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Capillary and Moisture Control in Geotechnical Foundation Structures

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ABSTRACT

Geotechnical engineers have long strived to control capillary rise and pore water pressures in foundation systems. Doing so leads to dramatic improvements in subgrade loading characteristics and the long-term health of the designed system. The consequence of moisture saturation due to capillary rise is a detrimental effect on subgrade soil strength, which can also lead to increased rutting on systems that are impacted by cyclic loads. The performance of systems like paved and unpaved roadways, railroads, and airport pavements will deteriorate due to subgrade pumping and soil fines migration. In certain regions, either due to subgrade soil type or climate extremes, the negative effect of capillary rise is well known. While the effect of subgrade strength loss is still present for both situations, the more detrimental aspect is the physical movement of the foundation subgrade due to a volumetric change. In the regions with extremely cold climates, these effects are commonly known as “frost heave” and “frost boil”. The other type of volumetric disturbance is marked by the expansion and contraction prevalent in regions afflicted with expansive soils.

Many solutions have been employed to mitigate or at least lessen the effect of capillary rise on foundation systems. These solutions sometimes have negative results on the foundation system and often create detrimental consequences to the stability of the underlying soil subgrade. The effect of capillary rise will also manifest itself in different ways, dependent on the climatic region, subgrade soil classification, and geographic region the foundation system is being constructed. This paper will review the effect of capillary rise on foundations and the various subgrade soil materials. It will also review new research available which studies solutions commonly used in the past along with new technologies available to minimize or mitigate the effect of capillary rise on foundation systems.

INTRODUCTION

Geotechnical engineers have always strived to control moisture conditions in foundation systems. By doing so, they know it will lead to dramatic improvements in subgrade loading characteristics and the long-term performance of the designed foundation system. The consequence of increased moisture saturation due to boundary conditions, such as surface infiltration, poor surrounding drainage and capillary rise, has a detrimental effect on subgrade soil shear strength. The performance of paved and unpaved structures, such as roadways, railroads and airport runways/taxiways, will deteriorate much faster than the assumed design life due to subgrade pumping, soil fines migration into the structural fill, and greatly decreased shear capacities of both the foundation soils and structural fills owing to the increased moisture content. For roadway systems, this leads directly to increased rutting and dramatically reduced performance.

In certain regions, either due to subgrade soil type or climate extremes, the negative effect of moisture variations is well known. Examples of these include frost-susceptible soils in cold climates and expansive soils in various geographies around the world.

In regions with extremely cold climates, these effects are commonly known as ‘frost heave’ and ‘frost boils’. Frost heave is caused when subgrade moisture is fed by way of capillary movement and it freezes when it contacts the freezing boundary in the subsurface soil. This moisture continues to collect and freeze at the boundary until it forms a subsurface lens. These lenses can cause differential expansion of the road surfaces in excess of 300 mm and have proven to be extremely detrimental to roadways and foundations.

The other type of volumetric disturbance is marked by the expansion and contraction predominant in regions afflicted with expansive, high-plasticity-index foundation soils. These soils are particularly troubling due to the lack of a suitable, long-term solution. The effect of expansive subgrades manifests itself in longitudinal cracks along the outer boundary of the roadway, increasing in severity over time. The general theory for cause is the effect of fluctuating moisture contents across the width of the roadway. This moisture differential creates a varying volumetric change in the subsoils, which in turn expands and contracts at differing degrees of severity at the roadway surface. During times of drought, the moisture at the outer edge of the roadway is much less than the moisture content at the center. This creates a contraction on the outer portion of the roadway, which in turn leads to surface longitudinal cracking. The effect of high-moisture events, such as long periods of rain, leads to the opposite effect, expansion of the outer edge in relation to the centerline. The effect of moisture in roadways and foundations is not limited to conditions of saturation either. The common mis- conception is that the foundation materials need to reach a level of saturation before the reduced shear strengths of both the structural base course and/or subgrade soils begin to fail. Soils with varying degrees of capillarity behave differently under fluctuating degrees of moisture content. Soils with larger particle sizes have a lower matric suction value and can carry higher moisture concentrations before being capable of drain- age by way of gravity. Soils composed of smaller particle sizes have greatly reduced shear strengths even with minute increases in moisture above installed optimum (Lin *et al*., 2016). Although unsaturated moisture contents are considered an issue, the ability to control them is extremely difficult. However, recent innovations now allow engineers the ability to control both saturated and unsaturated levels of moisture in roadways and foundations.

