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Dear Sir/Madam,

Thank you very much for your email on February 10, 2016 indicating that our submitted paper Ms. No. CFENG-1512 required further revisions and responses to the reviewers’ comments.

We would like to take this opportunity to wholeheartedly thank you for your great help during the review process. Please also do us a favor to pass our wholehearted thank to the reviewers for their time, patience, and constructive criticisms. We found that the reviewers’ comments are very valuable for us. We have modified the paper in order to address the third reviewer’s concerns.

Our responses to the reviewers’ comments are summarized as follows.

Reviewers #1 and #2 commented that the quality of some figures need be improved. In the new version, Figure 2, 3 and 4 have been improved according to the reviewer’s suggestion. Different dash lines have been adopted to distinguish the temperature and moisture variations for each sensor. Additional explanations have been added to Figure 8-10 to improve the readability of the paper. The authors also discussed the effectiveness of the arrangement of Figure 3 and 4 in terms of describing the temperature and moisture variations with depth. Extra paragraph describing the temperature and moisture developing process has been added in “Performance of Wicking Fabric at Different Climatic Conditions”. The specification of the basic properties of the wicking fabric has been added in the “Introduction” section. The permafrost depth in the test section is at least 2.5 m below the surface and the wicking fabric layers are installed in the active layer to take advantage of their wicking ability in the summer time. Therefore the depth of permafrost shall not be our major consideration. The authors also explain the feasibility of the application of this type of wicking fabric in humid areas.

Regarding reviewer #3’s comments, we agree with the reviewer’s comment that the fine content (especially silt content) is a critical factor that determines the frost susceptibility of a typical type of soil. However, we disagree with the reviewer’s conclusion that “there were no frost susceptible soils in the test section; the cross section consisted of sand and gravel and 6% fines”, and “the paper and conclusions are flawed”. A number of researchers (Casagrande 1931, Ruckli 1955, and Johnson et al. 1986) indicate that soils containing more than 3% of fines can be considered as frost susceptible soil and the frost susceptibility of a soil shall also consider the hydrological and geotechnical condition of the site. Therefore, the soil in our test section is indeed frost susceptible soil. Moreover, the harsh environment (nearly -40°C lowest temperature) and the relatively shallow groundwater table intensify the possibility of frost action. AK DOT&PF personnel have observed the “frost boil” issue at the end of April and early May every year. The following two figures show the temperature and moisture contours of the test section on April 26, 2011, and May 15, 2011, respectively. As can be seen from both figures, the thawing depths in both figures were less than 0.6 m (2 ft) from the surface. However, frost boils had occurred during the same periods at other locations without the wicking fabric. Since the soil beneath were frozen and therefor impervious and the depth of the ditch is 1.1 m (3.6 ft) below
the road surface. The only source of excessive water for the frost boils to happen is from thawing of water in the in-situ soils. This leads to the conclusion that there must be frost heave in the previous fall season.

Figure 4.35 Temperature and Moisture Content Contours at Noon of April 26, 2011
Figure 4.36 Temperature and Moisture Content Contours at Noon of May 15, 2011

I am now resubmitting the revised paper for publication in the Journal of Performance of Constructed Facilities. Enclosed please find revised paper and the responses to the three reviewers’ comments. We look forward to the reviewers’ further suggestions and comments. Once again, the reviewers’ help and patience are highly appreciated. Should you have any question regarding this new submission, please feel free to contact me at (979)-5716650 via my cell phone or xzhang11@alaska.edu via email.

Best regards,

Xiong

References


Long-Term Performance of Wicking Fabric in Alaskan Pavements

Chuang Lin¹, Wendy Presler², Xiong Zhang³, David Jones⁴ and Brett Odgers⁴

ABSTRACT

Beaver Slide is near 177.8 kilometer (110.5 mile) on the Dalton Highway and the road gradient is approximately 11%, built on a hill side. Each year, Soft spots, also commonly named as “frost boils”, were observed starting from late April and lasting for the entire summer. The “frost boils” have resulted in an extremely unsafe driving condition and frequent accident occurrences. Conventional repair methods cannot effectively solve this issue. A newly developed geotextile, which has high specific surface area, was installed in the selected test section to mitigate the “frost boil” issue in August 2010. This type of geotextile can provide high wettability and relatively high suction (capillary force), consequently be able to laterally transport water (a high directional transmissivity) under unsaturated condition. Test results over the initial two years had proved the effectiveness of the geotextile to alleviate frost heave and the subsequent thaw weakening issue. However, there were still some concerns regarding its long-term performance, such as clogging of the microscopic drainage channels and mechanical failures. The data collected during the past five years was used to analyze and evaluate the effectiveness of the wicking fabric. A scanning electron microscope (SEM) was used to explore the interaction between the wicking fabric and in situ soils, and to determine the condition of the fabric five years after installation.

CE Database subject headings: frost heave, thaw weakening, geosynthetic, wicking fabric, long-term performance

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INTRODUCTION

Beaver Slide is located at 177.8 kilometer (110.5 mile) on the Dalton Highway, which is about 8.0 kilometers (5.0 miles) south of the Arctic Circle. The road section is located on a downhill side heading north with about 11% gradient. The road is constructed on a side slope, where shallow groundwater drains down the slope starting each spring and lasts until early winter. Since Dalton Highway is the only and vital transportation line that connects the Prudhoe Bay oil filed with interior Alaska, it is critical to maintain the road in good driving condition. However, according to the frequent complaints from heavy truck drivers and maintenance personnel, soft spots, also commonly referred as “frost boils”, were often observed in this section. Heavy truck drivers tend to brake when encountering the soft spots and make the condition even worse. “Frost boils” are induced by the excess water that comes up and accumulates in the road embankment, and will eventually cause distresses and road damages. Due to the existence of the “frost boil” issue, the driving condition is extremely unsafe and frequent accidents have been reported in this section. Zhang et al. (2014) concluded that the “frost boil” issue was caused by two mechanisms: (a) frost heave and subsequent thaw weakening in early spring (Chamberlain 1987), and (b) upward pressurized water flow during lengthy rainy period during mid-summer and fall.

