Pavement Mechanic Response in Sulfate Saline Soil Area Based on FSI Model

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ABSTRACT: It is a consensus that salt heaving and frost heaving are typical distresses in the sulfate saline soil subgrade. To further investigate the mechanic response of pavement structure in sulfate saline soil area, a finite element (FE) model was established based on fluid-structure interaction (FSI) model in this paper. Then the mechanic response of the asphalt pavement under traffic loads, salt heaving and frost heaving was simulated and analyzed. It is shown that only under salt heaving and frost heaving, the tensile strength of asphalt surface course was seriously inadequate and that at the bottom of semi-rigid base course were negative, which may be helpful to crack resistance at the bottom of base courses. Besides, traffic loads could help to dramatically counteract displacement, tensile stress and strain. However, as a whole, in sulfate saline soil area, asphalt courses should strengthen crack resistance and foundation treatment.

KEY WORDS: sulfate saline soil subgrade, asphalt pavement, FEM, FSI

INTRODUCTION

Saline soil are widely distributed in costal area, alluvial plain and inland basin etc., including Shandong Province. According to the result of the second national soil survey\cite{1}, saline soil was distributed extensively in Shandong Province, mainly in the inland plain, strand plain and costal area. There were four types of saline soil in Shandong Province: salined flavo-aquic soil, inland saline soil, coastal saline soil and alkaline soil.

The strength of saline soil is very special and would be influenced by salt content, salt type, water content, environmental conditions, granule composition, etc\cite{2}. Furthermore, pavement distress, such as salt heaving, frost boiling, melt sinking and corrosion etc. would be caused by saline soil in subgrade. At present, in spite of the large amount of researches on salt expandability, collapsibility and corrosivity\cite{3} \cite{4} \cite{5}, there were few on the stress response of asphalt pavement under this special soil condition.

Shandong Province is located along the lower Yellow River and has vast sulfate saline soil area. Thus, there were hundreds of highway containing sulfate saline soil subgrade section and the task of highway construction and maintenance in this area was burdensome.

Jinan-Dongying Freeway passes the area of calcareous fluvo-aquic soil and salined flavo-aquic soil, which is a typical example of freeway containing sulfate saline soil subgrade section. In this paper, based on Jinan-Dongying Freeway, the stress response of asphalt pavement under effects of salt heaving, frost heaving and traffic loads was simulated and analyzed through FE Program (ANSYS).
DEFORMATION RELATION IN SULFATE SALINE SOIL SUBGRADE

The deformation of sulfate saline soil subgrade mainly resulted from salt heaving and frost heaving. The deformation of salt heaving was due to the precipitation of Na$_2$SO$_4$ and the consequent generation of Na$_2$SO$_4$·10H$_2$O. The deformation of frost heaving was because of the generation of ice. Thus, in the process of temperature decreasing, it was supposed that the volume expansion of sulfate saline soil subgrade could be divided into three stages (shown in Table 1$^{[6]}$):

| Stage   | I          | II         | III        |
|---------|------------|------------|------------|
| Temperature(℃) | >15        | 15~3       | <3         |
| Volume Variance | Salt heaving | Salt heaving + Frost heaving | Frost heaving |

First, the stage of salt heaving. In this stage, volume variation was constituted by two parts: the increase of the generated Na$_2$SO$_4$·10H$_2$O, due to the solubility reduction in the process of cooling; and the decrease of liquid water due to the generation of Na$_2$SO$_4$·10H$_2$O. Supposing water content before and after temperature decreasing was respectively $\theta_1$ and $\theta_2$ (shown in Figure 1); solubility was respectively $r_1$ and $r_2$; the original voidage of sulfate saline soil was $n$ and all of the volume decrease of water derived from the generation of Na$_2$SO$_4$·10H$_2$O.

According to law of conservation of mass, the volume increase of sulfate saline soil could be deduced as Equation(1)$^{[6]}$:

$$ \Delta = \frac{0.209(r_1 - r_2)}{(78.889 - r_2)} \theta_1 - (n - \theta_1) $$

Where, $\Delta$ is the volume expansion rate of sulfate saline soil.

