Sensitivity analysis on LTE of JCP using FEM modeling

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1. Introduction

Joints should be provided in Portland cement concrete (PCC) pavement in order to prevent the occurrence of premature cracks due to temperature or moisture changes (Huang 2004). The overall joint conditions can be assessed by determining the extent and severity of joint displacement and the ability of a joint to transfer the load, which is termed LTE. Load transfer between the slabs occurs through aggregate particles of the fractured surface below the saw cut at a joint, through steel dowels (if they exist), and through the base and subgrade. Changes in material properties of sublayers and variation in pavement layer thickness have long been recognized as important factors affecting JCP performance (Ball and Childs 1975).

Daily and yearly ambient air temperature and humidity cycles contribute to changes in the temperature and moisture of a concrete slab on an hourly and seasonal basis (Jeong et al. 2006). The expansion and contraction of the slab influence the widths of joints and the degree of mechanical interlock between the slabs. At the same time, drying shrinkage of the slab related to the evaporation of the water of the concrete develops over time when concrete is subjected to drying (Yu et al. 1998). The drying in concrete pavement occurs only near the pavement surface, even in very dry areas. Drying of the concrete near to the joint induces weakness of aggregate interlocking and dowel bar looseness, which decreases the load transfer between two adjacent slabs. Researchers recently suggested that conversion of the drying shrinkage distribution to an equivalent temperature gradient is a relatively reliable and feasible approach. The curling shape of the slab induces different contact interactions between the slab and the underlying layer and will change the performance, including in particular increasing the stress and displacement of the slab under a traffic load.

In this study, the LTE of joints with different geometry, material properties, and, in particular, temperature gradient of the slab are analyzed by a numerical simulation method. A 3-D model was built using ABAQUS to simulate the behavior of a slab under the application of FWD loading in order to analyze the vertical displacement and LTE of transverse joints of JCP.

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2. 3-D FEM modeling

For simulation of the behavior of a slab of JCP by a numerical method, a model of 3 slabs placed on a bound underlying layer composed of base and subgrade is built. Surface to surface contact interaction between the bottom of the slab and top of the base is selected in the modeling. The base and subgrade are constrained in the direction vertical to each boundary side. The assembly of the JCP structure on subgrade is shown in Figure 1. The properties of the materials and geometry of the slab used as the input data are shown in Table 1. The values in bracket are the control values for the sensitivity study. The coefficient of thermal expansion of the concrete selected for the curling analysis is $1\times10^{-5}/℃$. The layout of the FWD test and calculation of LTE are illustrated in Figure 2. For this study, the load level of FWD is 40KN. The vertical pressure applied at the middle of the transverse edge of the slab along the joint is 0.5MPa.

