A Review of Innovative Frost Heave Mitigation Techniques for Road Pavements

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ABSTRACT

Frost action (heaving and thawing) is a perennial problem encountered in the design, construction, and management of civil engineering structures, particularly road pavements in cold regions and areas that experience seasonal sub-freezing temperatures. This paper reviews the existing methods for frost heave mitigation and proposes an innovative approach through engineered water repellency. Soil was collected from a test plot at the Charlotte Douglas International Airport and treated with a commercially available organosilane. Preliminary results indicate an increase in the maximum dry density from 17.54kN/m^3 to 17.66kN/m^3 and a decrease in the optimum moisture content from 17.36% to 11.75% after treatment. Data obtained from performance tests carried out under sub-freezing weather conditions indicated that the treatment was effective in limiting the infiltration and migration of water into the soil matrix when compared with the untreated soil. As such, engineered water repellency may be a viable solution for Airports and Departments of Transportation seeking methods to mitigate frost action.

INTRODUCTION

Frost heave is caused by the formation of ice lenses within the soil matrix of frost susceptible soils. The creation and subsequent melting of such lenses, combined with the effects of repeated traffic loads, (e.g. in airport pavements), leads to long-term degradation. The uneven nature of this process adversely impacts utilities and leads to road closures, weight restrictions, and a reduction in the ride quality due to uneven heaving. This problem is exacerbated even further during the spring months when the thawing ice causes an increase in the moisture condition of road pavements, resulting in further reduction of pavement strength under imposed loads (thaw weakening). According to Doré et al (2005), seasonal freezing can contribute up to 75% of pavement degradation and it is estimated that over 2 billion is spent annually on pavement maintenance and restoration due to frost action in the US (FHWA,1999). In order to ensure good performance over the life cycle of the pavement, there is a need to explore alternative methods to mitigate the effects of frost heaving.

Traditional frost mitigation techniques focus on controlling either one or more of the three basic requirements for frost heaving; 1. The presence of frost-susceptible soils (FSS) (silt-sized fractions), which are soils that promote the migration of water towards a freezing front resulting in the formation of an ice lens. 2. Sub-freezing temperatures result in the freezing of water within the soil pores. The conversion of liquid water to solid ice has the effect of desaturating the pore space and increasing capillary suction, resulting in a negative pore water pressure. And as ice forms, it excludes ions that increase the osmotic suction. 3. A continuous supply of water can result in continued ice formation and soil displacement. In the presence of sub-freezing temperatures, FSS would not heave if dry or will experience limited heaving utilizing the in-situ moisture present. The degree to which ice lenses grow and heaving will occur within frost susceptible soils under sub-freezing temperature is a function of the availability of a water source, either as a groundwater table or perched water within the soil matrix.

This paper will focus on reviewing some of the methods and techniques used in frost heave mitigation in road pavements. It will also highlight the innovative, cost-effective solution of Engineered Water Repellency (EWR), a process where FSS are treated with Organo-Silane (OS) making them hydrophobic (water repellent). Preliminary results from characterization and performance tests carried out are presented and discussed, exploring the viability of EWR in pavement design.

FROST HEAVE MITIGATION TECHNIQUES

Frost susceptibility of soils

According to Chamberlain (1981), many definitions of frost susceptible soil (FSS) fit only partially, failing to address relevant processes. One of the earliest definitions comes from Casagrande in 1932: "under natural freezing conditions and with sufficient water supply one should expect considerable ice segregation in non-uniform soils containing more than three percent of grains smaller than 0.02 mm, and in very uniform soils containing more than 10 percent smaller than 0.02 mm." However not all soils that satisfy this condition lead to frost heaving. Improved, yet not still all-inclusive definitions, combine grain size distribution and soil water interaction (capillary rise e.g more 2 m (Beskow (1935)), (Freden and Stenberg (1980)), hydraulic conductivity) or soil mineralogy (Atterberg limits e.g. plasticity index greater than 35%, clay content, and particle diameter Vlad (1980)). Empirical classifications from direct observation in the field or through laboratory procedures are preferred because frost heaving is visible and tangible. However, empirical classifications are not standardized as different freezing setups could be used in the laboratory for FSS testing.

