Use of Wicking Fabric to Help Prevent Frost Boils in Alaskan Pavements

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Abstract:

Beaver Slide is near 177.8 km (110.5 mile) on the Dalton Highway and it is downhill when heading north. The road gradient is approximately 11% and the road prism is on a side hill. Each year, there are soft spots that usually appear in late April and remain all summer, which are also called “frost boils” by engineers at the Alaska Department of Transportation and Public Facilities (AKDOT&PF). The frost boils have resulted in extremely unsafe driving conditions and frequent accident occurrences. Past repair efforts indicate conventional road construction methods do not work. A new type of geosynthetic wicking Fabric has been recently developed which has a high specific surface area (consequently high wettability and high capillary action) and high directional permittivity. Preliminary laboratory tests indicate it has great promise as a cost-effective means to solve the frost heave-related problems on northern road systems. This study verifies the effectiveness of the wicking fabric to mitigate frost boils in Alaskan pavements. A test section was built at the Beaver Slide area of the Dalton Highway with installation of two layers of wicking fabric. The test section was instrumented with moisture and temperature sensors to measure the temperature and moisture variations for two years. Results were analyzed to evaluate the effectiveness of the wicking fabric to mitigate the frost boils in Alaskan pavements.

CE Database subject headings: frost heave, thaw weakening, geosynthetic, wicking fabric

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INTRODUCTION

Beaver Slide is near mile 177.8 km (110.5 mile) on the Dalton Highway and it is about 8.0 km (5.0 mile) south of the Arctic Circle. The road is downhill when heading north and its gradient is approximately 11%. The road prism is on a side hill. Each spring, there is shallow groundwater running down slope, which then comes up into the road embankment to cause soft spots and subsequent road damage. These soft spots are also called “frost boils” by engineers from AKDOT&PF since their first occurrences are often at the early spring. Figure 1 shows the frost boils that occurred on May 12, 2010. The soft spots remain all summer and go away after freeze up. The soft areas will heal up if there are periods with no rain, but as soon as there is a significant amount of rain they will reappear. When truck drivers saw the soft spots, they tended to brake, which added load to the road and made the conditions even worse. While their exact mechanism was not clear, the frost boils have resulted in extremely unsafe driving conditions and frequent accident occurrences. AKDOT&PF installed French drains at a skew to drain water out of the road section. Results indicated this conventional repair method did not work well. Another repair method was to remove the existing road section and replace with better material. However, it made the repair cost extremely high due to the long transportation distance to remote areas. In addition, these methods only fixed local frost boils and moved the problem down slope.

A new type of nylon wicking fabric is recently developed, which has high specific surface area (consequently high wettability and high capillary action) and high permittivity. Preliminary laboratory tests indicated it had great promise as a cost-effective means to solve the frost boil problem (Zhang and Belmont 2009). The purpose of this research was to verify the effectiveness of the wicking fabric to mitigate the frost boils in Alaskan pavements. A test section was built at Beaver slide of the Dalton Highway with installation of two layers of wicking fabric. The test section was instrumented with moisture and temperature sensors to measure the temperature and moisture changes for two years. Results were analyzed to evaluate the effectiveness of the wicking fabric to mitigate the frost boils in Alaskan pavements.

LITERATURE REVIEW AND PROJECT BACKGROUND

The frost boil problem was believed to be related to frost heave and subsequent thaw-weakening. As a
result, this literature review focused on a previous study on the use of geosynthetics to reduce the frost heave and thaw-weakening. Frost heave and subsequent thaw weakening cause extensive damages to pavement structures in Alaska and other northern regions. The three elements necessary for ice lenses and thus frost heave are (Holtz and Kovacs 1981): (1.) frost susceptible soil, (2.) subfreezing temperatures, and (3.) water (must be available from the shallow groundwater table, infiltration, an aquifer, or held within the voids of fine-grained soil). Unfortunately, all three conditions are met in many places of northern regions. Removal of any of the three conditions above eliminates or at least minimizes frost heave and thaw weakening. Numerous techniques have been developed to mitigate the damage to pavements and airfields caused by frost heave and thaw weakening. The best-known and most widely employed technique is to remove frost susceptible soils and replace them with non-frost susceptible soils at an adequate thickness to reduce the strain in the frost susceptible soil layers to an acceptable level (Removal of condition 1). AKDOT&PF stipulates that granular materials with fines content less than 6% be used as base course material (AKDOT&PF, 2004). Other methods include use of insulation to reduce the freeze and thaw depth (Esch 1994) (Removal of condition 2). In many remote areas where removal of frost susceptible soils and reduction of subfreezing temperature are difficult and expensive, removal of water could lead to savings in construction costs.

