Comparison of Geotechnical Freezing Characteristics between Korea and Kazakhstan Soils

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Abstract. The integrity of roadbed is an important element to resist the sustained load transmitted by the traffic load on the road surface. In the seasonal freezing climate both Korea and Kazakhstan can be significantly influenced to the integrity of roadbed. The soil specimens obtained from both countries are used for subgrade in the highway construction. The proper determination of magnitude of frost heave and heaving pressure by the influence of the cold freezing temperature during the winter season are necessary for design and construction highway.

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Shin and Park (2012) studied the soil freezing characteristics and temperature distribution in ground LNG storage tanks with consideration of several variables include soil type and heterogeneity, variation of soil temperature with time and depth, rate of freezing and availability of water.
Choi al. (2010) reported the rapid reduction of shear strength of railway roadbed soil. The strength reduction rate is not significant for the soil which is contained 25% of passing #200 sieve due to the freezing-thawing cycles.

The characteristics of frost heaving in the field is not easy to estimate because several factors are influenced as described previously including soil properties. Many researches were tried to propose the laboratory test procedure for the measurement of the frost heaving accurately since 1960’s (Grim, 1952; Hoekstra, 1966).

However, TRRL(Transport and Road Research Laboratory) method in England (Jones, 1981), US. Army Corps of Engineer’s method (American Society for Testing and Materials D 5918-96, 2006), the method proposed by Japanese Geotechnical Society (2003) are currently being used for estimation of frost heave ratio (\( \varepsilon \)) and frost heave rate (\( U_R \)). The frost heave ratio (\( \varepsilon \)) can be expressed in Eq.(1) as follows,

\[
\varepsilon(\%) = \frac{H_f}{H_i}
\]

where, \( H_f \) is the total amount of frost heaving after completed freezing, and \( H_i \) is the original height of soil specimen prior to freezing. The frost heave rate (\( U_R \)) can also be expressed in Eq.(2) as follows,

\[
U_R (mm/hr) = \frac{\Delta H}{\Delta t}
\]

where, \( \Delta H \) is the total amount of frost heave; and \( \Delta t \) is the elapsed time in hour.

Table 1. (a) Frost heaving criteria by different methods

<table>
<thead>
<tr>
<th>TRRL (U.K.)</th>
<th>JGS (Japan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>judgment</td>
<td>Frost heave ratio(%)</td>
</tr>
<tr>
<td>Negligible frost susceptibility(NFS)</td>
<td>Less than 12</td>
</tr>
<tr>
<td>Possible Frost Susceptibility(PFS)</td>
<td>Over 12</td>
</tr>
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<td></td>
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</table>
Current judgment criteria of frost heave is tabulated in Table 1. The amount of frost heave and the heaving pressure were experimentally studied previous by Taber (1929), Miller et al. (1960), Kinoshita and Ono (1963), Shin and Park (2003), Hoekstra et al. (1965), Yong and Oster (1971), Penner (1974), Domashuk (1982), Akagawa, S (1983), and Akagawa et al. (1985) were also studied regarding on the frost heave characteristics related to the specimen site, upright forces of structural foundation through the field and laboratory tests. Shin et al. (2012) conducted by using a large scale laboratory test in the freezing chamber sited in 3.2m(L) x 3.2m(B) x 2.4 m(H) to determine the change of plastic modulus caused by the cycle of frost heave and thawing for the paved roadbed. Pavement becomes distorted during winter causing increased roughness and cracking of the pavement surface as shown in Figures 1 and 2.

Fig. 1 Pavement cracking in the Astana (Kazakhstan)
The results of laboratory freezing test indicate that the Korea soil were much susceptible to the freezing temperature than that of Kazakhstan soil. The magnitude of frost heaving of Korea soil is about 25% higher than that of Kazakhstan. Also, the magnitude of freezing pressure of Korea soil is approximately 2 times higher than that of Kazakhstan. The percentage of number #200 passing in sieve analysis and Atterberg limits (LL, PL) are greatly contributed to the freezing heaving of soil.

