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3차원 유한요소 모형을 이용한 줄눈 콘크리트포장 하중전달의 민감도 분석

Sensitivity Analysis of Load Transfer of Jointed Concrete Pavements Using 3-D Finite Element Model

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요지

하중전달효율은 다웰이 설치되었거나 설치되지 않은 콘크리트포장 줄눈의 구조적 성능을 나타내기 위하여 사용된다. ABAQUS 소프트웨어를 사용한 줄눈 콘크리트포장의 3차원 모형이 본 연구를 통하여 구축되었다. 기층과 노상이 접착되어 구성된 하부층 위에 3개의 슬래브가 놓였으며, 스프링 요소를 사용하여 인접한 슬래브를 줄눈에서 연결하였다. 콘크리트포장의 다양한 줄눈강성을 모사하기 위하여 다양한 값의 스프링 상수를 입력값으로 사용하여 그 관계를 조사하였으며, 스프링 상수가 커질수록 줄눈의 하중전달효율이 증가하는 것으로 나타났다. 슬래브와 기층의 다양한 탄성계수와 두께를 사용하여 슬래브의 거동과 하중전달효율에 미치는 재료물성과 기하학적 형상의 영향을 분석하였다. 그 결과, 노상의 탄성계수는 기층의 탄성계수와 슬래브 및 기층의 두께보다 더 큰 영향을 미치는 것으로 나타났다. 또한, 양 또는 영의 온도구배에서보다는 음의 온도구배에서 슬래브의 거동과 하중전달효율이 더 민감하게 변화하였으며, 낮은 강성의 줄눈은 슬래브의 온도구배에 더 민감한 것으로 나타났다.

핵심용어 : 하중전달효율, 줄눈변위, 탄성계수, 슬래브 두께, 온도구배, 유한요소법

Abstract

Load transfer efficiency (LTE) reflects the structural performance of doweled and undoweled joints of Jointed Concrete Pavement (JCP). A 3-dimensional (3-D) model of JCP was built using ABAQUS software in this study. Three concrete slabs were placed on bonded sublayers composed of a base and subgrade. Spring elements were used to connect the adjacent slabs at joints. Different spring constants were input to the model to simulate different joint stiffness of the concrete pavement. The LTE of the joint increased with an increase of the spring constant. The effects of material properties and geometric shape on the behavior of JCP were analyzed using different elastic modulus and thickness of the slab and base in the modeling. The results showed the elastic modulus of the subgrade affected the behavior of the slab and LTE more than that of the base and the thickness of the slab and base. The effects of a negative temperature gradient on the behavior of the slab and LTE were more than that of positive and zero temperature gradients. Joints with low stiffness were more sensitive to the temperature gradient of the slab.

Keywords : LTE, joint displacement, elastic modulus, slab thickness, temperature gradient, FEM

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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). Deficiencies of joints of JCP may be manifested as several types of distress, including joint seal damage, separation, pumping, faulting, spalling, and cracking. In general, distresses result in weakening of the joint, which creates excessive deflections and reduced load transferfrom one side of the joint to the other side. 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. Reduced LTE leads to a low ratio of the load shared by the unloaded slab and additional joint deterioration and cracking, particularly for a loaded slab. LTE data of long term pavement performance (LTPP) show that LTE decreases with an increase of the JCP age and correlate with weak performance of pavement (Stubstad 2002). The measurement of LTE is easy and reliable, and hence LTE is used to appraise the performance of pavement and to predict distress and failure in JCP.

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. The stiffness of a joint is composed of shear and moment transfer and it is generally agreed that the load is transferred across a joint principally by shear (Huang 2004). Ball and Childs (Ball and Childs 1975) reported that some moment may be transferred through joints that remain closed, whereas moment transfer across joints with a visible opening is negligible. 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 slabon an hourly and seasonal basis (Jeong et al. 2006). The behavior of the slab is affected by temperature in two ways. First, short term (daily) variations in temperature cause vertical temperature gradients through the slab that in turn cause a convex curvature or a concave curvature of the slab, defined as curling down or curling up. Second, long term (seasonal) variations in temperature cause the panel to contract during cool periods and expand during warm periods. 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. The higher rate of drying of the top compared to the bottom of the slab induces a curling up state of the slab. Byrum (2000) found that most of the LTPP jointed concrete sections tested were in a curled up state, even though a large portion of the testing was performed during the day when the typical temperature gradients should have resulted in a curling down state. At the same time, drying of the concrete near to the jointinduces weakness of aggregate interlocking and dowel bar looseness, which decreases the load transfer between two adjacent slabs.

The distribution of drying shrinkage through a rigid pavement slab is not well understood despite its notably adverse effects on JCP behavior. Researchers recently suggested that conversion of the drying shrinkage distribution to an equivalent temperature gradient is a relatively reliable and feasible approach, and this was accepted as a JCP design module by the Guide for Mechanistic-Empirical Design. Under application of a temperature gradient coupled with a pure temperature gradient and drying shrinkage on the slab, the slab will show more complex and larger curling distortion. 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.

For a long term, the field test results have shown that LTE wereaffected by the material property of pavement structural layers evidently and got inconspicuous effects from geometry of them (Yun, et al. 1999). Noticeably, relationship between LTE and ambient temperature or temperature gradient of slab is diversiform. LTE increases with the increase of temperature at times (Chon et al. 2007) and sometimes shows an opposite trend (Yoo, et al. 2006), which makes the researchers disbelieve some results of their research. Hence, 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. The relationship between the LTE of joints and these variables will help reveal and predict the future evolution of pavement distress.

Basic analyses of a slab using closed form solutions (Westergaard 1927) often give unsatisfactory results due to the assumption that the slab and supporting layers are in full contact at all times. Some finite element method (FEM) codes can model rigid pavements, because they can simulate separation between the slab and supporting layers (Davids and Mahoney 1999 Andrew 2003). The commercial FEM software ABAQUS is often selected as an analysis tool for concrete pavement for its reliable advantages in nonlinear simulation comparedwith other FEM software (Hammons 1997; Yoo and Sim 2006). In the present study, a 3-D model was built using ABAQUS to simulate the behavior of a slab under the application of falling weight deflectometer (FWD) loading in order to analyze the vertical displacement and LTE of transverse joints of JCP.

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. Brick element is selected to simulate the concrete slab and base. The subgrade is divided into two sublayers, the upper half is simulated by brick element and the bottom half is simulated by an infinite element to get a more reasonable analyzed result and to save operation cost. The spacing of jointsis 6000mm, and the width and thickness of the slab is 4000mm and 300mm respectively. At the same time, the width of the gap of the joint between every two slabs is 3mm.The width of the base and subgrade is 6000mm, which means the sublayers are 1000mm wider than the slab at each longitudinal side of the slab. The thickness of the base and subgrade is 150mm and 450mm, respectively. 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.