For frost heave, during periods of freezing, water in large void space freezes into ice crystals as the freezing front is moving downward into the road. As water is drawn to the freezing front by capillary movement through the frost susceptible soils, the ice crystals continue to grow (Casagrande 1947; Csathy and Townsend 1962), causing the road surface to heave. During the spring, the ice lenses start to melt and the fine soil particles are separated from the matrix, which causes depressions and soft areas at the road surface (Taber 1930, 1978 and 1980).
Engineers from the Alaska Department of Transportation & Public Facilities (AKDOT&PF) tried several conventional methods to mitigate the frost boil issue but none have eliminated the issue. There are three necessary elements in the formation of frost heave (Holtz and Kovacs 1981): (1) frost susceptible soil, (2) subfreezing temperature, and (3) water. Therefore, removal or minimizing of the three conditions will mitigate the frost heave and thaw weakening potential. One potential method to solve this issue is to rehabilitate the section and substitute with better materials (for example, with non-frost susceptible soils). However, this method is not feasible due to the extremely high cost and long transportation distance to the remote site. It is also not feasible to artificially alter the environmental condition, which is the source of water. The most practicable way is to reduce the water content in the pavement structure. AKDOT&PF has tried to install French drains to reduce the water content in this road section. This conventional repair method does not work well because the French can only drain free water or runoff water from the road surface and drainage ditch. The capillary water in the pavement structure cannot be drained by conventional drainage methods. In order to break the capillary flow path, a capillary barrier can be an alternative way to stop frost action. A capillary barrier is a layer of coarse-grained soil or geotextile placed in a frost susceptible soil. Taber (1929) has reported a successful application of a coarse sand above the groundwater table to mitigate the severity of frost heave. He observed that the frost susceptible soils tended to absorb more water compared with non-frost susceptible soils, and enough water supply was one of the critical factors that contributed to the frost heave action. Similarly, Casagrande (1938) and Beskow (1946) also indicated that this type of capillary barrier worked effectively to reduce the frost heave severity of the underlying fine-grained soil. Later, Rengmark (1963) and Taivenen (1963) further proposed and extended the application of capillary barriers to break down the
capillary water from moving to the base layer. However, the capillary barrier only stopped the capillary water from moving upward. The excess water would be accumulated beneath the capillary barrier, and with time would finally reduce the stiffness of the pavement structure.

An effective way is needed to mitigate the frost heave and subsequent thaw weakening issue. A new type of woven geotextile with wicking ability was recently developed and had the potential to solve this issue. The basic physical, mechanical and hydraulic properties of the wicking fabric are presented in Table 1. This type of geotextile can provide high wettability and relatively high suction (capillary force), and is able to laterally transport water (a high directional transmissivity) under unsaturated condition. Series of lab tests, conducted by the researchers at University of Alaska Fairbanks, proved that this type of geotextile had great promises to solve the “frost boil” issue as a cost-effective methodology (Zhang and Presler 2012). Zhang and Belmont (2009) compared four different types of geotextiles to evaluate their effectiveness to drain water under unsaturated conditions. Test results indicated that the soils installed with wicking fabric obtained the lowest water contents after the test, which validated the advantages of wicking fabric to drain water out of soils comparing with conventional geotextiles.

In order to further analyze the performance of the wicking fabric to mitigate frost heave and subsequent thaw weakening issue, a test section installing two layers of wicking fabrics was built at the Beaver Slide area of the Dalton Highway (Zhang et al. 2014). In total 22 pairs of sensors were used to monitor the temperature and moisture content change in the 18.1 meter (60 foot) long road section. In addition, other useful data such as air temperature and relative humidity was also recorded. Performance of the wicking fabric was monitored under different climate conditions, such as rainfall events, freezing processes and thawing processes. The first two years of monitoring indicated good overall performance and field observation showed a
remarkable road surface difference between the test section and sections without the wicking fabric. No soft spots were observed during early spring and soil at the road shoulder of the down slope side was damp, while the other section without installing wicking fabric still had frequent “frost boils” occurrences. This indicated that water flowed along the wicking fabric and out of the road structure and the wicking fabric successfully eliminated the frost boil problem to a depth of 1.07 meters (3.5 feet). Even though soil 1.37 meters (4.5 feet) beneath the surface and lower showed the existence of excess water, it had limited effect on roadway performance.

Although both laboratory and field test results proved that the wicking fabric was a very promising drainage material to remove water from the pavement structure, the long-term performance of the wicking fabric still needed to be further evaluated. In addition, there were still some concerns regarding the extensive application of the wicking fabric. Firstly, the clogging effect might influence the long-term performance of the wicking fabric. Because the wicking fabric was directly in contact with the soil, there was a potential that the drainage paths (or deep grooves) might become blocked by the finer soil particles. Secondly, permanent deformation might also influence the wicking fabric long-term performance. During the construction process, the soil above the wicking fabric was compacted and introduced with relatively high loading pressure. The permanent deformation might be further developed with time due to heavy truck traffic on the road surface during its service life. Permanent deformation of the wicking fabric could also reduce the amount of water held in the deep grooves and might reduce the effectiveness of the fabric's wicking ability. Thirdly, aging and mechanical failure could influence the long-term performance of the wicking fabric. Both the hydrophobic and hydroscopic yarns of the wicking fabric would suffer from physical and chemical aging, but the rate and severity of aging were unknown.
This paper focuses on the long-term performance of the wicking fabric to mitigate the frost boil issue in Alaskan pavements in the past five years (2010-2015). It was found that water entered into the data acquisition station in August 2014 and caused malfunction of the datalogger. Consequently the pavement moisture and temperature variations for only four years (2010-2014) were recorded and analyzed. Macroscopic analyses of the wicking fabric's performance in various climatic conditions (such as rainfall events, freezing and thawing processes) were first discussed. Field samples of the fabric were collected at the end of the five-year period (September 2015) to evaluate the wicking fabric performance at a microscopic level, using a scanning electron microscope (SEM).

**TEST SECTION CONSTRUCTION AND INSTRUMENTATION**

The description of the test section construction process can be found in Zhang et al. (2014). The following is a summary of the test section construction and sensor installation processes. The test section was selected because AKDOT&PF identified it as the section of road on the Dalton Highway with the most soft spots (frost boils) observed in the spring of 2010. Fig. 1 shows the profile of the test section. The road section was originally built directly on the tundra with the degraded granite. Sieve analyses indicated that the soil was classified as gravel with sand, according to USCS classification, and contained about 6% or more fines (material passing the #200 sieve). At the west edge of the road about 0.91 meter (3.0 feet) below the ground surface, the original tundra was found at about 1.36 meters (4.5 feet) below the centerline of the road section. The degraded vegetation layer with dark yellow color was about 0.05-0.1 meter (1-2 inches) thick. *In situ* crushed rocks and sand were encountered below the degraded vegetation. Groundwater was 0.15 meter (6 inches) below the tundra surface. Additionally, during the
construction process, excess water was observed in the drainage ditch, which was located on the west side of the road.

In total, 22 pairs of sensors were installed in the pavement structure. Each pair of sensors consisted of a Campbell Scientific 107–L temperature sensor and a CS616–L moisture content reflectometer. An HMP45C air temperature/relative humidity sensor was also installed at the site to monitor the air temperature and relative humidity. Four layers of sensors were installed at depths of 0.45, 0.76, 1.06 and 1.97 meter(s) (1.5, 2.5, 3.5 and 6.5 feet) below the road surface. Two layers of wicking fabric were installed at depths of 0.76 meter and 1.06 meters (2.5 feet and 3.5 feet) below the road surface. In order to ensure that the geotextile could transport water in the direction parallel to the water flow direction, care was taken to make sure that the geotextile (wicking fabric) was installed along the transverse direction of the road section. On the east side of the roadway, the two wicking fabric layers were left exposed to the air at 1.21 meters (4 feet) off the shoulder. Sensor 22 was installed at the location closest to the drainage ditch, and could be used as a representation of the saturated moisture content in the pavement structure in summer time. The sensor wires were protected with aluminum conduit. A Campbell Scientific CR1000 data logger was adopted to record the data. All of the data acquisition devices were organized into an ENC14/16-NC-NM weather-resistant enclosure which was installed on the tundra about 6.1 meters (20 feet) from the west edge of the road.

