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NUMERICAL STUDY OF DOWELED EXPANSION JOINTS ON PLAIN CONCRETE PAVEMENT SYSTEM

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Abstract: In this paper, the ABAQUS / CAE 6.13.1 program is used to study the effect of several variables on the efficiency of the load transfer through an expansion joint in plain concrete pavement system under the influence of the static wheel load. The variables that have been addressed are the diameter of dowel bar (12, 16 and 20 mm), subgrade soil type (A-6) and (A-7-5), concrete type (normal strength concrete and high strength concrete), joint width (10, 20 and 30 mm), thickness of the concrete slab (125, 175 and 250 mm), position of static wheel load (corner load, internal load and edge load) and the effect of soil damage. The results showed, the load transfer efficiency (LTE) and joint effectiveness (E) are enhanced from 69.82% to 89.73% and from 82.23% to 94.59%, respectively as dowel diameter increases from 12 mm to 20 mm, from 60.48% to 79.64% and from 75.37% to 88.66, respectively as joint width decreases from 30 mm to 10 mm, from 64.24% to 89.73% and from 78.23% to 94.59%, respectively as slab thickness decreases from 250 mm to 125 mm and from 69.81% to 79.64% and 82.22% to 88.66%, respectively when CBR value of subgrade soil increases from 5% to 7%, while approximately the same LTE (about 80%) and E (about 89%) are resulted as the concrete compressive strength increases from 27 MPa to 43 MPa. Corner load reduces LTE and E from 84% to 70.49% and from 91.3 to 82.7, respectively as compared to internal load. Presence of weak or gap in subgrade soil reduces LTE and E from about 79% to 59% and 88% to 74%, respectively.

Keywords: *: ABAQUS, Load Transfer Efficiency (LTE), Joint Effectiveness (E), Jointed Plain Concrete Pavement (JPCP).*

دراسة نظرية في مفاصل التمدد الموتّدة للتبليط الخرساني غير المسلح

الخلاصة: في هذه الدراسة، تم استخدام برنامج ABAQUS لدراسة تأثير عدة متغيرات على كفاءة نقل الحمل عبر مفصل التمدد في التبليط الجاسئ غير المسلح تحت تأثير الحمل الساكن (Static Wheel Load) ، المتغيرات التي تم تناولها في هذه الدراسة هي قطر الحديد الاملس (Dowel Bars) للقياسات التالية (20,16,12 ملم)، نوع التربة (A-6) و(A-7-5)، نوع مقاومة انضغاط الخرسانة (خرسانة عادية المقاومة وخرسانة عالية المقاومة)، عرض المفصل(30,20,10 ملم)، سمك البلاطة الخرسانية (250,175,125 ملم)، موقع تطبيق الحمل الساكن (corner Load, internal Load, edge Load) و تأثير ضرر التربة. أظهرت نتائج التحليل العددي باستخدام برنامج ABAQUS أن كفاءة نقل حمولة (LTE) وفعالية المفصل (E) تتحسن من 69.82٪ إلى 89.73٪ و من 82.23٪ إلى 94.59٪ على التوالي عند زيادة قطر الحديد الاملس من 12 ملم إلى 20 ملم، ومن 60.48٪ إلى 79.64٪ و من 75.37٪ إلى 88.66 على التوالي عندما يقل عرض المفصل من 30 ملم إلى 10 ملم، ومن 64.24٪ إلى 89.73٪، ومن 78.37٪ إلى 94.59٪ على التوالي عندما يقل سمك البلاطة الخرسانية من 250 ملم إلى 125 ملم ومن 69.81% الى 79.64% ومن 82.22% الى 88.66% على التوالي عند زيادة القيمة CBR للتربة التحتية من 5٪ إلى 7٪، في حين LTE (حوالي 80٪) و E (حوالي 89٪) نفسها عند زيادة قوة مقاومة

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الخرسانة من 27 ميجا باسكال إلى 43 ميجا باسكال. تحميل الزاوية يقل LTE و E حوالي من 84٪ إلى 70.49٪ ومن 91.3% الى 82.7%، على التوالي بالمقارنة مع الحمل الداخلي. وجود فجوة او ضعف في التربة التحتية يقل LTE و E من نحو 79٪ إلى 59٪ و 88٪ و 74٪ على التوالي.

1. Introduction

The jointed plain concrete pavement (JPCP) consists of unreinforced concrete slabs (3.5 m to 6.0 m) in length and transverse and longitudinal joints between the concrete slabs. In jointed plain concrete pavement, one important issue of performance is the load transfer through the joint ,so two methods are used to supply load transfer through joints which are dowels and aggregate interlock[1]. In the rigid pavement, expansion joints are placed to supply space for expansion to accommodate the horizontal movement of the concrete slabs resulting from temperature and moisture changes. The expansion transverse joints reduce the compressive stresses by transfer of compressive forces between adjoining slabs. So, expansion transverse joints at regular interval can be used in rigid pavement instead of contraction joints[2,3].

2. Research Significance

Based on an experimental study on doweled expansion joints for plain concrete pavement[12], the ABAQUS program is used to develop full scale model for jointed plain concrete pavement system with larger dimensions than the experimental model and the effects of several variables on the efficiency of the load transfer (Load Transfer Efficiency (LTE) and Joint Effectiveness (E)) through an expansion joint study under the influence of the static wheel load. The variables that have been addressed in numerical study are the diameter of dowel bar (12, 16 and 20 mm), subgrade soil type (A-6) and (A-7-5), concrete type (normal strength concrete (NSC) and high strength concrete (HSC)), joint width (10, 20 and 30 mm), thickness of the concrete slab (125, 175 and 250 mm), position of static wheel load (corner load, internal load and edge load) and the effect of soil damage.