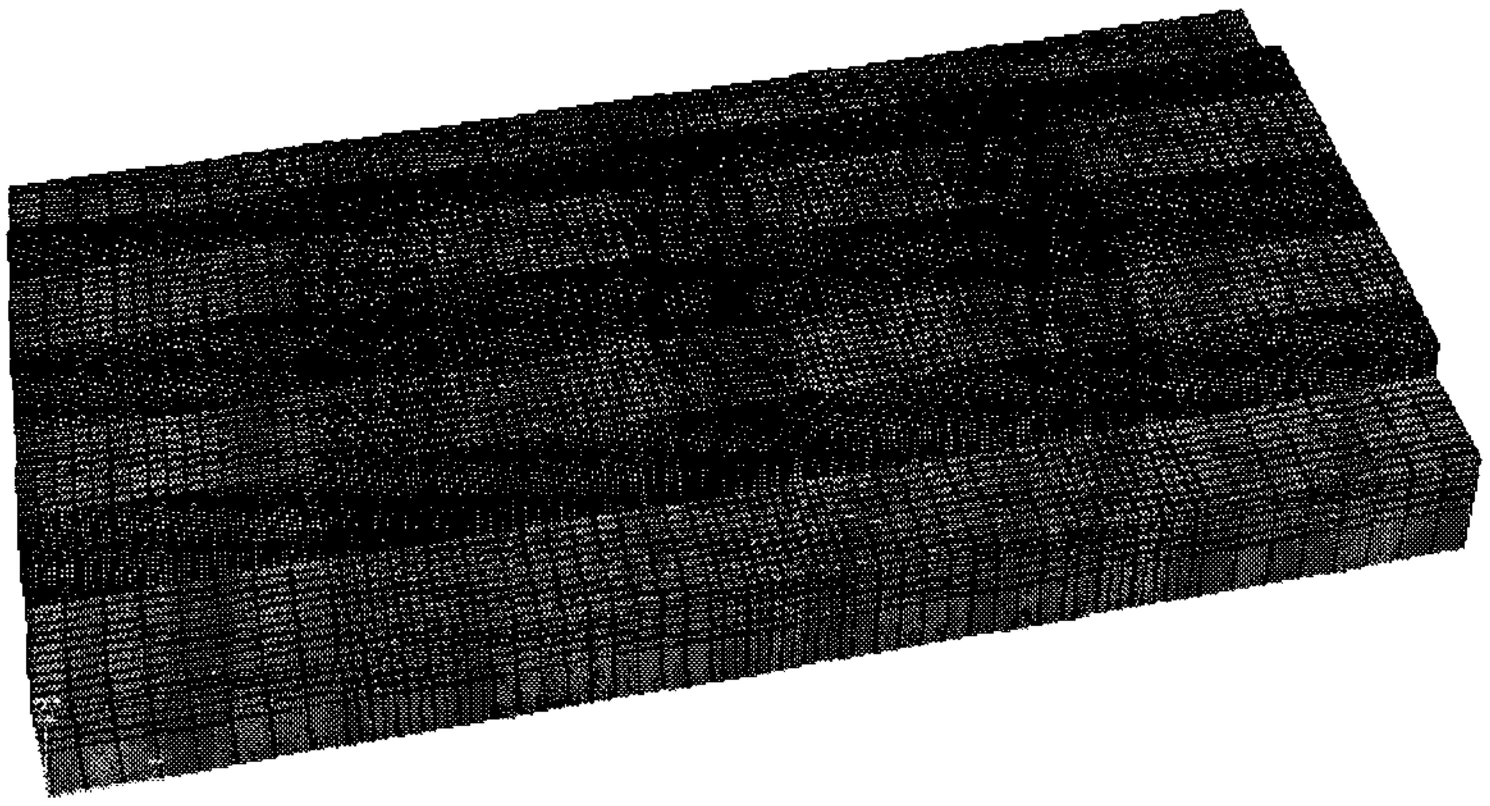
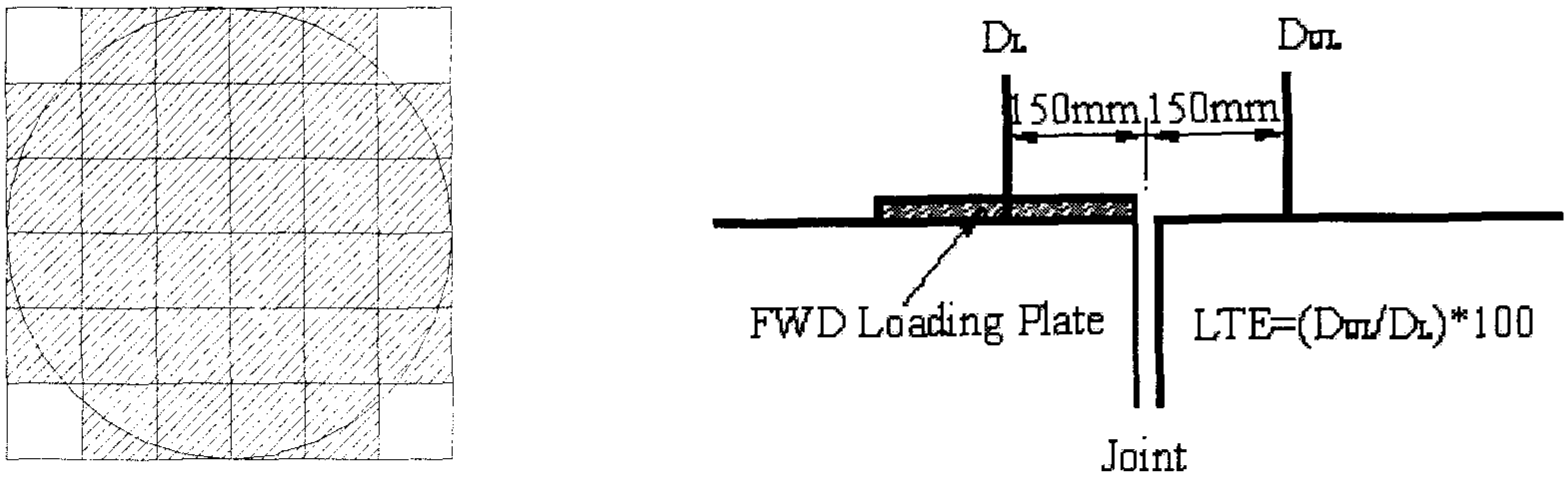


Figure 1. 3-D model of pavement on subgrade

Table 1. Material properties and geometry

Properties	Elastic modulus (MPa)	Poisson Ratio	Thickness (mm)	Length ×Width (mm)
Slab	27,580	0.15	250; (300); 350	6,000×4,000
Base	310; 2,070; (10,350)	0.2	100; (150); 200	12,000×6,000
Subgrade	49; (74); 98	0.45	450	12,000×6,000



(a) Area of FWD loading (b) Calculation of LTE

Figure 2. Layout of FWD test and calculation of LTE

Different linear temperature gradient range between 0.1℃/cm and -0.5℃/cm are input into the model for the sensitivity study. In order to analyze the effects of material properties and thickness of the structural layers on the LTE, 5000N/mm is selected as the control value of the spring constant. For the analysis of the effects of the temperature gradient on LTE, 100 N/mm, 1000 N/mm, 10000 N/mm, and 100000 N/mm are input into the model.