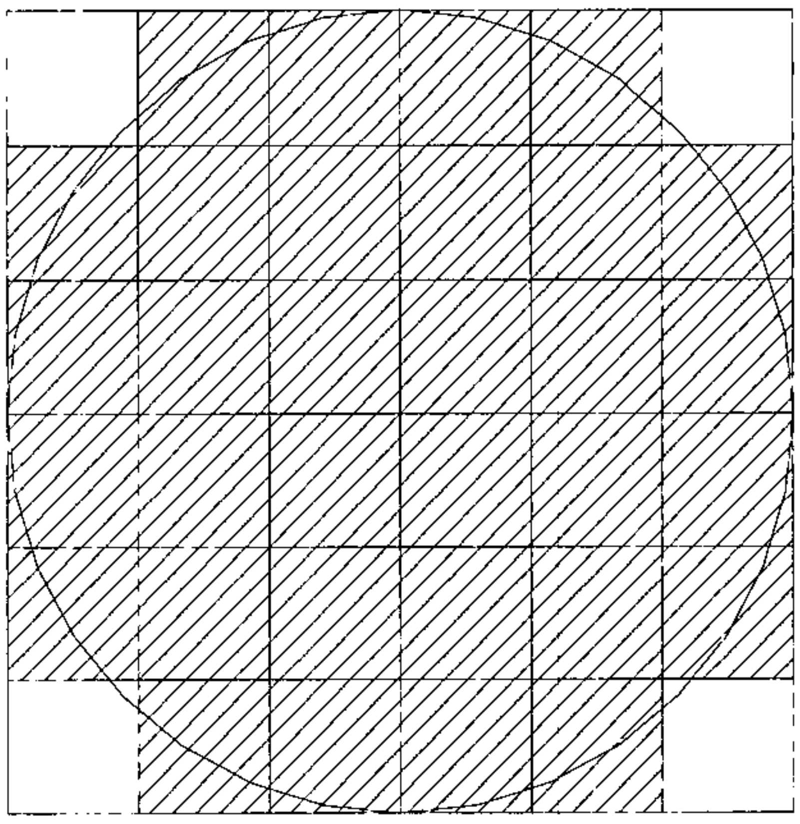
The properties of the materials used as the input data are shown in Table 1. An elastic modulus of concrete of 27580 MPa is used as generally applied in JCP structural analyses. For the sensitivity analysis, 3 different elastic moduli are selected for the base and subgrade, respectively, and control values of 10350MPa for lean concrete and 74 MPa for the subgrade soil are applied. The coefficient of thermal expansion of the concrete selected for the curling analysis is 1×10-5/℃ (Yoo and Sim 2006).

Figure 1. 3-D model of pavement on subgrade

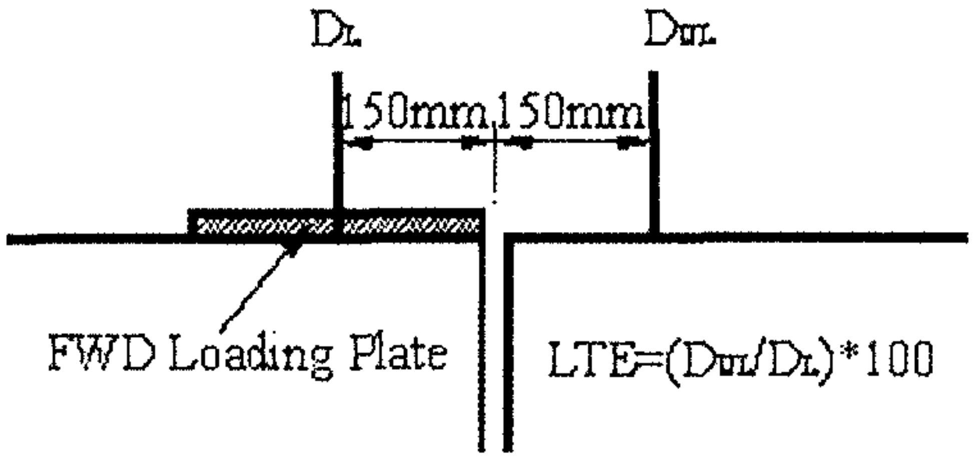
Table 1. Material properties

Material	Elastic modulus (MPa)	Poisson Ratio
Concrete	27580	0.15
Base	310	0.2
	2070	
	10350	
Subgrade	49	0.45
	74	
	98	

The FWD technique has been a widely accepted common practice for the evaluation of LTE of JCP. The fact that the test itself is purely dynamic makes the dynamic analysis models be more accurate and reasonable than static models, but they are rather complicated. Tam and Brown (1989) compared the surface deflectionbowel using static and dynamic models and concluded that the inertial effects of the structure are insignificant. The model in this analysis is static and 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 figure of the FWD loading plate is circular, and hencethe contact area of the plate and the surface of concrete slab should be circular. For convenience when using a brick element, the area of FWD loading in the model is assumed as shown in Figure 2(a) (Chon et al. 2007). Hence, the vertical pressure applied at the middle of the transverse edge of the slab along the joint is 0.5MPa. On the other hand, in order to simulate the behavior of the slab correctly, 2,295kg/m3 is selected as the density of the concrete for calculation of the gravity of the slab.



(a) Area of FWD loading



(b) Calculation of LTE

Figure 2. Layout of FWD test and calculation of LTE

The interlocking action from aggregate and dowel is assumed as a spring acting between the two slabs, as shown in Figure 3 (Chon et al. 2007). The mechanical relationship between force and displacement of a linear spring is constant, and the constant is defined as k. Hence, a spring having a different spring constant k can transfer different shear force between slabs and can induce different deformed shape of pavement and different LTE of the joint. In this study, spring constants ranging from 100N/mm to 1000000N/mm are input into the model.

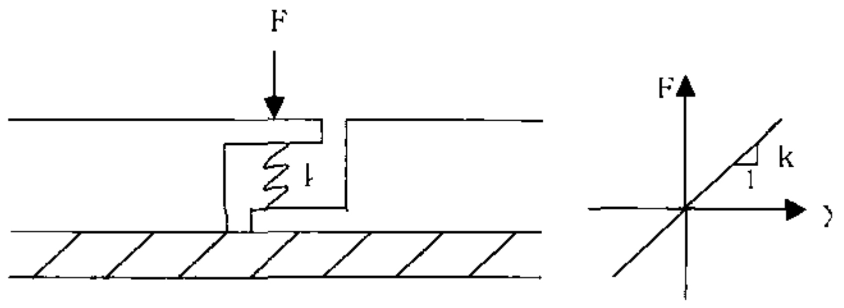


Figure 3. Simulation of load transfer between adjacent slabs using spring element

The relationship between LTE and the spring constant of the spring element is shown in Figure 4. From the figure, it is evident that the LTE increases with an increase of the spring constant, which means a spring with a large constant can transfer large shear force from a loaded slab to an unloaded slab. Atthe same time, when the spring constant is smaller than 100 N/mm or larger than 1E+05 N/mm, the LTE of the joint shows little variation. The range of change of LTE is between 66% and 88%, which is radically different from other analyzed results simulating the sublayers with aspring element whereby any value between 0 and 100% is gotten (Chon et al. 2007). This can be explained by the capacity of the high strength and stiffness of the solid element for sublayers to transfer a large load between the two slabs.

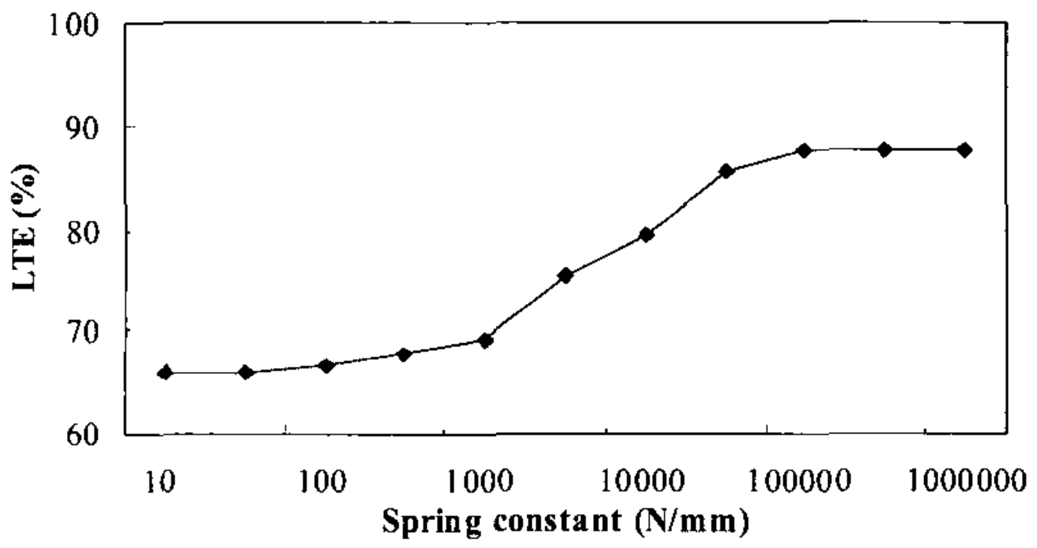


Figure 4. Relationship between LTE of joint and spring constant

Different slab and base thicknesses and a 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.

