Improved Roadway Resilience Through the Mechanical & Hydraulic Functions of a High Modulus Geosynthetic Moisture Management System

GeoCalgary 2022 October 2-5
Reflection on Resources

René Laprade, P.Eng.
TenCate Geosynthetics Americas, Aurora, ON, Canada

ABSTRACT
Engineering resilience refers to the functionality of a system with respect to hazard mitigation. There are four properties relating to engineering resilience: (1) Robustness to withstand unforeseen demands; (2) Redundancy to tolerate the loss or damage to a component; (3) Resourcefulness to identify a problem and to respond effectively; and (4) Rapidity to restore function quickly. This paper examines the benefits that a unique geosynthetic moisture management system provides to improve the resilience of current and future civil infrastructure projects, particularly roadways and working surfaces. Several third-party research summaries are presented to illustrate the ways this moisture management system improves structures through mechanical and hydraulic stabilization. After explaining the (1) why, (2) what, (3) how, and (4) where of this one-of-a-kind geosynthetic towards improving the resilience of civil structures in saturated and unsaturated soil conditions, this paper also shows how to quantify these mechanical and hydraulic benefits in flexible pavement designs.

RÉSUMÉ
La résilience fait référence à la fonctionnalité d'un système en ce qui concerne l'atténuation des risques. Il existe quatre propriétés liées à la résilience : (1) Robustesse pour résister à des demandes imprévues ; (2) Redondance pour tolérer la perte ou l'endommagement d'un composant ; (3) Ingéniosité pour identifier un problème et y répondre efficacement ; et (4) Rapidité pour rapidement restaurer la fonction. Cet article examine les avantages d'un système géosynthétique unique de gestion de l'humidité pour améliorer la résilience des projets d'infrastructure civile actuels et futurs, en particulier les routes et les surfaces de travail. Plusieurs résumés de recherche de tiers sont présentés pour illustrer les façons dont ce système de gestion de l'humidité améliore les structures grâce à la stabilisation mécanique et hydraulique. Après avoir expliqué (1) pourquoi, (2) quoi, (3) comment et (4) où de ce géosynthétique unique en son genre pour améliorer la résilience des structures civiles dans des conditions de sol saturées et non saturées, cet article démontre également comment quantifier ces avantages mécaniques et hydrauliques dans les conceptions de chaussées souples.

1 INTRODUCTION

Resilience and sustainability are more than just buzzwords used when talking about future developments. Wise business leaders realize that you don't have to choose between what's good for business and what's good for the planet when charting an organization's path looking forward. The two terms, resilience and sustainability, are sometimes mistakenly interchanged and, for the purpose of this paper, it is important to differentiate between them. Resilience is the capacity of a system to accommodate disturbance and still retain its basic function and structure (Walker, et al. 2012). Sustainability means meeting our current needs without sacrificing the future well-being of others (Brundtland, 1987). Sustainability scholar Charles Redman explains it this way: "sustainability prioritizes outcomes; resilience prioritizes process" (Redman 2014). Bruneau et al. (2004) refer to the four properties relating to engineering resilience as: (1) Robustness to withstand unforeseen demands; (2) Redundancy to tolerate the loss or damage to a component; (3) Resourcefulness to identify a problem and to respond effectively; and (4) Rapidity to restore function quickly. Geotechnical engineering, being positioned at the beginning stages of a project, provides a tremendous opportunity for sustainable and resilient development practices. A unique moisture management geosynthetic supports designers and owners with a powerful design and operations tool that helps deliver roadways with a high level of resilience, moving the needle closer to more sustainable civil infrastructures.

2 MOISTURE MANAGEMENT GEOSYNTHETIC

A moisture management geosynthetic (MMG) which appeared in 2012 has provided mechanical and hydraulic benefits which are unique in the geosynthetics industry. This MMG is a woven high-modulus geotextile manufactured primarily out of polypropylene resin. Deep-grooved nylon wicking yarns are interspersed within its cross-machine direction weave, allowing for the adsorption and transportation of water from soil and granular materials under saturated and unsaturated conditions (Figure 1). The wicking yarns have diameters between 30 and 50 µm and each groove is approximately 5 to 12 µm wide, which means that the grooves are not blocked by an average silt sized soil particle. This allows the MMG to effectively transport water in fine-grained soils. Polypropylene is a non-polar molecule and has a wetting angle greater than 90°, which means that it is inherently hydrophobic. The wicking yarns are made of nylon, which is polar and has a wetting angle less than 90°, making it hydrophilic and hygroscopic. Engineering properties are shown in Table 1.