By breaking the capillary flow path, frost action will be less severe (Removal of condition 3). A capillary barrier is a layer of coarse-grained soils or geosynthetic in a frost susceptible soil that (i) reduces upward capillary flow of soil water due to suction gradient generated by evaporation or freezing, and (or) (ii) reduces or prevents water from infiltrating from the overlying fine-pored unsaturated soil into the soil below the capillary barrier (Henry and Holtz 2001). In the latter case, if the capillary barrier is sloped, the infiltrating water flows in the fine soil downwards along the interface with the capillary barrier. Granular capillary barriers have been used successfully to reduce frost heave of roads. Taber (1929) found that placing a layer of coarse sand above the water supply in frost-susceptible soil specimens being frozen from the top down eliminated frost heave. He also noted that frost heaving requires substantially more water than is naturally available in the soil pores. Casagrande (1938) and Beskow (1946) described placing a layer of sand or gravel above the water table in road construction to reduce frost heave of overlying fine-grained
soil. Later, Rengmark (1963) and Taivenen (1963) documented using a sand layer above the water table to help prevent frost heave in overlying frost susceptible soil.

In recent years, geotextiles and geocomposites were evaluated as capillary barriers to reduce frost damage in pavement structures. Geosynthetic drainage nets have been found to serve as good capillary barriers under most conditions because of their large pore sizes. The performance of nonwoven geotextiles as a capillary barrier appears to be compromised by soil intrusion into their interiors, decreasing the pore size and increasing the affinity of the material to water. Hoover et al. (1981) and Allen et al. (1983) independently performed experiments indicating that certain geotextiles reduced frost heave when they were placed horizontally in upright, cylindrical soil specimens that were frozen from the top down with water freely available at the base. Henry (1988) noted the importance of the surface properties of the geotextiles, i.e., that hydrophobic geotextiles were much more effective in reducing frost heave than hydrophilic geotextiles. Henry (1996) concluded that properly selected geotextiles reduce frost heave in soils by functioning as capillary barriers and summarized guidelines for granular capillary barriers. It was also concluded that, besides serving as capillary barriers during freezing and to reinforce or separate and filter subgrade layers, or both, during thaw, geotextiles probably can be used for a combination of functions to reduce frost-related damage.

Guthrie and Hermansson (2006) reported test results which indicated that unsaturated granular base material became saturated due to water vapor flow during freezing. Henry et al. (2002) proposed geocomposite capillary barrier drain (GCBD) as a promising method to reduce frost damage in pavement structures under unsaturated environment. A GCBD consists of a capillary barrier layer sandwiched between transport layers. The function of the capillary barrier layer is to impede unsaturated flow, either upward or downward. The GCBD is similar to drains commonly used to minimize the impacts of frost. However, conventional drainage systems are not wholly effective in reducing water related problems in partially saturated soils (Beskow 1991) while soil above the ground water table is unsaturated and frost heave occurs through capillary rise of water. The GCBD is used to design a capillary break and drainage system which can suck water out of soil—that is, provide drainage while the soil is unsaturated. The key to the success of such a system is a material which has high wettability (which means it can absorb water from
unsaturated soils) and high permittivity (i.e. it can transport the absorbed water out of the pavement structure quickly). The transport layer used in Henry et al. (2002) was a very heavy, woven, multifilament material with a mass per unit area of 2370 g/m², a thickness of 3.2 mm, and an O₉₅ size of 0.075 mm. The infiltration test results indicated that the use of the GCBD to limit moisture changes in pavement subgrades and bases was very promising. Furthermore, the GCBD prevented the moistening of the subgrade at many of the infiltration rates tested. Whether the capillary barrier will reduce or prevent frost heave by preventing upward flow during freezing was not tested.

A new type of wicking fabric is made of special hydrophilic and hygroscopic 4DGTM Fibers with multichannel cross-sections as shown in Figure 2a. The multichannel cross-section has one of the highest available shape factors and has the greatest number of channels per fiber, which give wicking fabric great potential for maximizing capillary action and water transport in an unsaturated environment. Figure 2b shows the top view of the wicking fabric 2 layer weave. The specific surface area of wicking fabric is 3650 cm²/g and it has a permittivity of 0.24s⁻¹ (equivalent to a flow rate of 611 l/min/m²). Figure 2c shows a laboratory test on the wicking fabric to absorb and transport water along the horizontal direction at a zero hydraulic gradient. In 983 minutes, the wetting front of the water moves 1.86 m (73.3 inch) horizontally at a zero hydraulic gradient. Table 1 shows the technical data sheet for the wicking fabric. Zhang and Belmont (2009) performed a series of laboratory tests to investigate the performance of wicking fabric to mitigate the frost heave and thaw-weakening problem in Alaska’s harsh climate. The test results generally showed that wicking fabric can potentially be used as a capillary barrier to mitigate frost heave. Although the results on the frost heave were inconclusive, there were some definitive results indicating that the wicking fabric transports water under unsaturated conditions. However, there was no direct evidence to prove that the wicking fabric will work in the field to improve performance of the pavement. In addition, there were some concerns if the wicking fabric would work in the harsh climate of Alaska since water can be easily frozen in the winter and potentially make the wicking fabric lose its ability to transport water. After several discussions among the engineers at AKDOT&PF, researchers at the University of Alaska Fairbanks, and representatives from manufacturer, it was decided that it was worthwhile having a field implementation of the wicking fabric at the Beaver Slide to verify its effectiveness to mitigate the frost heave/thaw weakening
problem in Alaska.