3. The Finite Element Models

The 3-D finite element model consists of two slabs of plain concrete, each slab has length of (3600 mm) and width of (3600 mm). The two slabs are connected together across expansion joint by round and smooth steel dowel bars as recommended by the AASHTO[7]. The concrete is slab supported by the subgrade soil (the most common in rigid pavement, the concrete slab placed directly above the soil without the need to use a base or subbase layer).The depth of subgrade soil is assumed (1500 mm) and used for numerical analysis models in this paper. As recommended by the AASHTO specifications[7], the dowels in expansion joints must be fixed (dowel connect with concrete) in one side and free in the other, and has a gap provides a horizontal distance equal to the width of joints to allow movement of the pavement resulting from the change in temperature and moisture. So, three contacts was created, the first contact between Subgrade soil and concrete slab where the friction coefficient is assumed (1.5) according to Huang[4] , the second contact between each dowel bars and surrounding concrete in fixed side of slab and third contact also between each dowel bars and concrete surrounding but in free side of slab where the coefficient of friction (0.35 and 0.05 respectively) are assumed according to Al-Humeidawi[10], see Figure (1).

The problems are modelled using C3D8R element type. The C3D8R solid element has 8-nodes, each node have three translations at directions (x, y and z) without rotation(first order or linear). The nodes in face of the solid element C3D8R connected and arranged in a manner similar to arrange the bricks so also it called brick element. The element has the ability to represent linear or nonlinear analyses[11]

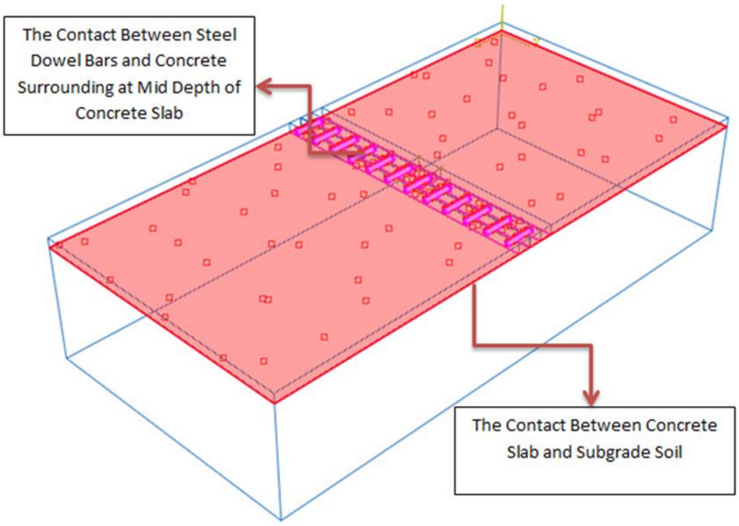


Figure 1. The Contacts used in the Models

Three types of materials are used (concrete, steel and soil), The properties of the materials used in this study are the results of an experimental study on doweled joints for plain concrete pavement[12], Table (1) shown properties of material.

Table (1): The Material Properties used in ABAQUS Models

Materials		Elastic Modulus (E) kPa	Poisson`s Ratio (μ)*	Properties of Material
Subgrade Soil	Type I (A-6)	50000	0.45	Isotropic and Linear Elastic
	Type II (A-7-5)	61000		
Concrete	NSC	24422000	0.15	Isotropic and Linear Elastic
	HSC	30819000		
Steel Dowel Bar		200000000	0.3	Isotropic and Linear Elastic

The Poisson's ratio values for all materials are assumed according to reference Huang*[4].

The load value of one tire of all models is 40 kN (In most states of United State (US), a standard axle load ranges (80 – 90 kN)[3]) and the uniform pressure of tire is

550 kPa as assumed Huang[4]. The tire contact area within pavement is assumed as an equivalent rectangular shape[3,4], see Figure (2).

The boundary conditions of all models, the four sides of pavement (subgrade soil and concrete slab) are fixed in x and z directions while the boundary condition of the bottom subgrade soil is not movement at x, y and z directions, see Figure (3).

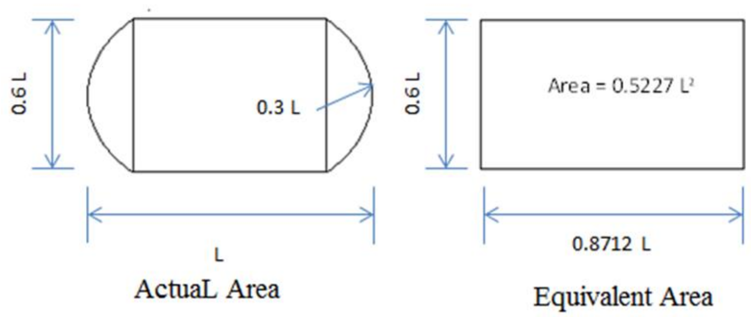


Figure 2. The Tire Contact Area[4]