Replacing frost susceptible soil with non-frost susceptible soils

According to Christopher *et al.* (2006), frost heave mitigation procedures include FSS replacement, placement, and compaction of non-susceptible materials above FSS, elimination of soil fines by chemical stabilization, or drainage, as well as increased pavement thickness. These procedures aim at preventing frost heaving by eliminating one or two conditions required for frost heaving to occur. FSS replacement eliminates the soil variable in the frost heaving equation, even with sub-freezing temperature and water supply. The 1993 AASHTO Guide for pavement structures, noted that removal of FSS is an acceptable practice towards frost heave mitigation. Removal of the FSS is governed by the depth of frost penetration and chosen approach (either Complete Frost Protection approach and Limited Subgrade Frost Penetration), grades, state Department of Transportation (DOT) policy, and other design considerations. Most DOTs in the USA have opted for a replacement, however to varying depths (Schaus & Popik, 2011). Studies by Evans *et al.* (2011) indicated that the performance of FSS replacement is dependent on the excavation depth to frost depth. A more significant replacement depth with proper drainage translates to better performance, as observed with complete frost heave elimination at near-total frost depth replacement. A constant site survey showed that when replacement is just about one-third of the frost depth, frost heave reduction is just about half (Evans *et al.*, 2011).

Temperature gradient

Polymer Injection

Given an FSS with a constant source of water supply, the temperature profile is the most dominant factor controlling frost heave in pavement structures. To impede the passage of subzero temperatures into the soil, polymer injection is used to create an insulation barrier below the road base material. This insulating blanket limits heat loss from the underlying subgrade layers. Therefore, the temperature of the subgrade remains higher, making it less likely to freeze (Edgar *et al.*, 2015). This technique involves the injection of a three-inch layer of polymeric or polyurethane foam into the subgrade. The appealing aspect of this method involves its application to any existing road pavement, as it does not require the removal of the overlying aggregate and surface layer within a short period. In addition, the foam supports the road surface. Edgar *et al.* (2015) tested Polymer injection successfully at the Battle Mountain Highway, Wyoming, where the temperatures below the polymer stayed at or above freezing, resulting in a decrease in the heave of 83 %.

Polystyrene boards

Synthetic insulation has been placed below a base to prevent the advance of freezing temperatures into the subgrade. Polystyrene, either expanded or extruded, is an excellent insulator, which thwarts freezing temperature from reaching the subgrade from the pavement. Extruded polystyrene boards were extensively used in Sweden from 1950 to the 1980s to mitigate frost heaving (Gandahl, 1988). The application of expanded polystyrene insulation was tested in some road sections in Canada between 1962 and 1965, with 7.6 cm thickness achieving complete prevention. However, joints between treated and untreated sections developed bumps (solved by staggering the ends by 47 inches)). Guo *et al.* (2018) showed that Polystyrene boards of 12 cm could reduce frost heaving up to 92.6% and frozen depth by 10.1 cm. Polystyrene boards performance depends on the thickness. Municipality of Anchorage (MOA) and the Alaska Department of Transportation and Public Facilities (ADOT&PF), recommends High-density polystyrene board with a minimum compressive strength of 413 kPa with maximum water absorption of 0.10 by volume; a minimum of 45.7 cm of gravel fill over the insulation board to protect it from heavy wheel loads during construction and minimize frost formation on the pavement surface and extend the insulated section limits.

Supply of groundwater

Given an FSS and a freezing temperature, water availability is the most dominant factor controlling frost heave in pavement structures (Hermansson & Guthrie, 2005). The depth of the water table to the freezing front determines how much more water could be drawn to the frozen fringe. Numerous studies such as Hermansson (2000) and Guthrie and Hermansson (2003) have indicated that frost heaving in the soil is due to both freezing of free in-situ water presence in FSS- subgrade, (primary frost heave) and more importantly, from water inflow towards the freezing front (secondary frost heave). As long as the water table is within the capillary range of the groundwater table, the water supply is continuous. The presence of water within 3 meters of frost penetration is considered a high frost hazard potential Oman and Lund (2018); Christopher et al. (2006). The influence of the water table is consistent with the studies by Hermansson and Guthrie (2005) and McGaw (1972), which indicated a reduction in frost heave and water uptake rates with decreasing water table height. The lower the water table, the lower the frost heave and water intake.