CONSTRUCTION OF THE TEST SECTION AND INSTRUMENTATION

A test section of 18.1m (60 ft) was constructed at a section of road with the most soft spots during 2010 spring break at the Beaver Slide from August 3-5, 2012. The construction was performed according to the procedure as follows. First, the east lane of the road was excavated to a depth of 1.06 m (3.5 ft) below the original road surface while the west lane of the road was not excavated to maintain the traffic. Before installing the first layer of wicking fabric, three excavation pits were made below the centerline, the edge of the original road, and the edge of the excavation line as shown in Figure 3. These pits were about 1.97 m (6.5 ft) below the original road surface (about 0.91m below the excavation level). At the bottom of these excavation pits, three pairs of sensors were installed as numbered 13, 6, and 2 respectively in Figure 3. Each pair of sensors consists of a Campbell Scientific 107-L temperature sensor and a CS616-L water content reflectometer. The excavation pits were then backfilled with soils originally taken out and compacted according to AKDOT&PF general construction procedures. Sensor pairs 1, 5, 9, and 12 were then carefully installed and the first layer of wicking fabric was installed. Since water transportation in the wicking fabric is directional, care was taken to make sure the direction of the wicking fabric was along the transverse direction of the road section, so that water in the road structure was transported horizontally to the road shoulder. The excavated soils were brought back to backfill the excavation area with a thickness of approximately one ft. The backfill was then graded and compacted on top of the wicking fabric. After the soils were compacted, sensors 4 and 8 were installed. Then a second layer of wicking fabric was installed as shown in Figure 3. The two layers of wicking fabric exposed to the air were about 1.21m (4 ft) at the shoulder. After the second layer of wicking fabric was placed properly, the excavated soils were brought back to backfill the excavation area with a thickness of approximately one ft. The backfill was then graded and compacted and then sensors 3 and 7 were installed. After that, the rest of the soil was brought back to backfill the excavation in the east lane to its original elevation. The next step of construction started from digging out the west lane of the road to a depth of approximately 1.06m (3.5 ft). To avoid possible introduction of water from the ditch to the road section, the west road shoulder was not excavated. After the
bottom of the excavation was graded, a pit was then excavated at about 5.44m (18 ft) from the center of the road to install sensor 20. The excavation pit was backfilled and sensors 16, 19 and 22 were also installed and a layer of the wicking fabric was placed. The same procedures as those in the previous day were followed. The excavated soils were brought back to backfill the excavation area with a thickness of approximately 0.30 m (one ft). The backfill was then graded and compacted. After the soils were compacted, sensors 11, 15, and 18 were installed. Then a second layer of wicking fabric was installed and the excavated soils were brought back to backfill the excavation area with a thickness of approximately another one ft. The backfill was then graded and compacted and then sensors 10, 14, and 17 were installed. After that, the rest of the soil was brought back to backfill the excavation to its original elevation. All the wires for the sensors were protected using aluminum conduit to prevent damage from the traffic loads. The aluminum conduits were grouped together, buried in a small ditch in the transverse direction, and connected to a Campbell Scientific CR1000 datalogger. Besides the temperature and moisture sensors inside the test section, an HMP45C Air Temp/Relative Humidity was also installed to monitor the air temperature and relative humidity at the test site. The panel temperature of the datalogger was monitored by the CR1000 as well. All the data acquisition devices were organized into ENC14/16 -NC-NM weather-resistant enclosure installed on the tundra on the west side of the road. The locations of the sensors were surveyed using a Leica NA720 and TBMW1 and TBMW2 in Figure 3 were benchmark locations. Figure 3 shows the soil stratigraphy for the test section based upon the observations made during the construction process. It was found that the road section was directly built on the original tundra on the hill using the degraded granite which can be classified as silt with gravel according to USCS classifications. Sieve analysis of the soils indicated that some soils have fines contents greater than 6%, indicating that some soils are frost susceptible. The original tundra was about 0.91m (3.0 ft) at the west edge of the road, 1.36 m (4.5 ft) below the centerline of the road section. It was about 2.72m (9 ft) lower than the road surface when it extended to tree line at the west shoulder of the road. The buried vegetation was degraded into a dark yellow layer which was about 0.05-0.1m (1-2 inch) thick. Below the degraded vegetation were the in situ crushed rocks with sand. Ground water was found 0.15m (6 inch) below the tundra surface once the tundra was removed. Additionally, water was found during the construction process in the existing drainage ditch.
along the west side of the road. On the east side of the road, water was found along the tree line sporadically. Ground water was also found when installing sensor 20. Figure 3 shows the approximate ground water table based upon the above observations.