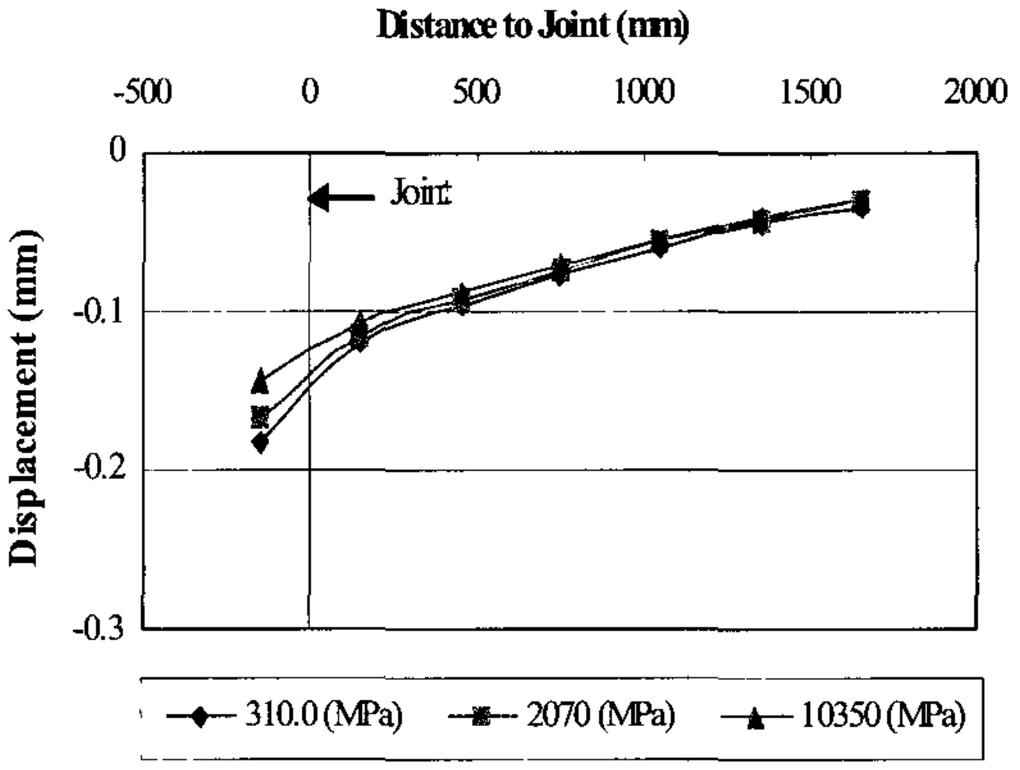
3. Sensitivity study on LTE of joint of JCP

The displacementsat 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.

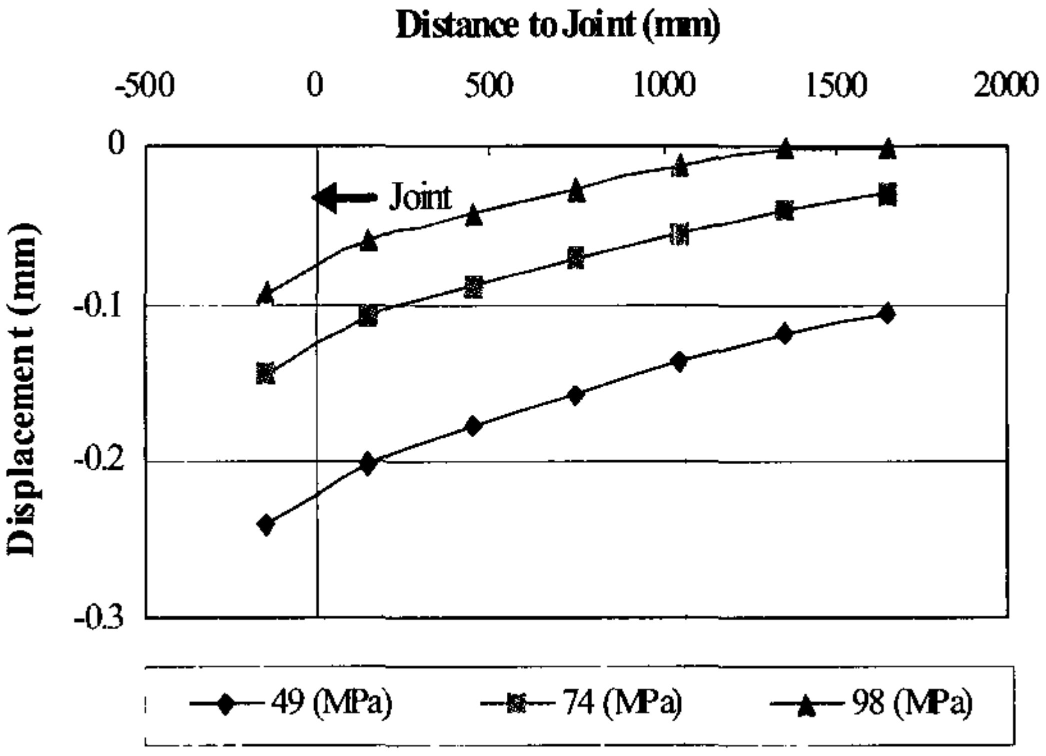
3.1 Effects of property of base and subgrade on LTE

The material used for the bound base in pavement construction includes cement-aggregate mixture, cement treated soil, dense graded asphalt cement, lean concrete, lime treated soil, open graded asphalt cement, soil cement, and sand asphalt. Thematerials used for unbound base included gravel or crushed stone, lime rock, and soil-aggregate mixture. 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 5 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.