Second, the stage of both salt heaving and frost heaving. In this stage, temperature constantly decreased and was below freezing point. Hence frost heaving would occur. At this time, the temperature was still above salt-heaving temperature and therefore salt heaving would also occur. Two parts of volume variation took place at the same time and they would influence and restrict each other mutually. Since the volume variation in this stage was quite complicated, in this paper it was ignored that ice and Na$_2$SO$_4$·10H$_2$O existed in each other to simplify the calculation (shown in Figure 2).
Therefore, the volume increase in this stage could be expressed as\[^6\]:
\[
\Delta = \left(\frac{322\rho_w}{180\rho_N} - 1\right) \left(\theta_{u_1} - \theta_{u_2}\right) + \left(1 + \frac{322r_w\rho_w}{14200\rho_N}\right) \left(\theta_{i_2} - \theta_{i_1}\right) - (n - \theta_{u_1}) \tag{2}
\]

Where, \(\rho_w\) is water density; \(\rho_N\) is density of \(\text{Na}_2\text{SO}_4\cdot10\text{H}_2\text{O}\); \(\theta_{u_1}, \theta_{u_2}, \theta_{i_2}\) and \(\theta_{i_1}\) are shown in Figure 2.

Third, the stage of frost heaving. In this stage, the temperature continued to decrease and was below salt-heaving temperature. Hence, only frost heaving occurred. It was supposed that the main reason for volume variance in frozen soil was that part of the original water and part of water migrating from other place froze\[^7\]. Therefore, the volumetric strain of Stage Three could be expressed as\[^8\]:
\[
\varepsilon^V = 0.09(\theta - \theta_u) + (\theta - n) \tag{3}
\]

Where, \(\varepsilon^V\) is the volumetric strain; \(\theta\) is the original volumetric water content \((\text{m}^3/\text{m}^3)\); \(\theta_u\) is the unfrozen volumetric water content \((\text{m}^3/\text{m}^3)\); \(n\) is the soil voidage.

**PAVEMENT STRUCTURE AND FE MODEL**

**Pavement Structure**

The pavement structure of Jinnan-Dongying Freeway and mechanical parameters of geomaterial are shown in Table 2.

| Course                  | Depth h(cm) | Dynamic Modulus E* (MPa) | Poisson’s Ratio \(\mu\) |
|-------------------------|-------------|--------------------------|-------------------------|
| SMA-13                  | 4           | 7000                     | 0.35                    |
| AC-16                   | 5           | 9500                     | 0.3                     |
| AC-20C                  | 6           | 9000                     | 0.3                     |
| LSPM-30                 | 12          | 7000                     | 0.3                     |
| Cement stabilized macadam | 36          | 1600                     | 0.2                     |
| Lime and fly ash stabilized soil | 18         | 800                      | 0.2                     |
| Subgrade                | ---         | 35                       | 0.35                    |

**The FE Model**

To simulate sulfate saline soil subgrade section of Jinan-Dongying Freeway, first general pavement structure model (shown in Figure 3(a)) was established; second the profile of pavement structure model in driving direction was get; and third fluid-
structure interaction model was established at 25cm, 50cm, 100cm, 150cm, 200cm and 250cm below the surface of subgrade (shown in Figure 3(b)).

![Figure 3. Pavement structure model.](image)

(a) General model (b) FSI model

**Soil condition of Jinan-Dongying Freeway**

The area Jinan-Dongying Freeway passes belongs to Yellow River alluvial plain. The depth of embedment of phreatic water is relatively shallow and normally 2~3meters. The degree of mineralization is 1~2g/L and it could be 5g/L in stagnant water zone. In this area, the content of \( SO_4^{2-} \) is usually 500mg/L.

The measured temperature of subgrade in winter is listed in Table 2 and the measured salt content in different depth is listed in Table 3.

| Date       | Temperature | Depth 25cm | Depth 50cm | Depth 100cm | Depth 150cm | Depth 200cm | Depth 250cm | Depth 300cm |
|------------|-------------|------------|------------|-------------|-------------|-------------|-------------|-------------|
| 11.15.2012 | 3.2°C       | 50°C       | 6.7°C      | 8.8°C       | 12.9°C      | 15.5°C      | 16.4°C      | 16.5°C      |
| 1.15.2013  | -5.9°C      | -1.9°C     | 0.6°C      | 5.0°C       | 9.7°C       | 14.0°C      | 14.0°C      |             |