**RESULTS AND ANALYSIS**

**General Climatic Conditions**

Figure 4 shows hourly relative humidity data at the test section in the past two years. In the winter months, the relative humidity generally varied from 70\% to 90\%, while in the summer months, the relative humidity has a larger variation from 20\% to 90\%. There were some days during which the relative humidity was higher than 95\% for short periods. These periods were considered to be rainfall events since there was no rain gauge installed at the test section. This assumption was verified by the visit on June 21, 2011 when there was a rainfall during the site visit, and the recorded relative humidity during the visit was between 95\% and 98\%. Figure 5a shows hourly air temperature data at the test section in the past two years. The annual average temperature is about -9.0°C. The air temperature drops to below zero the third week of September and rises above zero in mid or late April each year. The lowest temperature was found in February of 2012, which was -39.21°C. Most winter temperatures are approximately -20°C. The highest temperature was 24.95°C which occurred in late May 2011. Normally hourly temperatures varied a lot in one day and can be as much as 30°C. The air temperature dropped to below zero on September 23, 2010 and rose above zero on April 26, 2011. In 2011, the air temperature dropped to below zero on September 24, 2010 and rose above zero on April 16, 2012.

**Soil Temperature Changes**

Figures 5a through 5d show the soil temperature changes for sensors at 0.45, 0.76, 1.06 and 1.97 m (1.5, 2.5, 3.5, and 6.5 ft) below the road surface in the past two years, respectively. The air temperature was also plotted in these figures for comparison purposes. Generally, the temperature changes in the soils followed the temperature changing pattern in the air. But the soil temperature changes are much less dramatic than air temperature, mainly due to the insulating effect of the soil. The soil temperature changes
followed more closely with those in the air in the summer months from late April to early September than in the winter months from September to April.

As shown in Figure 5a, in the summer months when the soils were unfrozen, the soil temperatures were close to the average daily temperature while in the winter the soils were warmer than the air temperature, which was attributed to the insulation effect of the snow cover. Because snow has low density and high voids which trap a lot of air, it is a very good insulation material which keeps the shoulders relatively warm. In the winter, the soils (for example at sensors 7 and 10) at the center of the road were colder than the soil at the edges (for example at sensors 3 at the east lane and 10 at the west lane). The difference can be as much as 10 °C. This is mainly related to the AKDOT&PF Maintenance and Operation (M&O) snow removal process: during the winter, snow is pulled from the road surface and piled at the two shoulders. The center of the road, on the other hand, is exposed to cold air directly. Except for the two road lanes, the adjacent ground surface is covered by snow, which makes the overall soil temperature in the winter higher than the ambient air temperature.

Figure 5b shows the temperature changes for sensors at about 0.76 m (2.5 ft) below the road surface. It is worth noting that sensor 1 is at the shoulder just below the ground soil surface. The temperature changes at the sensor locations of 4, 8, 11, 15, and 18 followed a pattern similar to the air temperature changes. However, the soil temperatures were warmer in the winter and colder in the summer due to soil insulation. Again, the soil temperatures in the center were colder than those at the edge of the road section. Soil temperatures at the location of the sensor 1 followed the air temperature changes during summer months. The differences between the air temperature and temperature at the sensor 1 were due to the evaporation of water at the soil surface, which absorbed a lot of heat energy. In the winter months the soil temperatures at sensor 1 maintained relatively constantly at -7°C due to the thick snow coverage.

Figure 5c shows the temperature changes for sensors at about 1.06 m (3.5 ft) below the road surface at sensor locations of 5, 9, 12, 16, 19, 21, and 22. Sensor 2 is at the road shoulder with soil cover of approximately 0.91 m (3.0 ft). The temperature changing pattern was similar to those shown in Figure 5b and similar to air temperature changes. Due to the thicker soil coverage, the soil temperatures are much warmer than the air temperatures in the winter and the temperature differences among different sensor
locations were also more significant. In the winter months, the soil temperatures at different sensor locations varied from high to low by the following order: 2, 22, 21, 5, 19, 16, 12, and 9. That is, the soil temperatures in the center were colder than those at the edge of the road section. Soil at the sensor 2 location was the warmest.

Figure 5d shows the temperature changes for sensors 6, 13, and 20 at about 1.97 m (6.5 ft) below the road surface. The temperatures changed in a sinusoidal pattern similar to the air temperatures. However, there were clear reductions in the amplitudes of temperature variations and time lags in terms of the peak temperature values. The temperatures varied between $+7^\circ$C and $-11^\circ$C in the soil while the maximum temperature variations in the air were between $+23^\circ$C and $-40^\circ$C. The air temperature peaked normally in late June each year and were the lowest in late January, while the soil 1.97 m (6.5 ft) below the surface normally peaked in late July to even early September and were the lowest in mid-February to late March.