RESULTS AND ANALYSIS

General Climatic Conditions

Fig. 2 presents the hourly air temperature and relative humidity data, for the test section from August 2010 through August 2014. Fig. 2a indicates that in general, the average summer air
temperatures increased from 2011 to 2013, followed by a decrease in 2014. The average winter air temperature increased each year during the same period. Within year, air temperature dropped below zero in late September and rose above zero in mid to late April. The lowest temperatures recorded at the site were on February 23, 2010 (-36.8 °C), January 29, 2011 (-39.8 °C), December 17, 2012 (-35.2 °C) and January 13, 2014 (-34.8 °C). The highest temperatures recorded were on May 27, 2011 (24.4 °C), June 24, 2012 (22.9 °C), June 19, 2013 (26.2 °C) and July 6, 2014 (24.9 °C). The daily temperature variations in the summer times were smaller than those in winter times.

Fig. 2b presents the monitored hourly relative humidity data for the four year period from August 2010 through August 2014. In winter months, the relative humidity at the site was between 70% and 90%, due to relatively low air temperatures. However, the relative humidity varied from 20% to 90% in summer months. The relative humidity during daytime hours was lower than that at night. During significant rainfall events, the relative humidity increased rapidly over 95% in the test section, and then decreased below 85% very soon after the rain stopped.

Soil Temperature Changes

Fig. 3 presents the soil temperatures of the monitored 22 sensors from August 2010 through August 2014. Fig. 3a shows the temperature variations for sensors 10, 11, 12 and 13, which were located at the center of the embankment. The sensors were buried at depths of 0.45, 0.76, 1.06 and 1.97 meter(s) (1.5, 2.5, 3.5, and 6.5 feet), respectively. In general, the trend of temperature changes in the soil followed the air temperature trend. The temperature change in the soil decreased in magnitude as depth increased because of the soil insulating effect. For instance, sensor 10 was the closest sensor to the road surface, and its temperature variations
Followed the air temperature changes very closely during the summer. During the winter months, the temperatures at sensor 10 were higher than the air temperatures. In comparison, the temperature variations at sensor 13, which was installed 1.97 meters (6.5 feet) below the road surface, ranged from -12 °C to 3 °C for the entire year. The variations at sensor 13 were much smaller than air temperature changes, which were as much as 30 °C in winter and 16 °C in summer. It was also observed that the soil temperature 1.97 meters (6.5 feet) below the road surface only experienced temperatures above 0 °C for less than 3 months each year (i.e. July 20, 2012 to October 30, 2012). This indicates that the soil at this depth could be considered as a permeable layer for approximately 3 months, and as an impermeable layer for the rest of the year.

Fig. 3b-3e show the temperature changes at the sensor locations 0.45, 0.76, 1.06 and 1.97 meter(s) (1.5, 2.5, 3.5, and 6.5 feet) below the road surface, respectively, for the past four years. Fig. 3b-3c present temperature data for the sensors located at 0.45 and 0.76 meter (1.5 and 2.5 feet). In general, the amplitudes of temperature changes at 0.76 meter (2.5 feet) were smaller compared with those at 0.45 meter (1.5 feet). However, the soil temperature changes in both layers followed the air temperature trends during the summer, and were warmer than the air temperature in winter. Thus, soils 0.76 meter (2.5 feet) below the road surface could be considered a permeable layer during the summer, which were able to drain the melting snow from the road surface. Additionally, the soil temperatures observed in the center of the road were lower than temperatures at the edges during winter months; and soil temperatures at the west side of the road were lower than those at the east side. There are two reasons to explain this phenomenon: (1) snow was routinely removed and piled on the shoulders, insulating the shoulder
to make it warmer than the center of the road; and (2) the roadway on the east side received more solar energy than the west side, resulting higher temperature at the east side of the roadway.

Fig. 3d-3e shows the temperature change for sensors at 1.06 and 1.97 meters (3.5 and 6.5 feet) below road surface. The insulation effect became more obvious as depth below the surface increased. As can be seen in Fig. 3d, soil temperatures at 1.06 meters (3.5 feet) experienced approximately a 1 month time lag compared with the air temperature change (time difference for the starting dates of soil and air temperatures above 0 °C). As for soils at a depth of 1.97 meters (6.5 feet), this time lag could be as large as 3 months, as shown in Fig. 3e. This phenomenon indicated that during the early spring (late April or early May), the soils at 1.06 meters (3.5 feet) and below were still frozen and could not be considered as a drainage layer until 1-3 months later. In other words, since the second layer of wicking fabric was installed at 1.06 meters (3.5 feet) below the road surface, it would not be able to drain the water out of the embankment until early June. The first snowfall at the site was expected in early October each year, theoretically allowing the second layer of wicking fabric to remain functional until early November, when the soils at this depth became thoroughly frozen.

**Soil Moisture Changes**

Fig. 4 shows the soil moisture changes for the installed 22 sensors during the four year period from August 2010 through August 2014. As can be seen in Fig. 1, sensor 22 was buried at about 1.2 meters (3.9 feet) below the road surface, and was 1.5 meters (4.9 feet) away from the up-slope drainage ditch. Its elevation was 0.1 meter (0.3 foot) below the drainage ditch. The drainage ditch had water flow all year around except during winter months when everything was frozen. Since the moisture content at sensor 22 was controlled by the drainage ditch and
maintained saturated or nearly saturated, it was reasonable to use sensor 22 as a reference for comparison purposes in all figures. As shown in Fig. 4a, moisture contents at sensor 22 were relatively constant in the summers and winters between 2010 and 2014, and independent of the daily weather conditions. The recorded average volumetric moisture content continuously decreased from 0.38 in 2010 to about 0.32 in 2013, and slightly increased to 0.35 in 2014. However, the unfrozen water in winter months barely changed and was maintained within the range of 0.07-0.12. It is also worth noting that it took nearly 2 months to thoroughly freeze the soil at this depth in winter months, but only took about 2 weeks to thoroughly thaw the frozen soil in subsequent early spring. Taking the 2014 thawing season as an example, the unfrozen moisture content for sensor 22 was approximately 0.09 on April 10, 2014 when the average daily air temperature was -15.5 °C. However, this value increased to 0.14 on April 24, 2014, when the average daily air temperature changed to -1.1 °C. This phenomenon indicated that solar radiation is capable to increase the unfrozen water content in frozen soil even if the air temperature is still below zero.