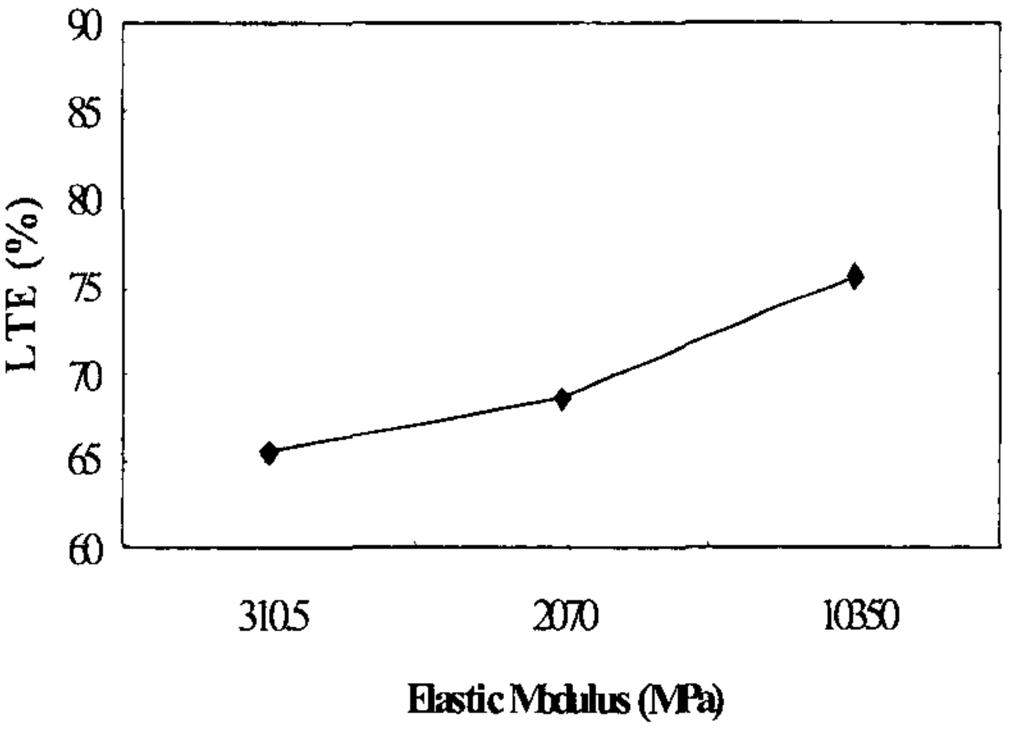
(a) Base



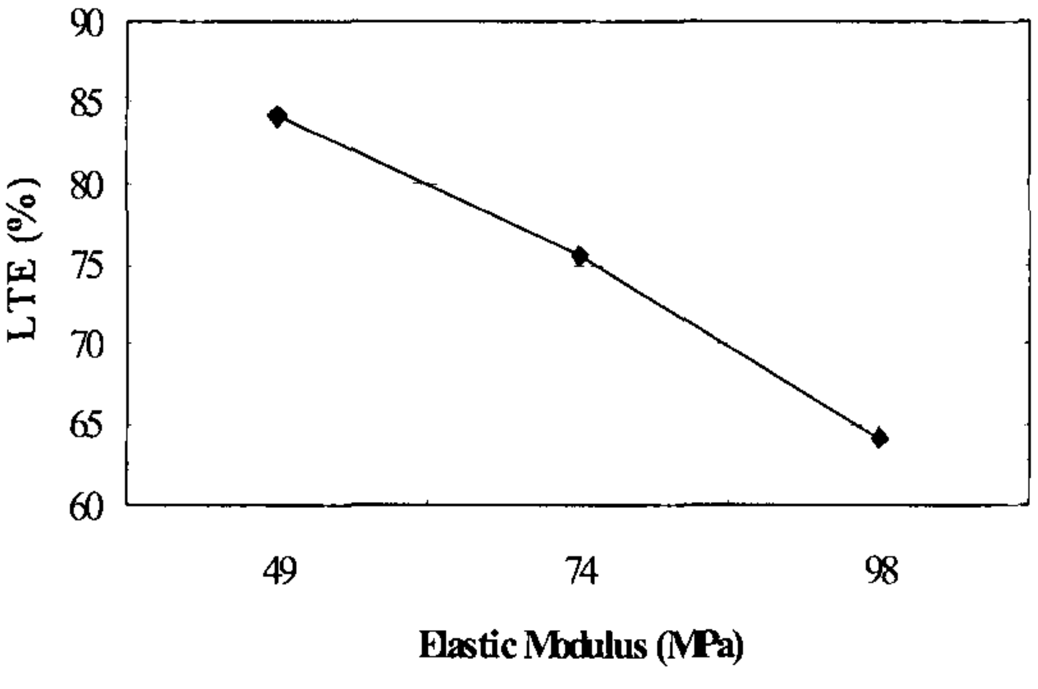
(b) Subgrade

Figure 5. 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 6. 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 mathematiclaw. 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 5.(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

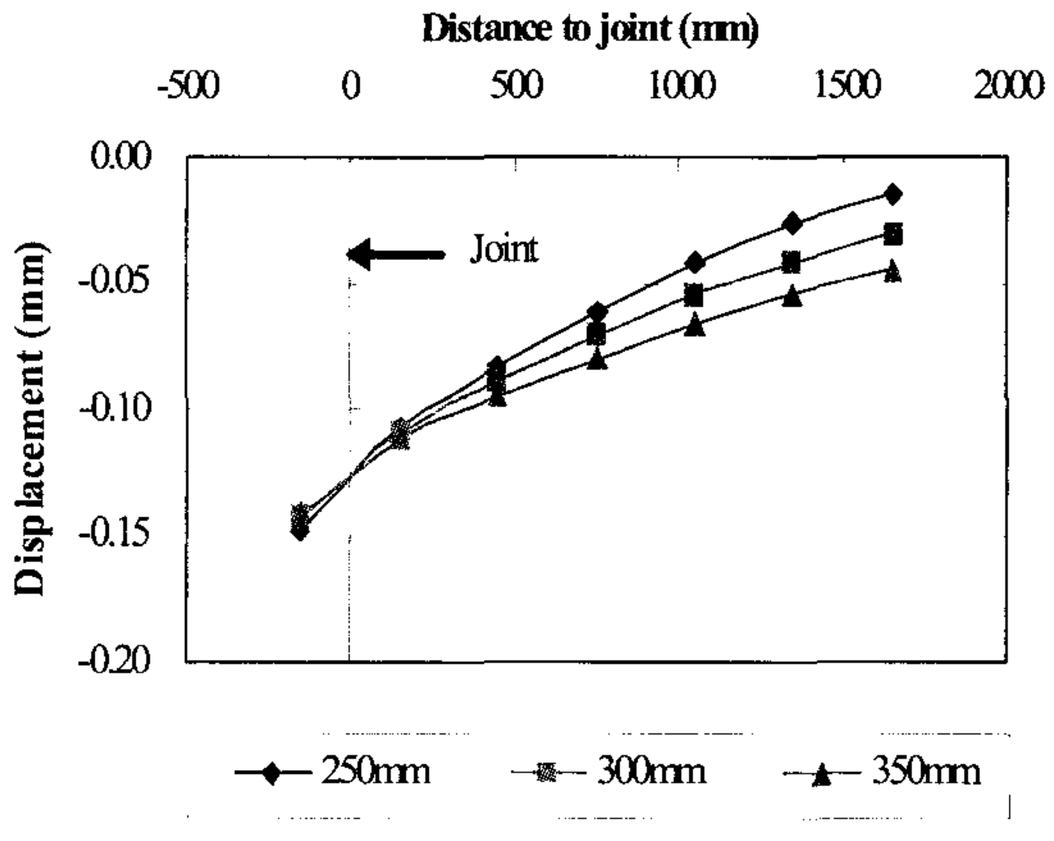


(b) Subgrade

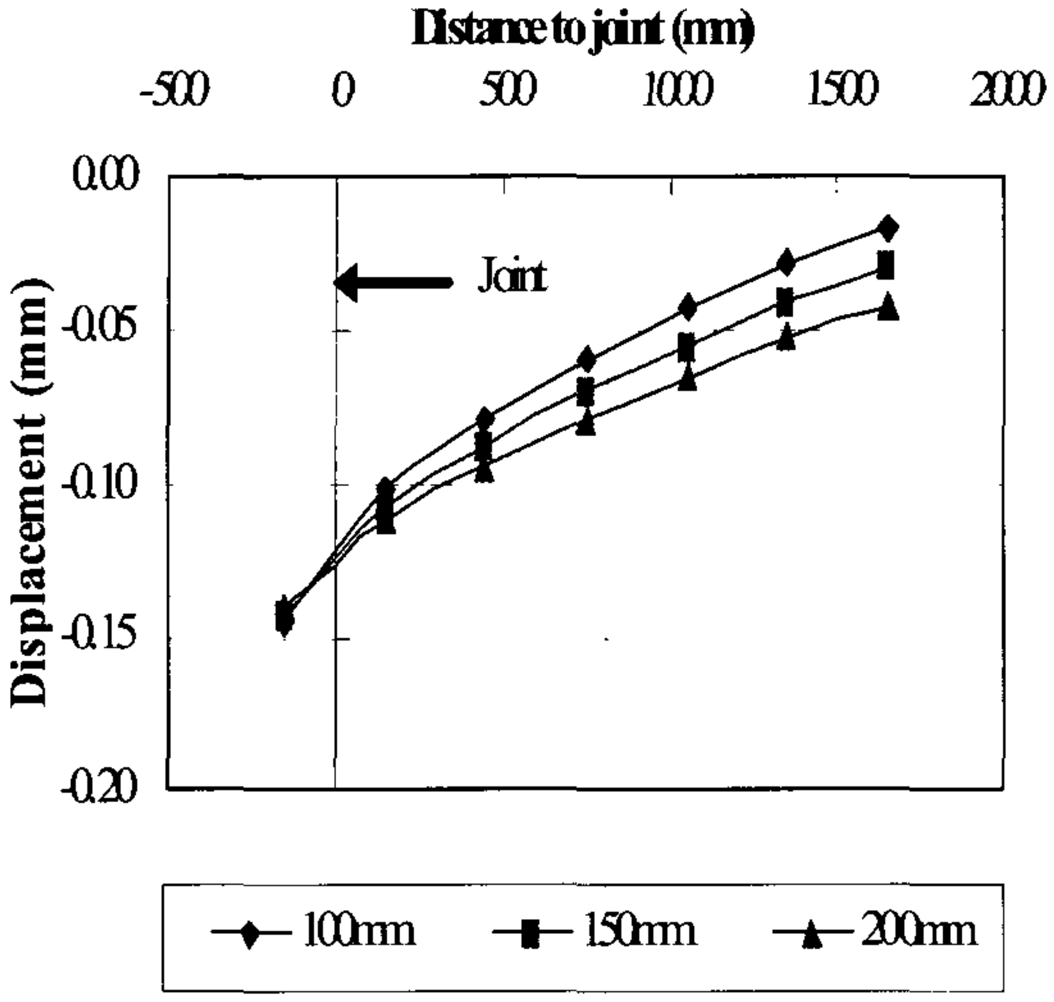
Figure 6. Effect of elastic modulus of sublayer on LTE of joint