**Soil Moisture Changes**

The CS616-L moisture probes measure the unfrozen volumetric water content in the soil. Figure 6a shows volumetric water content changes for sensors 3, 7, 10, 14, and 17 at about 0.45 m (1.5 ft) below the road surface. Soil moisture contents at sensor location 22 were also shown for comparison purposes. It was found that the volumetric water content of the soil during the 2011 summer months was constant at 37.2% when the soil was unfrozen. During the summers of the 2010 and 2012, the volumetric water contents of the soil at sensor location 22 were also relatively constant. Sensor 22 was installed at about 1.18 m (3.9 ft) below the road surface and closest to the drainage ditch at the west side of the road. The bottom of the ditch is about 1.09 m (3.6 ft) below the road surface and it was observed that there was constant water flow in the ditch during the summer months. Since the soils used for constructing the test sections were relatively uniform, sensor 22 was used as a reference to evaluate the moisture content at other locations. Figure 6a also indicated that the soil volumetric water contents decreased before the soil temperature decreased to $0^\circ$C. When the soils at the location of sensor 22 were completely frozen, the unfrozen moisture content of the soil varied from 5.9% to 7%, depending on the soil temperature.
Initially in August 2010, most soils were unsaturated and there were slight water content reductions in all soils with time. The moisture contents at sensors 3 and 17 suddenly increased on September 6, 2010, while soils at other sensor locations such as 7, 10, and 14, had similar but delayed increase. The relative humidity data indicated that from 3:00am to 9:00am on September 5, 2010, the relative humidity at the site was 100%. As a result, it was concluded that the moisture content increases during this period were due to a rainfall event. After the event, moisture contents at all sensor locations decreased, likely due to the drainage of water or reduced water supply. The unfrozen moisture content further decreased when the soils started freezing on October 10, 2010. After the soils were frozen, the values in unfrozen moisture contents at all sensor locations were very close due to the similar depths and associated temperatures. The unfrozen moisture contents varied narrowly between 7% and 12% when the temperature varied between -10°C and -20°C. In April 2011, when the temperature increased from -10°C to 0°C, the unfrozen moisture content increased. After thawed, the soil moisture contents at these sensor locations increased gradually with increase of temperature until the end of July and then decreased gradually with decrease of daily temperature until the next freezing process. It was also found that rainfall events had limited influence on the soil moisture contents. During thawing, the moisture contents were far below the saturation moisture contents, indicating that there was no frost heave in the first 0.45 m (1.5 ft) of soil. Table 1 summarized the moisture contents of soils at different sensor locations at 0.45 m (1.5 ft) below the road surface before frozen and after thawed. Table 1 indicated that after thawed, there were slight increases in moisture contents in nearly all sensor locations. However, no soil moisture content exceeded the saturated water content.

Figure 6b shows the air temperature and volumetric water content changes for sensors 1, 4, 8, 11, 15, and 18 at about 0.76 m (2.5 ft) below the road surface. This was also the location where the second layer of wicking fabric was installed. Similar to Figure 6a, when the soils were frozen, the moisture content for soils (except at sensor 1) had slight changes similar to the pattern of air temperature changes. When the soils were unfrozen, there were dramatic changes in moisture contents. These moisture contents were higher than those at the corresponding locations and 0.45 m (1.5 ft) below the soil surface as shown in Figure 6a. Under most situations, the soils closer to the west side (ditch) had higher moisture content.
Sensor 18 was at the west edge of the road section. Soils at this location might not be compacted very well and their moisture contents occasionally exceeded saturation. All other soils were unsaturated under most situations. The increases in moisture contents in the summer were usually very rapid and did not last long, indicating that the drainage of water was very quick in the test section. The moisture contents at sensor 1 were much lower than any other sensors in Figure 6b, mainly due to the short drainage path at that point.

Figure 6c shows the air temperature and volumetric water content changes for sensors 2, 5, 9, 12, 16, 19, and 21 at about 1.06 m (3.5 ft) below the road surface where the first layer of wicking fabric was installed. Compared with Figure 6b, the soils in Figure 6c had higher moisture contents maintained for longer time. The soils at the edges of the road section had higher moisture contents than those in the center of the road section. It is worth noting that sensor locations 19 and 21 were very close to the ditch and had elevations only slightly higher than the bottom of the ditch, while sensor 2 is below the exposed wicking fabric where water was drained. During the winter months, the variations of the unfrozen moisture contents in all soils were small and smooth. Similar to previous discussions, the unfrozen moisture contents of all soils in Figure 6c changed dramatically during freezing or thawing.

Figure 6d shows the air temperature and volumetric water content changes for sensors 6, 13, and 20 at about 1.97 m (6.5 ft) below the road surface. Soils at sensor 6 had lower moisture content than those at sensor locations 3 and 20, mainly due to its shorter drainage path. It is worth mentioning that sensor 20 was installed under water during the construction. Figure 6d indicated that soils at sensor 20 had moisture content higher than soils at sensor 22 in August 2010. The moisture content kept decreasing until completely frozen in December 2010. The average unfrozen water content during the winter of 2010-2011 was about 10%, 2% higher than soils at sensor 22. Soils at sensor 20 thawed in June 2011 and the moisture contents were very close to the soils at sensor 22 and decreased slightly with time. The average unfrozen water contents for soils at sensor 20 during the winter of 2011-2012 were similar to those in the previous winter at the same location. In June 2012, the moisture contents were very close to the soils at sensor 22 and remained constant. From these observations, it is concluded that soils at sensor location 20 were not fully compacted during the construction process and became more compacted with time due to the freeze-thaw cycle. Soils at sensor 13 had a trend opposite to that for soils at sensor location 20. The soil moisture
contents at sensor 13 were lower than those at sensor 22 in August 2010 and continued decreasing until completely frozen in December 2010 until the average unfrozen water was similar to soils at sensor location 22. Soils at sensor 13 in July 2011 had the moisture contents of 41.9%, 5% higher than soils at sensor 22 during the same period. The average unfrozen water contents for soils at sensor 13 during the winter of 2011-2012 were similar to those in the previous winter at the same location. From these observations, it seemed that soils at sensor location 13 experienced some frost heave which loosen the soil and subsequently resulted in higher saturated moisture content. The variations in moisture content for soils at sensor location 13 during August and September 2012 were unknown due to the limited monitoring time.