2 SOIL PROPERTIES AND FREEZING TEST

The special mold which can eliminate the side friction between soil and wall was used in the laboratory freezing test. Prior to the laboratory freezing test, geotechnical properties of the soils were determined throw the basic tests. The geotechnical properties of both Kazakhstan soil and Korea soil are presented in Table 2.

The specimen is remolded and prepared in mold which is appropriate for freezing chamber. Four molds were fixed in the freezing chamber and putted them into the freezing apparatus. However, all soil specimen molds were saturated in the water barrel. Only after saturation, they were putted in the freezing apparatus.

Table 2. Geotechnical properties of soil specimens

<table>
<thead>
<tr>
<th>Description</th>
<th>Kazakhstan</th>
<th>Korea</th>
<th>SP</th>
<th>SM</th>
</tr>
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</table>

Fig. 2 Pavement cracking in the Republic of Korea
<table>
<thead>
<tr>
<th>Property</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity (G_s, kN/m³)</td>
<td>2.62</td>
<td>2.63</td>
<td>2.63</td>
<td>2.67</td>
</tr>
<tr>
<td>Natural water content (w_n, %)</td>
<td>21</td>
<td>N.P</td>
<td>N.P</td>
<td>N.P</td>
</tr>
<tr>
<td>Particle size passed #200 (%)</td>
<td>52</td>
<td>66</td>
<td>19.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Liquid limit (LL, %)</td>
<td>27.01</td>
<td>50.50</td>
<td>N.P</td>
<td>N.P</td>
</tr>
<tr>
<td>Plastic limit (PL, %)</td>
<td>17.75</td>
<td>31.94</td>
<td>N.P</td>
<td>N.P</td>
</tr>
<tr>
<td>Maximum dry unit weight (γ_dmax, kN/m³)</td>
<td>1.79</td>
<td>1.27</td>
<td>1.92</td>
<td>1.93</td>
</tr>
<tr>
<td>Optimum water content (w_opt, %)</td>
<td>15.9</td>
<td>32.25</td>
<td>11.5</td>
<td>12.4</td>
</tr>
<tr>
<td>USCS</td>
<td>CL</td>
<td>OH</td>
<td>SP</td>
<td>SM</td>
</tr>
</tbody>
</table>

General view of freezing chamber filled in with soil and freezing equipment is presented in Figure 3. The grain size distribution curves of the soils are presented in Figure 4.

The first 24 hours is a conditioning period. Both the top and bottom plates are kept the temperature at 30°C. The first freeze starts at the beginning of the second 24-hours period. First recording the initial dial gage or transducer readings; take a reading for each device if both are being used. The temperature of the top plate was lowered and hold it up at -3°C. The temperature of the bottom plate was kept at 30°C for 8 hours.
Fig. 3 General view of the freezing equipment.

Fig. 4 Grain size distribution curves of Kazakhstan and Korea soils.

The temperature of the top plate ($T_t$) was lowered at -12 °C after 8 hours have passed, and the bottom plate ($T_b$) was kept at 0 °C. These temperatures were kept for 16 hours. The temperature of the water for opening system of testing is kept 4 °C + 0.5.
The first thawing process starts at the beginning of the third 24-hours period (ASTM, 2004). The top plate temperature and hold it up at 12 °C. The bottom plate temperature were also raised and hold it up at 3 °C for 16 hours. During the next 8 hours, keeping both the top and bottom plate temperatures at 3 °C. The second freeze starts at the beginning of the fourth 24-hours period. This procedure is the same as that used in the first freeze. Also boundary temperature conditions are presented in Table 3.

Table 3. Boundary temperature conditions

<table>
<thead>
<tr>
<th>Day</th>
<th>Elapsed Time (t), h</th>
<th>Top Plate Temperature (T_t), °C</th>
<th>Bottom Plate Temperature (T_b), °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>-3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>-12</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>48</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>72</td>
<td>-3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>-12</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>96</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>112 to 120</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

The second thawing process starts at the beginning of the fifth 24-hours period. This procedure is the same as that used for the first thawing process.

During freezing-thawing test, all temperature sensor and displacement transducers are recorded at least every half an hour throughout the first 8-hour of freezing and after then at 1-hour intervals.