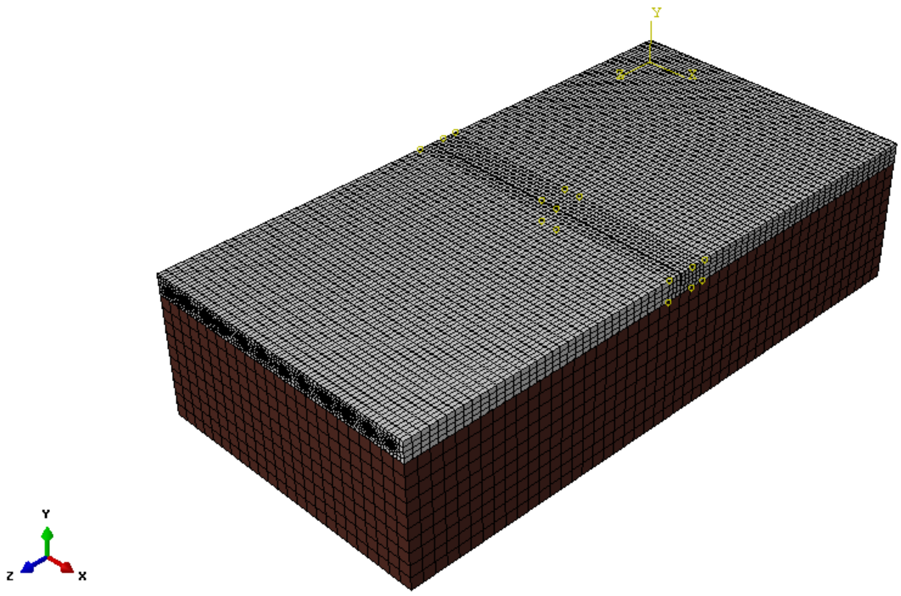


Figure 3. ABAQUSE Model

4. Load Transfer Efficiency

Load transfer efficiency expresses the ability of a joint to transfer part of the applied load on the loaded slab to the adjacent unloaded slab[5]. In jointed concrete pavement, when a traffic load is applied near a joint , both loaded slab and unloaded slab deflect because a part of the load applied is transferred from the loaded slab to the unloaded slab and lead to reduced deflections and stresses in the loaded slab[6]. Deflection load transfer efficiency (LTEδ) is the ratio of the deflection of the unloaded slab (δ_u) to the deflection of the loaded slab (δ_L) as follows[7]:

$$LTE\delta = \delta_u/\delta_L \tag{1}$$

Load transfer efficiency at the joint affected by temperature of concrete pavement, moisture content, age, construction quality, type of joint, volume and repetition of load[8]. The acceptable range of load transfer efficiency (LTE) is 70% to 100% for 40 kN wheel load[6].

The load-transfer efficiency at the joint is evaluated by means of joint effectiveness (E). Joint effectiveness (E) depend on the deflections of loaded and unloaded Slabs as follows[9]:

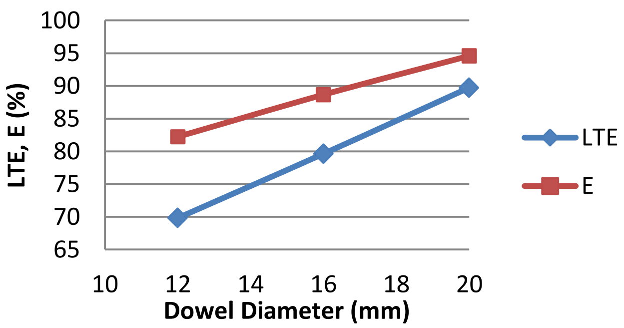
$$E = 2\delta_u / (\delta_L + \delta_u) \times 100 \qquad (2)$$

where:
E : Effectiveness of joint.
δ_u: Deflection of the unloaded slab (mm).
δ_L : Deflection of the loaded slab (mm).

If the deflection of the unloaded slab and deflection of the loaded slab at the joint are equal this means that the joint is 100% effective. but, if the unloaded slab at the joint has no deflection, this means that the joint is 0% effective. The American Concrete Pavement Association recommends an accepted effectiveness of 75% or more in joints of concrete pavement[8].

5. Effect of dowel diameter

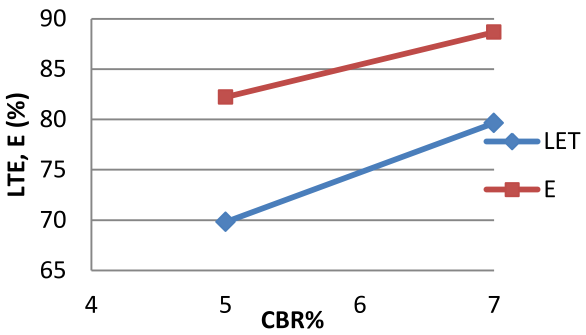
The deflection of unloaded slab increases with the increase of the diameter of the dowel. The unloaded slab deflection of 20 mm dowel diameter is greater than the unloaded slab deflection of 12 mm and 16 mm dowel diameter by about (22.2% and 10.1% respectively).The deflection of loaded slab decreases with increasing the dowel diameter. The loaded slab deflection of 20 mm dowel diameter less than the loaded deflection slab of 12 mm and 16 mm dowel diameter by about (5% and 2.7% respectively). This is because the increase of dowel bars diameter increases the value of flexural rigidity (EI) which leads to reduce the deflection of concrete slab generally and increase the deflection transfer to the unloaded slab. As a result that, increases the load transfer efficiency (LTE) and the effectiveness of joint (E) where (69.82%, 79.64% and 89.73%) load transfer efficiency and (82.23%, 88.66% and 94.59%) joint effectiveness for dowel diameter (12, 16 and 20 mm), respectively, see Figure (4).