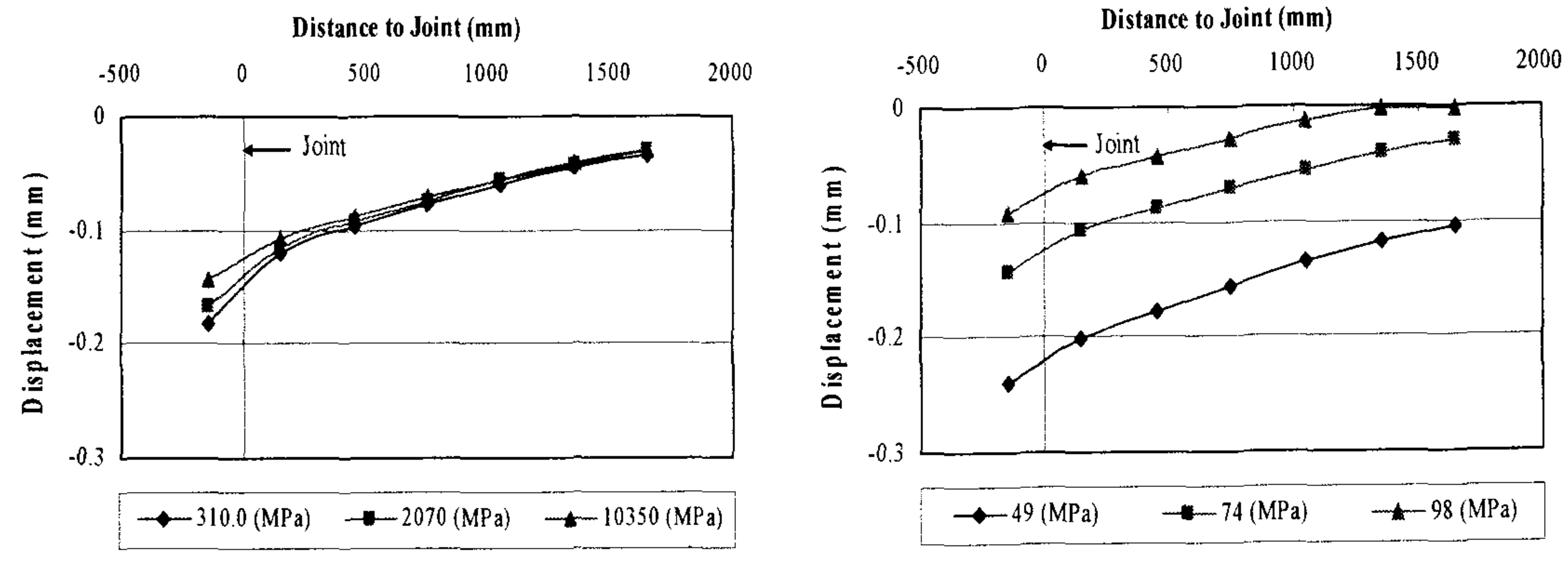
3. Sensitivity study on LTE of joint of JCP

The displacements at the 7 locations where the FWD sensors located are output and analyzed. One of the sensors is located at the center of the loading plate and other 6 are located on the unloaded slab with an interval of 300mm. The LTE of each situation is calculated and analyzed.

3.1 Effects of property of base and subgrade on LTE

Different kinds of underlying layers cause the pavement to show different behaviors. In this model, the input values of the elastic modulus chosen for the base are representative of the properties of a crushed stone, asphalt-treated mixture and lean concrete and the value for the subgrade is representative of the property of compacted soil generally used in Korean highway construction (Yoo and Sim 2006).

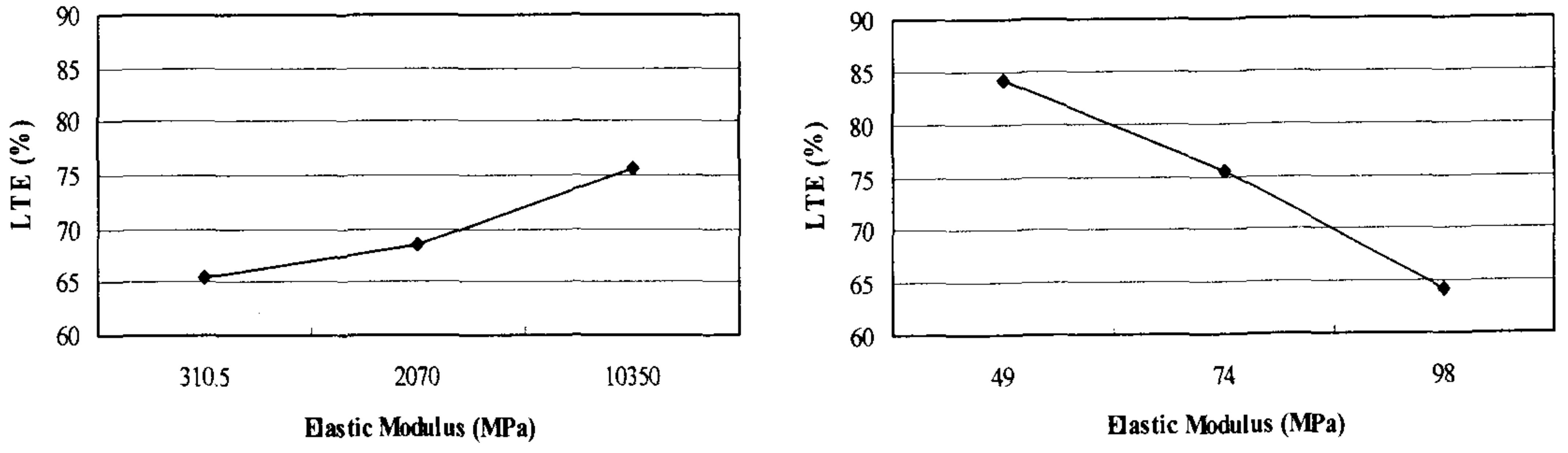
Figure 3 shows the effect of the elastic modulus of the sublayers on the displacement of the slab. The displacement decreases with an increase of the elastic moduli of the base and subgrade, and changes to the slab with different subgrade properties are larger than those with different base properties. These results can be explained by the thickness of the base layer being far thinner than that of the subgrade layer. Hence, in practical construction, in order to decrease the displacement of the slab under a traffic load, a viable method is to increase the elastic modulus of the sublayers, particularly of the subgrade.



