Interaction of subgrade resistance and dimensions of asphalt pavement surface cracks on propagation of secondary distresses

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Abstract: Reactions created in road construction and secondary distresses made in pavement are dependent on dimensions and geometry of cracks, resistance of subgrade and existing pavement layers. Thus, this essay assessed the effect of changes in crack's geometry and also the amount of subgrade resistance on settlement in the cracking place. Since pavement layers thickness has a drastic effect on the resistance of the layers, cracks propagation and secondary distresses, in this essay, different types of strong, semi-strong, and weak pavements have been considered according to combination of different thicknesses for the pavement layers which are respectively wearing layer with the thickness of 5, 10, 20 centimeters, base course with thickness of 10, 20, 40 centimeters and sub base with thickness of 15, 30 and 60 centimeter. Also, as pavement can be constructed in grounds with different resistance and so subgrade resistance has an important role in pavement settlement and distresses, in this essay, subgrade have been studied in three types of dense sand (strong soil), fine sand (semi-strong soil), and soft clay (weak soil) with different geotechnical properties. So, for preventing the mentioned problems, layers' behavioral properties are considered as Mohr Coulomb-plastic and by three-dimensional modeling with finite element software of ABAQUS, we studied the degree of subgrade and cracked pavement surface settlement with different forms of cracking in different types of pavement and subgrade situations, like different thickness and behavioral properties. Then, to check results and validating software, by field observation, level of settlement in different cracking places was gathered and compared to the numerical results of the software. Results of finite element software show that by 25% increase in crack opening, the level of settlement of the surface layer and the surface of subgrade would increase by 49% and 38% respectively. Also the level of the surface and subgrade settlement would rise by increase in crack depth; and the measurements for 25% increase in crack depth are 16% for surface and 13% for subgrade. In addition, by increasing in the width of crack in soils with different resistance, width line slope of crack-settlement in weak soil would be about triple compared to strong soil, and by increase in depth of crack in soils with different resistance, depth line slope of crack-settlement in weak soil would be about twice compared to strong soil. By the use of probabilistic analysis, It was determined that in 95% confidence interval, cracking on deformation of surface and subgrade, is significantly under the influence of subgrade type and as the subgrade weakens, the amount of deformation will increase more.

Keywords: resistance of subgrade; crack geometry and dimensions; distress propagation; settlement; numerical modeling.

1. Introduction

High amount of cracking increases costs of path maintenance and rehabilitation and also increases the rate of distresses propagation in structure of the path; so it is inevitable to pay more attention to their propagation and function. Nowadays, many researches have been done across the world to recognize the way cracking are made and their propagation in asphalt pavement, but less attention has been paid to impact of cracking on creation and extension of secondary distresses like surface deformation (rutting). The purpose of this research is to examine the effect of crack dimension and geometry on the vertical deformation of pavement and also to assess how the amount of this deformation varies by a change in the type of subgrade. With respect to occurrence of different cracking on path surface, especially top-down cracking in relatively warm countries like Iran, purpose of this research is to remind the role of pavement cracking in formation of other distresses and to create the possibility to use the results of this study to prioritize types of pavement cracking (due to subgrade stiffness).

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2. Literature review

In asphalt pavement, fracture made in cracking place would change bearing properties of pavement; as the fracture becomes more intense, the amount of load transfer between two disjointed parts of pavement in the cracking place increases, and also the possibility of surface settlement would increase. Cracks observed at the surface may have several causes and regarding the movement direction in depth, they can be top to down crack or TDC or down to top. It has been demonstrated that most cracks made in asphalt pavement in tropical areas are TDC. In studying the results of asphalt coring samples (cylindrical or slab shaped), it has been observed that most of these cracks form in excessive fine aggregates and voids which causes less bearing capacity and pavement fatigue strength [1].

Cracking has occurred in nearly all types of asphalt overlays due to mechanical and environmental loadings [2]. As crack causes water penetration, pavement weakness in subgrade, and surface roughness, the mechanism of cracking and ways of decreasing its unpleasant impacts has been examined in many studies.

Until now, different finite element software was used for modeling pavement; ANSYS finite element software is used mostly, which is used for modeling cracked pavement too [3]. Likewise, ABAQUS software is packaged software with a wide range of functions which has the ability to model many of the materials behavior like viscoelasticity, clay adhesion, Drucker-Prager and Mohr Coulomb-plastic modeling [4, 5]. Three-dimensional finite element models are the most efficient and logical ways of predicting and reflecting layer behavior in their implementation [6, 7].

The main capability of this software is solving pavement problems with modeling flexible path layers as followed:
-Thermal gradient analysis.
-Interface modeling with friction.
-Static and dynamic loading simulation.
-Cracking propagation modeling.
-Linear and nonlinear elastic, viscoelastic, and Elastic-plastic material modeling in two-dimensional and three-dimensional conditions.