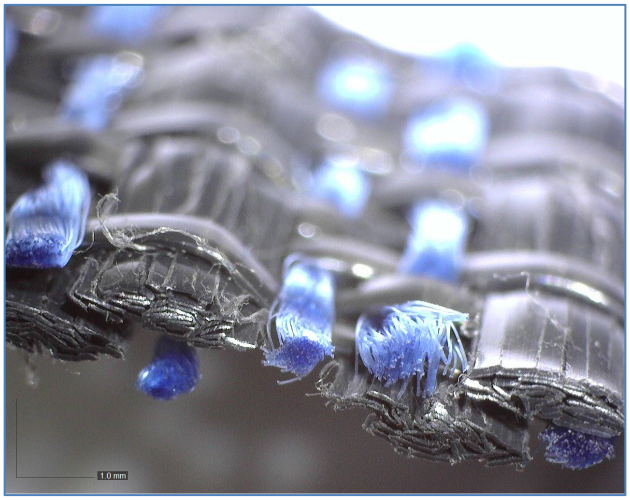

Figure 1 - Side view of Moisture Management Geosynthetic

3 MMG & RESILIENCE

According to Bruneau et al. (2004), robustness and rapidity are the desired ends that are accomplished through resilience-enhancing measures and are the outcomes that more deeply affect decision makers and stakeholders. Redundancy and resourcefulness are measures that define how resilience can be improved. Let's examine the high-modulus MMG as it pertains to providing positive benefits to the 4 R's of resilience.

MECHANICAL PROPERTIES	TEST METHOD	UNIT	MINIMUM AVERAGE ROLL VALUE	
			MD	CD
Wide Width Tensile Strength	ASTM D4595	lbs/ft (kN/m)	5280(77.0)	5280(77.0)
Wide Width Tensile Strength @ 2% strain	ASTM D4595	lbs/ft (kN/m)	480 (7.0)	1080 (15.8)
			MAXIMUM OPENING SIZE	
Apparent Opening Size (AOS)	ASTM D4751	U.S. Sieve (mm)	40 (0.425)	
MECHANICAL PROPERTIES	TEST METHOD	UNIT	MINIMUM ROLL VALUE	
Permittivity	ASTM D4491	sec^{-1}	0.4	
Flow Rate	ASTM D4491	$gal/min/ft^2$ ($l/min/m^2$)	30 (1222)	
			MINIMUM TEST VALUE	
Pore Size (050)	ASTM D6767	microns	85	
Pore Size (095)	ASTM D6767	microns	195	
Wet Front Movement [1] (24 minutes)	ASTM C1559[2]	inches	6.0 Vertical direction	
Wet Front Movement [1] (983 minutes) Zero Gradient	ASTM C1559[2]	inches	73.3 Horizontal direction	

Table 1 - Engineering properties of Moisture Management Geosynthetic

3.1 Robustness

Robustness relates to a system's ability to withstand a given level of stress or demand without suffering degradation or loss of function.

In a roadway, this can be quantified by improving its: (1) life expectancy, (2) ability to resist rutting, (3) ability to withstand differential movements from freeze-thaw cycles and the shrinking/swelling of expansive clays. According to AASHTO M288-21 (2021), a geosynthetic delivers subgrade stabilization when it provides the coincident functions of reinforcement, separation, and filtration. High-modulus woven geotextiles have proven their worth in providing robustness through stabilization to roadways over several decades through their capacity to offer these three functions. There are several other measures of robustness for roadways and civil structures that will not be covered in this document.

3.2 Rapidity

Rapidity is the capacity to meet priorities and achieve goals in a timely manner to contain losses and avoid future disruption.

In their triaxial testing on base course materials, Lin et al. (2016) showed that a 2% reduction in moisture content from optimum compaction levels increased the resilient modulus by more than 200%. They further demonstrated that a 2% increase in moisture content from optimum compaction levels could increase pavement deformation by up to 400%. Including a system that works in conjunction with the granular base course, which can more thoroughly evacuate moisture from the roadway, will certainly increase the rapidity with which the system can return to its intended performance. This is especially true in an unsaturated condition, where conventional drainage methods are no longer effective once the granular materials and subgrades are no longer saturated.

3.3 Redundancy

Redundancy relates to the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality.

There are two ways of viewing redundancy in our context. The first is looking at whether another system or geosynthetic is substitutable to the MMG. From this point of view, the MMG is not substitutable as there are no other system or geosynthetics which can remove moisture from a roadway or civil structure in unsaturated conditions. It is unique in that respect.

Water drainage within a roadway structure is primarily accomplished through the inclusion of a good quality base course material placed on a subgrade which has been graded at a crossfall, typically in the 2% to 3% range.

Ideally, this approach is sufficient to ensure the longevity of a roadway. What happens if the subgrade is weaker than what the structure was originally designed for? Subgrade rutting becomes a real concern. Water may be allowed to pool in the ruts, which exacerbates the problem. Similar problems can occur when high amounts of fines are included in the granular base/sub-base materials. Water will make matters worse as free drainage suffers. Including the MMG within such structures provides redundancy on two levels. First, the mechanical stabilization benefits can offset the weaker supporting subgrade, minimizing premature rutting. Second, the enhanced hydraulic stabilization function will provide additional drainage to the pavement structure, thus providing redundancy in terms of removing water.