(a)Base (b) Subgrade

Figure 3. Effect of elastic modulus of sublayer on displacement of slab

The effect of the elastic modulus of the sublayers on the LTE of the joint is shown in Figure 4. The results show that with an increase of the elastic modulus of the base, the LTE increases whereas with an increase of the elastic modulus of the subgrade the LTE shows an opposite trend. While this result may seem surprising, it can be explained by a simple mathematic law. The LTE is calculated by the displacements of given locations of the loaded and unloaded slab. Therefore, even though the slope of the changing line is similar to each other, as shown in Figure 3.(B), larger values of displacement of the slab must result in a larger LTE and, conversely, smaller values in a smaller LTE. Hence, it is determined that increasing the elastic modulus of the base will facilitate increasing the LTE of the joint while increasing the elastic modulus of the subgrade decrease the LTE of the joint, because subgrade has a more dominant effect on the displacement of the slab.

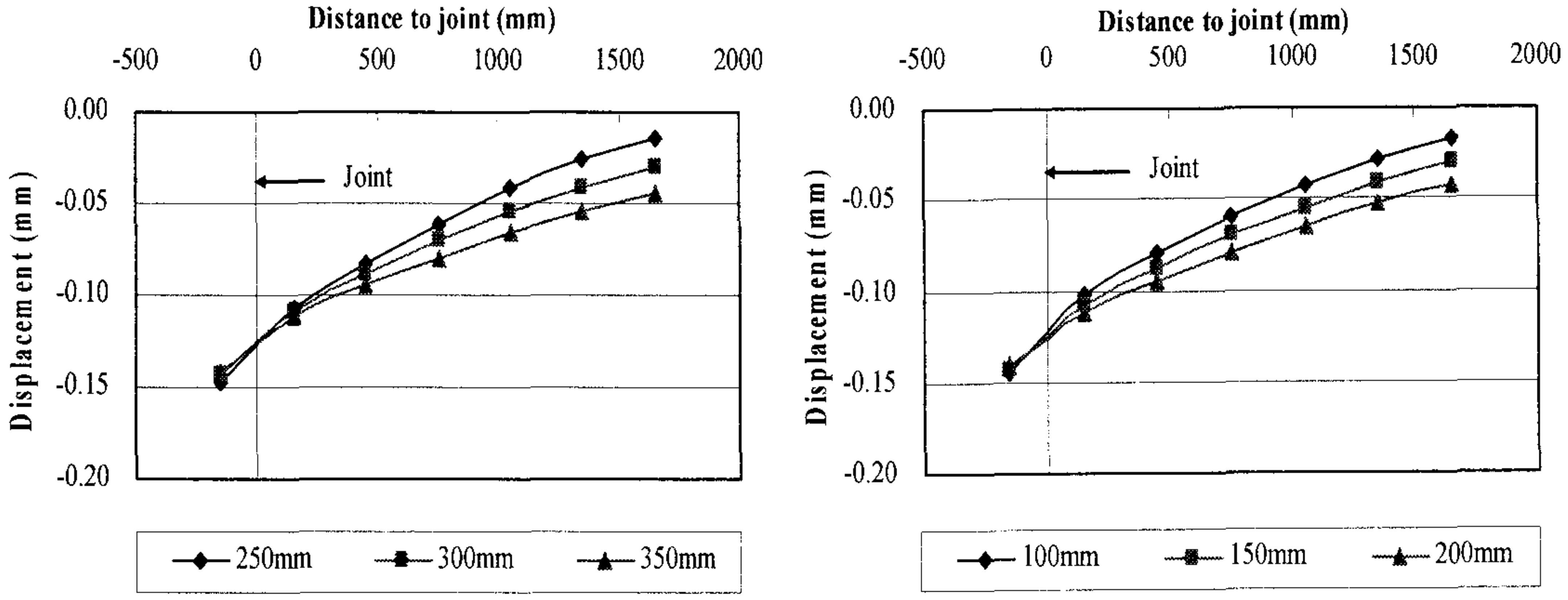


(a) Base (b) Subgrade

Figure 4. Effect of elastic modulus of sublayer on LTE of joint