MOISTURE REMOVING GEOSYNTHITICS

As previously mentioned, the negative effect of higher moisture in foundations is known, but effective solutions are limited and/or cost prohibitive. Since the advent of geosynthetics, one of the most daunting applications has been moisture control. If engineers could improve the moisture content of subgrades and/or mitigate moisture increases in structural base materials, it is expected that these structures would perform much more closely to designed expectations. These foundation systems could have a much better design performance, along with possible reductions in construction costs. It is known that even a modest 1% reduction in subgrade moisture content will yield an increase of 20% to the shear strength of fine-grained silty soils (Budhu, 2010). Based on recent advances in geosynthetics, engineers are now able to control moisture in roadway and foundation structures. Additionally, this improvement can occur in both saturated and unsaturated conditions.

Geosynthetics commonly used as a capillary break are typically composed of a non-woven textile. The capillary break effect occurs at the interface between fine-grained materials where P_a is the pore air pressure, P_w is the pore water pressure, h_c is the capillary rise in a pipette of radius R, ρ_w is the density of water, g is the acceleration of gravity, σ_{aw} is the surface tension between water and air and γ is the wetting contact angle, Figure 1.

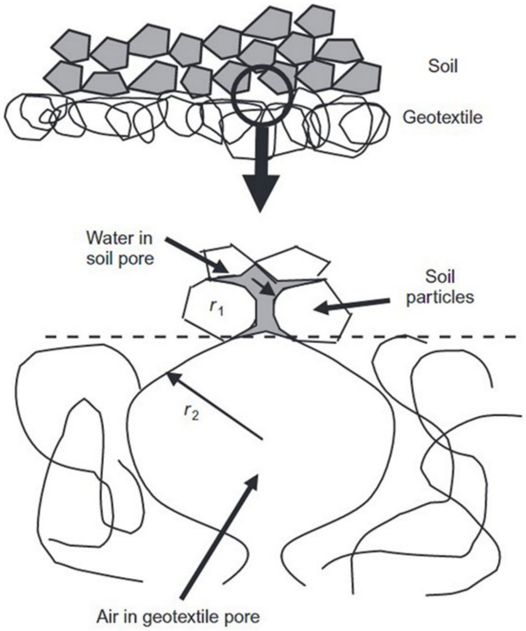

Figure 1. Nonwoven and soil capillary interface (Zornberg et al.)

$$\psi = P_a - P_w = h_c \rho_w g = \frac{2\sigma_{aw}\cos\gamma}{R} \quad (1)$$

Where P_a is the pore air pressure, P_w is the pore water pressure, h_c is the capillary rise in a pipette of radius R, ρ_w is the density of water, g is the acceleration of gravity, σ_{aw} is the surface tension between water and air, and $\gamma$is the wetting contact angle.