Results of two-dimensional asphalt modeling, which had cracks with different size on it show that increase in width and depth of crack causes rutting depth increase in wheel-path [8]. Also with the same modeling done with ANSYS software, the role of subgrade and each layer in deformation of pavement surface was demonstrated [9].

Other researchers studied the growth of top to down cracking based on fracture mechanics, and also impacts of overlay and base layer thickness and their stiffness on propagation of this kind of crack on asphalt pavement. It has been shown that an increase in tire loading has unsuitable impact on crack tip stress intensity factor and its fatigue life would decrease; thick overlay and bases would make less stress intensity factor. It should be mentioned that results show stiffness of overlay and base layer has less effect on propagation of crack [9].

In 2008, Kumar et al., based on the results of numerical modeling with the help of the layered theory of high temperature and over loading impact on propagation of TDC, show that tensile strains and shear stresses near the surface are much higher for pavements subjected to overloading and high tire pressures. Also, their result show high magnitudes of transverse tensile strains develop at the tire-pavement contact area, suggests the potential for initiation of TDC on path construction and maybe the more important point is that it increase the horizontal shear stress which is efficient in rutting growth and propagation of TDC at the same time [10].

3. Statement of the problem

Thickness of pavement layers is one the most important points in pavement resistance and has a major role in pavement behavior in response to distresses and settlements caused by incoming loads. Regarding combination of different overlay, base and sub base layers thickness (as shown in table (1)), three types of pavement can be considered; strong pavement with thickness of 20 centimeter for overlay layer, 40 centimeter for base and 60 centimeter for sub base, semi-strong pavement with thickness of 10 centimeter for overlay layer, 20 centimeter for base and 30 centimeter for sub base layer and weak pavement with 5 centimeter for overlay, 10 centimeter for base and 15 centimeter for sub-base layer. According to [11], such range of thickness leads to difference in pavement regarding its resistance and causes pavement to divide into three types of strong, semi-strong and weak. The subgrade resistance also is very efficient in pavement resistance and in suction, distribution and control of loads transferred from the upper layers, and at last in control or propagation of pavement distresses. For this purpose, according to table (1), three types of subgrade (dense sand, medium sand, and soft clay) with different tectonic properties are considered respectively as strong, semi-strong, and weak subgrades. So in this research, for studying the impact of subgrade properties on the amount of distress propagation, settlement in the place of top to down cracking was estimated by a numerical study using three-dimensional finite element software. In this study, first three different pavement types on strong, semi-strong and weak beds with the same assumptions and with different size cracking was made on the surface of pavement, and then amount of surface drop (surface settlement or rutting of tire path), as secondary distress was presented for each different condition and they were compared.

4. Numerical modeling

In this part, flexible cracked pavement which is under tire loading is examined by use of finite element method. As the stress and strain created in different layers of pavement are used as a way of predicting pavement fracture and also as the problem of this part is studying the process of surface settlement and rutting, use of three-dimensional modeling and nonlinear behavior of materials should be considered.

Since the model is symmetrical and also for saving time, just half of path structure model was modeled using 8-node element model.

4.1 Geometric and structural modeling, pavement loading and layers behavioral properties assumptions

Pavement system is flexible and consists of four layers of asphalt concrete, base, aggregate subbase, and natural bed. According to table (1), in order to compare the impact of cracking in different types of pavements and subgrade regarding their strength, geometric model and layers resistance assumptions in three different pavements based on their dimensions were considered. Thickness of pavement layers and elastic modulus and subgrade Poisson's ratio was increased at the same time to create considerable difference in pavements strength. Logical responses from pavement can be seen in finite element software when model's boundaries lie at least in 50 times the radius circular load in the vertical direction and 12 times the radius circular load in horizontal direction [12, 13].

Although tire load contact area on asphalt can be one of the forms of circle, rectangular, square, oval and combination of two semicircle with a rectangular, and there is no difference between these forms in stress and strain caused by tire loading imposed on pavement, but the most widespread forms of tire loading are circular and rectangular. If we consider that tire loading would be standard with circle contact area, load would be in the form of a circle with 11 centimeter diagonal and intensity of its vertical tensile stress would be 8590 kPa [19].

In order to note critical situations, tire load was considered at the edge of crack. An example of a section of pavement modeling, loading and boundary conditions and the model mesh in numerical analysis are shown respectively in figures (1), (2) and (3).