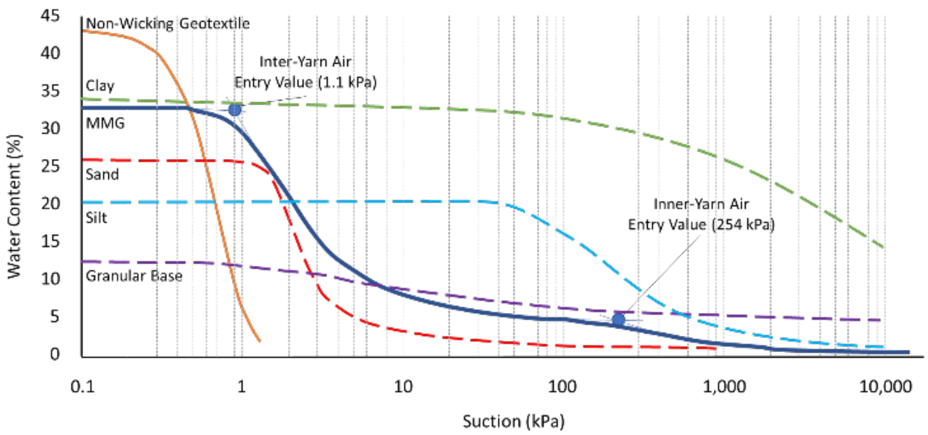

Figure 2 - Soil & Geotextile Water Characteristic Curves (Lin et al. 2015)

3.4 Resourcefulness

Resourcefulness refers to the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis.

Moisture/water is the #1 threat which causes premature roadway deterioration. It's easy to conclude that a system that can remove excess water from such civil structures and prevents rutting and surface cracking is a very resourceful addition. The MMG's previously mentioned exceptional ability to remove moisture in saturated and unsaturated conditions makes it an especially resourceful means that designers can add to their arsenal of design tools, and owners can include in their roadway assets.

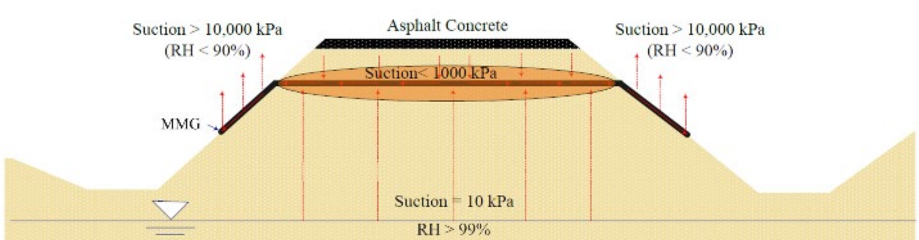

Figure 3 - Relative humidity levels in and around a roadway (Zhang et al. 2014)

4 HYDRAULIC MECHANISM OF THE MMG

The wicking yarns of the MMG are hydrophilic and hygroscopic. This means that the small pore sized yarns attract water both in liquid and vapour states, absorb and adsorb this water until a suction draw pulls this moisture out of the geosynthetic. These small openings within the deep grooves lead to high air-entry suction values and they can generate higher capillary forces. In other words, these grooves remain saturated under unsaturated conditions and have a high ability to hold and transport water compared with a conventional non-wicking geotextile. Lin et al. (2015) determined that the inner-yarn air entry value for the MMG is approximately 250 kPa. This means that the MMG is capable of drawing water out of any soil until that soil's reduced moisture content causes it to reach a suction value of 250 kPa. Figure 2 shows the Soil Water Characteristic Curves (SWCC) for various soils as well as the Geosynthetic Water Characteristic Curves for the MMG and another high-modulus geotextile without wicking capabilities.

To illustrate the meaning of these curves, the MMG has the capacity of reducing the moisture content of the fully saturated silt from approximately 20% to approximately 10%. Clays, especially those with high plasticity indices, have inherently higher suction. This means that the overall moisture reduction is less than in cohesive materials such as silts and sands. However, according to Budhu (2008), the undrained shear strength of fine-grained soils can increase by about 20% for every 1% reduction in moisture content. Based on this statement, even a 3% to 4% reduction in moisture content in cohesive soils can have a tremendously positive impact on the soil's bearing capacity.

Having seen the way by which the MMG attracts water to its wicking yarns, we now need to understand how moisture is removed from the geosynthetic. In simple terms, the process is dependant on suction and relative humidity. Figure 3 shows a roadway cross-section with levels of relative humidity within and outside the structure, Zhang et al. (2014).

Suction is inversely proportional to relative humidity. As relative humidity levels within the soil and the MMG are typically greater than 95% and the relative humidity of the air around roadways is relatively low (typically lower than 50%), this relative humidity difference can generate large suction gradients within the geotextile. Zhang et al. (2014) pointed out that the suction in an unsaturated soil within a pavement system is typically less than 1,000 kPa, while the suction in the MMG induced by the relative humidity difference can range from 1,000 to 100,000 kPa. This suction difference between the MMG and the soil can draw water out of the soil and transport it to the exposed portion of the geosynthetic. Also, owing to the relative humidity difference between the MMG and the air, some of the water evaporates when exposed to the air and the remainder drips freely at the end of the geosynthetic. This process continues until the moisture content of the soil decreases and the soil suction equals the suction in the MMG.

