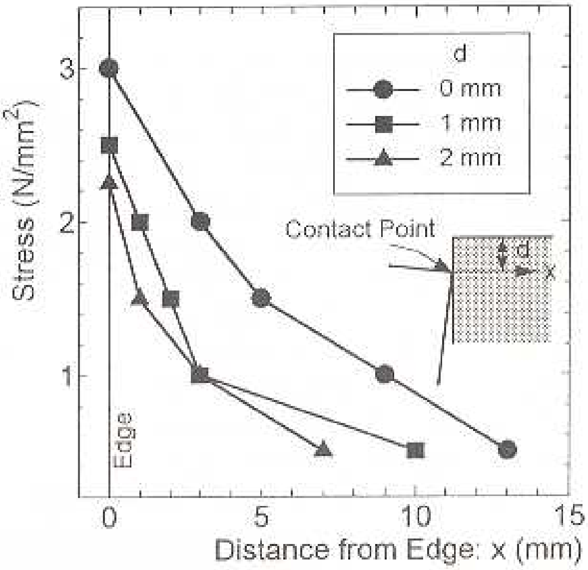


Figure 2 Shear Stress Distributions

3. FEM ANALYSIS OF EXPERIMENT

Numerical simulations were performed for the photo-elastic experiment described above. In the simulation, a plane stress model as shown in Figure 3 was employed. Dimensions of the specimen were the same as the experiment. The material constants used in the simulation are also presented in Figure 3. Displacements of nodes on the right side and under side edges were fixed. Contact point was modeled as a distributed load which was applied at a corner of the specimen. The magnitude and the width of the load were 3 N/mm^2 and 1 mm, respectively. The contact point was varied as at the top, at 1mm down from the top and at 2 mm down from the top (Case 0, Case 1 and Case 2, respectively). Furthermore, to examine the effect of edging of block on the stress distribution in the block, the specimen was edged at a loaded corner and the load was applied at the under side of the edge as shown in Figure 3. Two sizes of the edge, 1 mm and 2 mm, were assumed (Case 3 and Case 4, respectively).