Performance of Wicking Fabric at Different Conditions

The hourly temperature and moisture data at different sensor locations were used to generate temperature and moisture contours to analyze the spatial distributions of the temperature and moisture to evaluate the performance of the wicking fabric. Moisture variations at three different conditions were considered: during a rainfall event, during the freezing process, and during the thawing process.

During a Rainfall Event

Figure 7 shows the typical moisture variations in the test section when there was a rainfall event in the September 2010. Since the soils were completely unfrozen, the corresponding temperature contours were not relevant and not shown. Figure 7a shows the moisture contour in the test section on September 4, 2010 after several days without rain. The soils at the east side (near the exposed wicking fabric) were the driest while the soils near the ditch at the west side were near saturation. The hourly relative humidity data indicated that there were several rainfall events form September 5 to 8, 2010 which resulted in some alternative increases and decreases in moisture content in the road section. On September 6, the soils in the road section were nearly saturated for all soils 0.91m (3 ft) below the road surface (Figure 7b). From September 9 to 14, the relative humidity at the test site was generally decreasing, implying that there was no rainfall. As a result, the moisture content in the road section was decreasing. Figure 7c shows the soils started drying from the east side to west side along the wicking fabric. It is also found that soils below the exit of the wicking fabric were nearly saturated. This near-saturation zone extended horizontally to the center of the road between the two layers of wicking fabric. There was another near saturation zone at the center of the road and its location coincided with the excavation pit for the sensor 13 installation, which
implied that compaction at the excavation pit was not good and resulted in a channel with relatively high permeability. The soils at sensors 19 through 22 were close to the drainage ditch and saturated. Figure 7d shows the moisture content contour on September 17. Compared with Figure 7c, the soils in the east lane of the road were much drier, especially at the exit of the wicking fabric. The high moisture content protrusion at the center of road had a clear reduction in size, while the soils near the drainage ditch had no change in the moisture content. Figures 7e and 7f show there were further reductions of moisture content in the road section. It is clear that the drying proceeded from the east to west along installed wicking fabric layers, indicating that the wicking fabric had higher permeability than the unsaturated soils and allowed faster drainage of the water. The soils at sensors 19 through 22 remained saturated during the whole process, indicating that there was continuous water supply from the ditch.

*During the 2010-2011 Freezing Process*

The air temperature at the test site dropped to below 0°C on September 23, 2010. Freezing reduced free water in the soil and the subsequent ground water supply. As a result, the moisture content in the road section was decreased as shown in Figure 8a for the moisture content contour on September 24, 2010.

Figures 8b through 8e show the temperature and moisture content contours for the road section when the freezing front penetrated to approximately 1.5, 2.5, 3.5, and 6.5 feet below the road surfaces on October 10, October 17, October 2, and November 9 of 2010, respectively. It can be seen from these figures, the temperature and moisture contours for frozen soils are similar (the unfrozen moisture content for partially frozen soils depended upon temperature only). The 0°C isothermal curve almost coincided with the locations of 20% volumetric water content curve in all corresponding contours. For soils in the unfrozen zone, there was no clear relationship between the temperature and moisture content contours. It was also found that before the soils were frozen, the moisture contents had been significantly reduced in all figures. Possible reasons for this phenomenon include: (1) reduced water supply from the upward tundra due to freezing, (2) increased drainage due to the drier freezing environment, and (3) upward movements of water due to frost heaving. The third possibility is related to the frost boils/soft spots problem. Available data at this time can only eliminate possibility 2 since the soils at the exit of wicking fabric were frozen first, as shown in Figures 8b through 8e. A following analysis of the 2011 spring thawing data indicated that there were no frost heave occurrences for this period. As a result, there was reduced water supply from the upward tundra. Figure 8f shows the temperature and moisture content contours for the road section on
March 12, 2011 when the road section was completely frozen. The moisture content was not greater than 10% anywhere in the test section.

**During the 2011 Thawing Process**

When the air temperature rose to above zero on April 26, 2011, the whole road test section remained frozen and the unfrozen moisture content was very low and similar to those as shown in Figure 8f. Figures 9a and 9b show the temperature and moisture content contours of the road section on May 15 and May 22 of 2011 when the thawing depths were 0.45 and 0.76m (1.5 and 2.5 feet) below the road surface, respectively. Although the moisture content in the thawed soils increased, the soils did not reach saturation at any place in the test section. Soils at sensor 22 near the ditch remained frozen. It is also worth noting that in the previous years, the frost boils/soft spots had come out at this period of time. It is therefore concluded that the frost boils/soft spots at the early spring each year in the previous years were caused not by the ground water from the tundra, but by thawing of in situ water in the soils. Since an excess amount of water is needed to form frost boils/soft spots (Taber 1929), they must come from thawing of ice lenses caused by frost heave. Figures 9a and 9b indicate that the soil moisture content in the road section remained low, which implied that there was no frost heave in the soil 0.76m (2.5 ft) below the road surface. In other words, the wicking fabric successfully eliminated the frost heave and subsequent thaw weakening in the early spring of 2011.