3.2 Effects of thickness of slab and base on LTE

Stress of a concrete slab decreases with an increase of the thickness of the slab and base (Kim et al. 2006), but the effects of the thickness of the slab and base on the displacement and LTE of the joint are seldom analyzed. In this model, slabs of 250mm and 350mm and bases of 100mmand 200mm are selected to input into the model to assess the effects of the layer thicknesson the behavior of the JCP, and the results are shown in Figure 7. 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.



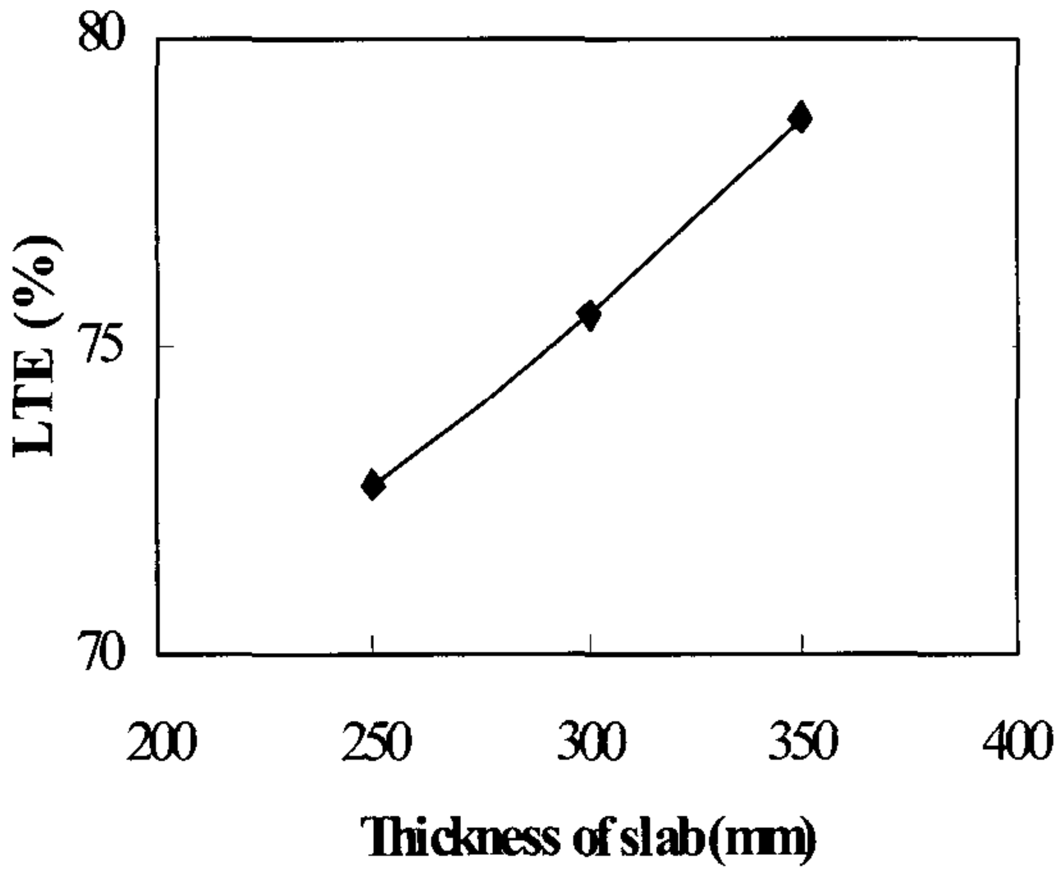
(a) Slab



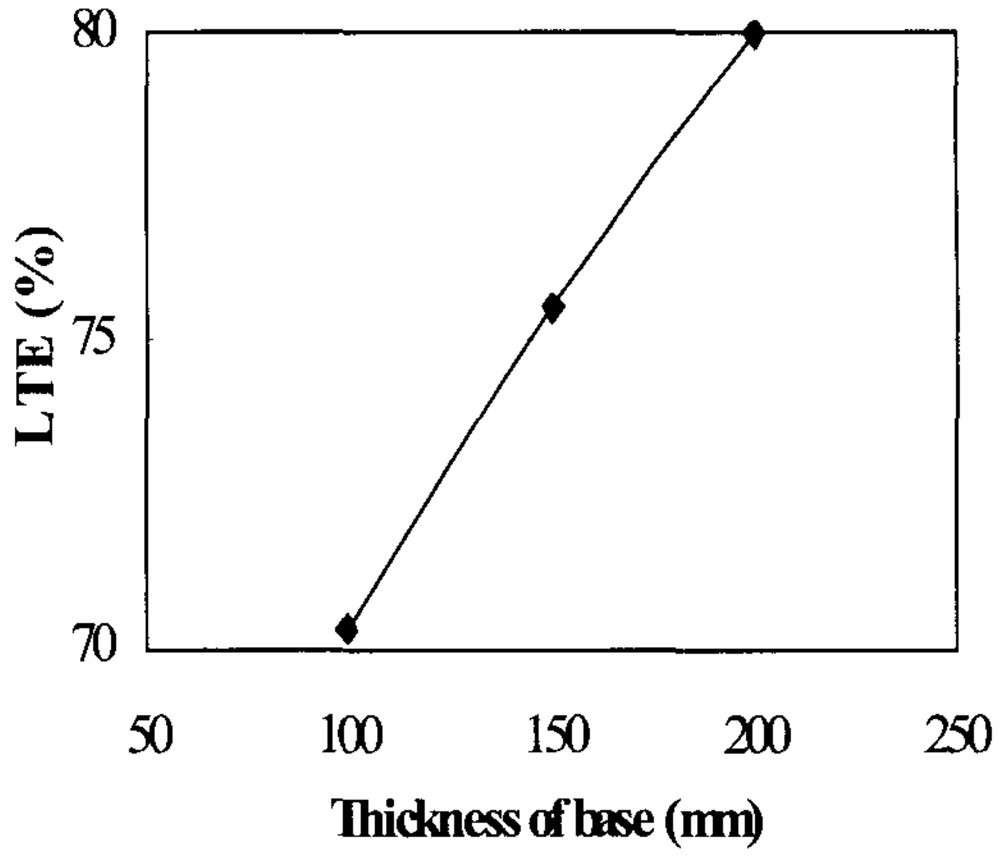
(b) Base

Figure 7. Effect of layer thickness on displacement of slab

The effect of layer thickness on the LTE of the joint is shown in Figure 8. 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



