Impact of Pavement Drainage Design Practices on Subsurface Moisture and Stiffness

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ABSTRACT: Pavements are surface structures constructed above the ground water table and are routinely exposed to seasonal climate conditions. Subsurface equilibrium water contents under the pavement are generally below saturation and thus, are more consistent with unsaturated rather than ground water aquifer hydrology. However, current pavement drainage design is based on saturated flow models and thus does not appear to have a broad application for pavement subsurface drainage. Data from the Minnesota Road Research test facility (MnROAD) and from a State Aid highway project were used to investigate the effect of drainage design on pavement performance, and the effects of a new Geocomposite Capillary Barrier Drain on pavement base and subgrade moisture and stiffness. The studies and data presented show that the moisture conditions in the pavement subsurface layers are primarily unsaturated. It is also shown that conventional pavement drainage designs based on saturated flow had little influence on the pavement base and subgrade moisture content and material stiffness. It appears that the pavement drainage design presently recommended by the Federal Highway Administration has little influence on material stiffness. Instead, pavement stiffness is controlled by the material properties of the base and the subgrade and to some extent by climate conditions.

KEYWORDS: Pavement design, drainage, unsaturated, material properties.

1.0 INTRODUCTION

Pavement structures are typically layered systems consisting of a surface layer of asphalt placed over a layer of aggregate material (base), over a compacted soil (subgrade). Pavement layer thicknesses and geometry vary depending on traffic volumes, available materials, and regional climate. Regardless of the variation in regional design, excess moisture in pavement base and subgrade materials has long been recognized as a major source of pavement distress and failure. Moisture infiltrates the pavement layers through joints and cracks, it enters as vapor transport from the capillary fringe, and as seepage from embankments. Manifestations of moisture related distresses in asphalt pavements include rutting, potholes, longitudinal and shrinkage cracking. These moisture related distresses not only diminish the structural integrity of the asphalt pavement but also lead to a decrease in the base and subgrade strength and stiffness.

Pavement drainage through good drainage design has been promoted as a solution to addressing moisture related distress in pavements. Drainage design models, based on ground water aquifer hydrology (ERES, 1999; Federal Highway Administration, 1994; Al-Qadi, 2003), have been developed to aid in the design process. The Federal Highway Administration (FHWA) developed the analytical model, *Drainage Requirements in Pavements (*DRIP), for pavement drainage design purposes (Mallela et al., 2001;, Moulton, 1980). DRIP is a 1-dimensional solution for computing a time to drain criteria based on the outflow of the base layer. Theoretical relationships and mathematical formulations developed by Casagrande and Shannon (1951) form the basis for the DRIP software. The progression of drainage through the pavement base layer is a function of the material's effective porosity and the width or length of the drainage layer (ERES, 1999; Al-Qadi, 2003; Christopher and Zhao, 2001; Roberson, 2007). Typically pavement drainage design methods use time-to-drain as the design variable that determines the quality of drainage (i.e. Excellent, Good, Fair, or Poor), the efficacy of the drainage system (system capacity), and thus pavement performance (layer strength and stiffness).

There are studies showing that water content in pavement aggregate base and subgrade layers are below saturation and thus flow is more consistent with unsaturated hydrology than ground water and aquifer hydrology (Oloo and Fredlund, 1998; Birgisson and Roberson, 2000; Rainwater et al., 2001). Under unsaturated conditions the hydraulic conductivity and water storage constants, commonly used in ground water hydrology, become non-linear functions and calculation of water flow becomes more complex (Schwartz and Zang, 2003; Boulding and Ginn, 2004). Additionally, local climate parameters and resultant surface-atmosphere interactions, such as evapotranspiration and freeze-thaw cycles, influence hydraulic potential and in turn water flow.

1.1 Objectives

The objectives of this research were to evaluate the effect of drainage practices on base and subgrade water content and stiffness. The specific objectives include: Evaluating (1) the effect of four drainage designs on pavement layer water content and stiffness, and (2) the effects of a geocomposite capillary barrier drain on pavement base and subgrade moisture and stiffness.