Figure 9c shows the temperature and moisture content contours of the road section on May 29 of 2011. The east lane of the road section had higher soil temperatures and thawed to a depth of 6 ft below the road surface while the west lane of the road thawed to a depth of 1.36-1.51m (4.5 -5.0 ft). Soil moisture contents at sensor locations 2, 5, 8, 9, 19, and 21 were high. There was a frozen soil protrusion at the sensor locations of 20, 16, 11, 12, and 13. This can be seen more clearly in Figure 9d which shows the temperature and moisture content contours of the road section on May 30 of 2011. The frozen soil protrusion reduced at the center of the road where sensors 12 and 13 were located. On both sides of the frozen soil protrusion, the soils were near saturation at the depth of 1.21m (4 ft) below the road surface. Compared with Figure 9c, the
soils at the east lane of the road were much drier as shown in Figure 9d. The soils at 1.66m (5.5 ft) below the road surface remained frozen.

Figure 9e shows the temperature and moisture content contours at noon of July 1, 2011 after a possible rainfall event in the morning of the same day. There were three saturated soil zones in the moisture content contour: one near the ditch, one at the center, and one at the east lane. Below the saturated soil zone at the center was a frozen soil core with low (unfrozen) water content. This seemed to imply that the non-uniform thawing of the soils caused ponding of water at the center of the road. With the installed wicking fabric, the road section dried out in a few days. Figure 9f showed the temperature and moisture content contours at noon of July 5, 2010. Comparing Figures 9f and 9g, it can be seen the wicking fabric can work as a siphon to drain the ponded water caused by non-uniform thawing. This is also consistent with the results from the laboratory tests by Zhang and Belmont (2009). Figure 9g shows the temperature and moisture content contours at noon of July 21, 2011 when the road section was completely thawed. The soils at 6 ft below the center of the road became saturated. The moisture content contour was similar but not the same as those in Figure 7 in the previous year. Figures 5 and 6 indicated that the variations of temperature and moisture contents in the test section were similar in the two years. Therefore the above discussions can be considered as representative.

FIELD OBSERVATIONS
Several trips were made to the test site to download the data. Visual observations were made to evaluate the performance of the test section. Figure 10 shows the road conditions at the test section on May 24, 2011 after treatment. Observations were also made by AKDOT&PF M&O personnel of the Dalton Highway during their routine road maintenance operations. It was reported that the test section has performed very well in the past two years. No soft spots or frost boils occurred in the test section treated with wicking fabric, while the soft spots or frost boils were observed during early springs or a particularly rainy period past both the upper and lower ends of the test section in the past two years. Some M&O personnel claimed they can clearly see whether the road is treated with Wicking fabric or not based upon the pavement surface
performance. Field observations also indicated that the wicking fabric exposed at the east shoulder was damp.

DISCUSSIONS

Mechanisms of the Frost Boils/Soft Spots Occurrences

AKDOT&PF M&O personnel reported the frost boils often occurred at the end of April till mid-May each spring. As shown in Figures 9a, 9b, and 9c, the soils remained frozen at 0.91 m (3 ft) below the road surface until the end of May. Consequently, the water which caused frost boils /soft spots is unlikely coming from the drainage ditch which is 1.09 m (3.6 feet) below the road surface. Instead, the water has to come from thawing of in situ water in the pavement structure. To form soft spots as shown in Figure 1, the soils must first be fully saturated and excess water must be available. The excess water can only come from thawing of ice lenses in the pavement structure. In other words, there must be frost heave in the previous winter. For this reason, it is concluded that the frost boils occurred in early spring is due to frost heave and subsequent thaw weakening as shown in Figure 11a.

AKDOT&PF M&O personnel also reported that the soft spots remain all summer and go away after freeze up. The soft areas will heal up if there are periods with no rain, but as soon as there is a significant amount of rain they will reappear. Figure 7 shows the moisture content variations during a rainfall event. It was found that the soils 0.6 m (2 ft) below the road surface never reach saturation. Careful examinations of snapshots of moisture contours in the past two years also indicated that soil wetting was not due to water coming from road surface (infiltration). Instead, water was found coming from the west side of the road near the drainage ditch. Since the road prism is built on the side hill, it is natural that water will flow from the high side (west) to the low side (east). The pressurized ground water can easily come out of the road surface in the transverse direction of the road, especially when there is a frozen (impermeable) soil core as shown in Figure 11b. Figure 8 indicated that the road section did not completely thaw until mid-July in 2011.

For scenarios as shown in either Figure 11a or 11b, it is very natural for the road section to form frost boils or soft spots. Figure 11c shows the reason. Figure 11c schematically shows the road section in
the longitudinal direction. The Beaver Slide is downhill when heading north and its gradient is approximately 11%. When there is water in the road section, as shown in Figure 11c, the easiest way for free water to drain is to flow out of the road surface under the influence of gravity because the flow path is shortest and the associated hydraulic gradient is largest.