3.2 Effects of thickness of slab and base on LTE

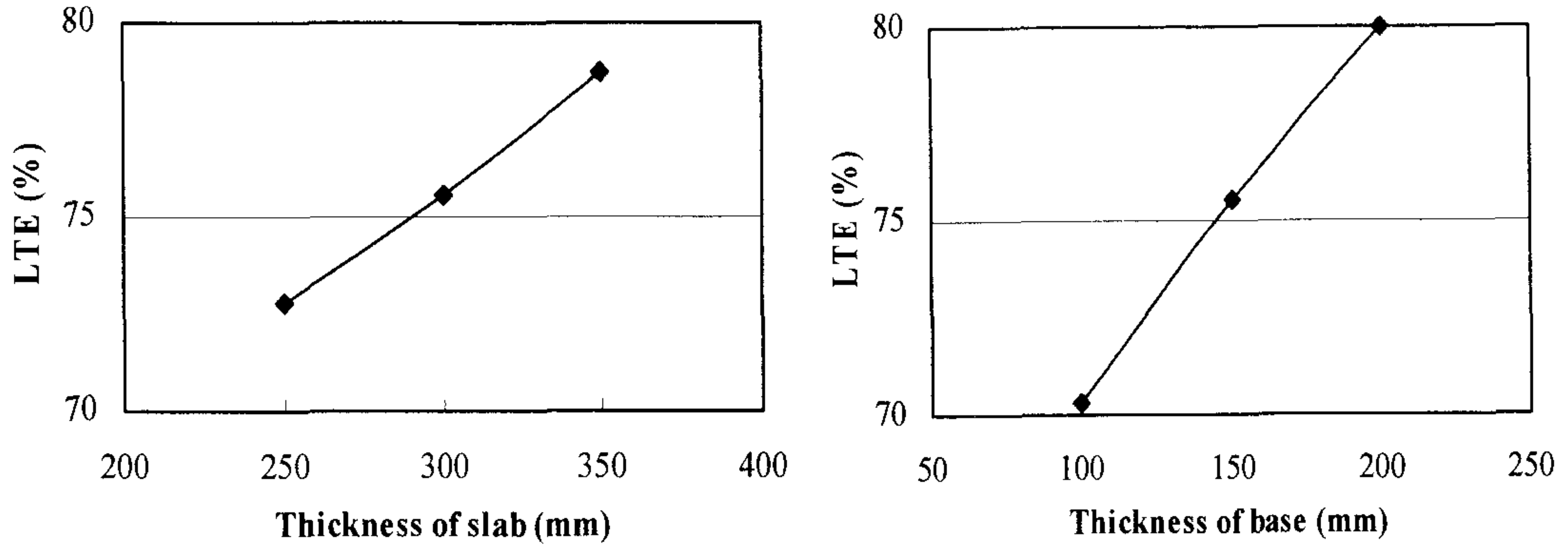
The effects of the layer thickness on the behavior of the JCP are shown in Figure 5. The displacements of the center of the plate decrease with an increase of the thickness of the slab or base but the displacements of the 6 other locations show an opposite trend, i.e., they increase with an increase of the thickness. This shows that a thick slab and base is helpful for sharing the load of the loaded slab and slightly decreasing the displacement of the loading location. There is not an evident difference between the results of changing the thickness of the slab and base. Hence, it can be concluded that the displacement of the slab is not sensitive to change of the thickness of the two layers of the pavement.



(a) Slab (b) Base

Figure 5. Effect of layer thickness on displacement of slab

The effect of layer thickness on the LTE of the joint is shown in Figure 6. The LTE of the joint increases with an increase of the thickness of slab or base and the effect of the slab is smaller than that of the base. This validates the finding that an increase of the thickness of the slab and base correlate with an increase of LTE.