(h_{slab} = 125 mm, CBR = 7%, f'_c = 27 MPa, W_{joint} = 10mm, edge load)
Figure 4. Effect of Dowel Diameter on LTE and E

6. Effect of the Strength of Soil

Two types of subgrade soil which are Type I (A-6,CBR=7%) and Type II (A-7-5,CBR=5%) are used. The increase in the CBR value of the soil leads to increase the deflection of unloaded slab. The unloaded deflection of Type I soil is greater than the unloaded slab deflection of Type II soil by about (2.16%). But, the deflection of loaded slab decreases with the increase in the CBR value of the soil. The loaded slab deflection of Type I soil is less than the loaded slab deflection of Type II soil by about (11.66%). As a result the support soil have a significant effect on the deflection of jointed doweled concrete pavement, and this in turn leads to increase the load transfer efficiency (LTE) by (79.64% and 69.81%), and increased effectiveness of joint (E) by (88.66% and 82.22%) for subgrade soil Type I and Type II respectively, see Figure (5).



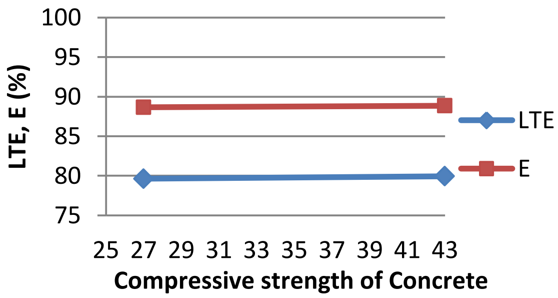
$(h_{slab} = 125\ \text{mm}, D = 16\ \text{mm}, f'_c = 27\ \text{MPa}, W_{joint} = 10\text{mm}, \text{edge load})$

Figure 5. Effect of Subgrade Soil Type on LTE and E

7. Effect of the Concrete Type

Two types of concrete which are normal strength concrete (f'c=27 MPa) and high strength concrete (f'c=43 MPa) are used.

In general, the slab deflection of high compressive strength is less than the slab deflection of the normal compressive strength. The deflection of unloaded and loaded slab of high compressive strength is less than the deflection of unloaded and loaded slab of normal compressive strength of concrete by about (9.1%) and (9.4%) respectively. The compressive strength of concrete has insignificant effect on the load transfer efficiency (LTE) (79.64% and 79.94) and joint effectiveness (E) (88.66% and 88.85%) for normal compressive strength and high compressive strength respectively, see Figure (6).

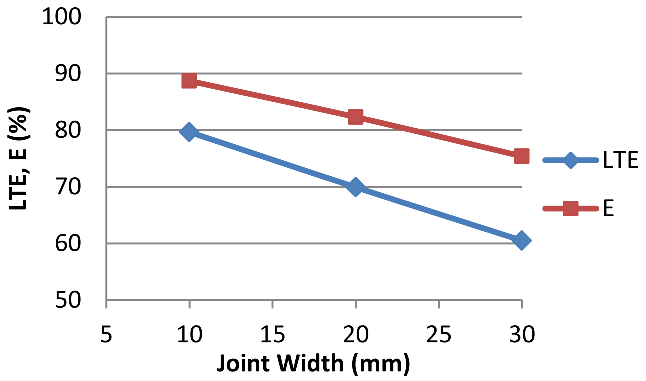


$(h_{slab} = 125\ \text{mm}, D = 16\ \text{mm}, CBR = 7\%, W_{joint} = 10\text{mm}, \text{edge load})$

Figure 6. Effect of concrete Type on LTE and E

8. Effect of Joint Width

This part study three variables of joint width which are (10 mm, 20 mm and 30 mm). The deflection of unloaded slab decreases with increasing the joint width. The unloaded slab deflection of 30 mm joint width is less than the unloaded slab deflection of 10 mm and 20 mm joint width by about (19.9 % and 11.4% respectively). The deflection of loaded slab is increased with the increase of the joint width where the loaded slab deflection of 30 mm joint width is greater than the loaded slab deflection of 10 mm and 20 mm joint width by about (5.5% and 2.4% respectively), this leads to decrease the load transfer efficiency (LTE) by about (79.64%, 69.9% and 60.48%) and decreasing the joint effectiveness (E) by about (88.66%, 82.37% and 75.37%) for joint width (10 mm, 20 mm and 30 mm) respectively, see Figure (7).



($h_{slab} = 125$ mm, D = 16 mm, CBR = 7%, $f'_c = 27$ MPa, edge load)

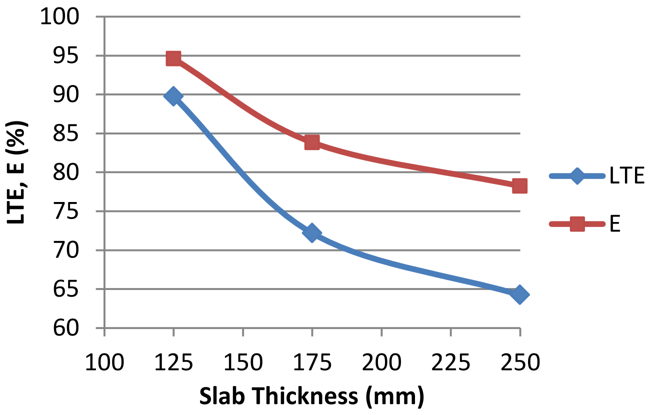
Figure 7. Effect of Joint Width on LTE and E

9. Effect of Slab Thickness

The three different values of the thickness of slab which are (125 mm, 175 mm and 250 mm) for (20 mm) diameter of dowel are used for models in this section.