The radius of the air or water meniscus changes from r_1 to r_2 at the interface between the small and large pores. Non-woven geotextiles are manufactured from randomly bound polymer fibers created in a needling process. This process and the resulting structure contain a random assortment of opening sizes. Inspection of Equation 1 indicates that the small soil pores of radius r_1 result in comparatively large suction, and water can move to the larger geotextile pores only when a significantly smaller suction (corresponding to the larger radius r_2 of the geotextile pores) develops in the system. In other words, the energy in the pore water must be sufficiently high to allow it to break into the large pore. Macroscopically, the capillary break effect prevents a measurable amount of water from flowing from the soil into the non-woven geotextile until a critical suction close to zero (saturation) is reached. At this point, water is capable of 'breaking' into the large pore from the small pore. Early field evidence of the impact of the capillary break was reported (Clough and French, 1982) and it was recently realized that non-woven geotextiles used as under- drains in unbound pavements can lead to an increase in the water content of the overlying soils (Zornberg *et al.*, 2010). Recent research has also shown that moisture build-up at these interfaces accumulates in the underlying soils as well (McCartney *et al.*, 2005). When the fabrics, or composite structures covered with the non-woven geotextile, are in contact with fine-grained soils, moisture accumulates at the entire interface. This accumulation builds until enough pressure, or water entry suction, is developed to force the wetted front into the non-woven geotextile. Based on this, the increase in moisture on the soil side of the wetted front has a dramatic increase in moisture content and a subsequent decrease in subgrade soil shear strength. Also, due to the stark capillary suction differential, these common separation/filtration fabrics become impermeable in unsaturated soil conditions (Zhang and Belmont, 2009). This creates an unsaturated drainage issue with the granular fills above the interface due to the lack of adequate suction. Once again, saturation must be achieved for moisture movement. It is due to all this referenced research that the use of non-woven and monofilament geotextiles, which are recommended for separation and filtration, are not suitable in soil structures requiring moisture control to achieve design parameters.

A new and innovative geosynthetic option is now available for moisture control. This material is showing great promise and can be best described as an active drainage geosynthetic (ADG). These geosynthetics with active moisture management potential are being researched for a multitude of applications. These can include soft subgrade improvement by reducing the moisture content of the subgrade soils. This improvement is not only at surficial levels, but moisture reduction has been shown to reach deeper into the subsoil strata. Another application is mitigating moisture movement into structural base materials by way of capillary rise or boundary infiltration. The reduction of even unsaturated levels of moisture in the structural base, returning moisture to optimum levels, has shown dramatic increases in shear capacity. Yet another application involves the improvement of foundations for frost heave and expansive subgrades. In both cases, being able to balance the moisture across the foundation soils creates a more uniform moisture profile, thereby reducing the expansion and contraction due to moisture imbalances.

This new and innovative ADG referred to in this paper consists of a high-strength geotextile comprises special hydrophilic members built within the structure. Each fiber of the bundled members has an engineered and uniform cross-sectional shape designed for efficient and effective capillary pull (Figure 2).

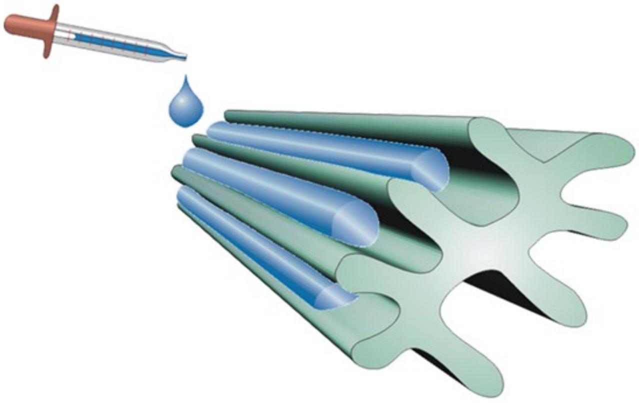

Figure 2. Active Drainage Geosynthetic Yarn

These special yarns are composed of engineered microchannels with sizes ranging from 5·7 to 47·8 μm in diameter. One of the main benefits created by this active composite is its ability to create such effective suction that moisture transport is possible even in unsaturated conditions. The capillary suction created by the engineered structure has been measured at 100 MPa (Zhang and Belmont, 2009), sufficient to create a negative gradient on the surrounding capillary pressures. This capillary suction creates moisture improvement deep into the subgrade, allowing for a greatly improved structure and effective moisture balancing at sufficient depths to minimize the differential move- mint of expansive foundation soils. The volumetric movement of moisture has also been measured for this ADG. The expected in-plane volumes range from 0·7 to 1·5 (l/d)/ linear meter (0·5–1·3 (gal/d)/linear foot), with moisture availability, ambient humidity and termination management controlling the expected field range.