5 SATURATED VS. UNSATURATED WATER FLOW

There are several ways of removing water from roadways that have been used for decades. The primary way is via surface runoff of a paved roadway. However, there is a significant amount of water that finds its way into aggregate base and subbase materials via infiltration through cracks and joints in the asphalt or concrete surface, as well as through roadway shoulders. In such cases, the rate of drainage depends on the quality of the aggregate materials. AASHTO (1993) rates aggregate materials on a sliding scale from Excellent (water is removed within 2 hours) to very poor (water will not drain).

This approach only considers water in saturated ground conditions; that is where every open pore space of the aggregate materials is filled with water. The effectiveness of an aggregate backfill in removing water in unsaturated conditions, where pore water pressures are negative, is greatly diminished. Standard geosynthetic materials such as polypropylene nonwoven geotextiles and geocomposites (a combination of nonwoven geotextile laminated to a drainage composite) are excellent at draining water in saturated conditions. However, their effectiveness is also significantly reduced in unsaturated conditions due to the hydrophobic nature of their polymer constituents.

Zhang et al. (2009) conducted some laboratory rainfall infiltration soil column tests which compared the drainage performance and behaviour of saturated columns of silt underlain by four different geosynthetics. There were two woven geotextiles, on geocomposite and the MMG. Figure 4 shows the results of the tests.

The MMG removed significantly more water than the other geosynthetics. The researchers concluded that "the differences in moisture content distributions in the soil columns are therefore mainly caused by unsaturated water flow induced by suction head difference". This is an

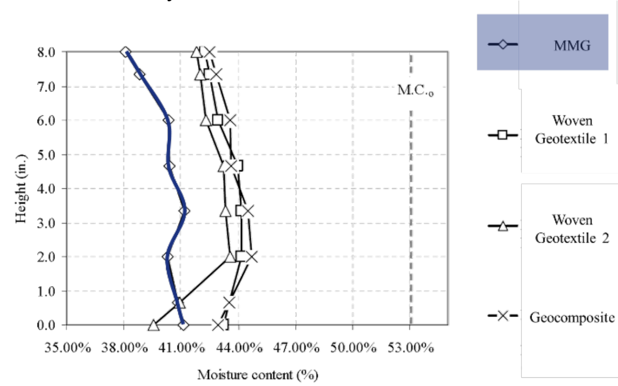

Figure 4 - Results of the University of Alaska rain infiltration tests (Zhang et al. 2019)

important conclusion as at the time of writing, the MMG is the only available geosynthetic capable of removing water in unsaturated conditions.

6 QUANTIFYING THE MECHANICAL & HYDRAULIC BENEFITS OF MMG

As the MMG provides both mechanical and hydraulic gains to roadways, it becomes valuable to quantify these in roadway design methodologies.

Moisture content of unbound aggregate base has a significant impact on both resilient and permanent strains of the material. Lekarp et al. (2000a and b) concluded from numerous previous studies that a combination of high degree of saturation and low permeability leads to high pore-pressure and low effective stress and consequently low stiffness, strength, and deformation resistance. They further added that the presence of moisture in an aggregate matrix has some lubricating effect.

6.1 Flexible Pavements

The AASHTO Guide for Design of Pavement Structures (AASHTO, 1993) and the Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO, 2008), are the most commonly used design methods for flexible pavements in North America. Both rely on the resilient modulus of the aggregate base to design a pavement. Both methods also consider the moisture effect on the aggregate base. In the 1993 AASHTO method, a drainage factor for the base layer is required in the calculation. In the MEPDG method, the resilient modulus of an unbound base is adjusted by the environmental effect model, which also takes the moisture of the base into consideration. As the MEPDG does not currently have a direct way of incorporating the benefits of geosynthetics, we will focus on 1993 AASHTO in this paper.

6.1.1 Mechanical Benefits

Geosynthetics have been designed into flexible pavement systems since the early 1980's (Hamilton et al 1982). Lacina et al. (2015) conducted full-scale accelerated load frame pavement testing on high-modulus woven geotextiles. The performance of those tests combined with other work by Hamilton et al. (1982) to account for the mechanical benefits provided by high-modulus woven geotextiles, including the MMG, in base reinforcement applications at different traffic levels and subgrade conditions. The results of this work provided Geosynthetic Structural Coefficient (GSC) values which can be applied to the structural number of the granular layer directly overlying the geosynthetic. This approach also meets the requirements of AASHTO R50-09 which states "because the benefits of geosynthetic reinforced pavement structures may not be derived theoretically, test sections are necessary to obtain benefit quantification." (AASHTO, 2018).

6.1.2 Hydraulic Benefits

Guo et al. (2017) 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 MMG. They also carried out six large-scale cyclic plate loading tests with rainfall simulations to evaluate the effect of the MMG on the permanent deformations of base courses over subgrades. These tests provided the relationships between base course water content and drainage time. They provided design guidelines incorporating the water content reduction benefit of the MMG which allowed for further modification of the 1993 AASHTO Pavement Design Guide as well as guidance to eventually incorporate the hydraulic benefits of the MMG into the AASHTO Mechanistic-Empirical Pavement Design Guide.