The slab deflection is decreased with the increase the slab thickness. The unloaded slab deflection of 125 mm slab thickness is greater than the unloaded slab deflection of 175 mm and 250 mm slab thickness by about (90.2% and 257.8% respectively) and the loaded slab deflection of 125 mm slab thickness is greater than the loaded slab deflection of 175 mm and 250 mm slab thickness by about (53% and 156.3% respectively).

The load transfer efficiency (LTE) and joint effectiveness (E) are decreased with increase the thickness of slab where load transfer efficiency (LET) is (89.73%,72.18% and 64.24%) and joint effectiveness (E) is (94.59%, 83.84% and 78.23%) for slab thickness (125 mm, 175 mm and 250mm) respectively, see Figure (8).



$(W_{joint} = 10\text{ mm}, D = 20\text{ mm}, CBR = 7\%, f'_c = 27\text{ MPa}, \text{edge load})$

Figure 8. Effect of Different Slab Thickness on LTE and E

10. Effect of Critical Location of Load

This section deals with effects of three variables of critical location of load which are (internal load, edge load and corner load), see Figure (9).

The highest value of the slab deflection for three cases of load is when the load at corner. The unloaded slab deflection at corner load is greater than the unloaded slab deflection at internal load and at edge load by about (163.5 % and 1.9% respectively) and the loaded slab deflection at corner load is greater than the loaded slab deflection at internal and at edge load by about (214% and 15.1% respectively). From the highest value to lowest value of load transfer efficiency (LTE) is (84%, 79.64% and 70.49%) and effectiveness of joint (E) is (91.3%, 88.66% and 82.7%) for internal load, edge load and corner load respectively, see Figure (10).

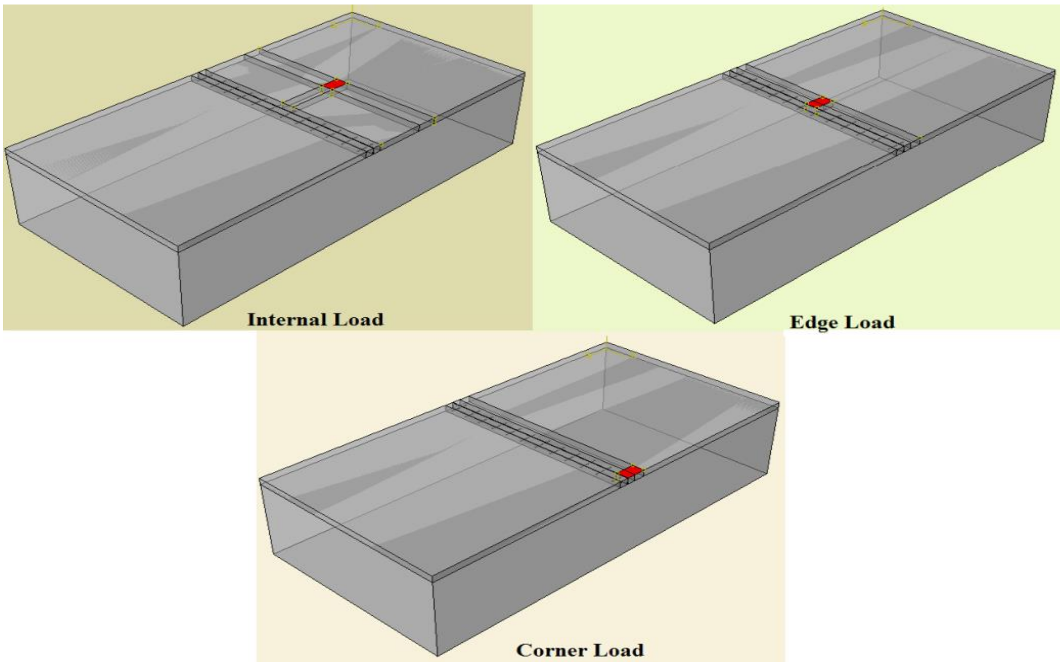
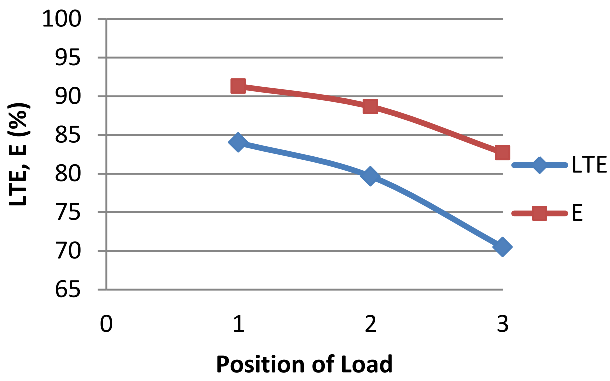


Figure 9. Positions of Load



(W_{joint} = 10 mm, D = 16 mm, CBR = 7%, f'_c = 27 MPa, $h_{slab} = 125\ mm$)

Figure 10. Effect of Position of Load on LTE and E

11. Effect of Damage in Subgrade soil

The water infiltrates to the subgrade soil in jointed concrete pavement because of the poor seal of joint in addition to poor drainage causes the accumulation of water under the slab which leads to the weakening of the soil. Continuously water infiltration with applied load of truck lead to move out the water with the soil particles material to the surface of pavement thus loss of subgrade soil, this is called pumping.