BASE COURSE IMPROVEMENTS

The use of an active moisture interceptor has been shown to greatly improve the shear capacity and loading characteristics of base course materials. These structural fills have high fines content and are susceptible to capillary moisture action and strength loss. This is especially true with base fills lacking aggregates and generally labelled as ‘select’. Owing to the lack of high-quality aggregate materials in many areas, locally available select fills are being used as engineered base fills. The cost savings can be dramatic and, if properly designed and constructed, a high degree of expected performance can be attained. This has, however, created an interesting issue. Usually, after a pavement structure is constructed, the moisture content in the pavement structure will increase due to the removal of evapotranspiration at the surface along with increased capillary suctions from beneath the base/subgrade interface. This phenomenon, combined with the use of fine-grained fills in the base section of roadways, could lead to dramatic moisture increases with an equally noticeable reduction in post-construction resilient modulus.

Normally, the base course is compacted under optimum water content and maximum dry density, but sometimes it is not feasible and/or cost effective to perform the compaction to specified moisture contents. Post-installation, the water content of the base course will immediately begin to achieve equilibrium with ambient moisture conditions (Yang *et al*., 2005), which also varies according to the seasonal conditions. For base course fills that contain even higher fines contents or regions with shallow groundwater tables, it is expected that the post-compaction water content will immediately increase by 1–2%. This excess water in the pavement structure will be much higher than the intended optimum moisture content when the soil was originally compacted. Numerous researchers (Barksdale and Itani, 1989; Hicks and Monismith, 1971), who studied the behavior of granular materials at various degrees of saturation, have reported the notable dependence of resilient modulus in direct relation to water content, with the modulus decreasing with growing saturation level. For instance, researchers (Haynes and Yoder, 1963) observed a 50% decrease in resilient modulus in gravel as the degree of saturation increased from 70 to 97%.

The consequence of these moisture increases is known and contributes directly to increased differential settlement and reduced shear strength of foundation structures. Based on recent research, it was concluded that the inclusion of the ADG in a pavement structure can lead to reduced moisture content (Zornberg *et al*., 2013), increased shear strength of the soil and reduced differential settlement. These are expected to significantly improve the performance of the pavement structure while increasing the expected service life. By implementing the ADG, the post-compaction water content can be kept at its optimum value, the resilient modulus can therefore be theoretically increased by three times and the permanent deformation can be reduced to half. It is worth keeping in mind that post-compaction water contents are typically 1–2% higher than the optimum values (Lin *et al*., 2016). Again, according to the research study, when the post-compaction water content of an evaluated structural fill increases to 10·8% from 8·5%, the base course cannot form its own shape and the resilient modulus will be considerably lower, close to 0 (Lin *et al*., 2016). They hypothesize that if the geotextile could maintain the base course post-compaction water content at optimum level, the stiffness of the base course could be maintained at the designed value (209 MPa). Furthermore, if the geotextile is effective enough to further reduce the post- compaction water content by 2%, the resilient modulus could be increased to 633 MPa, which is about three times higher than that value at 8·5%.

The ADG can not only mitigate this immediate moisture increase, but it can also reduce this post-compaction water content by 1–2% lower than the optimum value. This means the soil–fabric system has the potential to reduce the pavement system water content by 4% in total. Theoretically, the resilient modulus can be increased by almost 6, and the permanent deformation reduced by over 12 times (Lin *et al*., 2016).

The reduction of moisture provided by the ADG can increase the effective shear strength of structural fills, but the inclusion of high tensile capacity will also reduce differential settlements of foundations. This ADG provides a very high tensile strength with frictional interface, both of which provide lateral restraint of structural fill materials. The inclusion of these enhanced structural properties increases the engineered system's bearing capacity by reinforcing the potential local failure surfaces while also providing additional wheel load support (Holtz *et al*., 1998). All these benefits derived from the fabric can be expected to significantly improve the performance of the pavement structure and service life.