2.0 EFFECTS OF DRAINAGE DESIGN ON WATER CONTENT AND LAYER STIFFNESS

2.1 Pavement Drainage Design

The long-term performance of four pavement sections constructed with different subsurface drainage systems was investigated. The four test sections were constructed on Blue Earth County State Aid Highway 26, east of Mankato, Minnesota. One section was constructed without an edge drain system and three were constructed with an edge drain system. Test Section 1 (Control) is a typical undrained HMA pavement section, Test Section 2 (County Design) is a drained pavement designed according to Blue Earth County edge drain design procedures, Test Section 3 (MnDOT) is a drained pavement based on a "modified" MnDOT edge drain designs, and Test Section 4 (InvertOGAB) is an inverted open graded aggregate base design. All the test sections were paved with 140 mm of HMA, but differed in the depth of the drain pipe, distance to the pavement centerline (CL), and the type of trench backfill material (Table 2.1.1).

Inflow to the drainage system, material drainage characteristics, and pipe capacity were estimated using the Federal Highways Administration (FHWA) Drainage Analysis and Modeling Program (DAMP) Version 1.1 (FHWA-IP-90-012, 1990). DAMP is the precursor to the current FHWA pavement drainage design DRIP model (Mallela et al., 2001; Moulton, 1980). The model is used to calculate a time-to-drain criteria based on formulations developed by Cassagrande and Shannon (1951). Time to drain was computed for the aggregate base drainage layer for the four pavement sections. The dense graded base (DGB) had a saturated hydraulic conductivity of 1.13 x 10^{-3} cm/sec and an effective porosity (n_e) of 0.16. The time to drain 50% of the drainable water from this layer was 483 hours. According to drainage quality standards (ERES, 1999) this layer classifies as "poor" draining. The time to drain of open graded aggregate base (OGB) layer with a saturated hydraulic conductivity of 1.66 cm/sec and an n_e of 0.23, was 0.67 hours for 50% of the drainable water; giving this layer, a drainage classification of "excellent". Water content and pavement layer stiffness moduli measurement were made using a falling weight deflectometer (FWD) on each test section.

Table 2.1.1: Summary of pavement sections drainage designs.

a: HMA = hot mixed asphalt, DGB = dense graded base, and OGB = open graded base.
b: CL = centerline. c: na = not applicable. d: drainage quality classification refers to the AASHTO (1985) drainage recommendations.

Section	[a]Layer	Thickness (mm)	Lane Width (m)	[c]Pipe Depth (m)	[b,c]Distance from CL (m)	[c]Pipe Location	[d]Quality of Drainage Classification
Control	HMA	140	4	na	na	na	
	DGB	300	--	--	--	--	poor
County	HMA	140	4	1.7	5	Under shoulder	
	DGB	300	--	--	--	--	poor
MnDOT	HMA	140	4	1.4	4	Under lane-shoulder joint	
	DGB	300	--	--	--		poor
InvertOGAB	HMA	140	4.3	1.4	4	Under pavement	
	DGB	200	--	--	--	--	poor
	OGB	100	--	--	--	--	excellent

2.2 Effects of Pavement Drainage on Water Content

Table 2.2.1 summarizes the water contents measured in the aggregate base and subgrade. These data are the average of 11 measurements along the length of the test section; in general the pattern of increase and decrease in moisture content over the three years is about the same for all sections. In the aggregate base there is little difference in the water content within and between test sections, although the OGB moisture content is always slightly lower than the DGB water content in the InvertOGAB section. The DGB water content decreases from the fall of 1990 to the spring of 1991, and then increases from the spring of 1991 to the spring of 1995 in all test sections. The greatest decrease (-2.4%) and increase (0.8%) occurred in the MnDOT modified test section.