The work done by Guo et al. allows designers to incorporate historical local precipitation data to generate a Hydraulic Improvement Factor (HIF). This value can be obtained for any geographic location in North America. It is dependent on (1) frequency and duration of saturation rain events, (2) seasonal temperatures, (3) traffic load expectancy, and (4) structural integrity of the granular layer overlying the MMG. Figure 5 shows an example of North American HIF values for specific subgrade and traffic loading conditions.

6.2 Unpaved Roads

Giroud et al. (2004) developed a base course thickness design method, known as the Giroud-Han Method, for unpaved roads that considers distribution of stress, strength of base course material, interaction between geosynthetic and base course material, and geosynthetic in-plane stiffness. These are in addition to the conditions considered in previous methods: traffic volume, wheel loads, tire pressure, subgrade strength, rut depth, and influence of the presence of a reinforcing geosynthetic on the failure mode of the unpaved road or area. As the design method is theoretically based and experimentally calibrated, it more accurately predicts performance both for

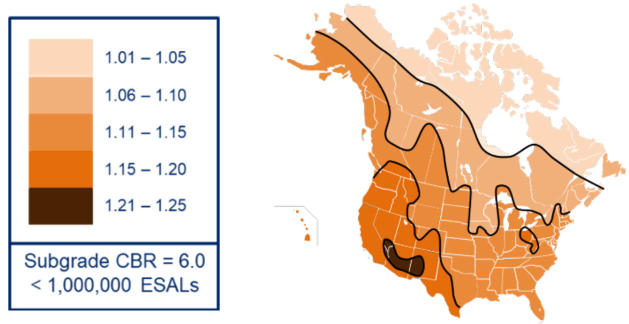

Figure 5 - HIF values for North America

geosynthetics-reinforced unpaved roads and for unreinforced unpaved roads than do earlier methods.

Full-scale laboratory cyclic box testing by Schwarz et al. (2011 (a) & (b), 2012) provided the necessary product calibration for several high-modulus woven geotextiles, including the MMG, for inclusion into the Giroud-Han method to provide accurate unreinforced and reinforced designs of unpaved roadways for over a decade.

The mechanical and hydraulic stabilization benefits obtained through the testing programs mentioned in sections 6.1 and 6.2 have been incorporated in an online design program available to registrants (TenCate MiraSpec Road Design Software, 2014). It allows users to perform flexible pavement designs using the 1993 AASHTO approach, as well as the CalTrans approach. The software performs unpaved roadway analyses following the Giroud-Han (2004) approach. Each of these approaches incorporates the manufacturer's engineered high modulus woven geotextiles, including the MMS.

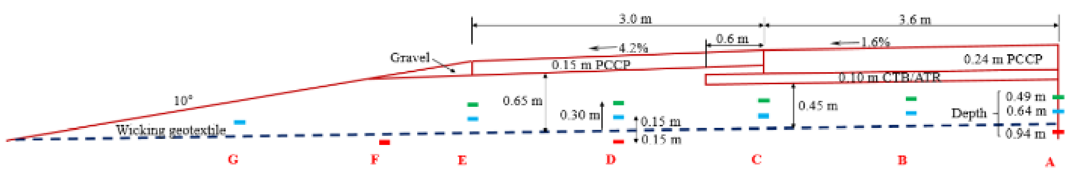

Figure 6 - Test sections 1 & 3 (Han et al. 2021)

7 APPLICATIONS

The MMG provides resilience in pavement systems and has been used to mitigate the effects of water in the following situations: (1) high water tables, (2) excessive moisture in subbase and/or base, (3) excess moisture in subgrade, (3) expansive clays, (4) frost susceptible soils. What follows are research summaries of such applications.

7.1 High Water Tables

The research team at the University of Kansas has conducted a series of laboratory tests to evaluate the effectiveness of the wicking geotextile to remove water in the Kansas aggregate base material (specifically the AB-3 aggregate) (Guo et al., 2017; Wang et al., 2017). The results verified the effectiveness of the MMG in reducing water content in aggregate base materials. Other researchers have also conducted laboratory tests (Lin and Zhang, 2018; Lin et al., 2019) and limited field studies (Connor & Zhang, 2015) to evaluate the effectiveness of the MMG. These studies focused on the use of the MMG in unpaved and asphalt paved roads.

Prior to incorporating the MMG in its concrete pavements, the Kansas Department of Transportation wanted to conduct an instrumented trial section. They decided to conduct a research project with the MMG on the re-construction of a badly deteriorated concrete pavement on US-169 in Allen County, Kansas. This project was completed in 2018 (Han et al. 2021).