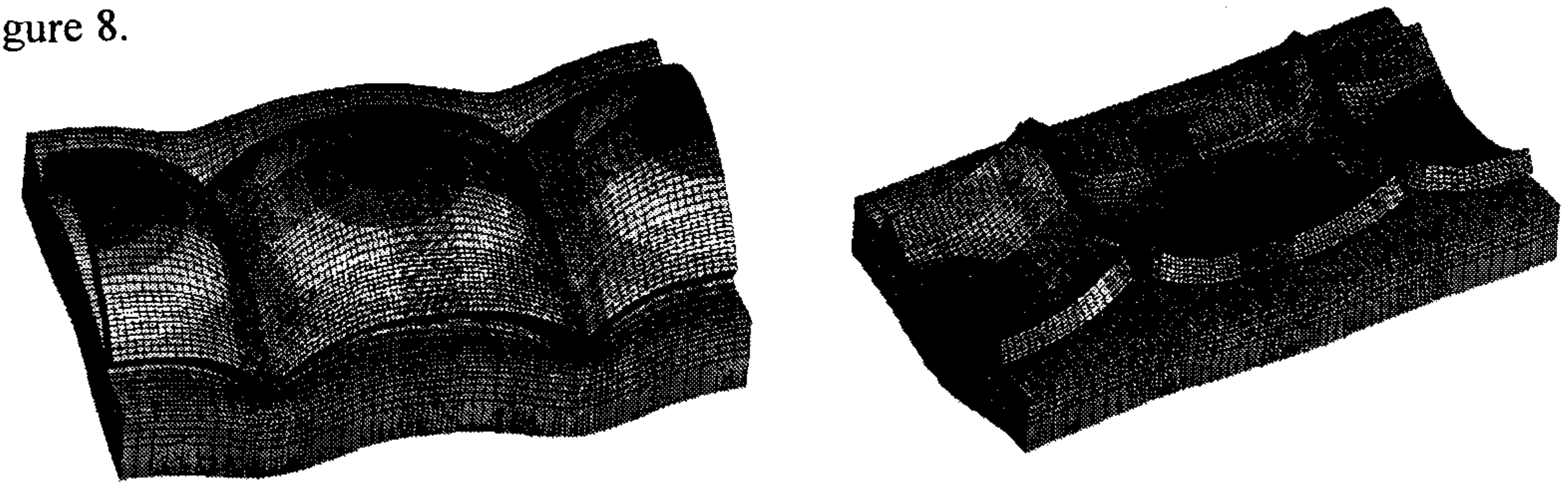


(a) Slab (b) Base

Figure 6. Effect of layer thickness on LTE of joint

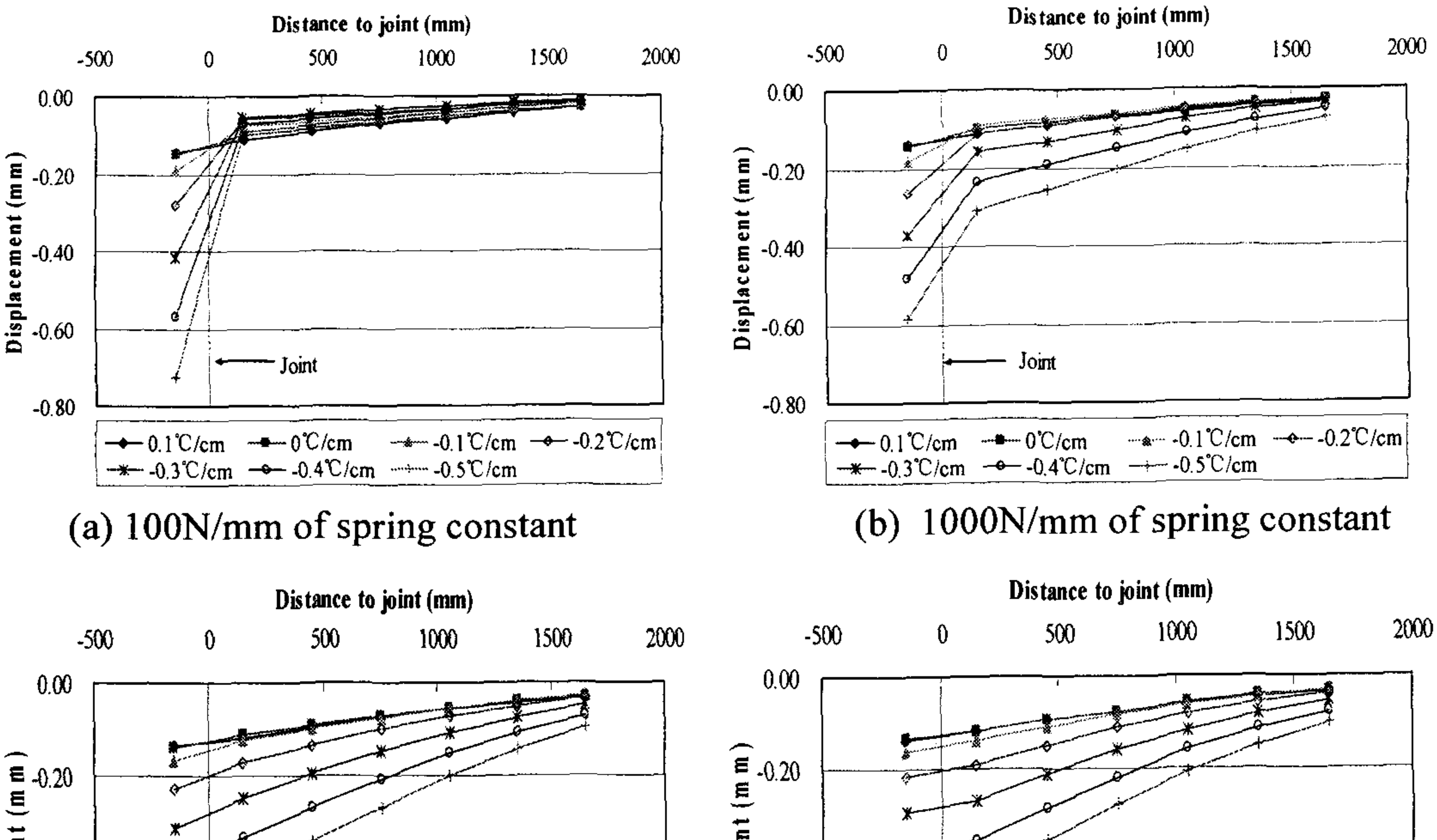
3.3 Effects of temperature gradient on LTE

The deformed shapes of the slab with the application of the temperature gradient are shown in Figure 7. Different curling down (Figure 7(a)) and curling up (Figure 7(b)) shapes can be observed. The application of FWD loading was simulated at the middle of the transverse edge of the slab along the joint. The displacements of the slab from the FWD load are shown in Figure 8.