The subgrade water content decreased over the three year period in all four test sections (Table 2.2.1). In the four test sections the greatest change in water content occurred between the initial subgrade moisture content (fall of 1990) and those measured in the spring of 1991. The greatest decrease in subgrade moisture content was -10.9% in the Control section, followed by the County (-8.1%), MnDOT (-7.7), and the InvertOGAB (-5.7%). The subgrade water content ranking among various drainage treatments was the same in all three years. The pattern of decreasing water content in the subgrade was also in the north and south direction along the roadway. The reasons for this trend are not apparent, because the grade change across the project was only 1% and the water table was well below the surface.

Precipitation was lower than normal in the fall of 1990 when the water contents were highest both in the base and subgrade layers. A precipitation high of 382 mm occurred in the spring of 1991, however an increase in precipitation from the fall of 1990 to the spring of 1991 actually corresponds to the biggest decrease in water content in both the base and subgrade for all four test sections. The expected impact of this annual precipitation pattern on the water content in the undrained Control section would be an increase in water content in the aggregate base and subgrade between the fall of 1990 and spring of 1991. Precipitation appears to have a minimal effect on the base and subgrade moisture content. It appears that material properties and surface- atmosphere interactions have greatest influence on water content rather than the presence or absence of a drainage system.

Table 2.2.1: Average gravimetric (g/g) water content measured in the pavement aggregate base and subgrade soil.

	Fall 1990	**Spr 1991**	**Spr 1995**	**Difference F'90 to Spr'91**	**Difference Spr'91 to Spr'95**	**Net change**
	Avg (%)	**Avg (%)**	**Avg (%)**	**%**	**%**	**%**
Control						
DGB	6.5	5.2	5.3	-1.3	0.1	-1.2
Subgrade	26.5	15.6	12.4	-10.9	-3.2	-14.1
County Design						
DGB	6.0	5.0	5.5	-1.0	0.5	-0.5
Subgrade	25.1	17.0	14.3	-8.1	-2.7	-10.8
MnDOT Modified						
DGB	7.8	5.4	6.2	-2.4	0.8	-1.6
Subgrade	25.1	17.4	15.4	-7.7	-2.0	-9.7
Inverted OGAB						
DGB	6.3	5.6	5.9	-0.7	0.3	-0.4
OGAB	5.7	4.3	5.7	-1.4	1.4	0
Subgrade	21.9	16.2	14.5	-5.7	-1.7	-7.8

2.3 Effects of Pavement Drainage on HMA, Base, and Subgrade Resilient Response

Resilient modulus of HMA, aggregate base, and subgrade were analyzed using one-way analysis of variance (ANOVA) and Tukey-Kramer means comparison to test for significant differences between different drainage treatments.

ANOVA results show there is no significant difference in HMA moduli between different drainage designs for the spring 1995, spring 1997, or summer 2004. However, there was a significant difference in HMA layer moduli in the fall of 1997 between the drainage treatments, with the County HMA modulus significantly higher than that of the InvertOGAB and MnDOT modulus. The greatest difference in HMA layer moduli occurred between the County and the MnDOT designs (Figure 2.3.1). Since the moisture data is limited and no samples were taken in fall 1997 it is difficult to determine whether the differences in pavement moduli are due to the subsurface moisture content.

ANOVA results for aggregate base layer moduli show no significant difference in base layer moduli between the four drainage designs for any given year (Figure 2.3.2). When taken in the context of the moisture content data in Table 2.2.1 the results indicate that the slightly higher moisture content in the DGB versus the OGAB had little affect on the overall base layer strength. The subgrade moduli show there was a significant difference in subgrade moduli in the spring of 1995, the subgrade modulus in the County design was significantly higher compared to the MnDOT design, with no significant difference between the Control and the InvertOGAB designs (Figure 2.3.3).