At the end of the second thawing period (120 hours after the beginning of the test), recorded that dial gage reading. The circulating liquid turning off to the temperature control plates. The dial gage and the displacement transducer assemblies are removed with the surcharge weights and the top temperature control plate assembly. The insulation of around the soil specimen makes a loose condition to allow access to the temperature sensors from the side of the specimen by pulling them gently away from the acrylic rings. The specimen assembly and the base plate are removed completely from the temperature control chamber.

3 LABORATORY FREEZING TEST RESULTS AND DISCUSSION

The laboratory freezing tests were performed for understanding frost susceptibility of the soil and predetermination possible frost action to the structure. The frost penetration into the specimen results of the freezing test are presented in Figure 5. There are some curves which show frost penetration depth of the Kazakhstan and Korea soil.
The frost penetration of Kazakhstan soil is about 3 cm more deeper than that of Korea soil. The horizontal numbers show the time in hour and the vertical numbers show depth penetration in cm. Frost penetration of Kazakhstan soil is more than 10 cm.

The rate at which soil frozen or frost penetration is depend on its thermal properties, moisture content, and the ambient air temperature. Probably the most important is the amount of water to be frozen, since it requires 144 heat units (Btu) for freezing each pound of water and by comparison only about 0.20 heat units to change the temperature of a pound of dry soil by 1°F. The density, conductivity of the soil particles and water content of the soil are all influenced by thermal conductivity of soil. Because clay particles have a higher insulation value than those of silt or sand particles and since clay soils normally keep more moisture than silt and sand, the depth of frost penetration is usually greater in silt and sand (light-textured soils) than in clays and silty clays (heavy-textured soils). Even the water content of Kazakhstan soil is less than Korea soil the frost penetration depth of Kazakhstan soil is greater than that of Korea soil. But the particle size of Kazakhstan soil is less passed through #200 sieve than that of Korea soil.

There are other factors that have influence to the depth of freezing. The insulating effect of snow deserves special attention. It has been shown that each foot of undisturbed snow reduces the depth of soil freezing by approximately to the same amount. Air temperature is probably the most significant than meteorological factors such as sunshine, precipitation, and wind velocity,

Using of "degree-days of freezing" as a guide for calculating frost depth for a given area illustrates the strong influence of air temperature to soil temperature. A
degree-day of freezing results when the mean outside air temperature for one day is 1 °C degree below 32°C. For example, if the average air temperature for a given day is 31°C this is one degree-day of freezing. The "freezing index" is simply the total number of degree-days of freezing for a given winter.

Using of the freezing index to predict the depth of frost penetration must be used with caution since based only on air temperature and does not take into consideration other factors such as soil type, snow cover and local climatic differences. Freezing on a concrete platform are defined by heat exchange conditions on a ground surface, its structure and a condition. Depth of freezing depends on basically on following four characteristics: average annual temperatures of soil, annual amplitudes of temperatures on a surface, structure and humidity of a ground. The decision of private problems for cases of freezing at continuously occurring phase transitions, and also taking into account process of migration of a moisture show that movement downwards borders of section of phases in many cases can occur under the law like \(d = \alpha \sqrt{t}\), where \(\alpha > 0\) is constant which determine speed of freezing and depend on temperature and moisture, \(t\) - is time (Karlov, 2007).

There are curves which present temperature of the every soil layer. Sensors are putted every 1 cm in sample which height is 20 cm. It means that 19 sensors putted to the soil during the preparation to the freezing test.

The sensor which putted on the top of the soil sample have the maximum low temperature -4 °C. The sensor which putted in the toe of the soil sample have the high temperature +4 °C on the chamber lowest temperature -12 °C. Also there is changing the temperature penetration among two circumstances of the freezing during the test.

At freezing a ground the water filling a pore between particles, turning to ice, extends and deforms a ground which freezing together with a base body, heaving it up. Such phenomenon in freezing through soil carries the name frosty heaving, and soil are called heaving soil.