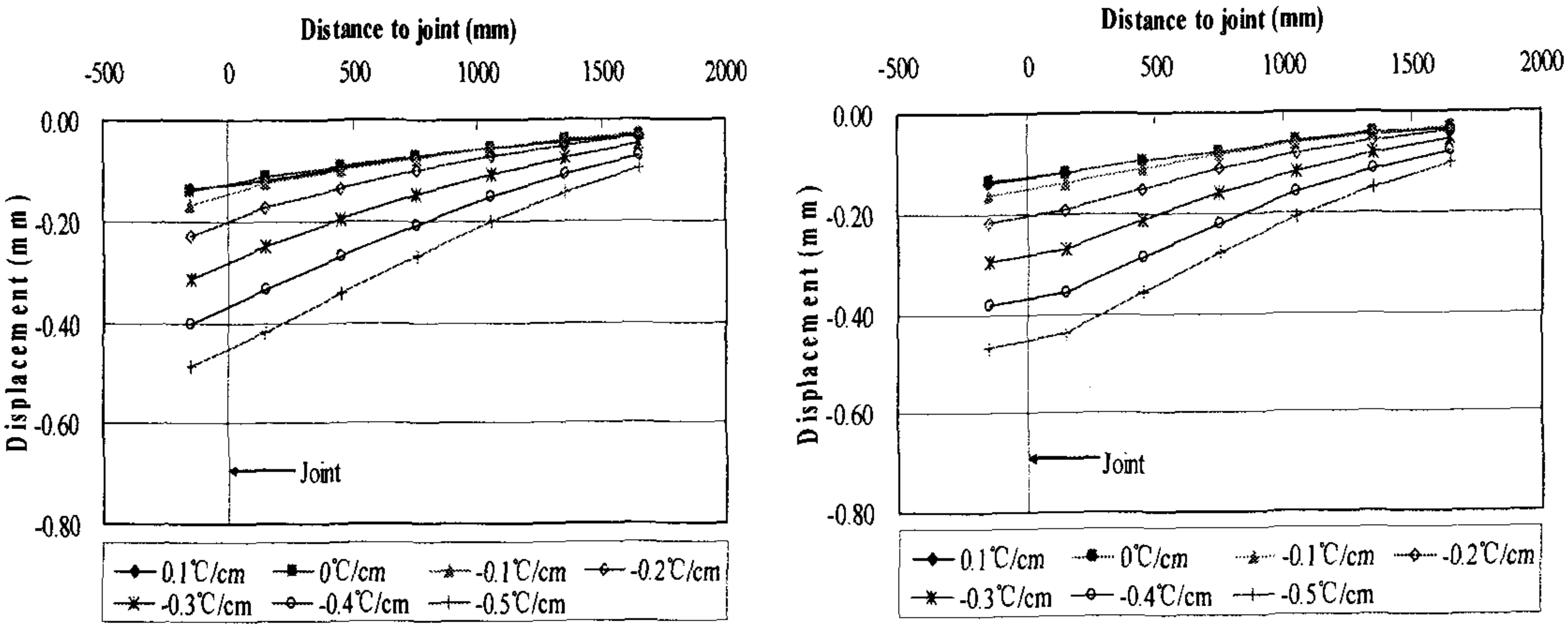


(a) Curling down of slab (b) Curling up of slab

Figure 7. Deformed shape of slab under positive and negative temperature gradients



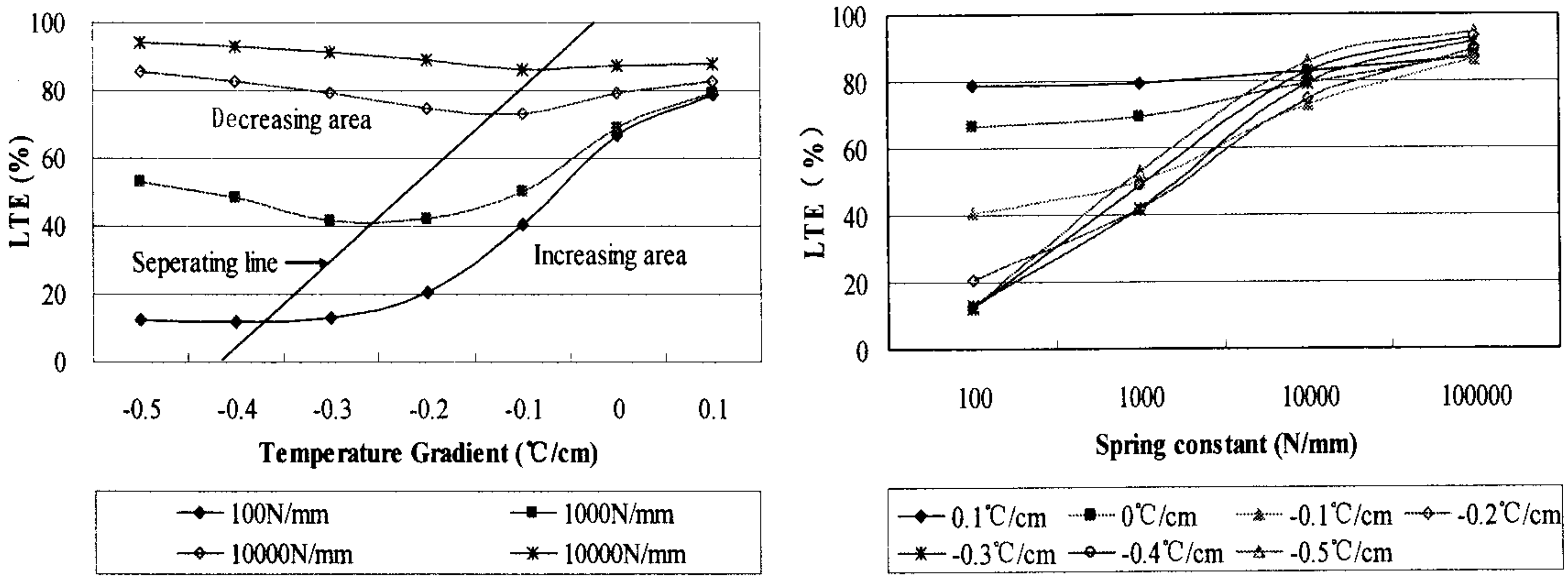
(a) 100N/mm of spring constant (b) 1000N/mm of spring constant