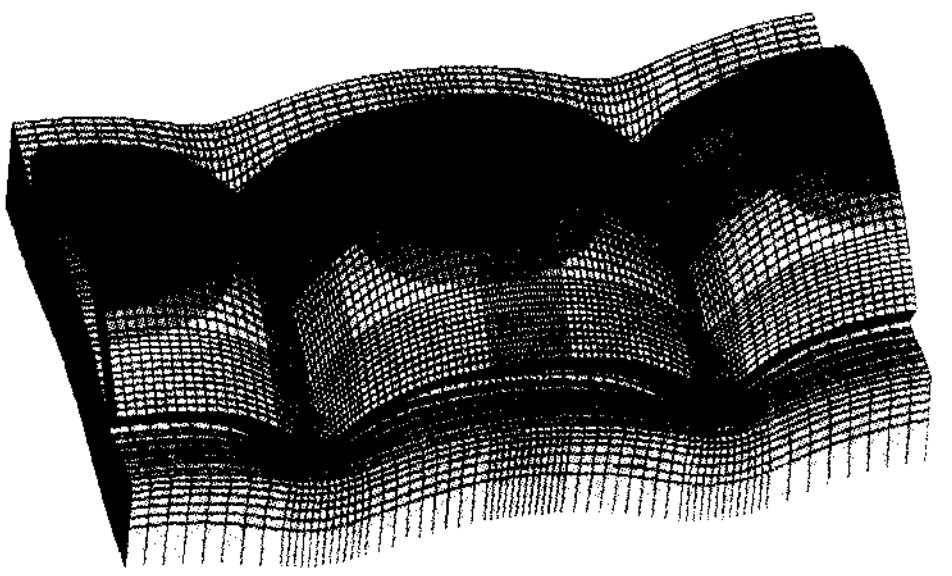
(b) Base

Figure 8. Effect of layer thickness on LTE of joint

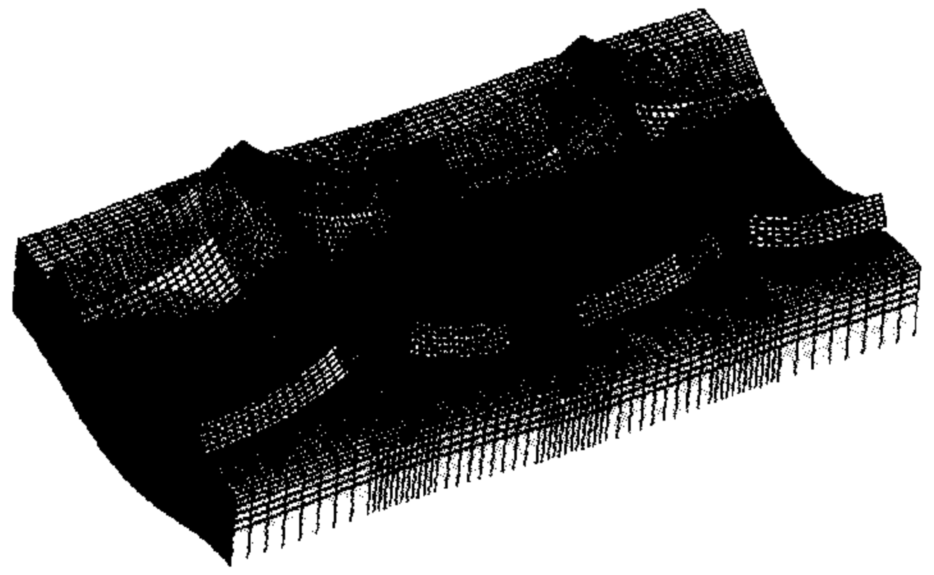
1.3 Effects of temperature gradient on LTE

As the foregoing analysis has shown, temperature gradient and drying shrinkage of a concrete slab induce various deformed slab shapes and their coupled action can be expressed as the action of the temperature gradient. At the same time, the cool and dry weather of Korea possibly causes the concrete slab to curl up more, thus affecting the behavior of the pavement, and therefore a larger negative temperature gradient was selected in the modeling. Positive temperature gradients of 0.1℃/cm and 0 ℃/cm and different negative temperature gradients of -0.1℃/cm, -0.2℃/cm, -0.3℃/cm, -0.4℃/cm and -0.5℃/cm along the depth of the slab were applied.

After running the model with application of the temperature gradient on slab, the results were checked. The maximum displacement of the slab under a temperature gradient -0.5℃/cm was 1.9mm at the corner, which is smaller than that (2.5mm)measured in JCP test sections constructed in Palmdale (Heath and Roesler 1999). This difference may be attributed to the distribution of the temperature and the drying shrinkage not being even and linear, respectively, which the changes of the temperature and drying shrinkage at the corner were more than at the interior of slab (Sun et al. 2007). The deformed shapes of the slab are shown in Figure 9. Different curling down (Figure 9(a)) and curling up (Figure 9(b)) shapes can be observed. There are voids beneath the center of the curled down slab and beneath the edges of the curled up slab. Hence, if FWD loading is applied on the deformed slab, the new slab shape will be related to the original deformed shape.