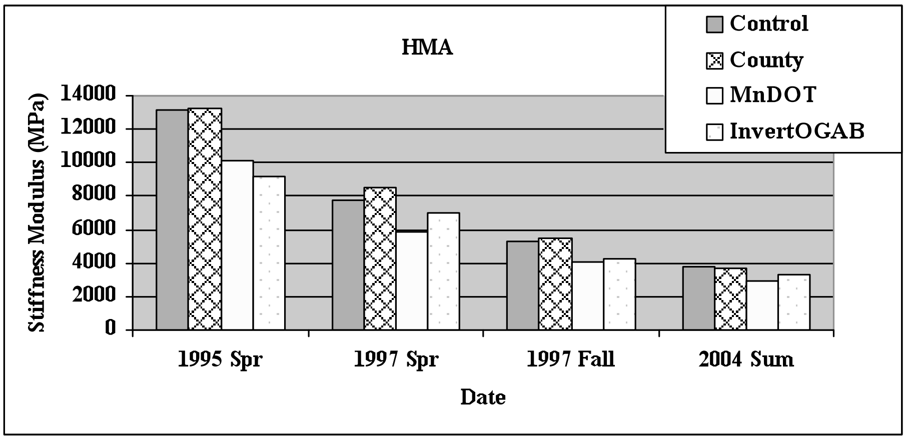

Figure 2.3.1: Effects of drainage design on asphalt stiffness.

Examination of climate data showed that spring precipitation was higher than normal in 1995. Additionally water content in the subgrade in the spring of 1995 was greater in the MnDOT section than in any other test section. A comparison of the County design and MnDOT design showed that the only difference between the two pavement sections was the location of the edge drain pipe. In the County design it is under the shoulder, approximately 5 m from the pavement centerline and 1.7 m below the pavement surface. Comparatively the edge drain pipe in the MnDOT design is located at the lane shoulder joint approximately 4 m from the centerline and 1.4 m below the surface. Significantly lower subgrade moduli of the MnDOT design compared to the County design indicates higher moisture content in the subgrade. But it appears that the absence of a drainage system (Control) proves to be no worse than the presence of a subsurface drainage system when considering subgrade stiffness. Year to year differences in pavement layer moduli appear to be more influenced by climate than by the presence or absence of a drainage system.

3 EVALUATION OF GEOCOMPOSITE CAPILLARY BARRIER DRAIN

In pavement engineering, geosynthetics serve as reinforcement, separation, filtration, stress absorption, drainage, and as moisture barriers. Geosynthetics are reported to improve the strength and performance of the overall pavement structure by acting as a moisture barrier to prevent stripping of asphalt due to accumulation of moisture at the base of the asphalt layer, and by providing drainage for the aggregate base (Al-Qadi, 2003; Christopher and Zhao, 2001). A geocomposite called the Geocomposite Capillary Barrier Drain (GCBD) has been designed to prevent saturation of pavement subsurface from infiltration and capillary rise. (Henry et al., 2002; Henry and Stormont, 2002). A comparison of the moisture and stiffness distribution in the aggregate base and subgrade of pavement test sections constructed with (Test) and without (Control) a Geocomposite Capillary Barrier Drain (GCBD) was conducted.

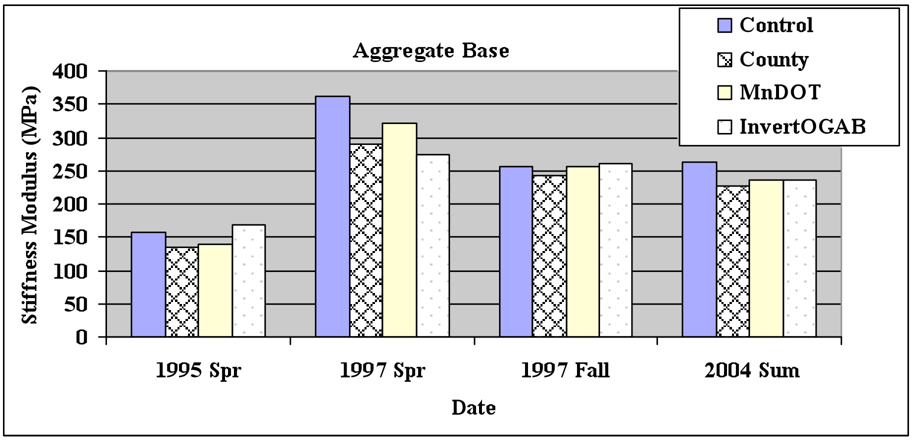

Figure 2.3.2: Effects of drainage design on aggregate base stiffness.