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Table 1 Thickness and mechanical properties of layers

Layer's name	Layer type	Thickness (cm)	Properties					
			Elastic			Mohr Coulomb-plastic		
			Especial weight $\gamma(kg/m^3)$	Modulus Of Elasticity E (MPa)	Poisson's ratio ν	Internal friction angle (degree)	Dilation angle (degree)	Adhesion (kPa)
Pavement	Asphalt	5-10-20	2200	4000	0.35	42	12	250
Base	Blended Coarse Aggregate	10-20-40	2000	240	0.30	41	11	0
Subbase	Blended Coarse Aggregate	15-30-60	1800	140	0.30	38	8	0
Subgrade type (natural surfaces)	Dense sand (strong)	250	1800	90	0.35	36	6	0
	Medium sand (semi-strong)			80	0.30	33	3	0
	Soft clay (weak)			70	0.20	23	0	22

4.2 The assumptions of crack distress on the surface of overlay

After determining the structural properties of pavement, it is necessary to determine distress properties for making surface cracking. As shown in figure (4), the modeled crack made in the software is U-shaped. Assumptions of cracking were selected as follows like a normal asphalt pavement cracks:

Crack depth: 0.2 h, 0.4 h, 0.6 h, 0.8 h (h thickness of overlay)

Crack width opening (mm): 5, 10, 15, and 20 so pavement without distress and 16 different distress forms were modeled. In general, regarding to the size of layers, subgrade resistance and also depth and width of cracks, 51 modeling was done.
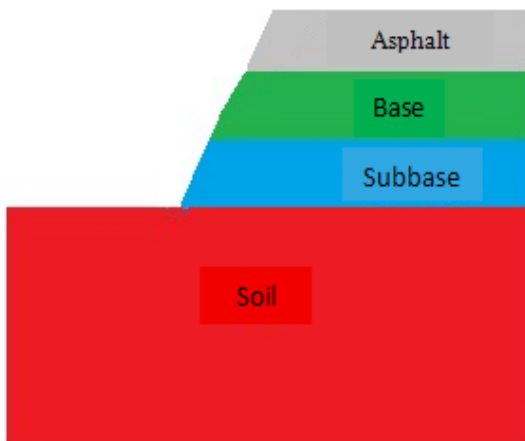
Fig. 1 Schematic representation of pavement modeling section.
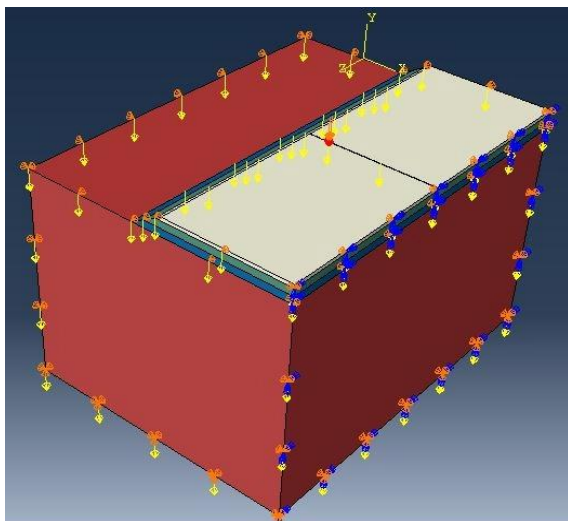
Fig. 2 Schematic representation of boundary condition and loading.
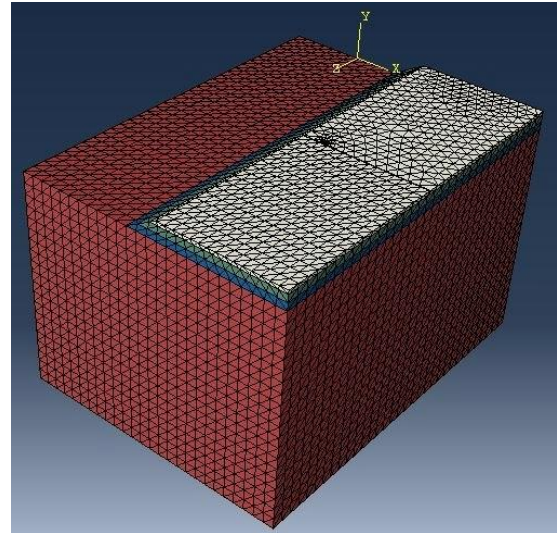
Fig. 3 Schematic representation of mesh modeling.
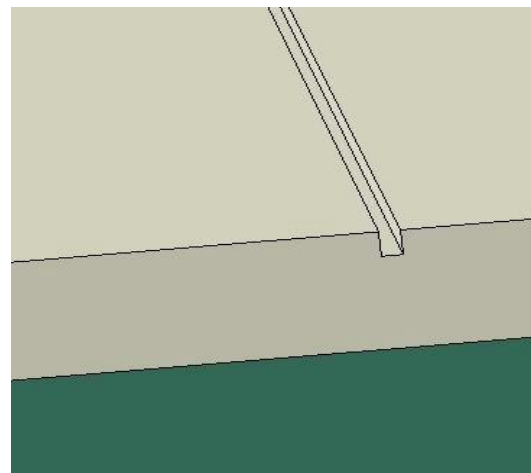
Fig. 4 Scheme of U-shaped crack modeled in the Software.