Techniques to the lower groundwater table

When FSS removal is not possible, the next step is to prevent continuous water supply. Water restriction could be achieved through various means, widely through the subsurface drainage systems. The core objective is to intercept and remove infiltrating water before it contributes to frost heave and curb water infiltration into overlying fine-pored unsaturated soil. Deep drains, capillary barriers, or a combination of both can be used to minimize water supply to the subgrade. Other methods include the utilization of Vertical Drains (Gravel mixed with sodium chloride or calcium chloride, rather than gravel alone) (Taivainen, 1963), improved ditching or ditch cleanout, or the installation of perforated sub drains beneath the shoulder of the highway

Chemical Stabilization

Soil stabilization by additives has shown considerable performance in frost heave mitigation. Lime and cement are the most widely used additives for frost heaving control due to processes such as cation exchange, flocculation and agglomeration, cementitious hydration, and Pozzolanic reaction (Nourmohamadi, *et al.*, 2022). For lime application, an extended curing period is necessary to prevent the formation of FSS. Weakly cemented material usually has less capacity to endure repeated freezing and thawing without degradation than firmly cemented material. Cement additive makes FSS less sensitive to moisture, and the hydration products will reduce frost heaving. But the impact of cement within the soil varies as the number of freeze-thaws increases (Lu *et al.*, 2020; Shidi and Kamei, 2014; Baldovino *et al.*, 2020). Other materials incorporated or used alone includes fly ash (Zhang *et al.*, 2016), cotton fiber (Liu *et al.*, 2020), jute fiber, steel fiber (Gullu and Khudir, 2014), polypropylene, basalt, glass, and microbially induced carbonate precipitation (MICP) (Sun *et al.* 2021; Gowthaman *et al.*, 2020). The major drawback is the long curing period. Furthermore, it is a time-consuming process with massive soil operations and machinery.

Capillary barriers

Capillary barriers include horizontal geocomposite drains (Henry and Holtz, 2001; Nourmohamadi, *et al.*, 2022) or an open-graded gravel layer sandwiched between two layers of geotextile separators, porous insulating layers (sand) (Rengmark, 1963). Studies have shown their effectiveness in preventing water from being drawn up to the ice front, yet, frost heave could still occur. FSS can be replaced and compacted above the capillary break layer. In general, the thickness of the capillary break must supersede the height of the capillary rise of water. Then, the capillary break must be placed above the water table and as deep in the soil as possible below the depth of frost penetration. In addition, the drainage system must be placed below it, and lastly, clogging must be prevented through the use of filters at the top and bottom (Henry, 1996).

Geotextiles

Geotextile in frost heave mitigation could serve as a capillary barrier, as filter layer (or as separator layer) (Roth, 1975; Roth, 1977; Clough and French, 1982), or to reinforce soil during freezing and thawing (Hoover *et al.*, 1981; Henry, 1996). They are good capillary breaks because of their relatively large pore sizes compared to FSS. Numerous experimental works, such as Allen *et al.* (1983) and Hoover et al., 1981, have shown that geotextiles can reduce frost heaving. Shoop and Henry (1991) indicated that when the water table was above the geotextile, the geotextile did not influence frost heave or the distribution of water in the soil. Studies by Zhang *et al.* (2014), Zhang and Belmont (2009), Galinmoghadam *et al.* (2019), and Zornberg *et al.* (2017), showed the efficiency of wicking fabric in preventing frost boiling as it absorbs water from surrounding soils and effectively drains it out.

Geofoam

Insulating materials can be used to lessen the heat exchange between the cooling surfaces and adjacent soils. The soil temperature can be maintained above the freezing point Liu *et al.* (2019). Recent studies are focusing on the application of geofoam as a thermal insulator to the culvert and transition sections. Studies such as Moussa *et al.* (2019), and Hua *et al.* (2014), recommended the utilization of geofoam of about 75 to 100 mm thickness. However, more studies need to be performed to standardize the geofoam's depth of placement and thickness.

Engineered Water Repellency

Every technique geared toward frost heaving reduction involves removing FSS, limiting or cutting water flow, and insulating the soil against freezing temperature. However, they do not provide a permanent solution as clogging, soil deposition, cost of implementation, and changing soil boundary temperature have reduced their efficiency (Henry, 1996). Also, the majority of these techniques are costly and labor-intensive, requiring extensive cost and life-cycle analysis. A new cost-effective approach is to make existing soil hydrophobic, thereby preventing water migration. To achieve hydrophobicity, the soil is treated with organosilane (O.S.), a silica-based organic coupling agent. The effectiveness of O.S., terms from the modification of the soil surface by grafting organic molecules without providing any interparticle bonding. Studies by Sage and Porebska (1993), Mahedi *et al.* (2020), and Daniels *et al.* (2021) have demonstrated that OS-treated soils achieve higher contact angles than untreated FSS corresponding to reduced water flow, indicating frost heave mitigation. These studies showed that hydrophobic soils take far less water than FSS layers. Therefore, the heaving rate or height is negligible; the treated soil is hence classified either as low or negligible potential FSS.