(c) 10000N/mm of spring constant (d) 100000N/mm of spring constant

Figure 8. Effect of temperature gradient on displacement of slab with different spring constants

First, it can be observed that the temperature gradient has significant effects on the displacement of the slab. Generally, the displacement of the slab increases with a decrease of the temperature gradient from positive to negative. The change of the negative temperature gradient is larger than that of the positive and zero temperature gradients and as the negative temperature gradient is increased, the extent of variation becomes larger. This shows that the curled up slab, and in the case of large curling up in particular, is sensitive to the traffic load action. Second, the change of the displacement is highly correlated to the spring constant of the modeling. The graphs of low spring constant of 100N/mm and 1000N/mm change more acutely than those of high spring constants of 10000N/mm and 100000N/mm. Because a larger spring constant helps the unloaded slab share more traffic load of the loaded slab, the displacements of the 6 locations of the unloaded slab decrease with an increase of the spring constant. This illustrates that the effects of the negative temperature gradient on the slab with a joint having a smaller spring constant are evident: the smaller the spring constant, the larger the effects. The LTE of the joint was also calculated. The relationship between the LTE and the spring constant of the joint with different temperature gradients applied to the slab are shown in Figure 9.



(a) LTE vs. Temperature gradient (b) LTE vs. Spring constant

Figure 9. Effect of temperature gradient on LTE of joint with different spring constant

From the relationship between the LTE and temperature gradient on the slab, shown in Figure 9(a), it can be seen that the LTE of joints with different constants change differently. We can find an approximate line separating the lines into two parts, as shown in the figure. The LTE decreases on the left and increases on the right with an increase of the temperature gradient. From these results, it is apparent that the temperature gradient substantially affects the LTE of the joint and an increase of the temperature gradient does not inevitably result in an increase or decrease of the LTE. The effects of different temperature gradients on the LTE are not consistent and the variation of the effects is related to the spring constant of the joint.

It can be seen from Figure 9(b), the LTEs of the joint increase with an increase of the spring constant regardless of the temperature gradient, but the trends are different. The line of a positive temperature gradient shows little change while the line of 0℃/cm change slightly more than that it. The lines of the negative temperature gradient show considerably greater change: as the negative temperature gradient becomes great, the changes become according higher. This results in similar LTE at small constants and larger LTE at larger constants under the larger temperature gradient. This confirms the effect of the spring constant on the LTE of joint. Also, the negative temperature gradient of slab affects the behavior of the joint much more than the positive and zero temperature gradients on the slab. Furthermore, the LTE of the joint is much more strongly affected by negative temperature, and at lower spring constants the effects are more pronounced.

Same as explained in section 3.1, larger displacement values with similar slope are likely to result in a larger LTE. Hence, the effect of the temperature gradient on the LTE will be different from that certain effect on displacement.

The LTE values at -0.3℃/cm, -0.4℃/cm, and -0.5℃/cm are similar when the spring constant is 100N/mm, as shown in Figure 9, which verifies that when the spring constant is low, the load transfer between slabs mainly originates from the action of the sublayers.

The results suggest that low joint stiffness and large negative temperature gradient are the main factors that induce a small LTE of the joint and increase the possibilities of joint distress and damage. A high LTE value, especially under a large negative temperature gradient, can reflect the situation of load transfer between the slabs but cannot indicate a safe behavior of slab for the possible displacement shown in this study. Hence, it is important to understand the effects of temperature on the LTE for analyzing the behavior of concrete pavement, which will be helpful for forecasting distresses.

4. Conclusions

The sensitivity study of the material properties and thickness of the structural layers show that the displacement and LTE are strongly affected by the elastic moduli of the sublayers, especially that of the subgrade, and slightly affected by the thickness of the slab and base. The analysis of concrete slabs showing different curling shapes revealed that the displacement of the slab and the LTE of the joint are powerfully affected by the temperature gradient. Generally, the displacement increases when the temperature gradient decreases from positive to negative. The effects of different temperature gradients on LTE are not consistent. The effects of a negative temperature gradient of the slab on the LTE of the joint are much greater than those of positive and zero temperature gradients on the slab. A joint having low stiffness is more sensitive to the temperature gradient on the slab than a joint with high stiffness. Low joint stiffness and a large negative temperature gradient are the main factors that induce a small LTE. High LTE values can possibly be attributed to large stiffness and a large negative temperature gradient.

Acknowledgment

This study was performed in support of Korea Research Foundation.

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