Draft Final Report

Contract No. NCHRP-113
“Geocomposite Capillary Barrier Drain for Limiting Moisture Changes in Pavements: Product Application”

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submitted to:
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IDEA Program
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Summary

The overall purpose of this project is to facilitate the transfer of the GCBD technology to engineering practice through demonstration and documentation of GCBD fabrication, field installation and performance, and the development of the capability to incorporate the GCBD in subsequent designs. The project is organized into three stages. Each successive stage is built upon the product of the previous stage. The first stage involves selecting materials for the GCBD field test, developing a method to terminate the GCBD in an edgedrain trench, and provide specifications and details for field installation. The second stage involves construction and installation of the field test at MnDOT’s test facility, including installing numerous measurement systems to quantify the GCBD performance. A parallel effort of this project is to contact geosynthetics and other manufacturers to advise them of the possibility of licensing this technology for commercial applications. The third phase of the project is to develop design guidance for the use of the GCBD.

The transport layer is the key element of the GCBD, and a material referred to as TGLASS was selected as the best possible transport layer material. This material was used in the MnROAD field test. There has been discussion with a geosynthetic manufacturer regarding the production of a lower cost transport layer. A method to connect the GCBD to the edgedrain pipe system was developed in the laboratory and used in the MnROAD demonstration. Details and specifications regarding the field installation of the GCBD system were developed and implemented at MnROAD.

Construction of the field test took place between June 19, 2006 and August 16, 2006. Activities included removal of existing pavement, preparing the subgrade, installation of the GCBD, placement of base course, and paving. In addition, measurement systems were installed to monitor water content, suction, temperature, electrical conductivity, water table depth and drainage. The water content data indicate that the base course layer in the pavement section with the GCBD is substantially drier than the base course in the control section. The GCBD appears to be limiting upward flow from the subgrade into the base course. FWD data suggest the base course in the pavement section with the GCBD has a greater modulus than the base course in the control section.

Design calculations reveal the benefit of the GCBD in terms of reducing the saturation of the base course and the subgrade for a wide range of base course and subgrade materials. The calculations indicate that although the GCBD performance is a function of the climate, a GCBD has benefits in terms of lower saturations in all climates.

The laboratory testing, field measurements and design calculations conducted during this project indicate that the GCBD provides specific benefits, including:

- Reduced equilibrium water content in base course
- Positive pressures are prevented in base course
- Wetting of underlying subgrade due to infiltration is greatly reduced
- Capillary rise of water from subgrade into base is prevented
IDEA Concept and Product

The Geocomposite Capillary Barrier Drain (GCBD) is a method to suck water out of soil—that is, provide drainage while the soil is unsaturated. When placed between a base and subgrade, it can drain the unsaturated base and reduce its water content as well as prevent water from reaching the subgrade. In contrast to the GCBD, conventional drainage is designed for saturated flow, even though the positive pore water pressures required for saturated flow reduce strength and lead to rutting, heaving, and failure.

The geocomposite capillary barrier drain (GCBD) comprises three layers that are, from top to bottom: a transport layer (a specially designed geotextile), a capillary barrier (a geonet), and a separator (geotextile). The principal function of the GCBD is illustrated in Figure 1.1. Water infiltrating through the base is prevented from moving into the underlying subgrade by the capillary barrier formed by the geonet. The transport layer (a special geotextile) becomes increasingly hydraulically conductive as it wets. If the GCBD is placed to dip from horizontal, water will drain along the slope in the transport layer. If the transport layer does not become saturated, no water will break through into the capillary barrier. The bottom separator protects the geonet from becoming filled with subgrade soil. The GCBD also cuts off capillary rise of water in the underlying soil, and if the overlying base and transport layer become saturated due to an extraordinary infiltration event, it provides saturated drainage in the geonet.