MATERIALS AND METHODS

Material

The soil utilized in this study was collected from the south side of the Charlotte- Douglas International airport, North Carolina, USA, where a proposed taxiway and de-icing pad are currently being constructed. Disturbed samples were collected in 15-gallon buckets and were mixed and quartered on delivery at the laboratory. The soil was first oven-dried at 110ºC in an oven and cooled down to room temperature before use. The grain size distribution of the soil was carried out in accordance with ASTM C136/C136M (ASTM 2014a). The soil is classified as a silty sand according to the Unified Soil Classification System (USCS) and A-6(2) based on the AASHTO classification system, with about 48.43% passing through the No.200 (<0.075mm) sieve (Fig.1). The specific gravity of soil, G_s, was determined to be 2.69 (ASTM D854, ASTM 2014b). The optimum moisture content and maximum dry density of the soil were 17.54kN/m^3 and 17.36% respectively (ASTM D698-12).

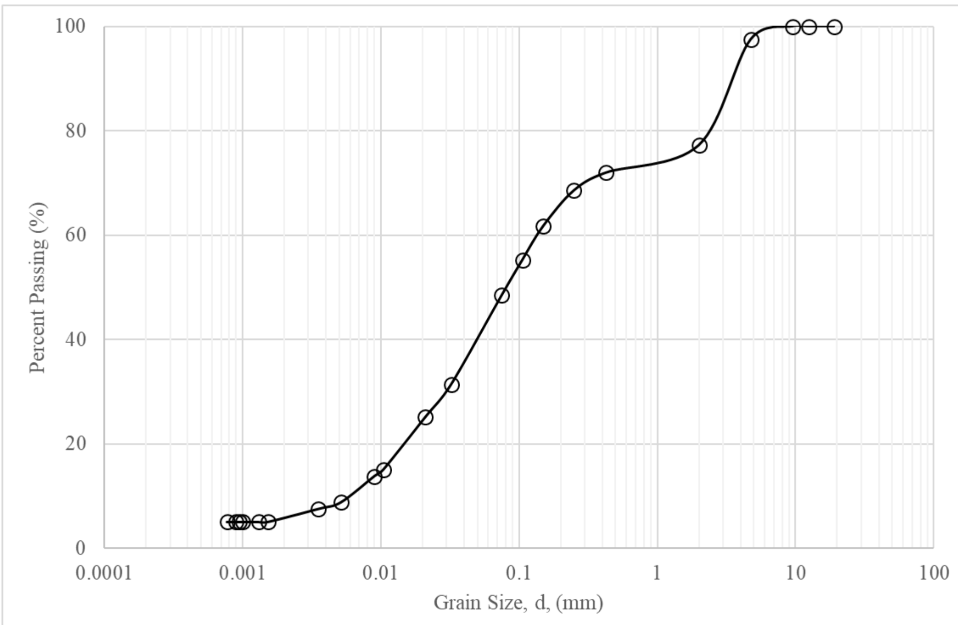

Figure 1: Particle size distribution of the soil used in this study.

Treatment

For tests involving treated samples and specimens, the soil was treated with commercial-grade Organosilane product, Terrasil from Zydex Industries. Terrasil is a viscous, water-soluble, and reactive soil modifier that permanently modifies the soil surface, making it hydrophobic. is a mixture of ethylene glycol, benzyl alcohol, and hydroxyalkyl-alkoxy-alkyl (Pandagre and Rawat, 2016). Terrasil is non-leachable and safe chemistry and is able to coat most soil types. It has been successfully utilized in the stabilization of soft clays and expansive soils (Daniels et al. 2009; Meeravali *et al.*, 2020; Ewa *et al.*, 2016; Zahoor and Jassal, 2020; Singh, 2017; Patel *et al.*, 2015), and was able to render soils hydrophobic and improved compaction properties (Oluyemi-Ayibiowu and Uduebor, 2019). Treatment was carried out at a mix ratio of 1:40 (OS to Soil), batched by weight. Terrasil was mixed with DI water (EC ~ 1µS/cm) to fully saturate the specimen and when compaction was required, the OS mixture was utilized as the molding water used for the mixing of the soil samples.