**Mechanisms of the Wicking Fabric to Mitigate the Frost Boils/Soft Spots at the Beaver Slide**

It seemed that wicking fabric successfully eliminated the frost heave problem at the Beaver Slide test section. The potential mechanism is to drain the water out of the road embankment and form a capillary barrier as discussed in the literature review section. As shown in Figure 8a, before the soils were frozen, the moisture content in the test section was low, especially in the east lane where the volumetric moisture content was lower than 20% for most soils. This corresponds to a degree of saturation of 54% for the soil. For soils with such low degree of saturation, the unsaturated permeability of the soils is normally very low. Consequently, when there is heat loss toward the road surface and subsequent freezing downwards, the water supply from the lower soils is not sufficient to keep the ice crystal growth in the freezing front. Consequently most of the ice in the frozen soils comes from freezing of in situ water in the unsaturated soils. Table 1 shows there are slight increases in water content for soils at 0.45m (1.5 ft) below the road surface after thawed in 2011. However, the increase in water contents cannot cause the soil to reach saturation. As mentioned in the literature review, frost heaving requires substantially more water than is naturally available in the soil pores (Tabor 1929). By draining water out of the road embankment and keeping the top soils dry, the wicking fabric worked as a capillary barrier and eliminated the frost heave in the test section, as suggested by Henry and Holtz (2001).

The wicking fabric is an excellent material for transporting water out of the pavement structure. As shown in Figure 3, the wicking fabric was purposely sloped during installation. The slope can help drain the water only when the soils are saturated. It is worth noting that when the soils are unsaturated, the wicking fabric relies on the suction gradient generated by evaporation to drain the water out of the road embankment. Figure 12 shows the suction in the air at the Beaver Slide using the Kelvin’s equation (Fredlund and Rahardjo 1993):
\[ \psi = -\frac{RT\rho_w}{M_w} \ln(RH) \]  

(1)

where, \( \psi \) = total suction (kPa), \( R \) = universal gas constant (8.31432 J mol\(^{-1}\) K\(^{-1}\)), \( T \) = absolute temperature, \( \rho_w \) = density of water as a function of temperature (kg/m\(^3\)), \( M_w \) = molecular mass of water vapor (18.016 kg/kmol), and \( RH \) = relative humidity.

Compared with thousands of kilopascal of suction in the air, the unsaturated soils in the pavement structure have suction values normally less than 1,000 kPa. The difference in suction is the driving force for the wicking fabric to move water out of the road section. This is why it is important to have at least 3 ft (0.91 m) of the wicking fabric to be exposed to the air as shown in Figure 3.

CONCLUSIONS

This paper evaluated field performance of wicking fabric to mitigate the frost boil/soft spots at the Beaver Slide area of the Dalton Highway. The following conclusions were made:

1. The obtained data indicated that there are two mechanisms for the “frost boils/soft spots” at the Beaver Slide: (a) frost heave and subsequent thaw weakening which occurred in early spring, and (b) upward pressurized water flow to road surface during lengthy rainy periods similar to artesian water.

2. The test section was built at an area with the most “soft spots” in the previous years. The same materials as those in the problematic zones were used for the construction of the test section, which reduced construction cost significantly. Surface observations made by M&O personnel of the Dalton Highway indicated that the wicking fabric was able to eliminate the damage caused by both mechanisms. The test section has performed very well in the past two years. No soft spots or frost boils occurred in the test section treated with wicking fabric, while the soft spots or frost boils were observed during early springs or a particularly rainy period just beyond both the upper and lower ends of the test section in the past two years.

3. Changes in volumetric water content clearly indicated that the water was flowing along the direction of the wicking fabric to the shoulder of the pavement. Field observations indicated that the soil at the shoulder was damp.
4. Changes in volumetric water content and temperature in the pavement structure tended to indicate that the frost boils occurring in early spring were due to thaw-weakening only, since the soil above the ditch line was still frozen when frost boils appeared.

5. The wicking fabric successfully eliminated the frost heave and thaw weakening in the first 1.06 m (3.5 ft) below the pavement surface (below the second layer of wicking fabric). The observed volumetric moisture contents indicated that the soils did not reach saturation in the test section. For the soils used in the Beaver Slide, it is an indication of no frost heave at all. However, for soils 4.5 feet below the center pavement surface which is beyond the treated zone, there was an indication of excess water due to frost heave. However, it was too deep to cause damage the pavement structure.

6. The wicking fabric is an excellent material for draining water out of the pavement structure if properly used. The material itself has a high ability to absorb water from surrounding soils. It also has a high ability to transport water under differential water pressure. The pressure difference can be generated by exposing the wicking fabric to the atmosphere.

ACKNOWLEDGMENTS

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<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Test Method</th>
<th>Unit</th>
<th>Minimum Average Roll Value</th>
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<td>73.3 Horizontal direction</td>
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1ASTM D4751: AOS is a Maximum Opening Diameter Value
2STP: Standard Temperature and Pressure
3Modified
Table 2 Moisture contents of soils at 0.45 m (1.5 ft) below the road surface.

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