Figure 1.1 – GCBD between base course and subgrade illustrating how water laterally drains in transport layer.
**Organization of report**

Following an Introduction, data from the MnROAD demonstration project is given in Chapter 2. These data include water content data, tipping bucket data and falling weight deflectometer results. In Chapter 3, calculations are presented that show the expected performance of pavement sections with and without the GCBD. Calculations are performed for infiltration through the pavement surface as well as upward and lateral flow. These calculations utilize various base courses, subgrades, and climates. Chapter 4 includes Conclusions and Recommendations for further advancement of the GCBD technology.

The first two reports produced from this effort, from Stage 1 and Stage 2, provide additional information and details regarding the properties of the GCBD, laboratory test performance, and field construction details and specifications. These reports are included as appendices.
Chapter 2
MnROAD demonstration

Summary of field demonstration

Pavement test sections were constructed between June 19, 2006 and August 16, 2006. Complete details of the test construction are in the construction report prepared by MnROAD personnel. A principal objective of the project was accomplished with this installation; namely, to demonstrate that a full-size GCBD can be installed and tied into a drainage collection system.

There were two MnROAD cells that were constructed in this project (Figure 2.1): one with a GCBD system (cell 27) and one without (the control, cell 28). Sub-surface instrumentation was placed in the base course and subgrade to monitor water content, suction, and temperature. Tipping buckets were used to collect drainage, and pressure transducers were installed to measure groundwater level. These sensors are grouped together in vertical arrays (Figure 2.2). The locations of the arrays was selected using a random block design to capture the spatial variability within the test and control sections.

![Figure 2.1 – Plan view of MnROAD test cells and station locations.](image-url)

<table>
<thead>
<tr>
<th>Sensor Location</th>
<th>Station Number</th>
<th>Offset from CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>175+70</td>
<td>0&quot;</td>
</tr>
<tr>
<td>2</td>
<td>176+80</td>
<td>3.25&quot;</td>
</tr>
<tr>
<td>3</td>
<td>176+80</td>
<td>-9.27&quot;</td>
</tr>
<tr>
<td>4</td>
<td>177+80</td>
<td>-3.25&quot;</td>
</tr>
<tr>
<td>5</td>
<td>178+80</td>
<td>9.75&quot;</td>
</tr>
<tr>
<td>6</td>
<td>179+80</td>
<td>-3.25&quot;</td>
</tr>
<tr>
<td>7</td>
<td>181+50</td>
<td>3.25&quot;</td>
</tr>
<tr>
<td>8</td>
<td>183+50</td>
<td>3.25&quot;</td>
</tr>
<tr>
<td>9</td>
<td>184+50</td>
<td>9.75&quot;</td>
</tr>
<tr>
<td>10</td>
<td>185+50</td>
<td>-3.25&quot;</td>
</tr>
</tbody>
</table>
Data are produced two ways in the field test: periodic, discrete measurements and sensors connected to data loggers. Falling weight deflectometer measurements, crack surveys, and frost heave surveys were to be done periodically. Crack surveys have not revealed any cracks (except in a small section of cell 28 that failed). No frost heave survey results are available.

### Data from field test

Temperature, water content, suction and drainage sensors sent data to the data loggers. These data are then downloaded from the data loggers and imported into a database. There were numerous issues with these data. First, the pressure transducers to measure the groundwater level did not survive construction. Consequently, there are no groundwater level data. The ECHO water content probes used a factory-supplied calibration, and the results are often non-physical. Consequently, they are considered unreliable and are not considered further. The data produced from the heat dissipation sensors were difficult to interpret; it is believed that the calibration procedure for these measurements yielded non-representative calibration curves. The tipping buckets were hand-made units constructed by MnROAD personnel, and the calibration that relates number of tips to quantity of flow is considered only approximate. The calibration for the water content from the reflectometer probes was adjusted based on field water content measurements. Due to these issues, the data presented here focuses principally on the water content measurements from the reflectometers.
Water content data

Water content data from the water content reflectometers is shown in Figure 2.3 and 2.4 for measurements made in the base course, and Figures 2.5 and 2.6 for measurements in the subgrade. All of the measurements at a single depth are given in each figure. The legend indicates the cell (27 or 28) the measurement was made. The base course values show a remarkably consistent result: the water contents in cell 27 with the GCBD are always lower than that in cell 28. The subgrade water contents are not substantially different for cell 27 and 28.