Table 3. Measured salt content of sulfate saline soil subgrade in different depth.

| Date       | Salt content | Depth 25cm | Depth 50cm | Depth 100cm | Depth 150cm | Depth 200cm | Depth 250cm | Depth 300cm |
|------------|--------------|------------|------------|-------------|-------------|-------------|-------------|-------------|
| 11.25.2012 | 0.001        | 0.003      | 0.004      | 2.021       | 0.025       | 4.5         | 23.3        |
| 1.10.2013  | 0.02         | 0.0012     | 0.025      | 2.542       | 0.202       | 6.4         | 48.3        |
| 3.13.2013  | 0.0018       | 0.0022     | 0.018      | 1.802       | 0.008       | 3.5         | 20.5        |

**SIMULATION RESULTS AND ANALYSIS**

**Simulation results under salt heaving and frost heaving**

The simulation results of asphalt pavement structure under effects of salt heaving and frost heaving were listed in Table 4. This simulation model would be called Model 1 in the following text.

680
Table 4. Simulation results under salt heaving and frost heaving.

| Position                                      | Vertical displacement(mm) | Tensile stress(MPa) | Tensile strain (με) |
|-----------------------------------------------|---------------------------|---------------------|---------------------|
| Pavement surface                              | 2.730613                  | 1.8383              | 919.684             |
| The bottom of SMA-13                          | 2.742709                  | 1.5177              | 800.249             |
| The bottom of AC-16                           | 2.755839                  | 1.2547              | 664.839             |
| The bottom of AC-20C                          | 2.769146                  | 0.8558              | 513.308             |
| The bottom of LSPM-30                         | 2.790507                  | 0.3848              | 278.743             |
| The bottom of cement stabilized macadam       | 2.851876                  | -0.6806             | -480.01             |
| The bottom of lime and fly ash stabilized soil| 2.97027                   | -0.5392             | -752.161            |

From Table 4, it could be found that the tensile stress on pavement surface was up to 1.8383MPa, but according to Specifications for Design of Highway Asphalt Pavement (referred to as Specifications for Design), the tensile strength of SMA-13 was only about 1.4~1.9MPa. At the same time, the tensile stresses at the bottom of AC-16 and AC-20C were 1.2547MPa and 0.8558MPa respectively, but the tensile strength of AC-16 and AC-20 was about 0.8~1.2MPa, also according to Specifications for Design. In this case, the tensile strength of asphalt surface course was seriously inadequate and it was clear that cracks in pavement surface were probable to emerge under salt heaving and frost heaving.

Besides, for base course, the tensile stress and strength of LSPM-30 were also very close to each other, which were 0.3848MPa and about 0.4~0.6MPa respectively. Although the tensile stresses at the bottom of semi-rigid base course were negative and this seemed helpful to crack resistance on base course, however once cracks emerged on pavement surface course, under the coupling effects of traffic loads it was very likely that cracks on pavement surface would be transferred downward.

Simulation results under coupling effects of wheel loads, salt heaving and frost heaving

Model 1 only simulated pavement under effects of salt heaving and frost heaving. In this part, 120km/h traffic loads were applied on the model to make a comparison between the stress response of structure in saline soil area under traffic loads or not. This simulation model would be called Model 2 and the simulation results were listed in Table 5.

Table 5. Simulation results under coupling effects of wheel loads, salt heaving and frost heaving.

| Position                                      | Vertical displacement(mm) | Tensile stress(MPa) | Tensile strain (με) |
|-----------------------------------------------|---------------------------|---------------------|---------------------|
| Pavement surface                              | 1.390591                  | 0.3840              | 312.605             |
| The bottom of SMA-13                          | 1.407608                  | 0.5066              | 393.005             |
| The bottom of AC-16                           | 1.431364                  | 0.5726              | 421.909             |
| The bottom of AC-20C                          | 1.456584                  | 0.4956              | 405.370             |
| The bottom of LSPM-30                         | 1.510191                  | 0.2636              | 258.422             |
| The bottom of cement stabilized macadam       | 1.621312                  | -0.2861             | -140.101            |
| The bottom of lime and fly ash stabilized soil| 1.764671                  | -0.3178             | -199.766            |
From Table 4 and Table 5, it was shown that due to the effects of traffic loads, vertical displacement, tensile stress and strain dropped dramatically. For example, tensile stress on pavement surface of Model 1 was 3.79 times than that of Model 2 and tensile strain on surface of Model 1 was 1.94 times than that of Model 2. At the same time, vertical displacement on pavement surface of Model 2 was merely half, compared with that of Model 1.