SUBGRADE IMPROVEMENTS

According to Lin *et al*. (2016), the use of an ADG has also been shown to improve high-moisture-content subgrades under- lying engineered foundation structures. Improvements in the subgrade can occur by either reducing the moisture content in the subgrade itself, or by providing a capillary break at the base/ subgrade interface. The inclusion of a drainage layer at this interface will allow subgrade pore water release while also theoretically improving the unsaturated moisture content in the soils. Several approaches have been employed to mitigate the effect of capillary rise on foundation systems. These approaches sometimes have negative results on the foundation system itself and often create detrimental consequences in terms of the stability of the underlying subgrade, as discussed earlier with non-woven geosynthetics. The effect of capillary rise will also manifest itself in different ways, dependent on the climatic region and subgrade soil classification where the foundation system is being constructed. The increase in moisture content caused by capillary rise decreases the available strength of the foundation soils, or subgrade. As the moisture content approaches saturation levels, the available subgrade shear strength can greatly decrease. Often, the proper prediction of significant strength loss is overlooked or underestimated. This can lead to significant reductions in the predicted design life of the foundation and underperformance of roadways and other foundation structures.

A capillary barrier refers to either soils, such as sand or gravel, which have large pore size, or a non-woven geotextile structure as discussed earlier. These are often adopted to break capillary water from rising to the base course and wetting the aggregates while also providing a drainage path to mitigate saturation of the subgrade soils. Both these materials have larger pore sizes and very low air entry value of <1 kPa when compared to the surrounding soils (Bouazza, 2002; Bouazza *et al*., 2006). The hydraulic conductivities for these capillary barriers are much smaller than for the ambient soils under the unsaturated condition, therefore issues do exist when this imbalance occurs. When typical capillary barriers dry and reach a level of unsaturation, the surrounding soils with smaller pore size must reach saturation to break the air entry barrier into the open- graded sand or non-woven textile. Researchers have also proven that large amounts of capillary water still exist within sandy materials (Zhang and Belmont, 2009), which are often considered good capillary barriers, as shown in Figure 3.

Figure 3. Moisture Buildup in Sand Capillary Barrier (Lin et al., 2016)

In contrast, placing the ADG at the base/subgrade interface can mitigate base course moisture saturation and acts as a capillary break, mitigating moisture movement and improving base course structural capacity. Figure 4 shows this clearly. The soil above the ADG is dry (material on the right-hand side) while the subgrade below is wet (material on the left-hand side). It will also act as an active moisture improvement method in unsaturated conditions within both the base and subgrade materials. The ability of this active fabric to improve these unsaturated soils, both open graded and fine grained, can greatly enhance the structural capability of designed roadways and foundations. The unsaturated hydraulic conductivity of the ADG is generally higher than that of the surrounding base course and subgrade soils (Lin *et al*., 2016) due to the general uniformity of the engineered fibers, which dramatically improve the relative difference in tortuosity, drag forces and suction. This means the ADG can continuously wick water out of the pavement structure, even in unsaturated conditions.

Figure 4. Active Drainage Geosynthetic acting as capillary break.

Research (Lin *et al*., 2016) has postulated that a pavement structure without the inclusion of the ADG can behave as follows. The capillary suction linearly decreased with depth into the subgrade and the corresponding water content increased from 6·5% at the surface to ~11% at the bottom of the section. The resilient modulus value decreased in this control section, from 623 MPa at the surface to about 320 MPa at a depth of 2·5 m. In contrast, for a pavement structure which included the ADG (implemented at 0·3 m from the road surface), the suction could be maintained at 200 kPa to a depth of 0·3 m based on the same subgrade material capillarity. Suction would then linearly decrease to 0 at a depth of 3 m where the groundwater is encountered. After balance is achieved, the corresponding water content would then be maintained at 4·9% at the base/subgrade interface, and then increased to about 9·4% at the bottom of the test section. The resilient modulus value would be 819 MPa at the surface and decrease to about 650 MPa at a depth of 2·5 m. This value of 650 MPa represented the lowest value of resilient modulus for the section with the ADG, and the maximum encountered in the control section. Compared with the control section, which had a measured moisture content of 8·47%, the resilient modulus of the ADG increased by three times and the permanent deformation of the section reduced to half.

DESIGNING WITH DRAINAGE IMPROVEMENTS

The University of Kansas recently conducted an extensive research program with the goal to incorporate and quantify the benefits of the ADG in flexible pavement design methodologies such as AASHTO Guide for Design of Pavement Structures (AASHTO 1993) and AASHTO Mechanistic-Empirical Design Guide (AASHTO-ME).