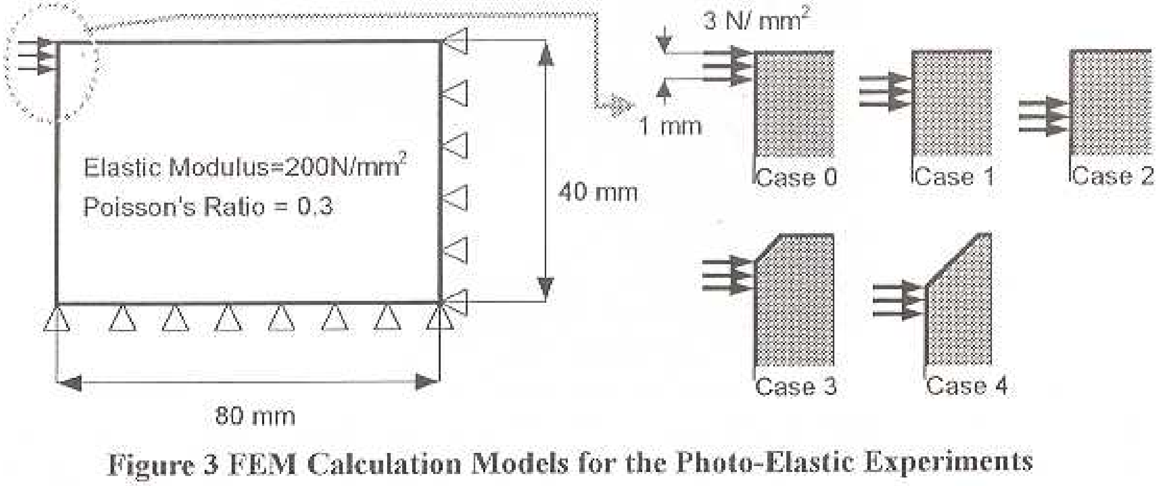
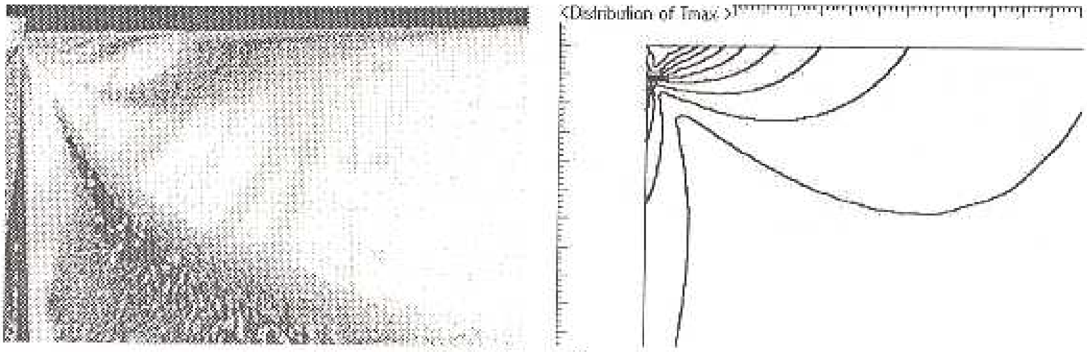
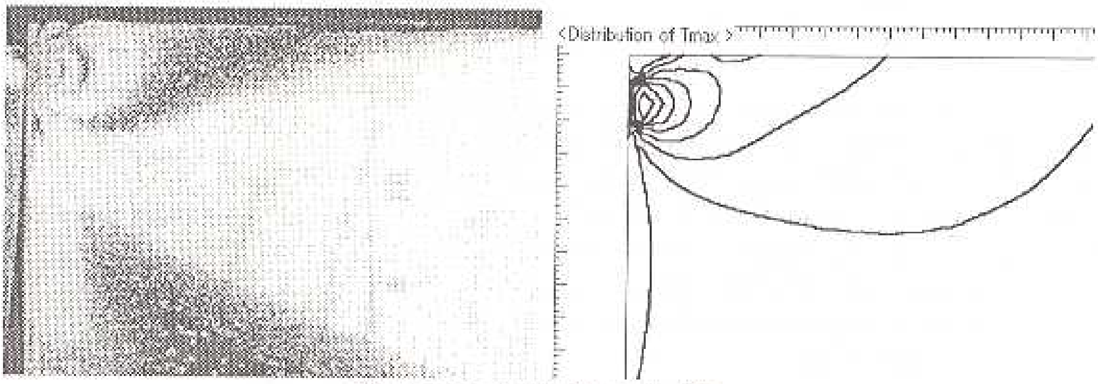


Figure 3 FEM Calculation Models for the Photo-Elastic Experiments

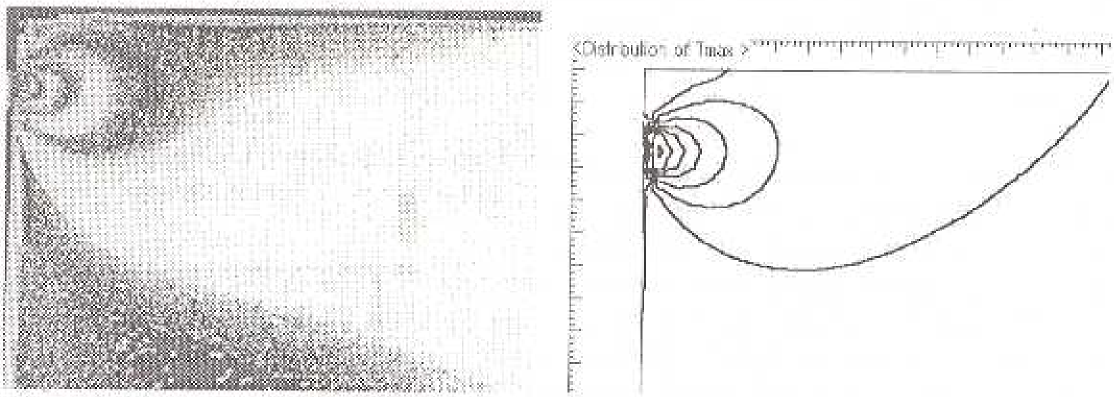
Figure 4 shows the computed shear stress contours along with the results of the photoelastic experiment. It can be seen that large stresses appear at the loading point and that the contour lines of FEM simulations are quite similar to those in the photographs in all cases.