In this section, the damage in subgrade soil represented by two ways which are weak soil under expansion joint and existing gap in subgrade soil under the expansion joint.

11.1. Effect of Gap Subgrade soil Damage

This section studies the effect of three conditions of subgrade soil under the expansion joint which are subgrade soil with gap under expansion joint in load area (Soil Gap I) , subgrade soil with along gab under expansion joint (Soil Gap II) and without gab in soil (Soil), see Figure (11).

In general, the slab deflection is increased with increasing the damage of subgrade soil, so the highest value of the slab deflection for three conditions of subgrade soil under expansion joint at Soil Gap II model where the unloaded slab deflection at Soil Gap II is greater than the unloaded slab deflection at Soil model and Soil Gap I model by about (9.3% and 16.6% respectively) and the loaded slab deflection at Soil Gap II model is greater than the loaded slab deflection at Soil model and Soil Gap I model by about (47.8% and 37.7% respectively). As a result, the load transfer efficiency (LTE) and joint effectiveness (E) are decreased with increasing the subgrade soil damage where the load transfer efficiency (LTE) (79.64%, 69.55% and 58.9%) and effectiveness of joint (E) (88.66%, 82% and 74.14%) for subgrade damage Soil model, Soil Gap I model and Soil Gap II model respectively, see Figure (12).

11.2. Effect of Damage in Subgrade soil

This part studies three conditions of soil which are weak subgrade soil under expansion joint in load area (Weak Soil I), weak soil along subgrade soil under expansion joint (Weak Soil II) and origin soil (Soil), see Figure (13). The CBR value of weak soil is assumed (1%).

The unloaded slab deflection at Soil model is greater than the unloaded slab deflection at Weak Soil I model and Weak Soil II model by about (9.8% and 18.2% respectively). But, the loaded slab deflection at Weak Soil II model is greater than the loaded slab deflection at Soil model and Weak Soil I model by about (13.4% and 9% respectively). So, the highest value of load transfer efficiency (LTE) and joint effectiveness (E) at Soil model where (LTE) (79.64%, 69.68% and 59.4%) and (E) (88.66%, 82.13% and 74.5%) for models of subgrade damage: Soil, Weak Soil I and Weak Soil II respectively, see Figure (14).

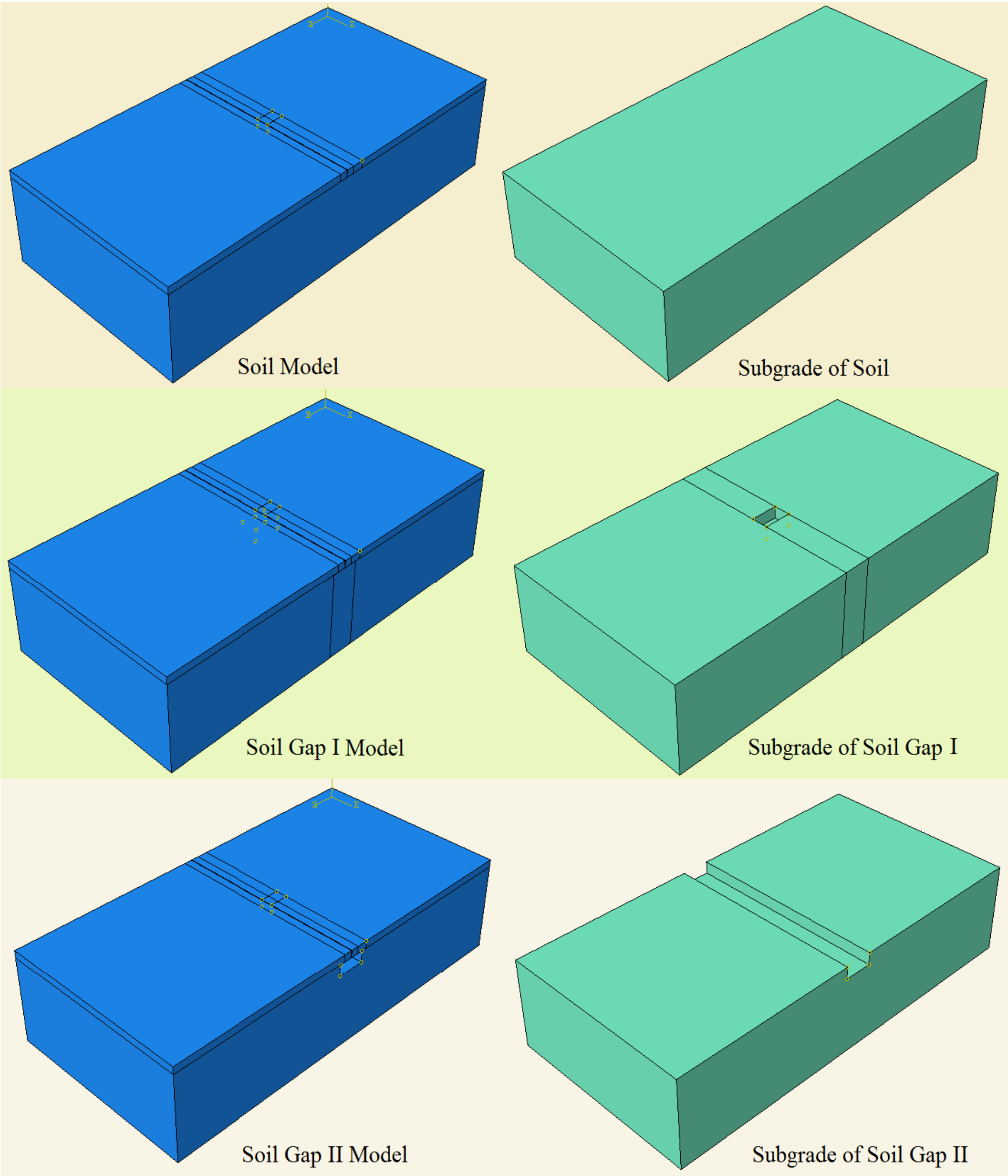
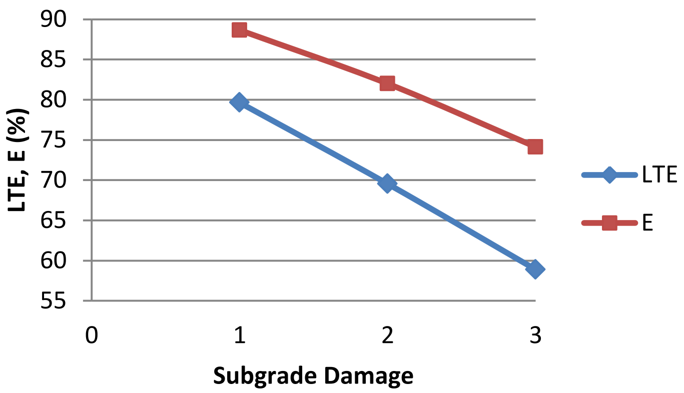