![Base course 15.2 cm depth](image)

Figure 2.3 – Water content data from reflectometer probes at 15.2 cm depth in base course.
Figure 2.4 – Water content data from reflectometer probes at 25.4 cm depth in base course.

Figure 2.5 – Water content data from reflectometer probes at 33 cm depth in subgrade.
Figure 2.6 – Water content data from reflectometer probes at 61 cm at subgrade.

Water content data for three days during 2007 are shown in Figures 2.7, 2.8, and 2.9. These figures include both base course and subgrade water contents, and are shown as a function of position (station). The cell 27 values are on the left (from station 17530 to 18030) and the cell 28 data is on the right of these figures (from station 18100 to 18600). The legend indicates which data is from the upper and lower portions of the base course and subgrade.
Figure 2.7 – Water contents in base course and subgrade as a function of position (station) for April 1, 2007.
Figure 2.8 – Water contents in base course and subgrade as a function of position (station) for July 15, 2007.
Figure 2.9 – Water contents in base course and subgrade as a function of position (station) for October 31, 2007.

The results in these figures indicate that the base course in the cell with the GCBD is substantially drier than the base course without a GCBD. This result is consistent with water from below (water table) or laterally from adjacent soil being blocked from entering the base course due to the capillary barrier effect of the GCBD. The biggest difference between base course water contents occurs during the summer months, which is typically when the groundwater level is the shallowest. The best estimate of water table depths at the cell 27 and 28 are in the range of 1 to 3 m, with shallower depths expected during the summer.

The hypothesis that the water is entering from below or the side is consistent with the pavement being in good condition and maintaining a low conductivity, as would be expected only about a year after construction, and not allowing much if any infiltration. Visual observations of the pavement surface have not revealed any detectable cracks.

**Tipping bucket data**

Tipping bucket data are given in Figure 2.10. There were two tipping buckets, one on the north side and one on the south side of cell 27. Precipitation is also shown on the figure. It is important to consider that the source of water collected by the tipping bucket cannot be
discerned. The water can be from the GCBD (which is tied into the collector pipes) or from infiltration into the trench from pavement run-off.

Figure 2.10 – Tipping bucket and precipitation data.

Substantial collection is observed during the spring of 2007, coincident with the spring snowmelt. During the summer of 2007, in spite of substantial precipitation, there was no water collected in the system. This is likely because a lot of precipitation will evaporate during the summer months. The tipping bucket data does not allow for a direct evaluation of the performance of the GCBD. Continued data collection may allow such an evaluation.

FWD data

Periodic falling weight deflectometer measurements have been made on cells 27 and 28. These data allow back calculation of layer moduli to be made. The back-calculation of moduli was conducted by MnROAD personnel.

A schematic of the FWD test locations for cell 27 and 28 are shown in Figure 2.11 and 2.12. For each cell, there were nominally ten locations along the length of the cell. There were 7 lanes on which FWD measurements were made.
Figure 2.11- FWD measurement locations for cell 27.
Figure 2.12 – FWD measurement locations in cell 28.
Because of the test schedule, there are few days on which comparable measurements were made on cells 27 and 28. Day 239 of 2007 provides data for both cell 27 and 28 for paths 1 and 7. These results are presented below in Figures 2.13 and 2.14.

Figure 2.13 – Results from FWD testing on day 239 of 2007, lane 1.
These results indicate that the base course in the pavement section that included the GCBD has a greater modulus than the pavement section without the GCBD. These results are consistent with the base course being drier in the pavement section that includes the GCBD. Continued testing should indicate whether this preliminary conclusion is substantiated with time.

**Conclusions and status from MnROAD demonstration**

A principal outcome from the MnROAD demonstration is that the GCBD can be practically installed in a full-scale application. The installation, detailed in the Stage 2 report, required some special attention, but largely because it is a new product. In particular, a means to tie the GCBD into an edgedrain collection system was devised and implemented.