Method

Field Performance Test

Two identical test setups were constructed for performance testing of both untreated and treated samples. An acrylic cylinder with a thickness of 1.27 cm, an internal diameter of 19.05 cm, and a height of 22.5cm was first filled with a sand layer to a height of 5 mm, after which soil samples (untreated and treated) were compacted using three lifts of 7.33 mm at the OMC and MDD using the standard proctor compaction effort. The soil samples were compacted to a height of 22cm and instrumented with one TEROS 12 and TEROS 21 sensor (Meter Group) each at a depth of 11 cm into the sample. The TEROS 12 is a sensor for monitoring volumetric water content (VWC), the temperature in soil and soilless substrates, and Electrical Conductivity. The TEROS 21 Soil Water Potential Sensor measures soil water potentials as well as soil temperature. The sensors were connected to the ZL6 Data Logger (Meter Group), and readings were logged at 10-minutes intervals. Fig. 2 below shows a schematic drawing of the setup. The complete setup was placed out in the yard within the University premises, where a weather station was situated to monitor real-time precipitation temperature and other weather data. Data from the Zentra was collected every day and results were analyzed.

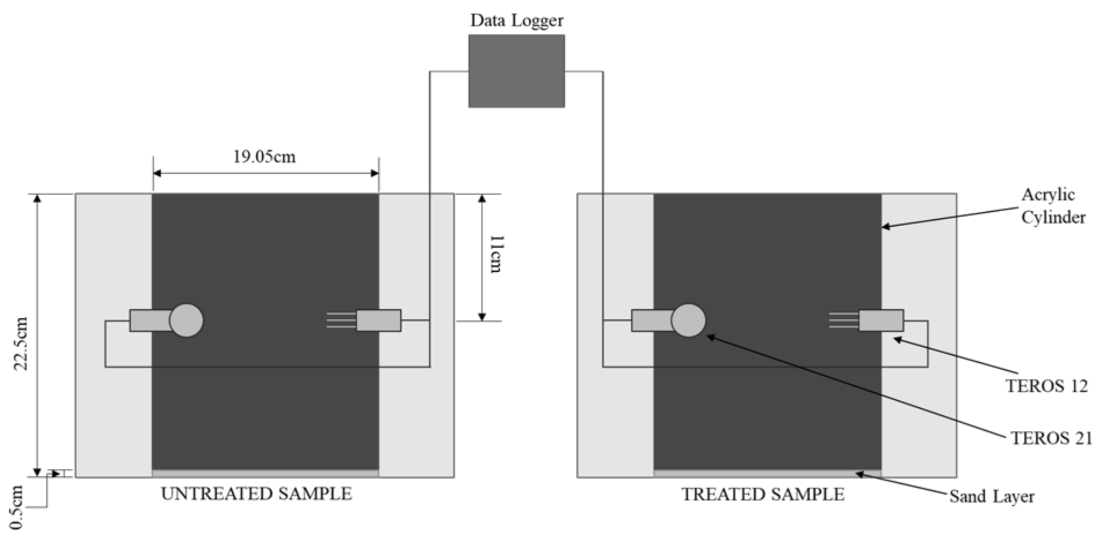

Figure 2: Schematic of the performance test setup

RESULTS AND DISCUSSIONS

Physical Properties

Compaction test results from untreated and treated samples indicated an increase in the maximum dry density from 17.54kN/m^3 to 17.66kN/m^3 as well as a decrease in the optimum moisture content from 17.36% to 11.75% after treatment. This increase in dry density can be attributed to chemically bonded alkyl chains in the OS that provide lubricity and charge shielding to the soil particles during the compaction process (Zydex Industries). This allows for better compaction of the fine-grained soil particles.