5. Determining of the amount of surface settlement for each pavement

At the end of the software analysis process, for each 51 types of pavement and cracking, the amount of pavement settlement was estimated which shows beginning and propagation of rutting distress at tire crossing surface. The distress estimated varies between 1.71 centimeters for strong un-cracked pavement to 7.40 centimeters for weak pavement with crack with 0.8 depths, height of overlay and 20 millimeter width on the surface of asphalt. To determine the share of each subgrade layer with different strength in amount of surface deformation, the deformation of subgrade was estimated too. Figure (5) shows an example output of one of implemented models.
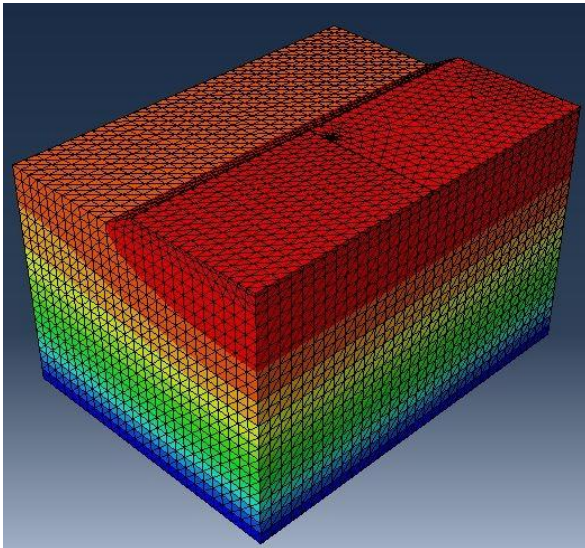
Fig. 5 Scheme of settlement changes, example of implemented three-dimensional analysis pavement model

## 5.1 Determining the impact of amount of fracture on pavement and soil settlement

By pavement model loading, the amount of settlement was determined in five amounts of fracture (crack width) which consists of un-cracked pavement, and other models with 5, 10, 15, 20 millimeter opening. Figure (6) ((a) to (h)) shows changes of surface settlement for settlement at surface and settlement on subgrade for threefold pavement (strong, semi-strong, and weak). It should be mentioned that WC refers to crack width. Checking the results shows that it has suitable conformity with the results of reference [11].

5.2 Determining the impact of crack depth on pavement and soil settlement

An analysis was done to determine the impact of crack depth on the amount of pavement settlement. For this purpose, five pavement forms were selected which
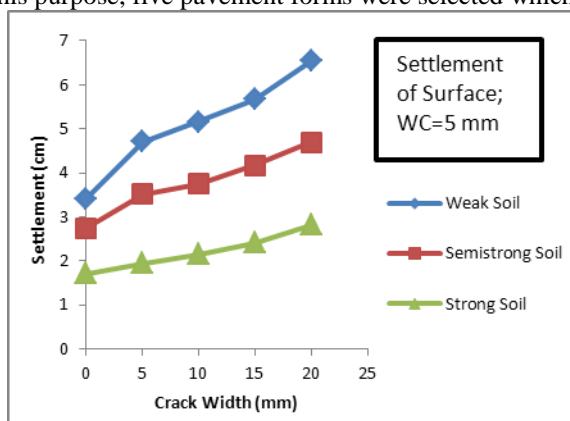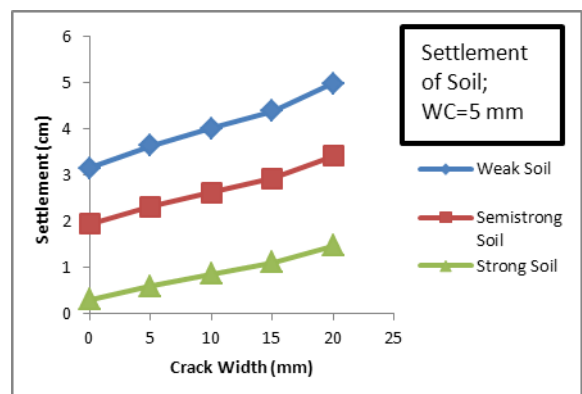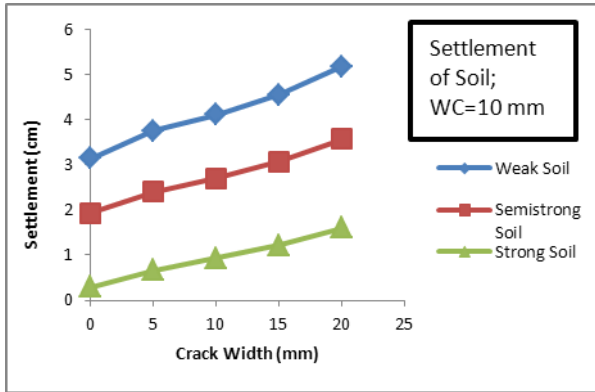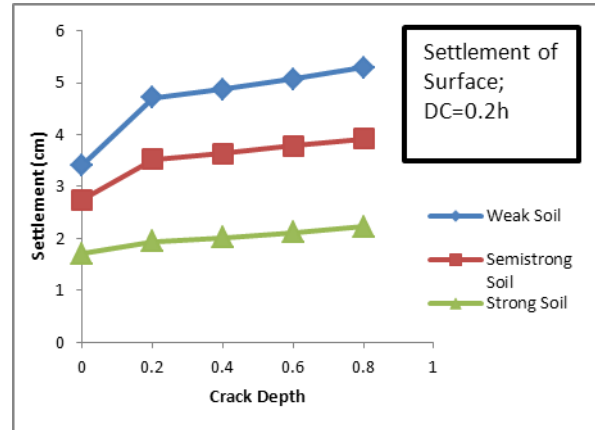