It is visible that in a case of deepening the base below possible depth of freezing lateral surfaces of the base will influence \(\tau\) – force tangents heaving. The total size of tangents of forces heaving for strong heaving soil can exceed weight of a two-stored building, i.e. even to lift a building upwards.

In a case of deepening the base above possible depth of freezing lateral surfaces of the base will influence both \(\tau\) – force tangents heaving, and \(\sigma\) - normal forces heaving. The total size of tangents and normal forces heaving for strong heaving soil is that can exceed weight even a five-floor building.

Thus, at depth definition installing the base in freezing through heaving soil, it is necessary to aspire to decrease in negative influence of forces heaving, deepening the bases below settlement depth of freezing in the given area. The constructive decision on removal of tangents of forces heaving by the device not frozen a plastering of lateral surfaces of the base is in certain cases admissible.

Heaving are subjected to dusty sand, loams and clay – soft plastic and fluid.

The scheme of a low arrangement of level of ground waters concerning depth freezing that at a finding soil in a firm and semifirm condition allows not to consider practically heaving.
At such low humidity (a firm and semifirm condition) heaving makes about 1% from freezing through thickness that is considered insignificant and calculation isn't accepted. However at designing it is necessary to consider that humidity, in the course of building could change, for example as a result removal of a grassy cover or infringement of a natural drain of water.

Heave amount of the soil also is the main determination of frost susceptibility of the soil. The heave amounts of Kazakhstan soil and Korea soils are illustrated in Figure 6.

The heave amount of Korea soil is 5 times higher than that of Kazakhstan soil. The reason of this difference is the sieve analysis of Korea soil is finer than Kazakhstan soil. Also the initial moisture content and unfrozen water content of the soil are different but the condition of the freezing is the same situation. The heaving of the frozen soil more clearly should be understandable by the ice formation of the soil during freezing process. Ice formation is the main process which causing the heaving process during freezing of the soil. By Beskow theory of ice formation the soil particles are enveloped by water films in which the water pressure is considerably higher than the pressure of water in the middle of pores in the soil. Due to the high pressure, the freezing point of the water in the water films is lower than that of the “free water” inside the pores (Williams, 1962).

![Fig. 6 The frost heaving amount of the Kazakhstan (Astana) and Korea soils](image)

The freezing pressure during testing Kazakhstan and Korea soils is presented in Figure 7. Obviously Korea soils show more heaving pressure than Kazakhstan clay soil.
Fig. 7 The freezing pressure curves of Kazakhstan (Astana) and Korea soils

When the temperature of the soil goes down, the first ice crystals are formed in the center of the pores. The molecules of the outer water films also start to join with the ice crystal by decreasing temperature. The water films have a tendency to return to their original thickness in places where the ice crystal has penetrated the film and therefore the film pushes the ice crystal further away from the soil particles. However, some water molecules frozen to the crystal will also be pushed further, that is the reason why the ice crystal will grow by the water molecules stolen from the water films (Keinonen, 1960). Figure 8 shows the ice formation process in the soil during freezing process.

Fig. 8 The forces created during the growth of the ice crystal tend to push the crystal farther from the soil particles. Because of these forces the soil particles A, B, C and D move away from each other.

During cold winter months, frost penetrates pavement materials and subgrade soils. While progressing in the pavement structure, frost causes interstitial water to expand and can also cause segregation ice to form in unbound granular materials. Notwithstanding the fact that the latter phenomenon is generally considered insignificant in pavement granular materials, it causes the loosen materials. Frost heaving of pavement surfaces reaching 10 to 15 mm are systematically being observed on experimental test sites before the front reaches the subgrade soil. When the frost
front reaches frost susceptible subgrade soils, water is sucked toward the frozen fringe where ice lenses are formed. Frost heaving of the pavement surface resulting from these phenomena can reach and even exceed 150 mm for climatic conditions prevailing in cold regions like as Kazakhstan. If the magnitude of the frost heaving were uniform, it would not be damaging for pavements. However, the frost action is generally uneven because of the variability of subgrade soil characteristics and because of the embankment geometry. Differential frost heaving is therefore a major factor affecting winter roughness of roads built in cold regions.