(a) At Top Corner



(b) 1 mm down from the Top



(c) 2 mm down from the Top

Figure 4 Comparisons of Shear Stress Contours between Experiment and FEM

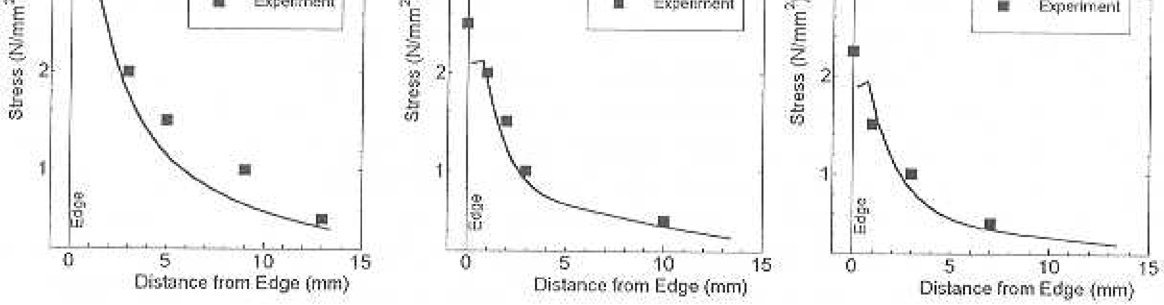
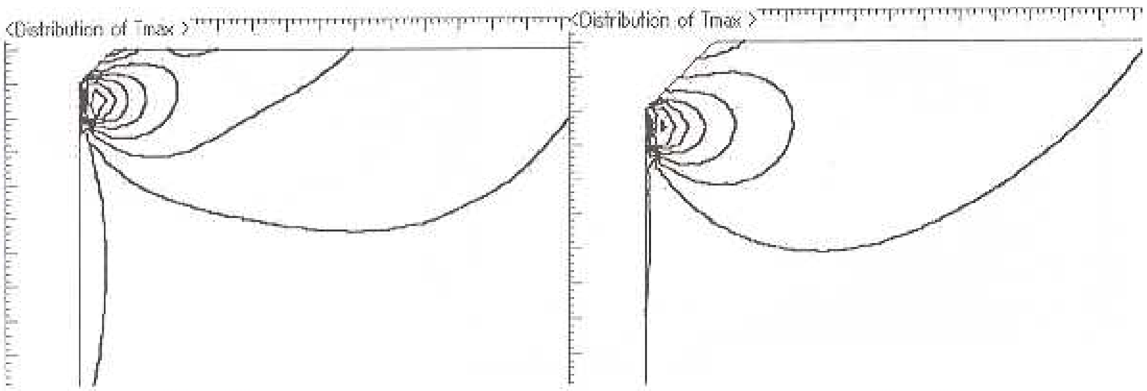


Figure 5 Comparisons of Shear Stress Distribution between Experiment and FEM



(a) Case 3 **(b) Case 4**

Figure 6 Shear Stress Contours for Case 3 and Case 4

Figure 5 shows comparisons between the computed shear stress distributions and the measured ones. The computed stresses agree well with the measured ones, which indicates that FEM simulations are valid to quantitatively analyze the stress state around contact area where large stress concentration which would be a cause of spalling occurs.

Figure 6 shows the shear stress contours for Case 3 and Case 4. The stress states of these cases are quite similar to Case 1 and Case 2, respectively.