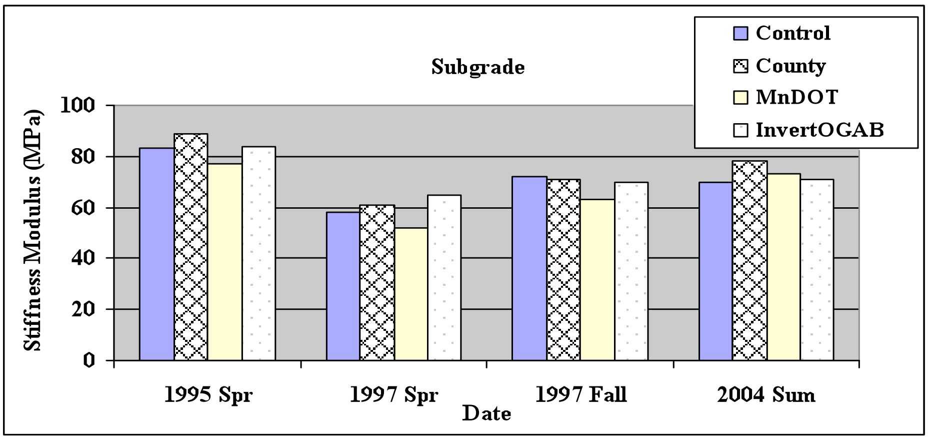

Figure 2.3.3: Effects of drainage design on subgrade stiffness.

The GCBD is designed to prevent saturation of the pavement subsurface from infiltration and from capillary rise. The principal functions of the GCBD are illustrated in Figure 3.0.1. Water in the base layer is wicked into the transport layer and directed to the edge drain. The center geogrid layer acts a capillary barrier preventing water from moving into the base from the subgrade via capillary rise. The non-woven geotextile on the bottom prevents subgrade soil from migrating into the geogrid and transport layers. The GCBD system is designed to maintain a hydraulic potential gradient between the aggregate base and transport layer, along the width of the pavement, and from the transport layer to the edge drain. Water moves into the transport layer from the base under a matric potential gradient, through the transport layer toward the drain pipe due to matric and gravitational potential gradients, and from the transport layer into the drainpipe due to a gravitational potential gradient (Figure 3.0.1).

3.1 Pavement Construction:

Two pavement sections (Test and Control) each 122 meter in length were constructed in July 2006 at the MnROAD facility in Albertville, MN. The structural designs of the Test and Control sections were identical, each section consisting of 102 millimeters of HMA, over 152 millimeters of dense graded aggregate base over a silty clay subgrade. The sections were constructed with 4 meter driving lanes and 1.2 meter aggregate shoulders on a lateral grade of 1-2%. The Test section was constructed with the GCBD installed between the base and subgrade. The Tenax Roadrain™ and the woven fiberglass transport layers were rolled out longitudinally, from east to west with the north and south edges of the Roadrain™ and transport layer joining prefabricated edge drain segments. Approximately 0.5 meters of the geocomposite exited the pipe and trench so that it covered a portion of the pavement shoulder (Figure 3.0.1). Water flow through the transport layer is given in equation 1 and the geogrid layer flux is given in equation 2.