Fig. 4a shows the soil moisture changes at 0.46 meter (1.5 feet) below road surface. It is obvious that the moisture content at this depth was far below the moisture content at the reference location (sensor 22). On one hand, the infiltration water could be easily runoff due to the existence of both longitudinal and transverse slopes. On the other hand, the evaporation process at the road surface was much faster owing to an easy access to the open air. Because the elevation of the ground adjacent to the roadway at the west side of the road was higher than the east side, it was reasonable that the moisture contents of the soils on west side were higher than soils on the east side. Fig. 4a was consistent with the observations made by AKDOT&PF
maintenance and operation personnel who reported no soft spots were observed at the test section and were very satisfied with the performance of the wicking fabric in the past five years.

Fig. 4b shows the soil moisture changes for sensors at 0.76 meter (2.5 feet) below road surface, where the first layer of wicking fabric was installed. In general, the soil moisture contents were not higher than the referencing sensor (sensor 22), except for some long and intensive rainfall events. Any sudden, large variation in soil volumetric moisture content change indicated a rainfall event. Compared with Fig. 4a, soils at this depth, 0.76 meter (2.5 feet) were more affected by the rainfall events. However, the soil moisture contents dropped back quickly after the rainfall event stopped, which indicated that the drainage condition at this depth was favorable. Since the soils at 0.45 meter (1.5 feet) remained unsaturated in the four years, the excessive water at the depth of 0.76 meter (2.5 feet) was from the horizontal direction.

Fig. 4c shows soil moisture changes at 1.06 meters (3.5 feet) below road surface, where the second layer of wicking fabric was installed. Sensor 1 was buried fairly shallow on the east side of the road shoulder, and the moisture content was much lower than that for the reference sensor 22. Similarly, the moisture contents for sensors on the east side were lower and the moisture contents for sensors on the west side were all higher compared with the referencing sensor. The amplitudes of moisture content changes after intensive rainfall events were also higher at 1.06 meters (3.5 feet) than the previous two depths discussed. This phenomenon could be the results of (1) accumulated water at the drainage ditch, and (2) the one-month time lag to melt the frozen soil at this depth. Since the snow started to melt in early May, and the elevation of the ground adjacent to the road on the west side was higher than on the east side. Soils at 1.06 meters (3.5 feet) and below would not start to melt until late May or early June and the water source was therefore not from the drainage ditch. A large amount of water was probably trapped
in the drainage ditch, which provided a large quantity of water to the roadway structure. The freezing temperatures and excess moisture resulted in a hard, frozen core at the center of the road, impeding the drainage path. The higher moisture content in west side of the road was caused by the trapped water in the pavement structure.

Fig. 4d shows the moisture content changes for sensors at 1.97 meters (6.5 feet) below road surface. The moisture content distribution followed the trend presented in Fig. 4c. All of the sensors on the west side had moisture contents higher than at the east side. It is noteworthy that sensor 13 (located at the centerline of the embankment) did not fully melt until mid-August, which was nearly 3 months after snow melting began. As discussed previously, the frozen soil impeded the natural water flow and caused excess water to become trapped on west side of the road. Moreover, because the melting process took such a long time, soils on the west side of the road embankment could hold more water during the summer time, allowing the unfrozen moisture contents to remain approximately 4% higher than the moisture contents at the reference sensor in winter months, and intensifying the frost heaving process. In contrast, the moisture contents on the east side were much lower than at the reference sensor location, except for during some intensive rainfall events.

Performance of Wicking Fabric at Different Climatic Conditions

The monitred hourly temperature and moisture data at the 22 sensor locations, as shown in Fig. 1, were used as controlling points to generate temperature and moisture contour maps with time. The meshgrid in Matlab® was firstly used to generate the interpolation locations among the sensors and then the Delaunay triangulation was used to generate the mesh upon which linear interpolations were used to compute the moisture and temperature values at the
desired locations. After that, contour maps for temperature and moisture were generated for a specific time. The contour maps were then displayed with time to generate videos to show the energy and moisture movements in the embankment in the past four years. The long-term performance of the wicking fabric could be visualized via different climatic conditions: during rainfall events and during freezing and thawing processes.

*During Rainfall Events*

Table 2 summarizes all of the major rainfall events for the four-year period monitored. Since the relative humidity in the air during the summer time was about 50% without rainfall, the water evaporation rate was faster than the water infiltration rate during light rainfall events. Moreover, the water could easily runoff via the longitudinal and transverse slopes if the rainfall events were not intensive. Therefore, it was reasonable to assume that light rainfall events were not able to raise the relative humidity above 95%. Table 2 only summarizes the duration of rainfall events in which the recorded relative air humidity was greater than 95%. The total amount of rainfall hours were thoroughly recorded for three years: 530 hours in 2011, 617 hours in 2012 and 376 hours in 2013, respectively.

In a summary, the effect of rainfall intensity was limited due to the good drainage condition of the base course (gravel with sand). Therefore, only the effect of rainfall duration is discussed in this section. Fig. 5 shows the comparison of two rainfall events to demonstrate this effect: one is a short duration event lasting several hours, and the other is a long duration rainfall lasting for several days. As shown in Fig. 5a, the first recorded rain fall occurred at 10 pm on August 28, 2013 and lasted for 5 hours. By looking up the recorded data, it was determined that no other significant rainfall events occurred within a week prior to this event. The 3 moisture
contour figures show the soil moisture distribution before the rainfall, 1 hour after the rainfall and 1 day after the rainfall. It was apparent that the soil moisture distribution did not change significantly as a result of this event. This phenomenon indicated that a 5-hour rainfall was not long enough to change the water moisture distribution within the pavement structure.

In comparison, another rainfall occurred at 11 pm on July 8, 2013 and continued on the following day. The total rainfall duration was about 27 hours from July 8 to July 9, ending around 2 pm on July 9. Fig. 5b shows the soil moisture distribution at the beginning of the rainfall event, 7 hours after the rainfall and about 1 day after the rainfall. The soils in the east side of the roadway were significantly drier than the soils in the west side of the roadway prior to the rainfall. 7 hours after the rainfall event, more water had accumulated in both the east and the west side of the road structure. The saturation zone in the west side was larger because water flowed into the pavement structure via a drainage ditch up-slope and adjacent to the west side of the embankment. Meanwhile, on east side of the road, the saturated zone was observed at the location of the wicking fabric layers. This phenomenon indicated that the wicking fabric was able to suck the water from the surrounding soils and laterally transport it to the shoulder. The third contour figure shows that 1 day after the rainfall event, the saturation zone was smaller than before in the west side of the roadway. The soils near the wicking fabric were comparatively drier than the rest of the soils on the east side of the embankment, where no apparent saturation zone was observed.