Figure 11. The Simulated Gap in ABAQUS Program



$(W_{joint} = 10\ \mathrm{mm}, D = 20\ \mathrm{mm}, CBR = 7\%, f'_c = 27\ \mathrm{MPa}, h_{slab} = 125\ mm,\ edge\ load)$

Figure 12. Effect of Gap Subgrade Damage on LTE and E

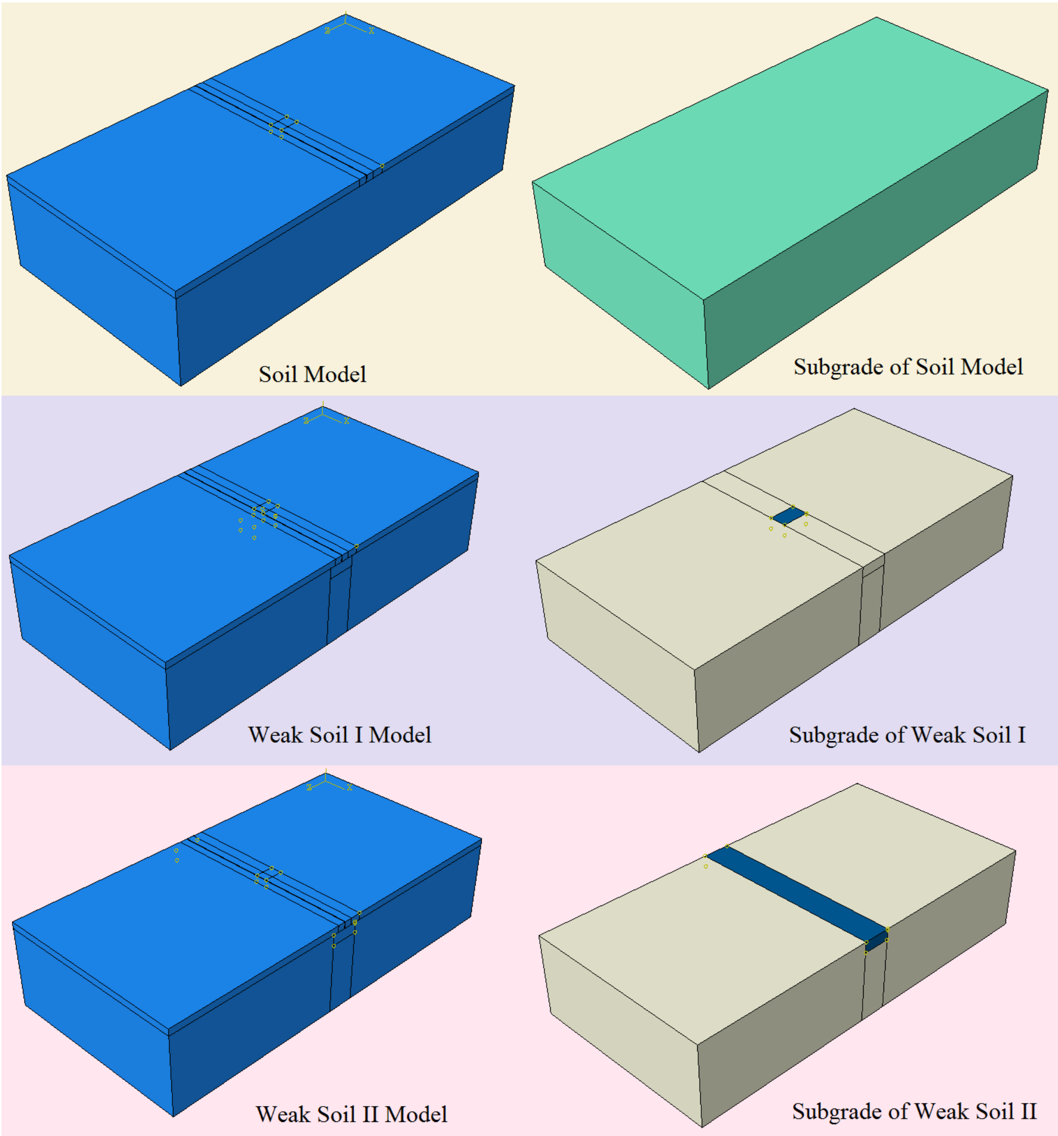
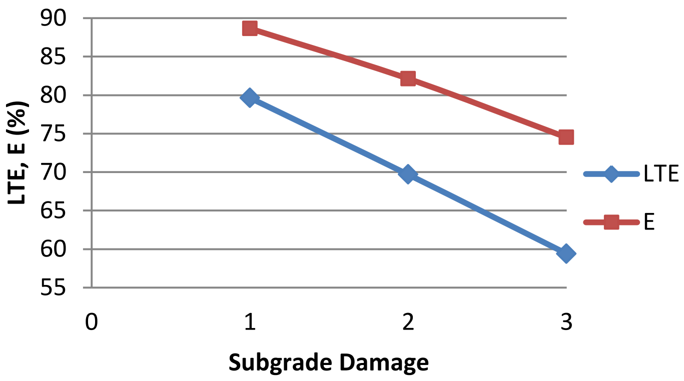