The water content data reveal that the base course in the cell with the GCBD is lower than that in the cell without the GCBD. This result is consistent with water from the adjacent soil, likely from below, being blocked from entering the base course due to the capillary barrier effect of the GCBD. The FWD data are consistent with the base course being drier in the section that includes the GCBD; that is, the base course with the GCBD possesses a greater modulus than the section that does not include the GCBD.
It is unclear the amount, if any, of lateral drainage out of the GCBD at this point in time. With continued deterioration of the pavement over time, more water will enter the base course through the pavement surface, and the lateral diversion capacity of the GCBD would be expected to be utilized. Continued monitoring of the test cells over time will provide more insight into the performance of the GCBD.
Chapter 3
Design calculations

3.1 Introduction

The impact of the GCBD on a pavement system can be approximated through simple “design calculations.” These calculations estimate how the GCBD will change the storage and routing of water in a pavement section for different combinations of base course materials, subgrade materials, water table depths, and climatic conditions (precipitation). From these results, generalizations about GCBD performance can be made, and extrapolation to specific situations can be made.

The design calculations utilize simplified models. They models do not intend to capture the ”physics” of water movement within the pavement section; rather, they use water balance approach to approximate the routing and storage of water in pavement systems. While the models produce reasonable results, they should not be considered predictions of drainage quantity and saturation values. Instead, the results provide relative results that serve as a basis for comparison of pavement systems with and without a GCBD. More complete, complex models are available, but the detailed input requirements and numerical issues preclude their use in the parametric simulations for this study.

The direct “measure” of the impact of the GCBD is the change in saturation of the base course and subgrade. The saturation, in turn, affects the strength and deformation characteristics (moduli) of these layers in a pavement system. The results in the following sections are largely presented as saturations; a next step would be to interpret strength and modulus from these saturations.

The layer of concern for a pavement system will depend on the specific conditions. In some cases, the most important consideration for pavement drainage design may be a moisture sensitive subgrade. In this case, it may be crucial that saturation changes in the subgrade be minimized. In other cases, limiting the saturation or preventing complete saturation of a base course layer may be the most important consideration.

Problem description

Water can move into a pavement system from three general sources: through the pavement, laterally from adjacent soil, and upward from a shallow water table (Figure 3.1).
Infiltration into the base course from infiltration has long been considered a source of water in pavement sections, and is generally treated as infiltrating uniformly through the pavement or through discrete cracks. Water that infiltrates can, in general, increase the saturation of the base course, laterally drain, or move downward into the subgrade.

A shallow water table is another source of water. Water is drawn up through the subgrade and into the base course. Water movement is in response to suction differences above the water table. Water can also move laterally from the adjacent soil into the base course and underlying subgrade. This water moves largely in response to suction differences. The adjacent soil can be wetted from precipitation events, including the additional wetting from pavement surface run-off that is concentrated at the shoulder.

**Material and climate parameters**

Four base course materials were selected for these calculations. These materials represent a wide range of potential base courses that may be used depending on material availability and cost, pavement design, drainage considerations, and design precedent. These materials were selected principally to provide a range of material properties, and are not meant to define the full spectrum of possible base course properties.
The four base course materials are referred to as dense graded, conventional, permeable and stone. The hydraulic properties of the dense graded material are those determined for Class 5 base course from Minnesota. The properties of the conventional base course were those measured on a well-graded sand base course from New Hampshire (reported in Stormont and Zhou, 2005). The permeable base course properties were those of coarse sand (reported in Stormont and Zhou, 2005), and has a saturated hydraulic conductivity in the range of permeable base course materials intended to be readily drainable (Richardson, 1997; Elyasyed and Lindly, 1996; Rudolph et al., 1996). The stone base course corresponds to a clean, uniform gravel or stone (Stormont, 1995), and has hydraulic properties that are comparable to AASHTO 57 stone.