(a)

(b)

(c)

(d)
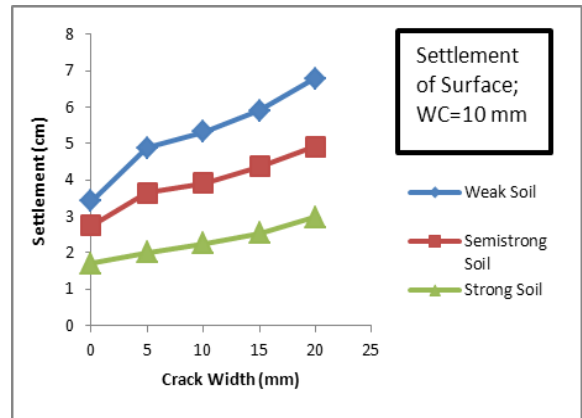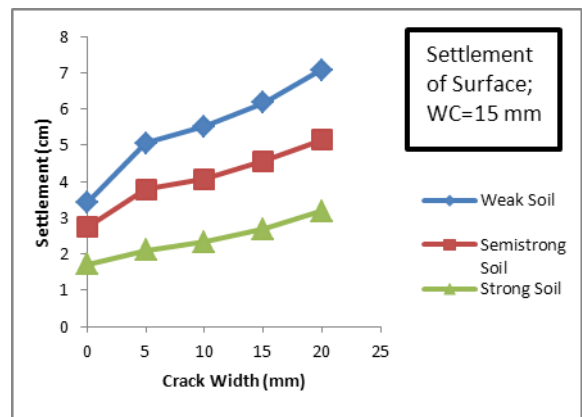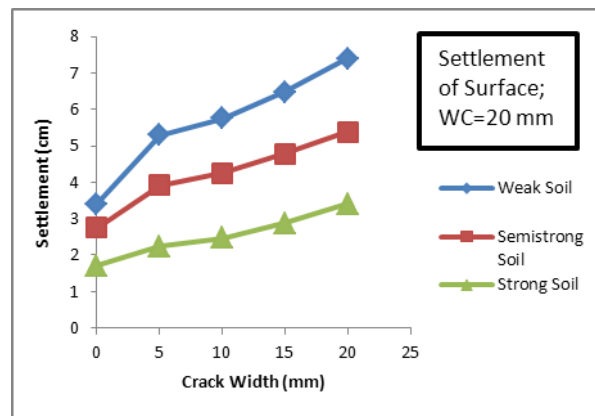
(e)

(f)

(a)
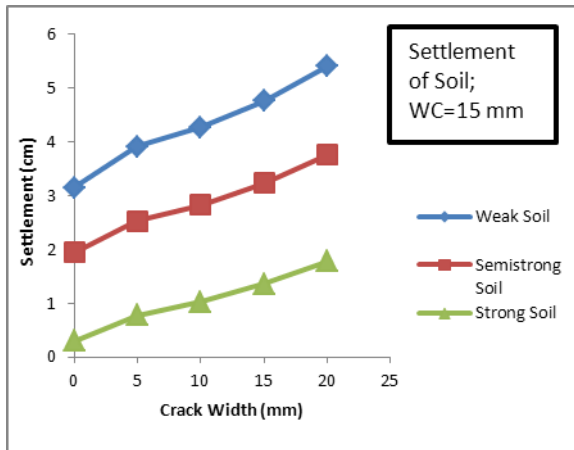
(g)
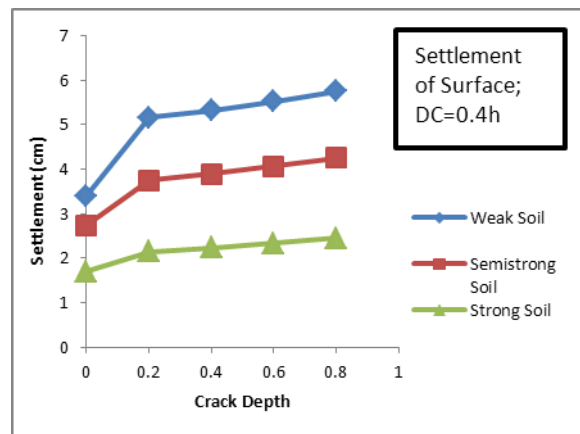
(b)