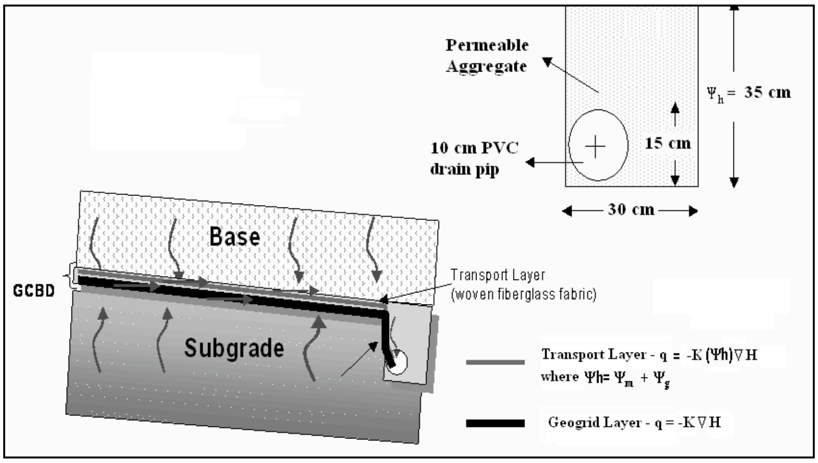

Figure 3.0.1: Schematic of pavement geometry illustrating the function of the GCBD. Component potentials, total hydraulic potential (Ψh), gravitational (Ψg), and matric (Ψm) are indicated and the direction of the positive hydraulic gradient is shown as being toward the edge drain pipe.

$$q = -K(\Psi h)\nabla H \text{ where } \Psi h = \Psi m + \Psi g \qquad [1]$$

$$q = -K\nabla H \qquad [2]$$

q is the water flux, K is the hydraulic conductivity, Ψh is the hydraulic potential, and H is hydraulic head gradient.

Water draining from the GCBD was collected in a 100 millimeter diameter edge drain pipe located at the lane-shoulder interface. Sensors for measuring water content were installed in the base and subgrade of each section at five locations. Pavement deflections were measured using a falling weight deflectometer (FWD). Elastic properties of the pavement layers were calculated using the applied load and the surface deflection data (Siekmeier, 1999).

3.2 Effects of GCBD on Subsurface Water Content

Water content measurements taken in the base and subgrade between September 1, 2006 and November 15, 2006 showed that both the Test and Control sections were below the saturated water content. Comparative statistics showed mean water content in the aggregate base was significantly lower in the Test section than the Control section ($\alpha = 0.05$). However, the mean water content in the clay subgrade for was not significantly different between the Test and the Control sections. This is expected because the GCBD wicks water from the base and transports it to the edge drain.

3.3 Effects of GCBD on Subsurface Stiffness

ANOVA results showed no significant difference in stiffness of the HMA layer between the Test and Control sections Also, the stiffness of the aggregate base in the Test section was not significantly different than the stiffness of the aggregate base in the Control section (Table 3.2.1). Considering that there was a significant difference in the aggregate base moisture content between the Control and Test sections, these data suggests that the level of water content differences observed in this study has little or no effect on the aggregate base stiffness. The subgrade stiffness in the Test section was also not significantly different than the subgrade stiffness in the Control section.

Table 3.2.1: One-way ANOVA results for back calculated elastic modulus. (November 9, 2006). LS = least squared. a: p-value at $\alpha = 0.05$, b: t-ratio is positive if the first mean is larger than the second and negative if it is smaller.

	Elastic Modulus (MPa)			
	Test (GCBD)	**Control (undrained)**	**ANOVA Results**	
	LS Mean	**LS Mean**	**^{b}t-ratio**	**^{a}p-value**
HMA	1720	1875	-1.29	0.2061
Base	194	245	0.21	0.8314
Subgrade	65	97	-0.00	0.9994

3.4 Spatial Analysis

Geostatistical analysis was used to show the spatial distribution of water content and pavement layer stiffness in the Test and Control sections. Water content, matric potential, and stiffness distributions in the Test and Control sections were generated using ArcMap™ 9.1 Spatial Analyst (ESRI® 2005). Kriged surfaces of the moisture content are based on an average value calculated from hourly data collected between September 1 and November 15, 2006. Stiffness surface maps were generated from FWD data collected on November 9, 2006. Data grids were generated using the default Kriging algorithm found in ArcMap™ Spatial Analyst extension. Water content distributions in the aggregate base were used to evaluate the effects of the GCBD on pavement subsurface moisture. Spatial distributions of stiffness were compared to moisture distributions to identify the effects of moisture on stiffness in the aggregate base and subgrade.