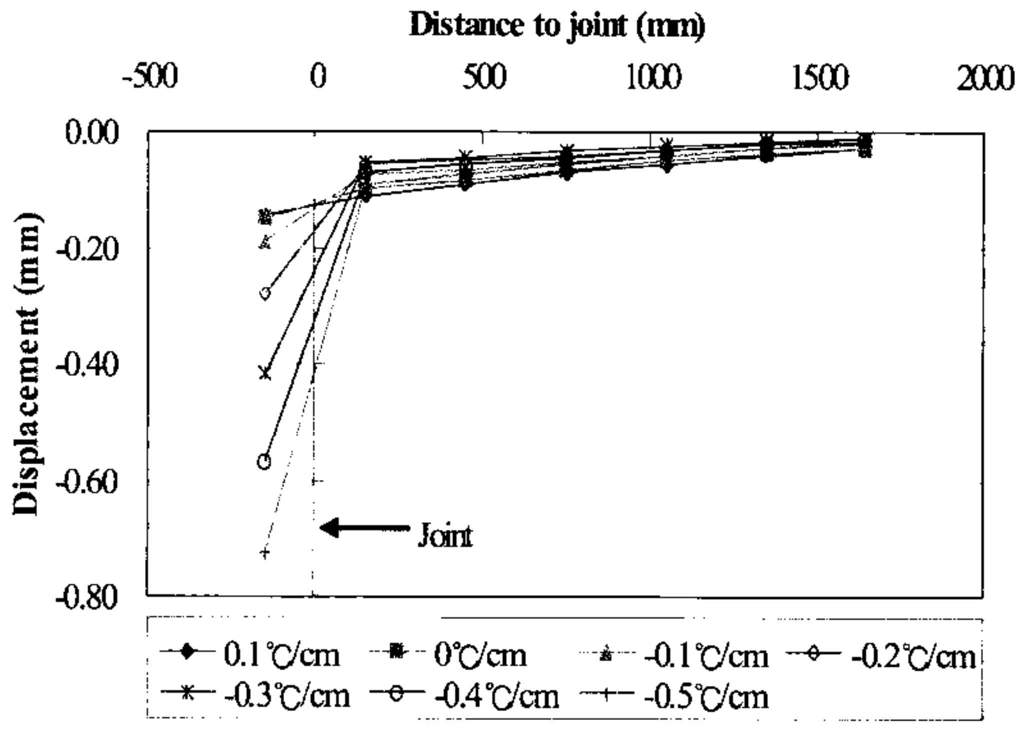
(a) Curling down of slab



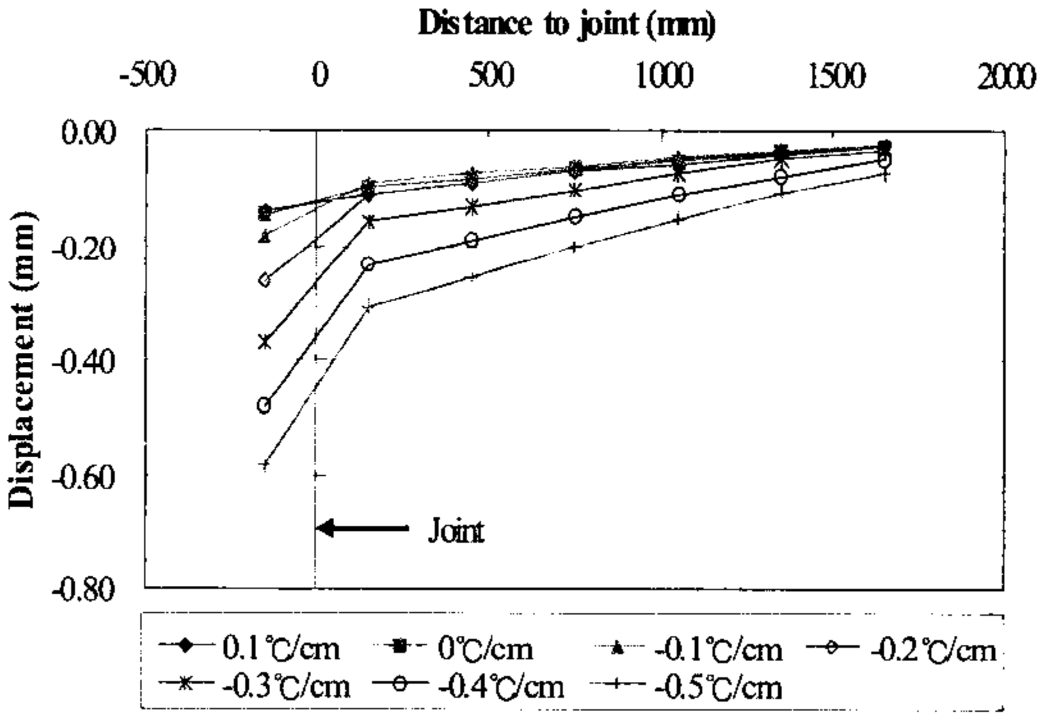
(b) Curling up of slab

Figure 9. Deformed shape of slab under positive and negative temperature gradients

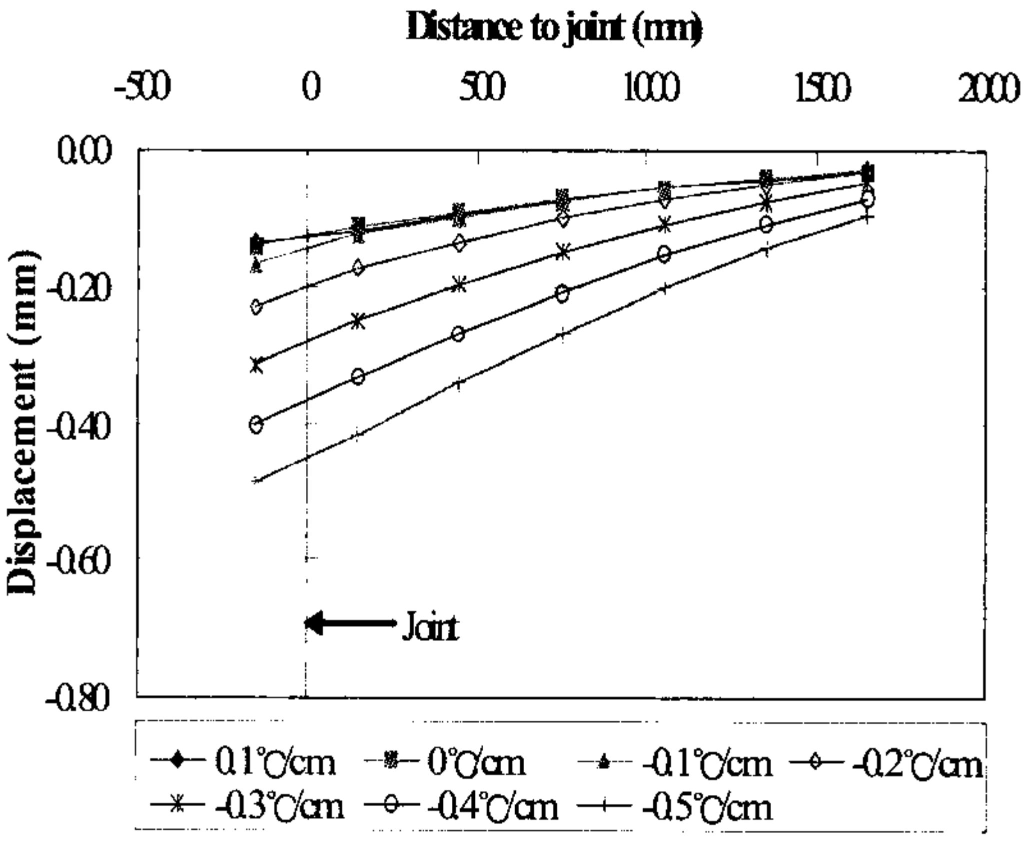
After curling of the slab, application of FWD loadingwas simulated at the middle of the transverse edge of the slab along the joint. The displacements of the slab from the FWD load are shown in Figure 10.