A typical means to quantify a base course is to calculate the “time-to-drain,” which specifies a time to drain to an allowable saturation. According to AASHTO, classification of “excellent” results if the time-to-drain to 50% saturation is less than 2 hours, “good” for less than one day, and so on (Mallela et al., 2000). Although this approach is concerned with “de-saturation” of the base course, the equations are based solely on saturated flow. Shown in Table 1 are the classifications with respect to the “time-to-drain” for base course materials that are 15 cm thick and have a drainage length of 400 cm: the stone and permeable bases are classified as “excellent,” the conventional base is classified as “good,” and the dense graded material is ”poor.”

Hydraulic properties are tabulated below for each base course material, including the porosity ($\phi$) and the saturated hydraulic conductivity ($K_{sat}$). The unsaturated hydraulic properties are described by the van Genuchten model (1980). The volumetric water content, $\theta$, and suction head, $h$, are related by

$$\theta = \theta_r + (\theta_s - \theta_r)\left[1 + (\alpha h)^n\right]^{-m}$$

(1)

where the subscripts $s$ and $r$ indicate the saturated and residual values of the water content, $\alpha$, $m$ and $n$ are fitting parameters, and $m = 1 - 1/n$. The fitting parameters can be determined from moisture characteristic curve data.

By adopting the model for hydraulic conductivity proposed by Mualem (1976), the hydraulic conductivity as a function of either water content or suction head can be predicted using the van Genuchten fitting parameters and the saturated hydraulic conductivity.
Table 3.1 – Base course material properties

<table>
<thead>
<tr>
<th>Base course material</th>
<th>θr</th>
<th>θs</th>
<th>φ</th>
<th>α (1/cm)</th>
<th>N</th>
<th>Ksat (cm/s)</th>
<th>Time to drain classification (50% saturation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dense graded</td>
<td>.067</td>
<td>.212</td>
<td>.40</td>
<td>.054</td>
<td>2.42</td>
<td>2.8e-4</td>
<td>Poor</td>
</tr>
<tr>
<td>conventional</td>
<td>.078</td>
<td>.239</td>
<td>.38</td>
<td>.031</td>
<td>2.75</td>
<td>1.3e-2</td>
<td>Good</td>
</tr>
<tr>
<td>permeable</td>
<td>.02</td>
<td>.25</td>
<td>.375</td>
<td>.043</td>
<td>3.1</td>
<td>.46</td>
<td>Excellent</td>
</tr>
<tr>
<td>stone</td>
<td>.0005</td>
<td>.25</td>
<td>.42</td>
<td>1</td>
<td>2.19</td>
<td>10</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

The moisture characteristic curves for the base course materials are given in Figure 3.2. These curves indicate the amount of water the material retains at different values of suction. The base course materials are all coarse-grained materials, and they tend to not retain significant water at low to modest suctions. The stone base course in particular retains very little water under almost all values of suction.

Figure 3.2 – Moisture characteristic curves for base course materials.
The GCBD is assumed to have a transport layer on top, a geonet, and a separator geotextile on the bottom. The transport layer is a very heavy, woven, multifilament material with a mass per unit area of $2370 \text{ g/m}^2$, a thickness of 3.2 mm, and an O$_{95}$ size of 0.075 mm. The hydraulic properties of the transport layer are given by Stormont and Ramos (2004), and are given in Table 3.2. The GCBD is assumed to have a breakthrough head of 2 cm.

### Table 3.2 – Transport layer properties

<table>
<thead>
<tr>
<th></th>
<th>$\theta_r$</th>
<th>$\theta_s$</th>
<th>$\alpha$ (1/cm)</th>
<th>N</th>
<th>Transmissivity, saturated (cm$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>transport layer</td>
<td>.00</td>
<td>.83</td>
<td>.211</td>
<td>1.39</td>
<td>1e-1</td>
</tr>
</tbody>
</table>

Three subgrades types were included in the calculations: clay, clay loam and silt. These materials were selected to encompass a range of possible subgrade materials that a pavement section may be constructed upon. Fine-grained subgrades (e.g., clay and clay loam) can be problematic due to volume change that accompanies saturation changes. The silt is more likely to be a soil that experiences less volume change, but its strength and deformation characteristics will change with changing saturation.