The spatial distribution of the aggregate base water content, matric potential, and stiffness for the Test and Control sections are shown in Figure 3.4.1. The distribution of moisture content in the aggregate base of the Test section shows a low degree of saturation in the area of the GCBD, with the lowest degree of saturation near the center of the GCBD (Figure 3.4.1a). Figure 3.4.1b gives the spatial distribution of the matric potential, estimated from water retention curves, with the matric potential > 10000 kPa at the center of the GCBD then decreasing more rapidly from the center to the south and gradually from the center toward the east and west to approximately 1000 kPa . In the Test section the matric potential gradient is predominantly from the SE to the center and from the NW to the center of the aggregate base. Efficient and effective performance of the GCBD would require a positive hydraulic gradient be maintained from the centerline toward the north and/or south edge drains, occurs in neither section.

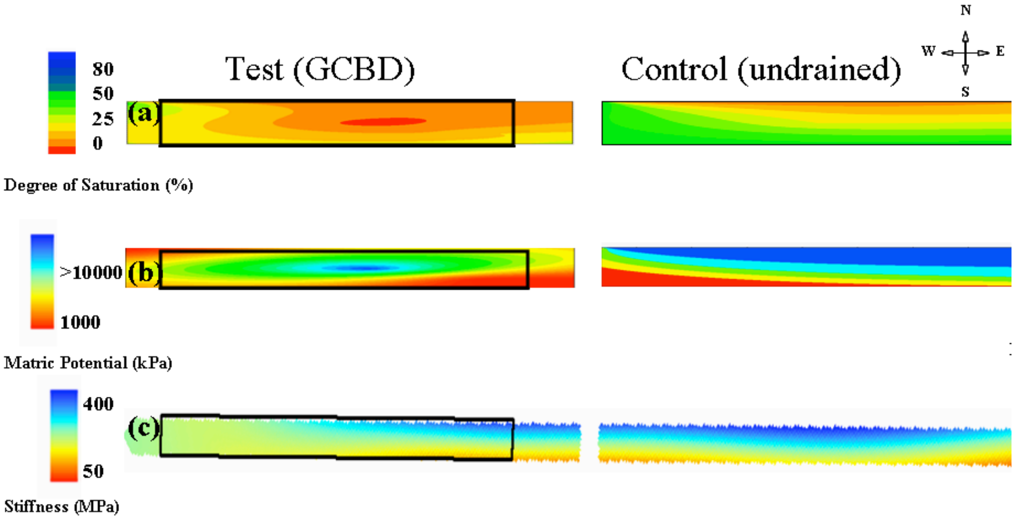

Figure 3.4.1: Spatial distribution in aggregate base of water content, matric potential, and stiffness. (a) water content, (b) matric potential, (c) stiffness.

The stiffness distribution in the aggregate base is shown in Figure 3.4.1c. Areas with relatively high moisture content (low matric potential) are expected to correspond to areas of lower stiffness. Conversely, areas of relatively low moisture content (high matric potential) should correspond to higher stiffness. Stiffness in the aggregate base of the Test section would be highest at the center and decreasing in the east and west directions. Spatial distribution of stiffness in the aggregate base and subgrade of the Test section did not correspond well with the moisture distribution. The moisture content distribution in the aggregate base and subgrade of the Control section followed more closely the expected stiffness distribution. The mean subgrade water content was not significantly different between the Test and Control sections. However, the spatial distribution of moisture content in varies between sections. It appears that the GCBD alters the pattern of moisture distribution in the aggregate base thus making it difficult to characterize base and subgrade layer stiffness as a function of water content. The presence of the GCBD did not enhance the base layer stiffness, but instead introduced a confounding variable.

4 CONCLUSIONS

The moisture conditions in the pavement subsurface layers are primarily unsaturated. It has been shown that conventional pavement drainage designs based on saturated flow had little influence on the pavement base and subgrade moisture content and layer stiffness. Additionally the presence of a geosynthetic, the GCBD, did not significantly increase or decrease the stiffness of the aggregate base or subgrade. Pavement stiffness appears to be controlled by the material properties and surface-atmospheric interactions, which control moisture in the base and the subgrade layers, and to some extent by climate conditions.

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