During Freezing Process

For purposes of this discussion, the moisture contours when the air temperature dropped below zero during the recorded four year period were summarized and compared, as shown in Fig. 6. It
was critical to determine the moisture content distribution before the freezing front moved downward, because the severity of the thaw weakening in the following spring was directly related to the amount of water stored in the pavement structure before the freezing process started in the previous year. In other words, the soft spots in the following spring, if frost boiling was observed, would be expected where the saturation zones were observed before the freezing process started in the previous year. It should be noted that the areas of the saturation zones decreased with time. For instance, there were two saturation zones that were connected together in 2010 and 2011 (Fig. 6a-6b); however, the saturation zones became separated into two smaller zones on October 11, 2012 (Fig. 6c). The less the amount of water stored in the pavement structure, the less severity of the frost heave would be expected during the freezing process (less negative pore water pressure would be generated due to the water phase changing from liquid state to solid state). Moreover, since the soil moisture contents were lower than the previous years, it took less energy to move the freezing front downward. In comparison, the freezing front had already penetrated to 0.9 meter (2.95 feet) on October 11, 2012, which was about 0.3 meter (0.98 foot) deeper than the previous year. Furthermore, the saturation zone continued to decrease at the bottom of the roadway in year 2013, as shown in Fig. 6d. This phenomenon could be apparent because: (1) precipitation variation may cause such variations in the soil moisture content distribution, and (2) the wicking fabric worked effectively to reduce the moisture content in the soil. Because the rainfall event summary presented in Table 2 indicated that there were no significant rainfall events that occurred right before the selected days, precipitation was not the reason that caused the decrease in soil moisture contents. Therefore, the wicking fabric did reduce the water content in the east side of the roadway embankment, and reduced the size of saturation zone in the west side of the road. However, the performance of the wicking fabric to
drain the water out needed to be further evaluated during the spring thawing process to validate its efficiency.

**During Thawing Process**

Fig. 7 shows the moisture contours on May 25 of each year. Firstly, the unfrozen water contents for sensor 22, which located nearest to the drainage ditch, remained below 0.1 within the monitored four years. This phenomenon indicated that the drainage ditch was still frozen at this time, and that there was no water supply from melting snow. Therefore, the water source that caused thaw weakening issue was major resulted from the melting of frozen soil within the pavement structure.

Secondly, it is important to point out that the mean monthly temperature for May, 2013 was lower than in previous years, so the thawing front only penetrated to 1.22 meters (4 feet) on the east side and 0.76 meter (2.5 feet) on the west side. For other years monitored, the distance between the thawing front and the 0 °C isothermal curve increased each year. This phenomenon can be explained by referring to the moisture contour during freezing process. Since the saturation zones in the pavement structure was decreasing during the monitored four years, the total amount of water stored in the pavement structure (including capillary water extracted from shallow groundwater) was also decreasing. The distance between thawing front and the 0 °C isothermal curve was expected increasing with time.

Thirdly, the highest moisture content areas were all located on the west side of the embankment, but no saturation zone was observed during the thawing process in the monitored four years. This phenomenon proved that the wicking fabric successfully eliminated the frost boiling issues. Moreover, the thawing front on east side of the embankment was deeper than that
on west side and reached to the elevations where the two layers of wicking fabrics were buried. This phenomenon indicated that the wicking fabric on east side of the pavement structure was partially functional and started to laterally drain the water out of the pavement structure in late May, 2014, as shown in Fig. 7d.

SEM ANALYSES

In addition to the macroscopic study discussed above, the interaction between the wicking fabric and the surrounding soils was investigated at a microscopic level. Therefore, field samples were collected at the edge of the embankment during a field trip in July 2015 and brought back for further laboratory testing. A JOEL JXA-8530F Electron Microprobe was used to analyze the wicking fabric microstructures. As mentioned previously, there were several concerns about the long-term performance of the wicking fabric, specifically the clogging effect, permanent deformation, mechanical failure and aging effect. In total, 30 samples were analyzed; the detailed process and illustration regarding SEM analyses follows.

Clogging Effect

Fig. 8a presents the woven structure of an intact sample at Beaver Slide with ×55 magnification. Large amounts of soil particles were detained on the surface of the wicking fabric. Because the soil contained approximately 6% of fines, the clogging effect was obvious at this level, and the deep grooved drainage paths were blocked by the fine materials. Fig. 8b shows a closer view of the wicking fabric at the surface with ×350 magnification. It further illustrated the fact that the deep grooved drainage paths were completely filled with fine soil particles. In comparison, Fig. 8c shows the wicking fabric fibers just beneath the surface layer. The deep
grooves beneath the surface were much cleaner than those above, and there were very few particles detained in the drainage paths. In other words, the fibers of the wicking fabric at surface served as a protective layer, preventing the fine soil particles from penetrating deeper into the fabric structure. Fig. 8d shows the comparison of the wicking fibers on the surface and the fibers just beneath the surface. It could be seen from the figures that even though the wicking fabric fibers on surface were filled with fine soil particles, the wicking fibers beneath the surface still were able to effectively drain water out of the pavement structure. It was worth noting that it was not fair to evaluate if the wicking fabric was clogged based upon the fibers on the surface since “surface” was a theoretic term and was difficult to define during the SEM analyses. If too many soils were left on the surface of the wicking fabric, there was no doubt that the wicking fabric would be covered by the soils. On the other hand, if we took all the surface soil away, the evaluation for the clogging effect was not objective. It seemed more reasonable to evaluate the clogging effect based upon the wicking fibers below the surface.

Permanent Deformation and Mechanical Failure

Fig. 9 presents the SEM images of samples that suffered permanent deformation and mechanical failure. Fig. 9a presents image of new wicking fabric, which was never used before. It was apparent that the wicking fabric fibers under the woven polypropylene yarns had already experienced some permanent deformation, and that the deformation was in the vertical direction. This deformation might have been caused by the pressure applied in manufacturing process, or it might have occurred during the transportation process. Fig. 9b shows the image of the wicking fabric that was collected from the field. The permanent deformation observed in the new materials had further increased. Due to additional vertical pressure, the wicking fabric fibers
were nearly flattened, and the deep grooves were not able to hold water under unsaturated conditions. Furthermore, Fig. 9c presents the front view of the wicking fabric. Deep grooves were seen not only in the vertical direction, but also tended to close in the horizontal direction.

Another mechanical failure known as “puncturation” is illustrated in Fig. 9d. “Puncturation” refers to the puncturing of the soil fibers by the large soil particles that are detained on the wicking fabric surface. The large soil particles, especially those with sharp edges, acted as a cutting edge that severed the deep grooves of the wicking fabric. This likely occurred due to the high overburden soil pressures and the dynamic traffic loads applied to the road surface. The drainage paths were broken and became unable to continue to laterally transport water; however, this phenomenon was only observed in 5 out of 30 samples. According to the observed macroscopic results at the Beaver Slide, it seemed that neither permanent deformation nor puncturation were major concerns, possibly for two reasons (1) there were relatively less percentage of the wicking fabric having permanent deformation or puncturation, and (2), surrounding fine soil particles might have “bridging effect” for water transport at locations where permanent deformation or puncturation occurred.