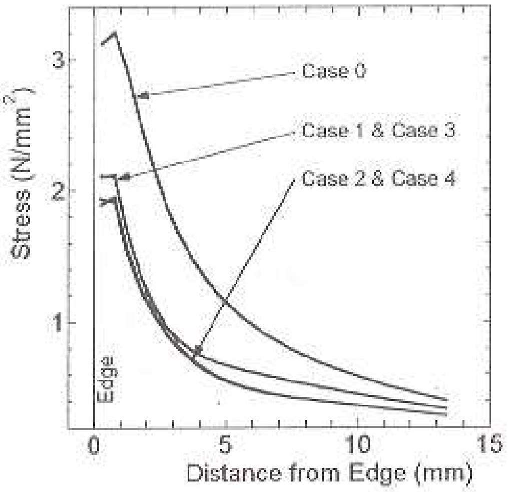


Figure 7 Effects of Contact Position and Edging on Shear Stress

Figure 7 shows the stress distributions obtained from the FEM simulation. In Case 0 where the contact load was applied at the top, the largest shear stress is observed at the edge. However, when the position of the contact load moves down a little from the top, the shear stress decreases by about 30 %. Case 1 (1mm down the top) and Case 3 (1 mm size edging) produce almost the same stress distribution. The same thing can be said for Case 2 and Case 4. It means that the edging has very little effect on stress distribution as long as the contact point is the same.

4. FEM ANALYSIS FOR TIRE LOADING

In this chapter, stress states of concrete block under tire load are examined by FEM simulations. Figure 8 shows a simulation model for FEM. We considered two blocks on bedding sand layer subjected to a tire load at the center of the two blocks. Assuming that the structural and loading conditions were symmetric for the axis which runs at the center of the two blocks, only single block was modeled as shown Figure 8. Length of the block was 200 mm and its thickness was varied from 80 mm to 120 mm to investigate the effect of block thickness on stress. The elastic modulus and Poisson's ration of the block were 3500 N/mm^2 and 0.2, respectively. Interface between the block and the bedding sand was modeled by Goodman's joint element which describes the sliding and opening displacements between the block and the bedding sand [3]. The block was edged at upper corners with a size of 5mm. Thickness of the bedding sand layer was 30 mm and its elastic modulus was varied from 10 to

100 N/mm^2 to investigate the effect of stiffness of the bedding sand. Contact area was modeled by fixing horizontal displacement at the nodes which correspond to the contact area. The width of the contact area was assumed 2.5 mm. Distributed load with a magnitude of 1.0 N/mm^2 and a length of 50 mm was applied at one side of the block. The simulation was preformed as a plane stress problem and the width of the model was assumed 100 mm.

Figure 9 shows a principal stress distribution and a contour of the minimum principal stress. Obviously, large stresses are generated at the contact area. These stresses are almost compressive and the direction of the compressive stress was toward the center of the contact area.