Figure 13. Different Types of Soil Models by ABAQUS program



$(\mathrm{W_{joint}} = 10\ \mathrm{mm}, \mathrm{D} = 20\ \mathrm{mm}, \mathrm{CBR} = 7\%, f'_c = 27\ \mathrm{MPa}, h_{slab} = 125\ mm,\ edge\ load)$

Figure 14. Effect of Weak Soil on LTE and E

12. Conclusions

1. The increase in the dowel bar diameter lead to increase in unloaded slab deflection and decrease in loaded slab deflection with the increase of the dowel diameter, Increase in load transfer efficiency (LTE) and joint effectiveness (E) values(69.82%, 79.64% and 89.73%) and (82.23%, 88.66% and 94.59%) for diameter of dowel bar (12, 16 and 20 mm) respectively.
2. Increase CBR value of subgrade soil from 5% to 7% lead to increase the unloaded slab deflection and decrease the loaded slab deflection thus increase (LTE) and (E) values are (79.64% and 69.81%) and (88.66% and 82.22%) for soil Type I (CBR=7%) and soil Type II (CBR=5%) respectively.
3. The slab deflection decreases with increasing the concrete compressive strength, the effect resulted from compressive strength of concrete on deflection at loaded and unloaded slab are approximately the same, so (LTE) and (E) values are (79.64% and 79.94) and (88.66% and 88.85%) for high concrete compressive strength and normal concrete compressive strength respectively. Approximately similar values are obtained for the two types.
4. The deflection of the unloaded slab decrease and the deflection of the loaded slab increase with increasing joint width, so decrease (LTE) and (E) values which are (79.64%, 69.9% and 60.48%) and (88.66%, 82.37% and 75.37%) for (10 mm, 20 mm and 30 mm) joint width respectively.
5. The increase in slab thickness leads to decrease in the deflection of unloaded slab and loaded slab. Increasing slab thickness decreasing (LTE) and (E) values which are (89.73%,72.18% and 64.24%) and (94.59%, 83.84% and 78.23%) for (125 mm, 175 mm and 250mm) thickness of slab respectively.
6. The corner load causes the greatest value of the deflection at unloaded and loaded slabs compared with internal load and edge load where (LTE) and (E) values for the internal load, edge load and corner load are (84%, 79.64% and 70.49%) and (91.3%, 88.66% and 82.7%) respectively.
7. The conclusion that drawn from damage subgrade soil effect are as the following:

7.1. The slab deflection increase with increase the damage soil gap along the joint. The models of subgrade damage: Soil (without gap), Soil Gap I (gap under load area) and Soil Gap II (gap along the joint) have (LTE) and (E) values are (79.64%, 69.55% and 58.9%) and (88.66%, 82% and 74.14%) respectively.

7.2. Soil without damage (homogenous) has higher deflection of the unloaded slab, the deflection of the loaded slab increase with increase the soil weakness along the joint. The values of (LTE) and (E) of the models: Soil (homogenous), Weak Soil I (weak under load area) and Weak Soil II (weak along the joint) are (79.64%, 69.68% and 59.4%) and (88.66%, 82.13% and 74.5%) respectively.

Abbreviations

AASHTO	American Association of State Highway Transportation Officials
TLE	Transfer Load Efficiency
E	Joint Effectiveness
NCS	Normal Compressive Strength of Concrete
HCS	High Compressive Strength of Concrete
W_{joint}	Width of joint
D	Diameter of Steel Dowel Bar
CBR	California Bearing Ratio of Subgrade Soil
f'_c	Compressive Strength of Concrete
h_{slab}	Thickness of Concrete Slab

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