The main objective of this project was to verify the effectiveness of the MMG to minimize capillary rise and reduce water content in pavements in the field with high groundwater tables. The test sections for the field trial were designed to answer three important questions: (1) whether the MMG can replace cement treatment of the natural subgrade, (2) whether the MMG can maintain low water content in the aggregate base, and (3) whether the aggregate type affects the effectiveness of the MMG. To answer these questions, moisture sensors were installed in the test sections to monitor the water content changes during a two-and-a-half year monitoring period.

Three test sections were constructed for this project. Sections I and III consisted of a subgrade, the MMG, a 0.45-m thick aggregate base, a 0.10-m cement treated base (CTB), and a 0.24-m thick Portland Cement Concrete Pavement (PCCP). However, the shoulder consisted of a subgrade, the MMG, a 0.65-m thick aggregate, and a 0.15-m thick PCCP. The transverse slopes for the lane and the shoulder were 1.6% and 4.2%, respectively to remove water on the pavement and shoulders quickly. Section II consisted of a subgrade, a nonwoven geotextile, a 0.30-m thick cement treated subgrade, a 0.15-m thick aggregate base, and a 0.24-m thick PCCP while the shoulder consisted of a subgrade, a 0.30-m cement treated subgrade, a 0.34-m thick aggregate base, and a 0.15-m PCCP. The red, blue and green dashes in Figures 6 and 7 indicate where the moisture sensors were placed within the test sections.

Test sections 1 and 2 used KDOT AB-1 aggregate base, while section 3 used AB-3 aggregate base. AB-3 aggregate base typically has more fines and higher Atterberg limits than AB-1 (Table 2).

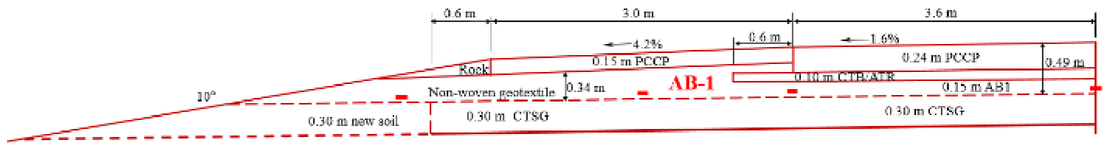

Figure 7 - Test section 2 (Han et al. 2021)

	% Retained - square mesh sieves									Plactic	Liquid
	50 mm	38 mm	25 mm	19 mm	10 mm	5 mm	3 mm	425 µm	75 µm	Index	Limit
AB-1	0	0-10		5-40		35-75	54-85	78-95	90-98	0-6	25
AB-3	0	0-5		5-30		35-60	45-70	60-84	80-92	2-8	30

Table 2 - Comparison of AB-1 & AB-3 aggregates (Han et al. 2021)

7.1.1 Test Results

The authors (Han et al. 2021) published the following conclusions from the two-and-a-half-year project:

- The AB-3 aggregate contained more fine particles than the AB-1 aggregate. It slowed water infiltration but kept moisture for longer than AB-1 aggregate due to slower gravitational drainage.
- The MMG was more effective at minimizing the capillary rise than the cement treated subgrade.
- During drying periods, the volumetric water content (VMC) in the aggregate with the MMG was lower than the section with the nonwoven geotextile.
- Unsurprisingly, the MMG did not prevent the water table from rising above it. When the water table remained below it, the MMG minimized capillary rise of ground water.
- The MMG reduced the VMC beyond the point that gravitational drainage could do in the aggregate base materials.
- The zone of influence of the MMG in the AB-1 and AB-3 aggregates was a minimum 300 mm.

7.2 Excess Moisture in Subgrade

The beneficial effects of the MMG in reducing moisture in subgrades was discussed in Section 4. As moisture contents of soils decrease, their matric suction values increase. Matric suction increases with decreasing soil particle size. The Soil and Geosynthetic Water Characteristic Curves of the MMG and various soil types show that the MMG can apply suction to soils up to an air entry value of approximately 250 kPa.

7.3 Excessive Moisture in Subbase and/or Base

Guo et al. (2017) performed cyclic loading plate tests on (1) the MMG, (2) another woven high-modulus geotextile without moisture management capabilities, (3) a control section. The loading tests with simulated rainfall were conducted in a large test box having a dimension of 2 m x 2.2 m x 2 m (WxLxH). Each test section consisted of a 0.9 m thick subgrade layer and a 0.3 m thick base course layer. The geosynthetics were placed at the subgrade/base interface and moisture sensors and pressure cells were placed as per Figure 8. The subgrade was 25% kaolin and 75% Kansas River sand by weight and the base was the same AB-3 aggregate material as for the high-water table tests. Three separate simulated rainfall events were conducted, and the system allowed to rest for set amounts of time after each rainfall before conducting the cyclic plate loading tests. The first rainfall occurred, and the system was allowed to rest for 7 days. Cyclic plate loading took place afterwards for approximately 15 hours. A two-day delay followed a second rainfall event, at which point a second cyclic plate load test was conducted for two days.

A third cyclic plate load test took place for two hours after the third rainfall. Subgrade CBR values for each set of tests were set at 3% and 5%.