Aging

Because the wicking fabric is buried under the soil, another concern involves the wicking fabric’s physical and mechanical aging issue, as shown in Fig. 10. Fig. 10a shows the aging severity of the wicking fabric under the woven polypropylene yarns. Because the fibers on the surface were directly in contact with the soil particles, the aging phenomena were usually observed at this location. Fig. 10b shows the fibers at the surface without the woven polypropylene yarns. As believed, the aging phenomenon was likely due to direct contact with
the soil particles. The aging effect at the bottom of the deep grooves was more severe than in the other areas of the wicking fabric. In comparison, Fig. 10c-d show the wicking fabric beneath the surface. No obvious aging effect was observed below the surface layer, and the deep grooves were much cleaner than those of the fibers on surface.

Table 3 summarizes the SEM analyses results. In general, all wicking fabric fibers on the surface suffered from the clogging effect. Clogging and permanent deformation were observed in every scanned sample. Therefore, these two aspects become the major potential issues that needs to be taken into consideration in evaluating the wicking fabric long-term performance. However, only 6.67% of the wicking fabric fibers beneath the surface suffered from the clogging effect. This indicates that even though the surface was contaminated and the drainage paths were blocked, the wicking fibers beneath the surface were well protected and worked effectively as a drainage material to transport water laterally under unsaturated conditions. Additionally, the permanent deformation was observed in every sample under the polypropylene woven area. The permanent deformations resulted from one, or both of the following two processes: (1) high pressure during the manufacturing process, and (2) high vertical overburden soil pressure and dynamic traffic load during its service life. The permanent deformation would likely affect the wicking fabric’s long-term performance, since the drainage paths were either cutoff or narrowed down, and the deformation would continue to develop with time. The aging effect and mechanical failure were not considered to be major concerns that would influence the long-term performance of the wicking fabric.

DISCUSSIONS

Factors Influencing the Occurrence of Frost Boils/Soft Spots
As previously mentioned (Zhang et al. 2014), the frost boils often occurred during the end of April through May each year. Based on the comparisons of the pavement performance during the monitored four years, the water sources that were available to form the frost boils came from the thawing of *in situ* ice lenses that developed in the pavement structure due to frost heave in the previous winter. The moisture content of the pavement structure at the beginning of the freezing process was one of the major factors that determined the intensity of the frost heave and the subsequent thawing in the next year. The larger the fully saturated zones were in the pavement structure, the more suction or negative pore water pressure (due to water expansion during the freezing process) it would generate. Since the freezing process penetrated the pavement structure from the top to the bottom, the only water source must be from the shallow water table beneath the pavement structure. Higher suction values would further increase the moisture content in the pavement structure and cause a zone of over saturation. The melting water from the over-saturated zone would provide sufficient water during the following spring to create soft spots at the surface, because the water was forced to the road surface when the soil beneath was still frozen.

   Another factor influencing the severity of the frost boils was when the thawing front penetrated down to the bottom of the pavement structure. The thawing front penetrated to the bottom of the pavement structure in late July or early August, which was almost three months after the thawing season began. Because the frozen soil in the west side of the roadway held a large amount of frozen water, it took a larger amount of solar energy to melt the frozen soil. The only drainage path for the melting snow and runoff water was to flow through the pavement structure. This would further reduce the soil stiffness and intensify the frost boil issue. Furthermore, the center of the pavement structure formed a hard, frozen core during the melting
season. The frozen core altered the water flow direction and trapped a large amount of water in the west side of the pavement structure, which intensified the frost heave action during winter time.

It was also worth noting that a large amount of rainfall would cause another issue called pressurized water overflow, which might also have generated soft spots on the road surface in summer time. Rainfall duration served as a more deteriorating factor to the pavement performance than rainfall intensity. The soft areas would heal up if there were periods of no rain. The moisture contents in the pavement structure beneath 0.47 meter (1.5 feet) experienced short periods of time of overly saturated. By carefully examining the rainfall events summary in Table 2, it was seen that there were several days of rainfall before the sudden increases in moisture content. Since the road prism was built on a side hill, the water naturally flows from west to east. Also, the 11° downhill slope made the hydraulic gradient the highest at the test section. These factors were evidence that the sudden increases in moisture content were due to pressurized water overflow to the road surface. Although the two issues presented the same superficial phenomena, the mechanisms causing the phenomena were different.

Wicking Fabric Long-Term Performance

Data collected during four years of monitoring indicates that the wicking fabric has worked effectively to prevent the frost heave and thaw weakening issues previously observed at Beaver Slide. During the rainfall events, the water could be drained out 1-2 days after the rainfall stopped. Moreover, the moisture contents were gradually decreasing within the pavement structure before the freezing process (Fig. 6). This indicated that the water supply for frost heave was decreasing, and that the moisture contents during the next thawing process were also
decreasing. As shown in Fig. 7, there were no saturation zones present in the pavement structure during the thawing process. Additionally, the wicking fabric successfully drained water laterally out of the pavement structure within several hours, even after heavy rainfall events, as shown in Fig. 5b. The moisture contents near the wicking fabric were much higher than moisture contents in other areas, demonstrating that the wicking fabric worked effectively to transport the water out of the embankment. The moisture contents on east (dry) side of the pavement structure reached equilibrium generally within 1 day of significant rainfall events.

In addition to macroscopic field observations of the improved road performance, the microscopic SEM analyses showed the interaction between the wicking fabric and the soil. One of the major concerns was whether the fines in the soil would be retained in the deep grooves and potentially restricted the drainage path. Fig. 8 clearly shows that even though the wicking fabric fibers at surface were covered by fine-grained soils, the fibers beneath them were relatively clean and no-clogging effect existed. The permanent deformation due to high vertical pressure might narrow down or even cut off the deep grooves, blocking their ability to laterally transport water in unsaturated conditions. This deformation might be induced by the high pressure during manufacturing process or traffic load. More research is needed in this direction. Aging and mechanical failure was observed in the SEM analyses. However, the occurrence percentage was relatively low and was not a major concern for the long-term performance of the wicking fabric.

**CONCLUSION**

The Beaver Slide project has been monitored for more than five years, and the results indicate that the wicking fabric has successfully eliminated the “frost boils” at the site. The following conclusions were summarized based on the previous analyses:
1. The soft spots observed during the early spring were caused by the ice formation and thaw weakening of the soils; however, the soft spots observed after heavy rainfall resulted from pressurized water flow. Although the phenomena were similar, the mechanisms were entirely different.

2. The severity of the thaw weakening in spring was relative to the moisture content present in the pavement structure before freezing began at the start of the previous winter. The monitoring data shows that the moisture contents were decreasing, and that the saturated zones were smaller each year after the fabric was installed. Moreover, the moisture contents in the pavement structure were not observed to exceed the saturation moisture contents. This indicates that the wicking fabric worked successfully to eliminate the ice formation and subsequent thaw weakening issue during the past five years. The wicking fabric exhibited promising long-term performance results. However, additional monitoring and data analysis should be performed to establish long-term performance.

3. Clogging was only observed in the surface fibers of the wicking fabric. The wicking fabric fibers beneath the surface layer were relatively clean. The clogging effect was not considered to be a major issue for the application of the wicking fabric.