The climatic conditions of Kazakhstan is more colder than the temperature of Korea and sharply continental. Coldest temperature in winter can reach \(-43^\circ\text{C}\) and \(+45^\circ\text{C}\) in summer season in Kazakhstan. Average temperature of January — from \(-19^\circ\text{C}\) to \(-4^\circ\text{C}\), average temperature of July — from \(+19^\circ\text{C}\) to \(+26^\circ\text{C}\) in Kazakhstan. By this climatic conditions the frost penetration can reach 2.5-2.7 meters, frost heaving and pressure high and getting peak in March. This climatic condition is more severe influence to the pavement system than that of Korea and also frost heave more than Korea soil. The problem with frost heave results mainly from the fact that the phenomenon is rarely uniform.

Differential frost heaving can be attributed to four major causes. The first cause, described by Peterson and Krantz (1998), is associated with the instability of the one-dimensional freezing process. The one-dimensional frost heave has the propensity to evolve into multidimensional differential frost heave as a function of soil properties and environmental conditions. The other causes of differential heaving are the variability in the frost susceptibility characteristics of the subgrade soil (including moisture availability), the variability of the thermal regime and the topography of the surface or the geometric characteristics of the earth structure (Guy Dore & Hannele K. Zubeck, 2009).

Two conditions must exist for the occurrence of problems related with differential frost heaving by Guy Dore and Hannele K.Zubeck. First, frost heave has to be significant. Frost heaving becomes more important with increasing frost depth, frost susceptibility of subgrade soil, and moisture availability. Second, frost heaving has to be uneven. Spatial variability of soil characteristics is the major factor contributing to the unevenness of frost heaving. If only one of these conditions is present in the field, differential frost heaving should not be a major problem. It should be possible to reliably predict poor winter performance of the pavement by applying the proposed model during preliminary studies of a road construction project,. It should be possible to modify pavement design or construction practices in order to mitigate the inconvenience caused by differential heaving. If variability seems to be the dominant problem, subgrade homogenization techniques can be used to reduce the differential effects of frost heaving. Moreover, if frost heaving is expected to be the dominant problem frost penetration could be reduced by increasing the thickness of a granular subbase or by placing an insulation layer in the pavement structure. In the longer term, increasing construction costs associated with these techniques would probably be compensated by a significant reduction in maintenance costs. They would also improve the winter and the long-term ride quality of the road, resulting in reduced vehicle maintenance and operation costs.
Another important differential heaving problem affecting pavement structures is the result of the important variations of thermal regime along the transversal section of the pavement. Mainly snow accumulation on the pavement sides impedes heat extraction at that location. As a result, frost penetration at the center of the pavement is much greater than at the edge of the pavement. Frost heaving being proportional to frost penetration, a transverse differential heaving is initiated in the pavement. The movement can be assimilated to a bending imposed to the pavement transverse section. It is likely to generate excessive tensile stresses and initial longitudinal or meandering cracks. Road users are not directly affected by the phenomena, but the resulting cracks can be highly detrimental to the structural performance of the pavement because they intercept running water at the surface, which then infiltrates the pavement structure.

4 CONCLUDING REMARKS

Laboratory freezing tests were conducted for the soil specimens obtained from Kazakhstan and Korea to understand the freezing characteristics of soils. The fine particles which passed the sieve number #200 for Korea soil is much greater than that of Kazakhstan soil, and the water content of Korea soil is also much lower than that of Kazakhstan soil. Therefore, the heaving amount of Korea soil is about 25% higher than the magnitude of Kazakhstan soil. Frost heaving and thawing are the major causes of creating damages on the pavement of road. It should be avoid this damages and reduce the influence of the extreme climatic conditions for transportation geotechnics. There are several ways to prevent the damageable influence of the frost heaving in Kazakhstan condition. The frost heaving susceptible soil is replaced by granular soil. The drainage system must be developed to dissipate the all the water sources from the road. Finally, the design and construction manual should be developed with consideration of frost penetration depth, asphalt binding material, freezing index, types and thickness of anti-freezing layer, height of embankment for road.