7.3.1 Results

Published conclusions of the tests were:

- The inclusion of the MMG significantly increased gravitational drainage.
- The MMG increased the rate of water content in the base course during the drying period following rainfall simulations.
- The MMG significantly reduced the permanent deformation of the test sections, especially in the first loading test at seven days after the first rainfall simulation.
- The MMG reduced the water content in the base course below those of the control sections and the non MMG woven high-modulus woven geotextile. In fact, the MMG reduced the water content in the AB-3 aggregate to levels that were below optimum compaction water contents.

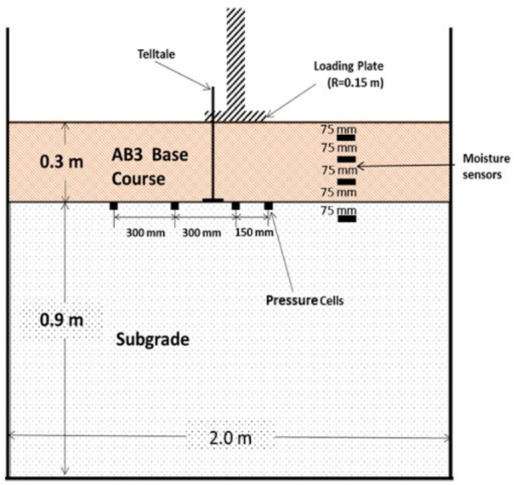

Figure 8 - Cross-section of cyclic loading plate tests (Guo et al. 2017)

7.4 Expansive Clays

The deterioration of pavement performance because of rutting, cracking, and differential heaving is a regular phenomenon in areas where expansive soils are present. These pavements experience distress due to the high swelling and shrinkage characteristics of high plasticity clays. Biswas et al. (2021) conducted small-scale laboratory and full-scale field studies with the MMG in an expansive clay area. The focus here is on the full-scale field studies.

7.4.1 Test Sections

Three sections were constructed for this test. The subgrade for each section was classified as a high plasticity clay (CH) in accordance with the Unified Soil Classification System. It had a free swell strain of 8.5%, indicating the high swelling potential of the soil. The control section included reclaimed asphalt pavement (RAP), while one test section included the MMG with RAP and a second section included the MMG with traditional crushed aggregate. These sections were constructed and monitored on a two-lane farm to market highway near Venus, TX. Instrumentation consisted of earth pressure cells, shape array accelerometers and moisture sensors. TxDOT design engineers commonly use FPS21, a linear analysis-based software (LEA), as a design tool for pavements. Input parameters are shown in Table 3.

One of the main limitations with this tool is its inability to include the benefits of geosynthetics on pavement layers. The authors decided to use an improvement factor of 2.2 based on Lin, et al. (2019). The modulus and Poisson's ratio of the asphalt and RAP aggregates considered in this study were obtained from Khan et al. (2020). The unbound resilient modulus for TxDOT Grade-1 FB material was estimated corresponding to standard crushed rock aggregates.

7.4.2 Results

The authors reached the following conclusions:

- The moisture contents of the base and subgrade layers in both test sections treated with MMG were substantially lower than the control section.
- During the rainfall event, the two test sections exhibited a different pattern of moisture redistribution. The subgrade soil and the base layer of Test Section 1 (RAP) indicated higher moisture content after a rainfall event as compared with Test Section 2. This was primarily attributed to the different natures of the two base materials as well as the natural soil gradient, and the presence of a drainage ditch.
- After 18 months of monitoring, the permanent deformation of the two MMG test sections was lower than the control section by 35 to 70%.
- The in-situ stresses recorded at the top of the subgrade were lower than the stresses calculated from LEA. The authors observed that the

Description	Parameters	Test Section 1 RAP Aggregate Base	Test Section 2 Traditional Aggregate Base	Control Section
Asphalt layer	Thickness (mm)	50	50	50
	Modulus (MPa)	3450	3450	3450
	Poisson's ratio	0.4	0.4	0.4
Base layer	Thickness (mm)	375	375	375
	Modulus (MPa)	275	350	275
	Poisson's ratio	0.3	0.3	0.3
Subgrade	Thickness (mm)	300	300	300
	Modulus (MPa)	135	135	135
	Poisson's ratio	0.3	0.3	0.3

Table 3 - Design & construction parameters (Biswas et al. 2021)

reinforcement and drainage ability of the MMG potentially improved the overall stiffness of the pavement layers. The rutting life of the test sections estimated from the field results was higher than the values predictions from LEA.

8 CONCLUSION

As the trend is towards sustainable construction practices and more resilient roadways, the need for innovative approaches has never been greater. Systems like the Moisture Management Geosynthetic discussed in this paper are an example of looking at things differently. Designers can now look at incorporating this system into their designs while quantifying how the MMS will benefit their client, mechanically and hydraulically. These benefits can be made from a structural perspective, where a designer can compare different physical layouts to optimize their solutions to clients. Additionally, these benefits can be customized to the exact geographic location of a project, as precipitation and temperatures are quite variable throughout North America. A few applications were discussed. It is simpler, however, to think of the locations where the MMG can provide quantifiable benefits this way: If water can affect a civil structure, the MMG can improve its performance and/or life expectancy.