4. The permanent deformation might be an issue that would affect the long-term performance of the wicking fabric. The deformed deep grooves would reduce the amount of water that the wicking fabric could laterally transport. The permanent deformation might develop further over with time due. The wicking fabric implementation depth and its influence on long-term performance should be studied further.

5. Mechanical failure and aging of surface fibers were observed in only a limited number of samples. Mechanical failure might be caused by compaction during the construction process and high vertical pressure during its service life. Aging was observed in the
surface fibers of the wicking fabric, where fibers were directly in contact with the surrounding soils.

In conclusion, visual observations made by AKDOT&PF Maintenance and Operation personnel and the authors through field trips as well as the measurements of moisture and temperature indicated that after five years, the wicking fabric is still working effectively to remove the water from the embankment, which has eliminated the frost boil problem in the test section.

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REFERENCES


Table 1. Geotextile specification

Table 2. Rainfall events summary

Table 3. SEM analyses summary
Table 1. Geotextile specification

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<th>Mechanical Properties</th>
<th>Test Method</th>
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### Table 2. Rainfall events summary

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**Total Rainfall Hours**

- **2010**: 423 hours
- **2011**: 530 hours
- **2012**: 417 hours
- **2013**: 378 hours
- **2014**: 350 hours
Table 3. SEM analyses summary

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2a Hourly air temperature data

2b Hourly relative humidity data

Fig. 2. Hourly climatic data at beaver slide test section
3a Soil temperature versus depth
3b 0.45 meter below road surface
3c 0.76 meter below road surface
3d 1.06 meters below road surface
3e 1.97 meters below road surface
Figure 4a

4a 0.45 meter below road surface
Figure 4b

Temperature (°C)

Volumetric Moisture Content

Date

08/18/10  11/18/10  02/18/11  05/21/11  08/21/11  11/21/11  02/21/12  05/23/12  08/23/12  11/23/12  02/23/13  05/26/13  08/26/13  11/26/13  02/26/14  05/29/14  08/29/14

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4c 1.06 meters below road surface
4d 1.97 meters below road surface
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**Fig. 10.** SEM images of aging effect
ASCE Authorship, Originality, and Copyright Transfer Agreement

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Ms. Ref. No.: CFENG-1512

Title: Long-Term Performance of Wicking Fabric in Alaskan Pavements

Responses to Reviewer #1’s comments:

Reviewer #1: 1) Quality of Figures: Some figures have low resolutions. Will they use the b&w or colourful figures (Figs. 2, 3 and 4) in their final version? If b&w figures are used, I don't think that those curves are identifiable.

Response: The authors appreciate the reviewer’s comment on the figures’ quality. Since the figure contains over 4 years’ data, if the original format of the figure is adopted, the file will be too big to submit. Regarding the reviewer's concern about the identification of each line in the figure, the authors have made further modification. For Figure 2, there is only one line is each figure, no modification is required except for adding the legend. For Figure 3, since the air temperature is the reference line, it has been changed to small dots so that it is much easier to make comparisons of temperature variations in both the soil and the open air. For other temperature lines, different dash types are adopted to distinguish from each other. The line sizes have been reduced to 1.5 pt for the purpose of a better demonstration.

Reviewer #1: 2) Contour plots shown in Figs. 5, 6 and 7 were created by limited datasets. Please state how many data points they used and which interpolation functions are assumed when creating these contouring diagrams.

Response: Based on the reviewer’s suggestion, the following statements are added to further demonstrate the process to establish the temperature and moisture contours in Figure 5, 6, and 7 in the section “Performance of Wicking Fabric at Different Climatic Conditions”:

The monitored hourly temperature and moisture data at the 22 sensor locations as shown in Figure 1 were used as controlling points to generate temperature and moisture contour maps with time. The meshgrid in Matlab® was firstly used to generate the interpolation locations among the sensors and then the Delaunay triangulation was used to generate the mesh upon which linear interpolations were used to compute the moisture and temperature values at the desired locations. After that contour maps for temperature and moisture were generated for a specific time. The contour maps were then displayed with time to generate videos to show the energy and moisture movements in the embankment in the past four years. The long-term performance of the wicking fabric could be visualized via different climatic conditions: during rainfall events and during freezing and thawing processes.
Reviewer #1: 3) Please add the location information of those SEM plots (Figs. 8-10), such as 'surface' or 'beneath surface' to improve the readability of the paper.

Response:

According to the reviewer’s comment, the subtitles of Figure 8 are modified as (a) Intact Sample (Surface), (b) Fabrics on Surface, and (c) Fabrics beneath Surface. Text boxes and arrows are used in Figure 8(d) to point at fabrics on and beneath the surface for comparison. For Figure 9, “Surface” are added to each subtitle of the figure to indicate the samples locations. The subtitle for Figure 9(d) changes to “Punctuation Failure (Surface)” to indicate the type of the mechanical failure. For Figure 10, sample locations are included in the subtitles to demonstrate their resources.

Summary:

The author wholeheartedly thanks the reviewer for his time, patience, and efforts to review the papers. The author considers the reviewer’s comments are very helpful to revise the paper. The paper has been significantly modified according to the reviewer’s comments to address the reviewer’s concern (The figures have been improved, the typos have been corrected, and additional sections have been added). We are now resubmitting the paper for the reviewer’s further review, and look forward to reviewer’s further suggestions and comments. Once again, the reviewer’s help and patience are highly appreciated.
Ms. Ref. No.: CFENG-1512

Title: Long-Term Performance of Wicking Fabric in Alaskan Pavements


Responses to Reviewer #2’s comments:

Reviewer #2: 1) The authors are suggested to provide basic properties of the used wicked geosynthetics such as strength, tensile stiffness, or pore size.

Response: The specification is added to demonstrate its basic physical, mechanical and hydraulic properties, as shown in Table 1. The corresponding modification is made in the section “Introduction” as follows: “An effective way is needed to mitigate the frost heave and subsequent thaw weakening issue. A new type of woven wicking fabric was recently developed and had the potential to solve this issue. The basic physical, mechanical and hydraulic properties of the wicking fabric are presented in Table 1.”

The specification resource is included in the reference:

Table 1. Geotextile Specification (TenCate 2015)

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Test Method</th>
<th>Unit</th>
<th>Average Roll Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Modulus @ 2% Strain (CD)</td>
<td>ASTM D4595</td>
<td>kN/m</td>
<td>657</td>
</tr>
<tr>
<td>Permittivity</td>
<td>ASTM D4491</td>
<td>Sec⁻¹</td>
<td>0.24</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>ASTM D4491</td>
<td>l/min/m²</td>
<td>611</td>
</tr>
<tr>
<td>Pore Size (O50)</td>
<td>ASTM D6767</td>
<td>microns</td>
<td>85</td>
</tr>
<tr>
<td>Pore Size (O95)</td>
<td>ASTM D6767</td>
<td>microns</td>
<td>195</td>
</tr>
<tr>
<td>Apparent Opening Size (AOS)</td>
<td>ASTM D4751</td>
<td>mm</td>
<td>0.43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tested Value</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Front Movement (24 minutes)</td>
<td>ASTM C1559</td>
<td>inches</td>
<td>6.0</td>
</tr>
<tr>
<td>Vertical Direction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet Front Movement (983 minutes)</td>
<td>ASTM C1559</td>
<td>inches</td>
<td>73.3</td>
</tr>
<tr>
<td>Zero Gradient</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal Direction</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Reviewer #2: 2) What is the permafrost depth of the test site? Was the wicked layer placed above or below the permafrost layer?