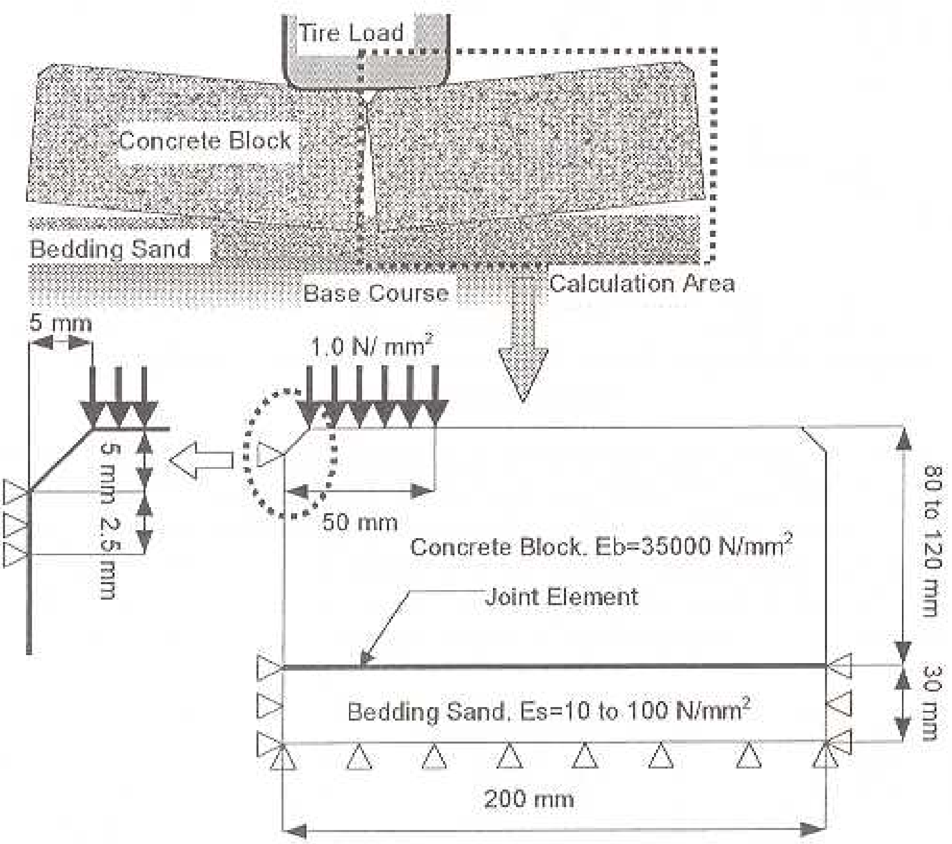


Figure 8 Simulation Model for Concrete Block under a Tire Load.

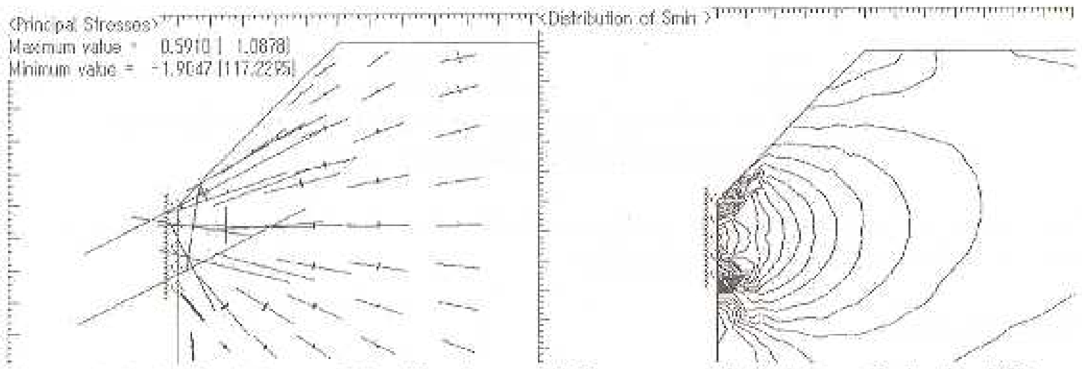


Figure 9 Principal Stress Distribution and Contour of Minimum Principal Stress

Figure 10 shows the effects of the block thickness on compressive stress, shear stress and deflection. The compressive stress and the shear stress are strongly affected by the block thickness while stiffness of the bedding sand has very little effect on the stresses. Since the stresses at the contact area decreases as the block thickness increases, increasing the thickness might be an effective measure to prevent the spalling of block. However, since the magnitude of the stresses is much less than the strength of concrete, only vertical loading could not cause the spalling at the corner. The deflection is mainly affected by the stiffness of the bedding sand is almost independent from the block thickness.