Besides, vertical displacements in both models shared the same variation tendency, while trends of tensile stress and strain were different between in Model 1 and Model 2. In Model 1, the peak values were on the pavement surface and they would decrease with the increase of depth. However, in Model 2, the peak values were at the bottom of AC-16.

Hence, it was obviously that traffic loads could effectively lower the probability of cracking on pavement surface and this was consistent with the experiment results in Reference[9] that overlying loads had inhibition on salt heaving.

**Simulation results in general area under traffic loads**

To make a comparison between the stress response of structure in saline soil area and general area, there was Model 3 that only 120km/h traffic loads were applied on. The simulation results were listed in Table 6.

**Table 6. Simulation results in general area under effects of wheel loads.**

| Position                        | Vertical displacement(0.01mm) | Tensile stress(MPa) | Tensile strain (με) |
|---------------------------------|------------------------------|---------------------|---------------------|
| Pavement surface                | -1.9791                      | 0.0282              | 4.9403              |
| The bottom of SMA-13            | -1.9737                      | 0.0252              | 4.4178              |
| The bottom of AC-16             | -1.9626                      | 0.0205              | 5.9013              |
| The bottom of AC-20C            | -1.9537                      | 0.0125              | 7.4073              |
| The bottom of LSPM-30           | -1.9501                      | 0.0995              | 11.6822             |
| The bottom of cement stabilized macadam | -1.9506                   | 0.0290              | 14.7810             |
| The bottom of lime and fly ash stabilized soil | -1.9779                   | 0.0210              | 20.7383             |

From Table 4, 5 and 6, it could be easily found that tensile stress and strain of Model 3 were far less than that of Model 1 and Model 2. Besides, the tensile stress at the bottom of cement stabilized macadam layer and lime and fly ash stabilized soil layer were both negative in Model 1 and 2, but that in Model 3 was positive. It suggested that in spite of the negative effect on asphalt courses, salt heaving and frost heaving were positive for crack resistance at the bottom of base course.

As for the vertical displacement, the absolute values in Model 1 were almost 150 times than that in Model 3. Although under effects of traffic loads, the absolute value of vertical displacement in Model 2 decreased dramatically, they were still about 80 times than that in Model 3. Besides, due to effects of salt heaving and frost heaving, the direction of vertical displacement in Model 1 and 2 was upward while that of Model 3 was downward. It suggested that although traffic loads would counteract half of vertical displacement in sulfate saline soil area (compared between Model 1 and 2), however bulging would still be possible to emerge, as well as cracks on pavement surface.
CONCLUSION

In this paper the stress response of asphalt pavement structure in sulfate saline soil area (Model 1 and Model 2) and in general area (Model 3) was simulated and analyzed. Therefore, it could be found that:

(1) In Model 1, only under salt heaving and frost heaving, the tensile strength of asphalt surface course was seriously inadequate and it clearly showed that cracks in pavement surface were probable to emerge. Although the negative tensile stresses at the bottom of semi-rigid base course seemed helpful to crack resistance, however once cracks emerged on pavement surface course, under the coupling effects of traffic loads it was very likely for cracks on pavement surface to be transferred downward.

(2) In Model 2, it showed that due to traffic loads, vertical displacement, tensile stress and strain dropped dramatically and it was obviously that traffic loads could effectively lower effects of salt heaving and frost heaving. Besides, although traffic loads would counteract half of vertical displacement compared with Model 1, there was still the possibility for bulging and cracks to emerge. At the same time, trends of tensile stress and strain were also changed.

(3) In model 3, vertical displacement, tensile stress and strain would further greatly decrease. The tensile stress at the bottom of semi-rigid base course however changed from negative to positive, which may suggest that salt heaving and frost heaving were helpful to crack resistance at the bottom of base course.

(4) According to the whole analysis on stress response, it is suggested that in sulfate saline soil area asphalt courses should strengthen crack resistance and foundation treatment.

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