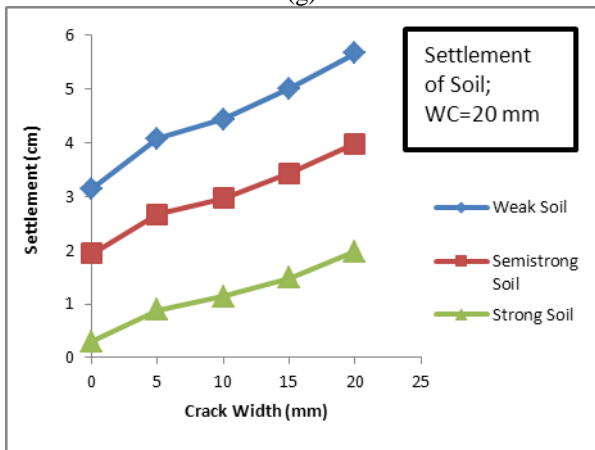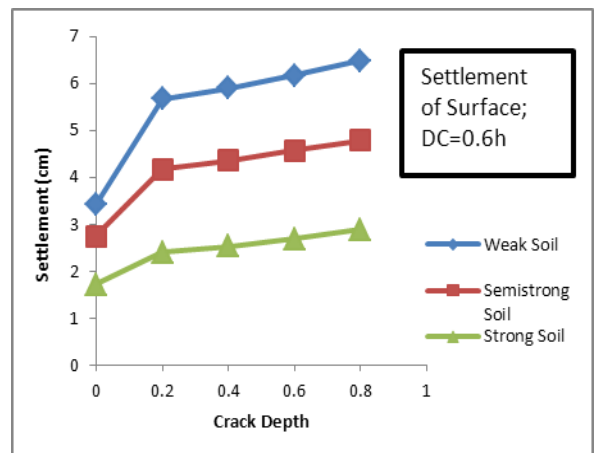(h)

(c)

Fig. 6 Settlement of subgrade and overlay surface based on changes in crack opening for its different depths.

consist of un-cracked pavement and pavement with crack with the depth of 0.2h, 0.4h, 0.6h, 0.8h in the surface layer (h refers to height of layer). In figure (7) ((a) to (h)), changes in pavement settlement on the surface layer and on subgrade, for three pavement forms are being compared. Also, DC refers to depth of crack which is considered according to thickness of overlay (h) (Horizontal axis of figure (7)).
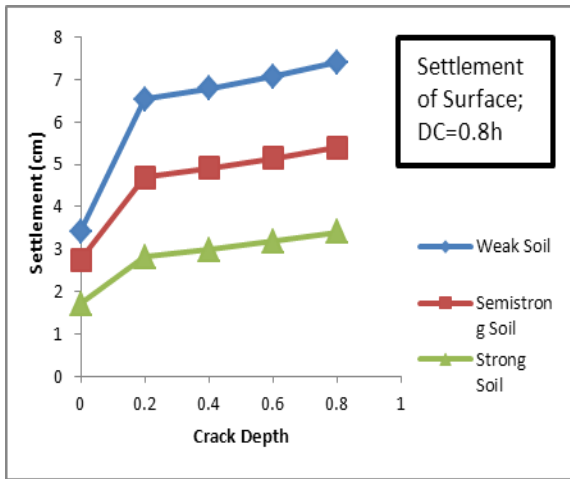
(d)
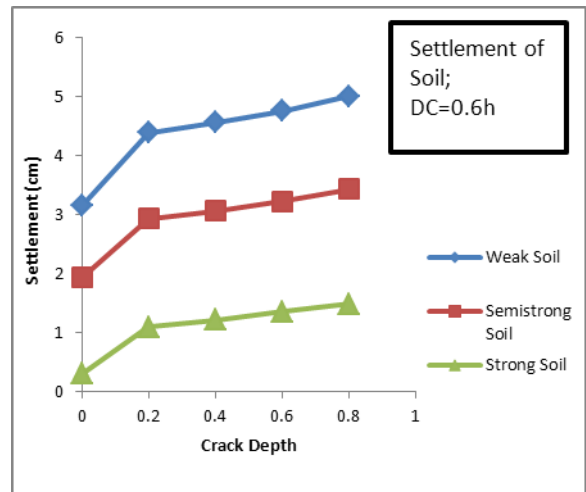
(g)