Field Performance

The results for the performance test carried out on both treated and untreated samples are given in Fig. 3. Both setups were subjected to occurring extreme weather conditions with cover , freezing, and thawing. It was observed that the temperature profiles within the two setups were similar indicating very little variation between the thermal conductivities of water repellent treated and untreated samples. The moisture content readings from the treated samples were fairly stable. This stable reading also indicates that there is no migration of water through the sample and that the treatment is effective in limiting infiltration into the soil. It is expected that under drier conditions the soil will lose moisture resulting in a decrease in the moisture content and an increase in the matric suctions recorded. The untreated soil sample had large variations in water content, even getting completely saturated (Matric Suction = 0 kPa). This increment is due to infiltration of water into the soil, while decrement is due to the formation of pore ice, resulting in a reduction of free liquid phase moisture within the soil (unfrozen water). Larger matric suctions (values) were recorded from the treated samples when compared to the untreated sample because of the lower moisture content of the treated sample.

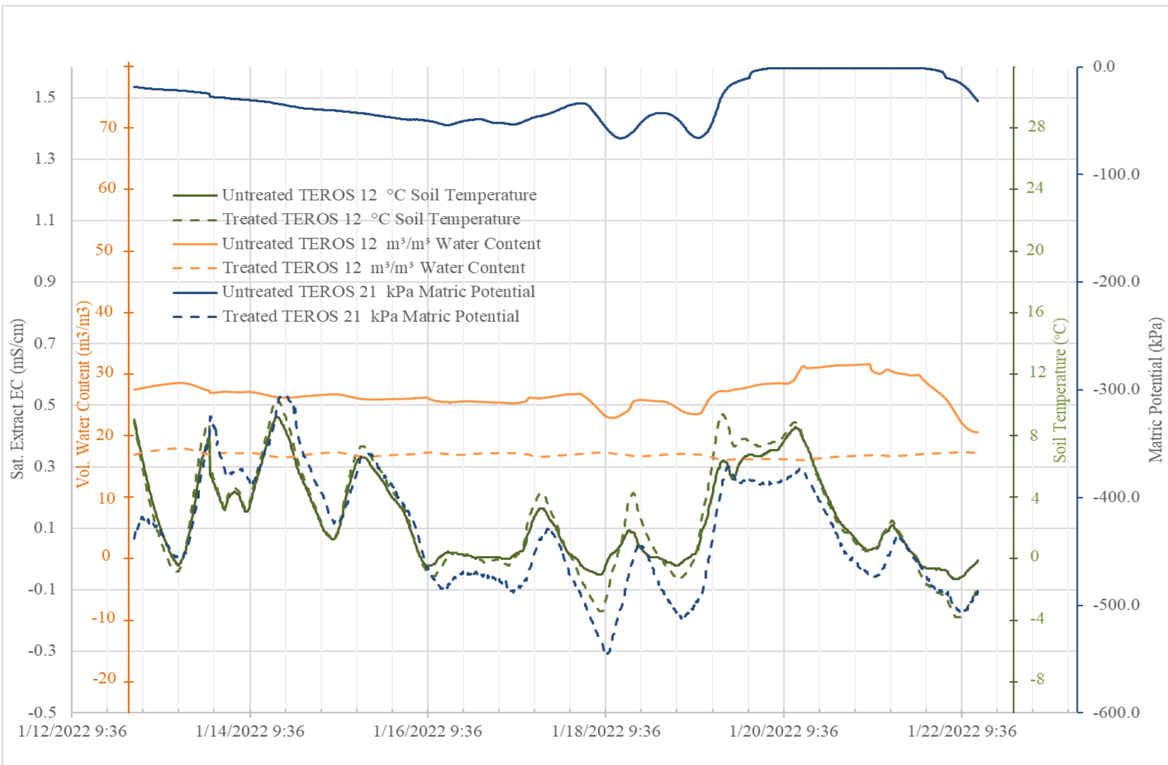

Figure 3: Comparison of field data obtained

CONCLUSION

There are a number of traditional and evolving methods for mitigating frost action, including engineered water repellency (EWR). EWR prevents moisture intrusion, increases dry density and decreases the optimum moisture content. In this study, the maximum dry density increased from 17.54 kN/m^3 to 17.66 kN/m^3, while the optimum moisture content decreased from 17.36% to 11.75% after treatment with a commercially available organosilane. Performance tests indicate that there was no infiltration of water and little variation in the water content of the treated sample.

Treatment also prevented moisture migration within the soil matrix and limited the formation of pore ice and subsequent frost heaving of the soil. Our preliminary tests indicate that the use of water repellent additives as a means to limit frost heaving in the pavement is a viable alternative to Airports and Departments of Transportation seeking technologies in mitigating frost action.

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