They conducted a series of laboratory tests, including demonstration tests, water tank removal tests, small box tests, and soil column tests to investigate the hydraulic characteristics of the ADG when in contact with water and/or soil. They also performed six large-scale cyclic plate loading tests with rainfall simulations of the ADG on the permanent deformations of base courses over weak subgrades. These tests also provided the relationships between base course water content and drainage times. Design guidelines that incorporate the moisture reduction benefit of an ADG were developed by modifying the AASHTO 1993 and AASHTO-ME design methods.

Analysis of the guidelines for the AASHTO-ME are on-going at the time of this writing, while the method to modify AASHTO 1993 is explained below.

DESIGNING WITH AASHTO 1993

In this design approach, damage to a pavement inflicted by vehicles depends on the axle loading and configuration. The design guide measures the traffic as an Equivalent Single Axle Load (ESAL), defined as an 18-kip single axle load. The equation to determine the equivalent component of ESAL loads is given as:

$$log_{10}(W_{18}) = Z_R \times S_o + 9.36 \times \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log_{10}(M_R) - 8.07$$

W_{18} = predicted number of 18-kip ESALs
Z_R = standard normal deviate
S_o = combined standard error of the traffic prediction and performance prediction
SN = structural number
ΔPSI = difference between initial and terminal serviceability index
M_R = resilient modulus (psi)

The structural number is defined as an abstract number expressing the structural strength of a pavement structure:

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3 + a_iD_im_i$$

a_i = structural layer coefficient
D_i = layer thickness
m_i = layer drainage coefficient

The structural layer coefficient of aggregate base is determined by:

$$a_2 = 0.249(\log_{10} E_{BS}) - 0.977$$

E_{BS} = resilient modulus of granular base material

The value for E_{BS} is not consistent during a 12 months calendar year. It is affected by environmental effects such as moisture from rain events and freezing temperatures. The concept of effective roadbed soil resilient modulus is introduced in AASHTO 1993 to represent varying seasonal moisture conditions. It is a weighted value that gives the equivalent annual damage obtained by treating each seasonal period independently and then combining this accumulated roadbed damage to achieve a factor related to serviceability loss. This is done in four steps:

1. Analyze the seasonal moduli in their respective time periods.
2. Compute the relative damage based on each modulus.
3. Calculate the average relative damage.
4. Determine the effective resilient modulus for the time frame to be studied.

By incorporating the ADG into this approach, a layer coefficient ratio for drainage improvement can be generated. This means engineers can now include drainage improvement into AASHTO 1993, and soon AASHTO-ME.

CASE STUDIES

The following are case studies with publications for further reference into the effectiveness of this wicking geotextile on foundations requiring moisture control. Both referenced studies show the difference between the ADG installed sections and the associated controls.

Yukon Highway Project. The Yukon Department of Highways and Public Works installed an ADG in 2015 in two instrumented test sections. These sections were monitored for temperature and moisture content from 2015 to the present (January 2018). One section had a 22 m plastic edge drain pipe connected to the edge of the ADG. This section had a relatively high flow of water (2·4 ml/s) out of the edge drain pipe ~2 h after a heavy rain event. In the analyses, the authors found that the ADG increased drainage by 1·5–2·5% in comparison with the sections that were not treated with this product. The moisture content was also reduced. Figure 5 shows that the ADG decreased the moisture content by 1·0–1·5% when compared with the control section (Thiam and Bradley, 2017).