(e)
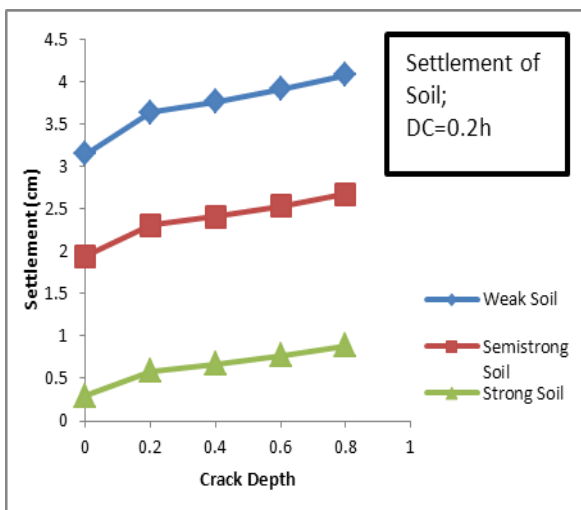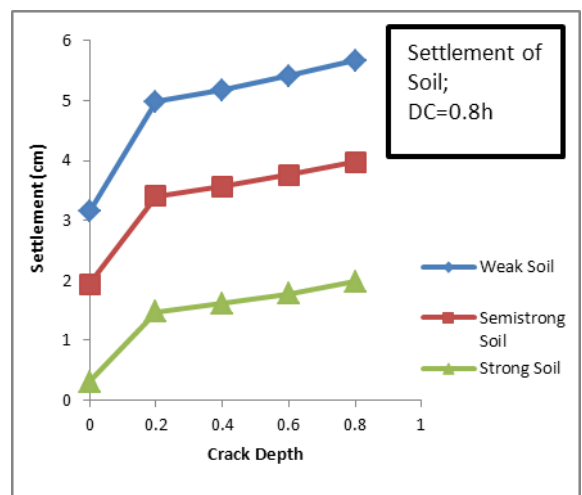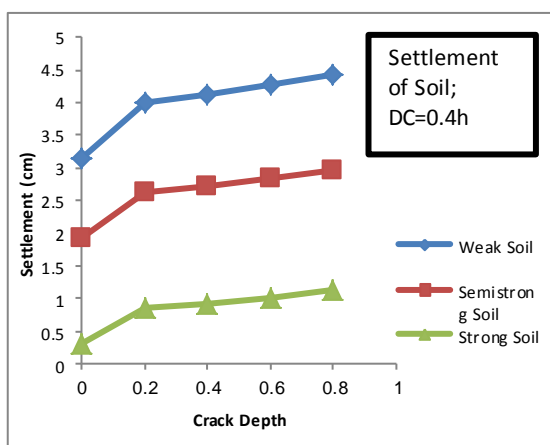

(h)

Fig. 7 Settlement of subgrade and surface overlay based on changes in depth of crack for its different widths.

Cont. Fig. 7 Settlement of subgrade and surface overlay based on changes in depth of crack for its different widths

(f)

6. Statistical and probability studies

One of the common ways in statistical analysis is difference of the mean of two populations in hypothesis testing of Student's t-test. In this approach, comparison of means of two populations which are μ_1 and μ_2 is done according to difference of μ_1- μ_2. First, we consider two populations with the size of n_1 and n_2, and then the difference between means of these two populations ($\overline{X}_1$-$\overline{X}_2$) can be considered as an estimation of μ_1- μ_2. If two independent variables of X_1 and X_2 has the distribution of N (μ_1, σ_1^2) and N (μ_2, σ_2^2), then the difference of $X_1 - X_2$ has normal distribution with mean of μ_1- μ_2 and variance of $\sigma_1^2 + \sigma_2^2$. So the 95% confidence interval for μ_1 - μ_2, when two populations have normal distribution, is [20]:

$$(\overline{X}_1 - \overline{X}_2) \pm 1.96 \sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}$$

This approach considers equal variances for two populations (σ^2), but according to the rules of this approach, as mostly the variance is unknown, we should estimate it with the use of data gathered from sample.

Best σ^2 estimation is to calculate weighted mean of s_1^2 and s_2^2 which is called integrated estimation s_p^2 (equation 1) and 95% confidence interval for $\mu_1 - \mu_2$ is according to equation (2) [20].

$$s_p^2 = \frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{(n_1-1) + (n_2-1)} = \frac{\sum_{i=1}^{n_1}(X_{1i} - \overline{X}_1)^2 + \sum_{i=1}^{n_2}(X_{2i} - \overline{X}_2)^2}{n_1 + n_2 - 2}$$

(1)

$$\mu_1 - \mu_2 = (\overline{X}_1 - \overline{X}_2) \pm t \times S_p \times \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

(2)

According to the student's t distribution table, t is the estimation with ($n_1 + n_2 - 2$) degree of freedom proportionate to 95% confidence interval. When 0 is in $\mu_1 -$ Where, μ_2 is confidence interval and it shows that there is no difference between two populations [20].

According to the equations (1) and (2) which are represented for normal distribution and data gathered from pavement numerical models, the results of possible analysis are shown in table (2).

Table 2. Statistical results for comparing results of overlay and subgrade settlement in weak and strong soil.