The hydraulic properties of the subgrade materials are given in Table 3.3. The moisture characteristic curves for these materials are given in Figure 3.3.

### Table 3.3 – Subgrade material properties.

<table>
<thead>
<tr>
<th>Subgrade material</th>
<th>$\theta_r$</th>
<th>$\theta_s$</th>
<th>$\alpha$ (1/cm)</th>
<th>N</th>
<th>Ksat (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>clay</td>
<td>.07</td>
<td>.36</td>
<td>.005</td>
<td>1.09</td>
<td>1e-7</td>
</tr>
<tr>
<td>clay loam</td>
<td>.095</td>
<td>.41</td>
<td>.019</td>
<td>1.31</td>
<td>2e-6</td>
</tr>
<tr>
<td>silt</td>
<td>.10</td>
<td>.38</td>
<td>.027</td>
<td>1.23</td>
<td>3.3e-5</td>
</tr>
</tbody>
</table>
Figure 3.3 – Moisture characteristic curves for subgrade materials.

Climate

Three precipitation inputs were considered: Minneapolis, Albany and Albuquerque. Cumulative precipitation for the year 2006 is shown in Figure 3.4. The cumulative precipitation for these three locations provides a wide range that encompasses the annual precipitation of majority of locations within the US.
Figure 3.4 – Cumulative precipitation for three climates used in design calculations.
3.2 Infiltration, lateral drainage and flow into subgrade

Design calculations that considered infiltration from above, lateral drainage out of the base course and flow into the subgrade were conducted with a daily water balance model implemented in a spreadsheet. The purpose of the calculations is to provide a quantitative measure of the impact of the GCBD on the amount of water in the base course and subgrade for various conditions. Calculations were conducted for the case that includes a GCBD between the base course and subgrade, and the case without a GCBD (Figure 3.5). Four different base course layers, three subgrade soils, and four climates were considered in the calculations. This model only considers downward infiltration in response to precipitation, and does not address upward flow from a shallow water table. In this way, the benefit of the GCBD can be estimated.

In this model, a fraction of the daily precipitation (if any) is allowed to infiltrate into the base course. The pavement layer is not included in this model. The water is allowed to drain laterally in the base course. Without a GCBD, water in the base course can move vertically downward into the subgrade. In the case when the pavement system includes a GCBD, water movement from the base course to the subgrade is prevented until the water entry suction head of the GCBD is reached. If the amount of water in the base course is sufficient to reduce the suction in the base course to the water entry head of the transport layer, water is drained laterally in the transport layer. If the transport layer capacity is exceeded, water will move downward into the subgrade (breakthrough). If the bottom of the base course becomes saturated, water can also laterally drain in the geonet layer of the GCBD.

Figure 3.5 – Schematic illustration of water balance model without (left) and with GCBD (right).
Infiltration and water distribution within the GCBD

For both the cases with and without the GCBD, water from precipitation enters the base course. This water is assumed to distribute itself within the base course to result in an equilibrium suction profile. Thus, the suction at the bottom of the base course will be lower than the suction at the top of the base course. To satisfy equilibrium, the suction varies linearly with depth in the base course. For example, if the suction at the bottom of the base course is 10 cm, the suction at the top of a 15 cm thick base course would be 25 cm. The model determines the appropriate suction profile for the amount of water in the base course after any precipitation is added. If the water from a daily precipitation event exceeds the saturation of the base course, precipitation is assumed to run-off rather than enter the base course.

Lateral flow in the base course

Lateral flow within the base course is estimated by assuming daily steady-state flow driven only by the lateral grade of the base course. These calculations divided the base course into 5 sub-layers. The unsaturated hydraulic conductivity for each sub-layer is determined using the suction head at the mid-point of each sub-layer. The effective lateral hydraulic conductivity of the base course is then calculated by averaging these values. The lateral flow (cm$^3$/sec per cm of pavement length) is then calculated as

\[ Q = k_{eff} \times i \times th \]

where i is the lateral gradient or grade, and th is the thickness of the base course.