9 REFERENCES

American Association of State Highway and Transportation Officials. 1993. *AASHTO Guide for Design of Pavement Structures*, The Association.

AASHTO Designation: M 288-21. 2021. *Standard Specification for Geosynthetic Specification for Highway Applications*, American Association of State Highway and Transportation Officials.

Biswas, N., Puppala, A., Khan, M.A., Congress, S.S.C., Banerjee, A. and Chakraborty, S. 2021. *Evaluating the Performance of Wicking Geotextile in Providing Drainage for Flexible Pavements Built over Expansive Clays*, Journal of the Transportation Research Board.

Brundtland, G. 1987. *Report of the World Commission on Environment and Development: Our Common Future*, United Nations General Assembly Document A/42/427.

Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, Ml, Tierney, K., Wallace, W. and Von Winterfeldt, D. 2004. *A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities*, 13th World Conference on Earthquake Engineering.

Budhu, M. 2008. *Soil Mechanics and Foundations*, Wiley.

Connor, B. and Zhang, X. 2015. *Evaluate H_2RI Wicking Fabric for Pavement Application*, Research report, the University of Alaska.

Giroud, J.P. and Han, J. 2004. *Design Method of Geogrid-Reinforced Unpaved Roads. I. Development of Design Method*, Journal of Geotechnical and Geo-environmental Engineering, ASCE, Vol. 130, No. 8, 2004, pp. 775-786.

Guo, J., Wang, F., Zhang and X., Han, J. 2017. *Quantifying Water Removal Rate of a Wicking Geotextile Under Controlled Temperature and Relative Humidity*, ASCE Journal of Materials in Civil Engineering.

Hamilton, J. M. and Pearce, R. A. 1982. *Guidelines for Design of Flexible Pavements Using Mirafi® Woven Stabilization Fabrics*, Law Engineering.

Han, J., Liu, H., Al-Naddaf, M., Parsons, R., Kakrasul, J.I. and Zhang, X. 2021. *Field Monitoring of Wicking Geotextile for Moisture Reduction in Pavements*, The University of Kansas & Missouri University of Science and Technology.

Khan, M. A., Biswas, N., Banerjee, A. and Puppala, A.J. 2020. *Field Performance of Geocell Reinforced Recycled Asphalt Pavement Base Layer*, Transportation Research Record Journal of the Transportation Research Board, 2674: 69–80.

Lacina, B., Sack, R., and Odgers, B. 2015. *Flexible Pavement Reinforcement using Geotextiles*, 2015 Geosynthetics Conference.

Lekarp, F., Isacsson, U. and Dawson, A. 2000a. *State of the art. I: Resilient response of unbound aggregates*, Journal of Transportation Engineering, 126(1), 66-75.

Lekarp, F., Isacsson, U. and Dawson, A. 2000b. *State of the art. II: Permanent strain response of unbound aggregates*, Journal of Transportation Engineering, 126(1), 76-83.

Lin, C. and Zhang, X. 2018. *Laboratory Drainage Performance of a New Geotextile with Wicking Fabric*, Journal of Materials in Civil Engineering.

Lin, C., Zhang, X. and Han, J. 2019. *Comprehensive Material Characterizations of Pavement Structure Installed with Wicking Fabrics*, Journal of Materials in Civil Engineering, Vol. 31, No. 2, 2019, p. 04018372. http://ascelibrary.org/doi/10.1061/%28ASCE%29MT.1943-5533.0002587.

Redman, C. 2014. *Should sustainability and resilience be combined or remain distinct pursuits?*, Ecology and Society.

Schwarz, L. 2011. *A Laboratory Evaluation of the Performance of TenCate Mirafi® Geosynthetics in Roadway Stabilization Applications – Georgia Silt Subgrade*, GeoTesting Express.

Schwarz, L. 2011. *A Laboratory Evaluation of the Performance of TenCate Mirafi® Geosynthetics in Roadway Stabilization Applications – Montana Clay Subgrade*, GeoTesting Express.

Schwarz, L. and Christopher, B. 2012. *A Laboratory Evaluation of the Performance of TenCate Mirafi® Geosynthetics in Roadway Stabilization Applications with GA Silt at CBR 2*, GeoTesting Express.

TenCate MiraSpec Road Design Software. 2014. http://fpd.tcmirafi.net/.

Walker, B. and Salt, D. 2012. *Resilience Practice*, Island Press.

Wang, F., Han, J., Zhang, X. and Guo, J. 2017. *Laboratory Tests to Evaluate Effectiveness of Wicking Geotextile in Soil Moisture Reduction*, Geotextiles and Geomembranes.

Zhang, X., Presler, W., Jones, D. and Odgers, B. 2014. *Use of Wicking Fabric to Help Prevent Frost Boils in Alaskan Pavements*, American Society of Civil Engineers.