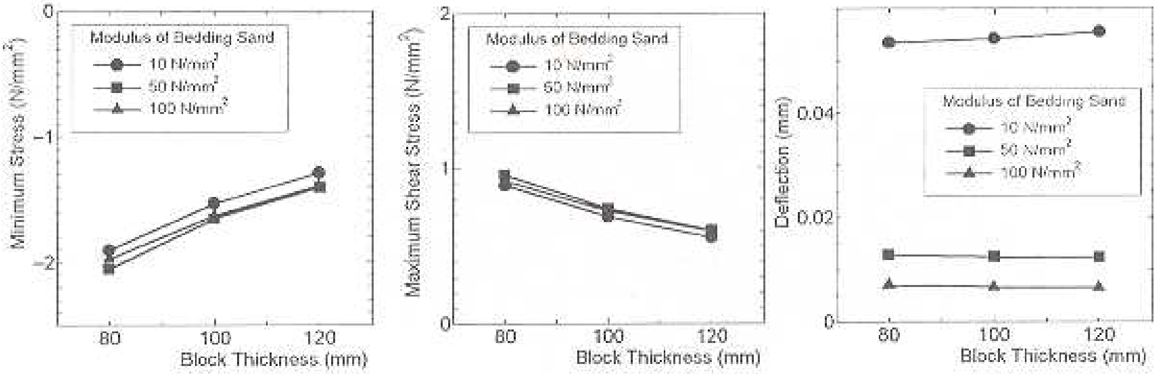


Figure 10 Effects of Block Thickness on Stresses and Deflection (Vertical Load Only)

Since the stresses at contact area were much less than expected, a horizontal load with a magnitude of 1.0 N/mm^2 was added in the same area at the same time. Figure 11 gives results of the vertical and horizontal loads. Although the magnitudes of the stresses become more than twice as much as those in the vertical load only, they are still much less than the strength of concrete. The reason of these rather small stresses may come from the fact that we do not have the exact data on the magnitude of tire load which actually applies to the blocks. In addition, another load combination, such as impact load or breaking load, might be considered to quantitatively identify the cause of spalling.

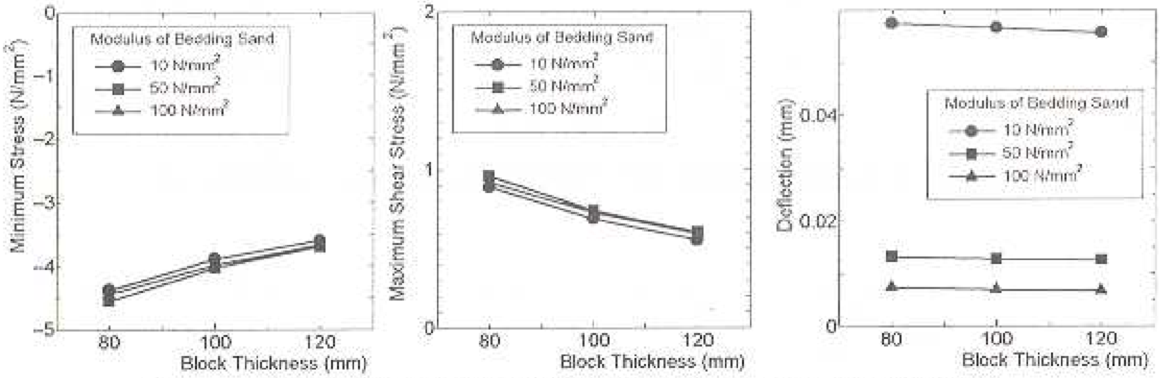


Figure 11 Effects of Block Thickness on Stresses and Deflection (Vertical and Horizontal Load)

5. CONCLSIONS

In this study, the mechanism of spalling of concrete block was investigated by the photo-elastic experiment and finite element analysis. From the results of the investigation, the following conclusions can be drawn:

1. Horizontal loading at the upper corner produces large shear stresses. The magnitude of the stress rapidly decreases as the contact point of the load goes down from the top corner.
2. Edging of the block has no effect for reducing the shear stress as long as loading point is apart from the top corner.
3. Tire loading produces large compressive stress at the top corner of block. The stress can be reduced by increasing the block thickness.
4. The magnitude of the stresses was much less than the strength of concrete, even if vertical and horizontal loads were applied at the same time. We should investigate load combinations and their magnitudes which actually apply to the blocks.

We have not been able to quantitatively identified the cause of spalling of concrete block, because the models used in the experiment and FEM simulation were too simplified and we do not have enough information on the actual load applied to the blocks. Also we should take into account interactions between many blocks, subbase deformation and complicated tire-pavement interactions. We are recognizing that these are future subjects of this study we should deal with.

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