Water movement into subgrade for the case without GCBD

Flow of water into the subgrade and the subsequent saturation changes in the subgrade is calculated based on the first 60 cm of the subgrade below the base course. Flow from the base course to the subgrade is limited by the hydraulic conductivity of the subgrade material. The unsaturated hydraulic conductivity is calculated for the suction head at the base course – subgrade interface. The gradient that drives flow is calculated from the suction at the base course interface and the average suction in the first 60 cm of the subgrade. Water flow out of the 60 cm layer to lower portions of the subgrade is calculated based on an unsaturated hydraulic conductivity of the 60 cm layer, and a unit gradient (gravity flow).

For the case of no GCBD, flow into the subgrade is calculated under all suction conditions at the base course – subgrade interface. With the GCBD, flow is only calculated when the breakthrough head of the GCBD is exceeded.

Water movement in GCBD

The transport layer will laterally drain water based on its transmissivity. The transmissivity (cm$^2$/sec) is calculated as a function of the suction at the base course-subgrade interface (Stormont and Ramos, 2004). Drainage (cm$^3$/sec per cm of pavement length) in the transport layer is calculated from
\[ Q = \text{tran} \times i \]

where tran is the GCBD transmissivity and i is the lateral gradient or grade.

The water in the base course on a given day is updated after subtracting the combined lateral drainage in the base course and the transport layer. If the updated suction head at the bottom of the base course exceeds the breakthrough head of the transport layer, water will move downward into the subgrade.

The amount of water in the base course is updated, and the suction head at the interface is calculated. If this value exceeds the breakthrough head, the excess water is removed laterally by flow in the geonet.

**Calculation inputs**

The material properties of the base course and subgrade materials as well as the precipitation data have been previously described. The calculations assume the 43% of the daily precipitation infiltrates into the base course. This value is the mean value of the range of infiltration amounts for asphalt pavement that the DRIP program uses (Malella et al., 2002), and is a long-standing traditional estimate of the amount of infiltration that may pass through an asphalt pavement (Ridgeway, 1982).

The calculations assume a constant lateral slope or grade of 2%. Most of the calculations assume the base layer is 15 cm thick, and has a lateral drainage length of 400 cm (nominally one traffic lane). Thicker base course and a longer lateral drainage length are also considered. The base course and the subgrade are assumed to begin at 50% saturation for all calculations.
Results and discussion

Results of 24 model simulations are presented in a series of figures that follow this section (Figures 3.6 to 3.53). Results are included from model simulations using 4 different base course, 3 different subgrades, 3 different climates, and different pavement geometries. Results from each set of conditions were used to produce two figures. In one figure, the saturations of the base course and subgrade layer both with and without the GCBD are presented for the year-long simulation. The other figure is an annual water balance for the model with and without the GCBD.

The results clearly demonstrate the GCBD functioning as a capillary barrier. With a GCBD, the capillary barrier effect of the GCBD prevents water from moving from the base course to the subgrade until the base course gets very wet. In contrast, without a GCBD, there is no barrier to water movement from the base course to the subgrade.

The consequence of the capillary barrier effect of the GCBD is that the subgrade is largely isolated from downward infiltrating water. This is quantified by the change in subgrade saturation and the amount of subgrade vertical flow shown in annual water balance figures. In every case, the GCBD results in less water in the subgrade compared to the same conditions but without a GCBD. In many cases, the 60 cm of the subgrade immediately below the base course saturates without a GCBD, whereas with a GCBD. For an example, see Figure 3.14.