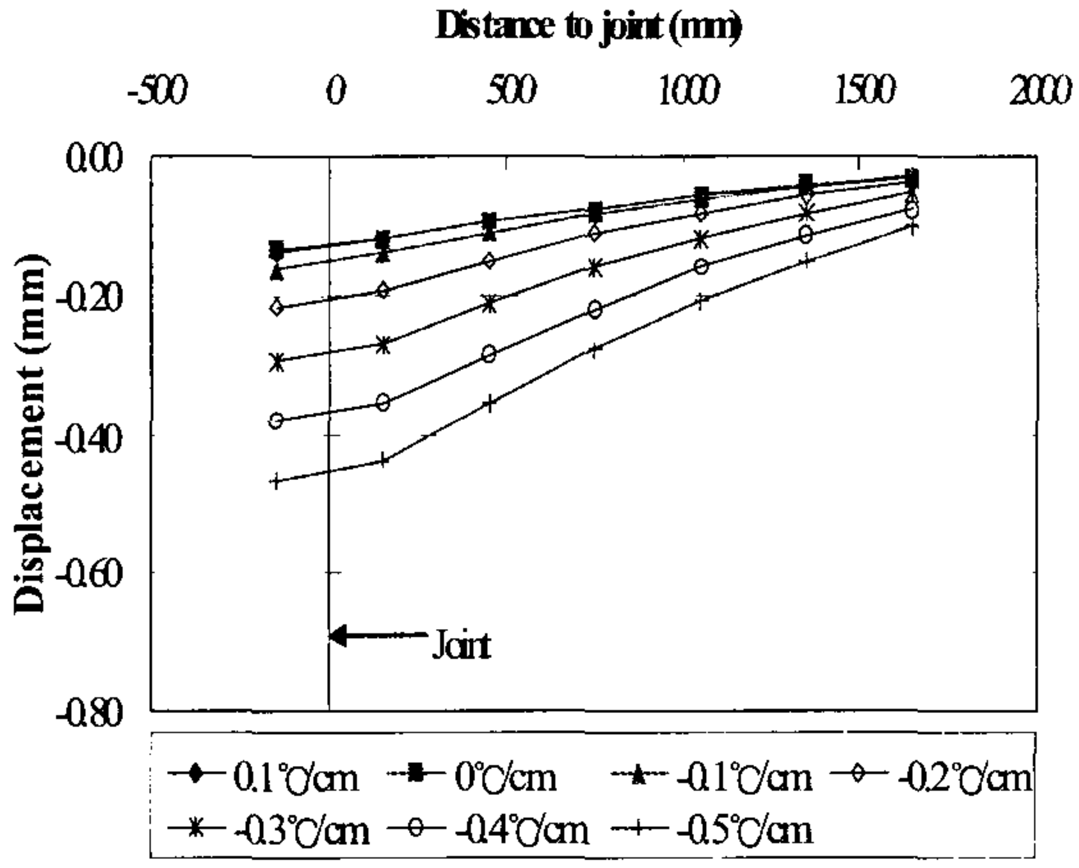
(a) 100N/mm of spring constant



(b) 1000N/mm of spring constant



(c) 10000N/mm of spring constant

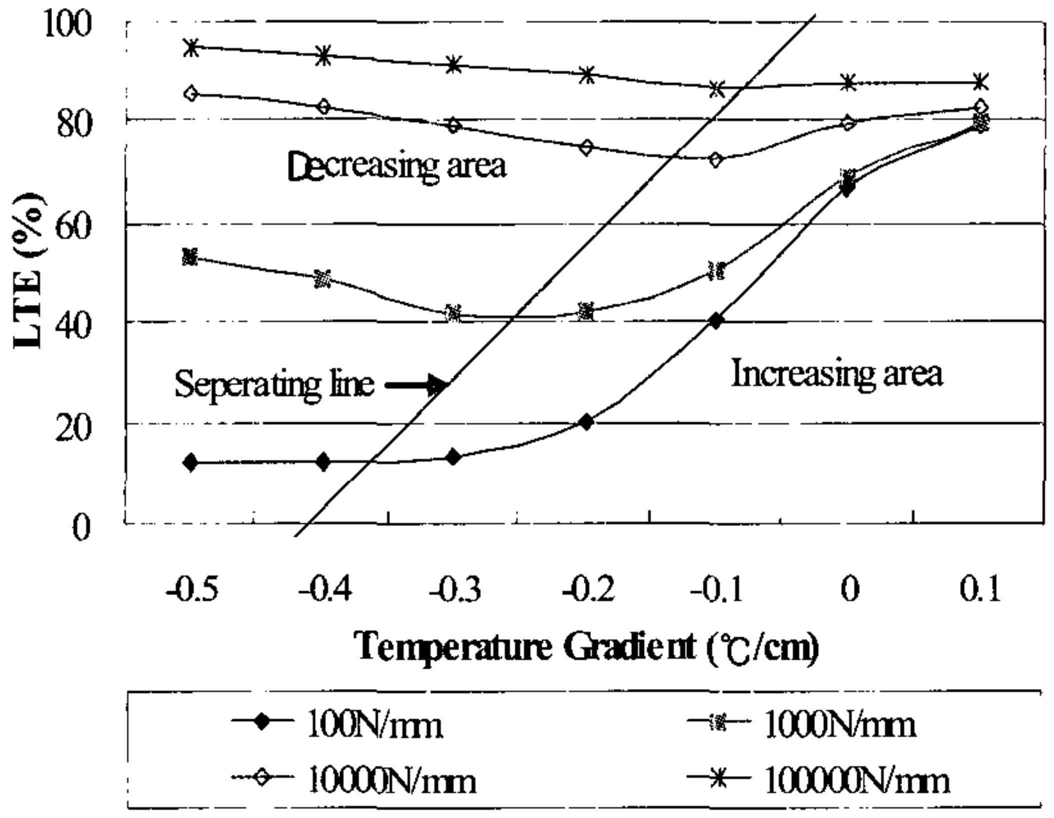


(d) 100000N/mm of spring constant

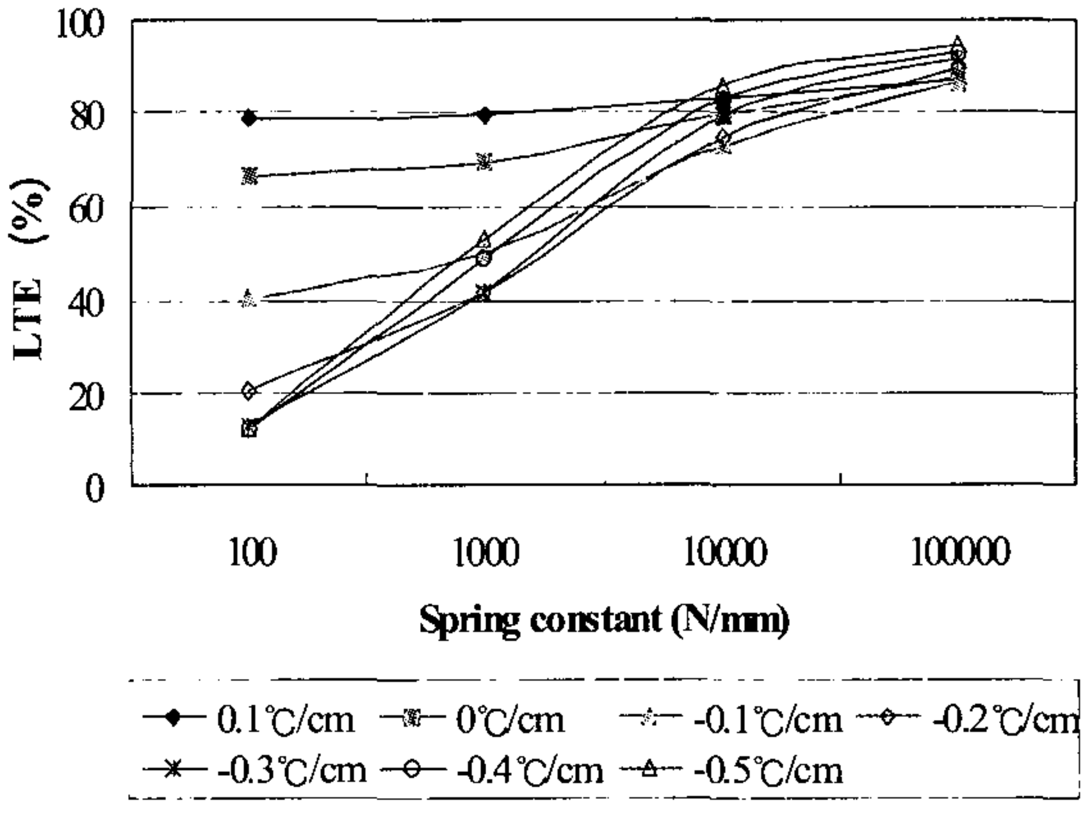
Figure 10. Effect of temperature gradient on displacementof slab with different spring constants

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 asthe negative temperature gradient is increased, the extentof 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 a negative temperature gradient on the deformation behavior of the slab are greater than those of positive and zero temperature gradients. 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 withdifferent temperature gradients applied to the slab are shown in Figure 11.



(a) LTE vs. Temperature gradient



(b) LTE vs. Spring constant

Figure 11. 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 11(a), it can be seen that the LTE of joints with different constants change differently. For the joint of 100N/mm, the LTE decreases slightly from a low value to the lowest value and then increases to a high value. For the joint of 1000N/mm, the LTE decreases from a relatively high value to a relatively low value and then increases to a high value. For the joint of 10000N/mm, the LTE decreases from a high value to a relatively low value and then increases to a high value. For the joint of 100000N/mm, the LTE decreases slightly from very high and stable values. These results are consistent with the results of LTE field test of 88 Expressway shown in Yang's research (Yang et.al. 2001), in which high and stable LTE of high joint stiffness and sharp changing LTE of low joint stiffness were indicated. We can find an approximate line separating the lines into two parts, as shown in the figure. The LTE decreases onthe 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. Theeffects 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 11(b), the LTEs of the joint increase with an increase of the spring constant regardless of the temperature gradient, but the trends of different lines are different. The line of a positive temperature gradient shows little change while the line of 0℃/cm change slightly more than that of positive. 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, theeffect 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 11, 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 combined with large negative temperature gradient is the main reasonthat 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.

4. Conclusions

The analyzed results obtained using a FEM model showthat the LTE of the joint increases with an increase of the stiffness constant of the spring element. The sensitivity study show some analyzed results as below:

1) The displacement and LTE are strongly affected by the elastic moduli of the sublayers, especially that of the subgrade.
2) The displacement and LTE are slightly affected by the thickness of the slab and base.
3) Generally, the displacement increases whenthe temperature gradient decreases from positive to negative.
4) 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.
5) A joint having low stiffness is more sensitive to the temperature gradient on the slab than a joint with high stiffness.

In the case of a joint of high stiffness with dowel bar, which can transfer shear force and moment, the beam element may be reliable and reasonable for the simulation of dowel. In future research, modeling with a beam element to simulate the doweled joint will be carried out and a comparison between different models will be made.

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