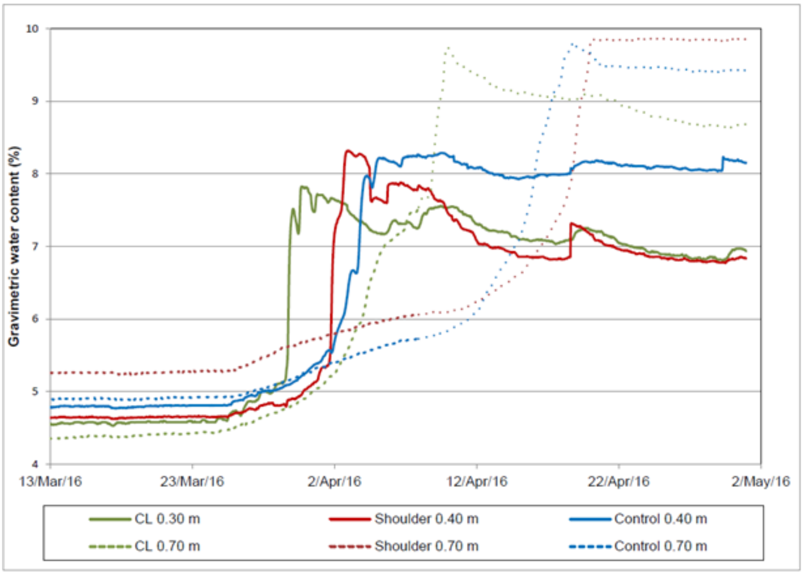

Figure 5. Measured Moisture Reduction.

Dalton Highway. In 2010, an ADG was installed on the Dalton Highway on a particularly challenging section of road called the Beaver Slide in a trial that was instrumented for temperature and moisture content. Every spring thaw, and after significant rain events, this section of road showed severe damage due to the presence of excessive moisture in the structural base materials (Figure 6). Since placement of the ADG, these issues have disappeared entirely. Figure 7 shows the same stretch of road as in Figure 6 taken one year later showing that the ADG used for the section has eliminated the damage caused by water. The moisture content map in Figure 8 shows that the upper 4 in (101·6 mm) that had thawed by May 22 had moisture contents below saturation levels (saturation of this soil is ~25–27%).

Figure 6. Moisture Induced Rutting.

Figure 7. Post Active Drainage Geosynthetic Installed Section.

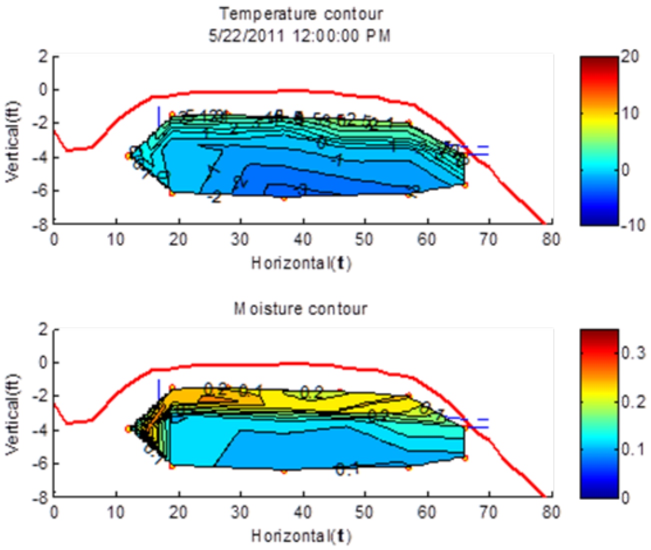

Figure 8. Measured Moisture Reduction.

CONCLUSION

Geotechnical structures are very susceptible to moisture and the typical methods of controlling moisture are proving difficult and many times ineffective. Roadway and foundation designers must consider the implications of moisture increases and the impact on greatly reduced design expectations. If design engineers can provide an effective moisture management procedure, it will lead to substantial improvements in subgrade loading characteristics.

The performance of paved and unpaved structures, such as roadways, railroads and airport runways/taxiways, will increase dramatically due to reductions in subgrade pumping and soil fines migrating into structural fill. Additionally, the shear capacities of both the foundation soils and structural fills will increase due to the reduction in moisture content.

Recent innovations in geosynthetics now allow engineers to control moisture and capillary movement in roadways and foundations. A newly engineered material is showing great promise and can be best described as an ADG. Research indicates that, with this material, it is now possible to control moisture, both at saturated and unsaturated levels, in a multitude of applications. Based on research data, there is a dramatic improvement in the structural capacity of foundations, yielding an improvement in the expected design life of the structure. Also, based on the tensile capacity and frictional interaction of the ADG, it is often possible to reduce the structural requirements of roadways or foundations to reduce the cost of the structure.

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