Mean	Variance	Sample size	Subgrade resistance	Place of settlement
$\overline{X}_1 = 5.85$	$\sum_{i=1}^{n_1}(X_{1i} - \overline{X}_1)^2 = 9.86$	$n_1 = 16$	Weak	Overlay
$\overline{X}_2 = 2.52$	$\sum_{i=1}^{n_2}(X_{2i} - \overline{X}_2)^2 = 2.78$	$n_2 = 16$	Strong	
$\overline{X}_1 = 4.51$	$\sum_{i=1}^{n_1}(X_{1i} - \overline{X}_1)^2 = 5.48$	$n_1 = 16$	Weak	Subgrade
$\overline{X}_2 = 1.18$	$\sum_{i=1}^{n_2}(X_{2i} - \overline{X}_2)^2 = 2.45$	$n_2 = 16$	Strong	

According to statistical analysis, for 95% confidence interval, overlay settlement for two conditions of weak and strong soil is estimated $t_{30} = 1.697$, $3.29 < \mu_1 - \mu_2 < 3.36$ and for 95% confidence interval, soil settlement in two conditions of weak and strong soil is estimated as $t_{30} = 1.697$, $3.17 < \mu_1 - \mu_2 <$

3.48. As 0 is not in $\mu_1 - \mu_2$ confidence interval, we can conclude that existence of crack in deformation of overlay surface and subgrade significantly is under the influence of type of subgrade and as subgrade becomes weaker, the amount of deformation increase more intensely.

7. Comparing field data with analysis of model

In order to compare numerical data with real situation and also to control and validate the obtained numerical results, writer of this essay has done field examination on the surface of pavement in Isfahan Province on 5, May, 2015 for three types of pavements with different overlay and base layer thickness in more than 25 places, shown in table (3). As it is shown, comparison of pavements was just based on the layer thickness and other parameters could be effective in determining resistance. Also, an example of changes of surface layer settlement in three kinds of pavement with cracks with different width, from field observations, is shown in figure (8). Based on minimum field studies done on different width of crack and by estimating mean of samples, the amount of deformation observed was about 1 to 8 centimeters (table (3)). As can be seen, changes in settlement in field researches were in such manner that with increase in crack width and decrease of pavement layer thickness (weakening of pavement), settlement of asphalt layer increases. This show the estimated results from field research are consistent with the settlement obtained by software analysis. The results of field research can prove numerical analysis and modeling to some extent.

Table 3. Pavement properties in field research.

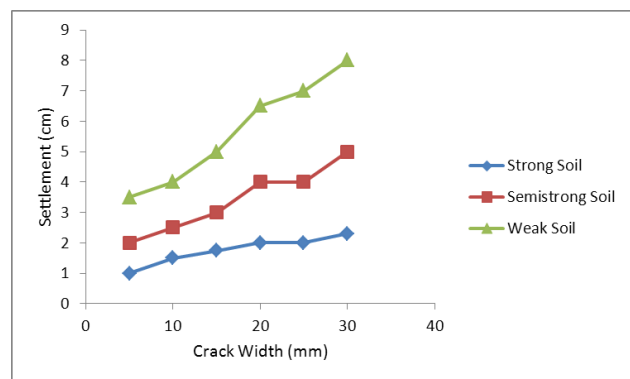| Thickness of subgrade (cm)	Thickness of overlay (cm)	Type of pavement
30	15	Strong
20	10	Semi-strong
10	5	Weak

Fig. 8 Changes of overlay settlement in three kinds of pavements with cracks with different width

8. Conclusion

Lack of attention to existing pavement distresses is one of the factors influencing the amount of damages caused on pavement and creating secondary distresses. Regarding resource constraints for pavement repairs (like crack sealing), priority of pavements should be considered in their selection. The results of this research show that weak pavements with cracks with high depth have more settlement distresses compared to weak pavements with more opened cracks, so they have high priority for repair. Regarding software analysis, probabilistic analysis and field research, the following results can be inferred:

Due to significant statistical difference of subgrade and overlay surface deformation in pavements with weak bed compared to pavements with strong bed for different cracks, it is shown that change in subgrade resistance has great impact on quality and function of surface pavement.

By increase in crack opening up to 25%, the amount of overlay settlement and soil settlement increase up to 49% and 38% respectively.

The amount of overlay and subgrade settlement will increase as depth of crack increases and it is 16% for overlay and 13% for subgrade for per 25% increase in depth of crack.

Increase in crack depth has less impact on settlement propagation compared to increase in crack width. By 25% increase in crack width, amount of overlay settlement increases 3 times more than when crack depth increases up to 25%.

By increase in width of crack in soils with different resistance, the slop of settlement-crack width line in weak soil is 3 times more than strong soil, and by increase in depth of crack in soils with different resistance, the slope of crack-settlement depth line in weak soil is 2 times more than strong soil. So we can conclude that not only increase in crack width compared to increase in its depth has more impact on settlement propagation, but also as subgrade becomes weaker, asphalt and subgrade settlement would increase with higher rate too.

The un-cracked pavement in strong, semi-strong, and weak conditions has respectively the lowest to highest settlement in surface of overlay and subgrade, and on average, from the whole settlement, the share of subgrade is respectively 14%, 11%, and 7%.

In this research, field researches done for validating model and process demonstrated that crack opening has more impact on the amount of secondary distresses compared to crack depth in different kinds of pavement and subgrade regarding their resistance. Its main reason can be the response of surface deformation to function of overlay. As fracture and lack of materials blending in overlay increases, due to more cracks on surface, amount of settlement would increase in both subgrade and surface of overlay.

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