Response: Based upon the measured data, depth of the permafrost layer at the test section is greater than 2.5 m. The two layers of wicking fabric were installed at approximately 0.7 and 1.0 m below the road surface, which are in the active layer to take advantage of their wicking ability during the summer.

Zhang and Presler (2012) described the construction process in detail and indicated that the excavation pit was filled with water, as shown in Figure 1 below. The groundwater was encountered about 2 m below the road surface. Observed temperature at 7 ft below the road surface indicated that all soils thawed at that depth. All these indicated that the permafrost should at least 2 m below the road surface.

![Figure 1 Installation of Sensor 20](image)

Reviewer #2: 3) The site had a relatively low humidity (50%), which may be the key that the wicked geosynthetic functioned well. How about the applications at the location with high humidity?

Response: This is a very good question. As mentioned by the reviewer, the relative humidity (relevant to suction) is a critical factor that determines the soil-geotextile functional range. However, it should not be a concern. Figure 2 below show the relationship between the relative humidity and the suction. As can be seen in Figure 2, when the relative humidity is 99%, the suction is already greater than 2000 kPa. Under this suction, most soils can be air-dried. This is also the reason why wet clothes can be air dried in even very humid condition, although it takes longer time. As a result, the wicking fabric can also be used in humid areas.
Reviewer #2: 4) Figure 3 contains numerous figures regarding soil temperatures at different locations. The authors can consider combining some of the figures and adding some description to avoid excessive figures. This comment also applies to Figure 4.

Response:

The authors appreciate the reviewer’s comment on Figure 3 and 4. However, the authors have tried other arrangements of the figures, but this type of organizing is the most effective way. Since Figure 3 and 4 compare the temperature and moisture variations at different depths. The authors have tried to combine the temperature data together, but it was hard to differentiate the temperature variation trend with depth. Moreover, the location of the two geotextile layers should be our major concern and therefore should be separated from other layers. This organization of the figures gives a better demonstration of the efficiency of the soil-geotextile system.

The authors have modified the temperature and moisture data lines with different types of dash types to facilitate the readability of the figures. Since the air temperature data in Figure 3 and...
moisture data for sensor 22 in Figure 5 are just for reference, the line type and color have been modified to have a better comparison results.

Summary:

The author wholeheartedly thanks the reviewer for his time, patience, and efforts to review the papers. The author considers the reviewer’s comments are very helpful to revise the paper. The paper has been significantly modified according to the reviewer’s comments to address the reviewer’s concern (The figures have been improved, the typos have been corrected, and additional sections have been added). We are now resubmitting the paper for the reviewer’s further review, and look forward to reviewer’s further suggestions and comments. Once again, the reviewer’s help and patience are highly appreciated.

Reference


Responses to Reviewer #3’s comments:

Reviewer #2: 1) I found that the paper and conclusions are flawed, because there were no frost susceptible soils in the test section; the cross section consisted of sand and gravel and 6% fines. Not known is the silt content in the fines. The silt content is the frost susceptible component. The paper requires a major re-write and revision.

Response: The author wholeheartedly thanks the reviewer for his time, patience, and efforts to review the papers. The authors take the reviewer’s comments seriously and look up a series of published papers regarding the frost heave and thaw weakening issues. A companion project report (Zhang and Presler 2014) has systematically described the construction process and the test section soil profile. Here the authors would like to re-emphasize the authors reasoning strategy. As discussed in the literature review, there are three basic conditions required for frost action to occur: 1) a frost-susceptible soil, 2) soil temperatures sufficiently low to cause some of the soil water to freeze, and 3) a supply of water.

The authors agree with the reviewer’s comment that the fine content (especially silt content) is a critical factor that determines the frost susceptibility of a typical type of soil. The authors disagree with the reviewer’s conclusion that “there were no frost susceptible soils in the test section; the cross section consisted of sand and gravel and 6% fines” and “the paper and conclusions are flawed.”

Casagrande (1931) discussed the role of particle size in frost-heaving and stated that nonuniform soils containing more than 3% of fines can be considered as frost susceptible soils. Ruckli (1955) further indicated that the frost susceptibility of a soil should also consider the hydrological and geotechnical condition of the site in question. Johnson et al. (1986) selected the U.S. Army Corps of Engineers frost design indicated that gravels with < 1.5% fines and sands with < 3% fines are considered as NFS (Non Frost Susceptible) soils. The range of possible degrees of frost susceptibility is very wide for most soils. According to this classification, the in-situ samples shall be classified as S1 and S2 frost susceptible soils (S1: low to medium and S2: very low to high frost susceptibility). For our soil with about 6% of fines (only limited soil specimens were used for particle size analyses), combining the harsh environment in the winter and the relatively shallow groundwater table, it is expected that the soil is frost susceptible.

In addition, the measurements of the moisture and temperature at the test section indicate that the water which caused “frost boils” during the early spring was from excessive water in the in-situ soils instead of ground water.
As observed by AKDOT&PF personnel, the “frost boil” first appears at the end of April and early May each year. From the measurements of the moisture and temperature at the test section, it was found that the thawing depths in the past four years are less than 2 ft (0.6 m). As shown in the following figure, there is a ditch at the west side of the road embankment. If there is ground water, it has to come from the west side to the east side due to its geometry. The bottom of the ditch is 3.6 ft below the road surface.

The following two figures show the temperature and moisture contours of the test section on April 26, 2011, and May 15, 2011, respectively. As can be seen from both figures, the thawing depths in both figures were less than 2 ft from the surface. However, frost boils had occurred during the same periods at other locations without the wicking fabric. Since the soil beneath were frozen and therefore impervious and the depth of the ditch is 3.6 ft below the road surface. The only source of excessive water for the frost boils to happen is from thawing of water in the in-situ soils. This leads to the conclusion that there must be frost heave in the previous fall season.
Figure 4.35 Temperature and Moisture Content Contours at Noon of April 26, 2011

Figure 4.36 Temperature and Moisture Content Contours at Noon of May 15, 2011
Summary:

The author wholeheartedly thanks the reviewer for his time, patience, and efforts to review the papers. The author considers the reviewer’s comments are very helpful to revise the paper. The authors have systematically explained the classification of frost susceptible soil according to the reviewer’s comments to address the reviewer’s concern that sand and gravel only with 6% of fines are not frost susceptible soils. The author also demonstrated the major water source that will result in thaw weakening issue according to the observed data and the corresponding moisture content contour. We are now resubmitting the paper for the reviewer’s further review, and look forward to reviewer’s further suggestions and comments. Once again, the reviewer’s help and patience are highly appreciated.

Reference