Water that is retained in base course above the GCBD due to the capillary barrier effect can drain laterally either in the base course itself or in the transport layer of the GCBD. The amount that drains in the transport layer vs. the base course depends principally on the base course properties. If the base course has a relatively low conductivity, it will not be effective in laterally draining water. This is the case with the dense graded base course (see Figures 3.12 through 3.17). If the base course retains little water, then water in the base course tends to reside at the bottom of the base course. The majority of the base course will have a low water content and a corresponding low conductivity, and consequently will not divert much water. The transport layer will be in contact with the wet portion of the base course, and will have the opportunity to remove this water. This is why the stone base course removes less water laterally than the GCBD transport layer (see Figures 3.24 through 3.29). In contrast, if the base course retains enough water to be conductive through much of its thickness, then most of the water will be laterally diverted in the base course. This is condition for the permeable base (see Figures 3.18 through 3.23). The conventional base response is intermediate between that of the dense graded and permeable base.

The capillary barrier effect often results in somewhat more water being retained in the base course compared to the case of no GCBD. The differences in saturation tend to be modest, usually less than 10%. When the base course is not an effective drainage medium such as the case of the dense graded base, then the saturation of the base course without the GCBD can be substantially greater than that of in the GCBD configuration (see Figures 3.12, 3.14, and 3.16).

The results indicate that the GCBD permits breakthrough into the subgrade under some conditions. Breakthrough is generally in response to large precipitation events. The amount of water that moves into the base course depends on the hydraulic conductivity of the base course.
For example, contrast the results obtained with a conventional base course but three different subgrade soils exposed to the Minneapolis climate (Figures 3.6, 3.8 and 3.10 for clay, clay loam and silt, respectively). In all cases, there is breakthrough in response to precipitation input around day 100 and day 220. The change in saturation in response to breakthrough is imperceptible for the clay, barely detectable for the clay loam, and noticeable for the silt. This is because subgrade soils with greater hydraulic conductivity will accept more water. If the subgrade does not accept much water, then the bottom of the base course may saturate and water will drain laterally in the geonet. Note that the silt has no geonet drainage, whereas there is geonet drainage for the clay and clay loam subgrades (Figure 3.7, 3.9, and 3.11).

The GCBD is restored after breakthrough. Water is removed from the base course through lateral drainage in the base course, transport layer and geonet, as well as any flow into the subgrade. After breakthrough, the GCBD is restored. In this way, the subgrade is once again isolated from the base course. This can be observed in results where there is a noticeable increase in saturation of the subgrade due to breakthrough, and then a reduction in the saturation as water in the subgrade moves downward (for example, see Figure 3.16).

The drainage length was increased from 400 to 800 cm for the case of dense graded and permeable base courses with the clay loam subgrade. The 800 cm length corresponds to a two-lane configuration. For the dense graded base course, more breakthrough into the subgrade occurs with the longer drainage length. This is because the lateral diversion capacity of the transport layer is exceeded more often for the case of the longer lateral drainage distance. Contrast the results for the 400 cm length given in Figures 3.14 and 3.15 with those with the 800 cm length given in Figures 25 and 26. For the permeable base course, there is virtually no difference between the results with the two different lengths (see Figures 3.20, 3.21, 3.34, and 3.35). This is because the majority of the lateral drainage occurs in the base course and not in the transport layer for these conditions.

Results with a thicker base course indicate little difference in the water balance. Refer to Figures 3.30 through 3.33 for results with a dense graded base and Figures 3.34 through 3.37 for results with a permeable base.

GCBD performance depends on precipitation stress, both the amount and timing. Most often, the greater precipitation, the more water is laterally diverted by the transport layer and the less breakthrough there is. Exceptions to this generality occur with the conventional and stone base course: the Albany climate results in less breakthrough than the Minneapolis climate even though there is substantially more precipitation (compare Figures 3.8 and 3.9 with Figure 3.46 and 3.47 for the conventional base course and Figure 3.28 and 3.29 with Figures 3.52 and 3.53 for the stone base course). This result is a consequence of the timing and magnitude of specific precipitation events.

The permeable base with a GCBD prevents any breakthrough for all climates (Figures 3.20, 3.21, 3.42, 3.43, 3.50 and 3.51). The dense graded base course performance, both in terms of how much water is diverted in the transport layer and how much (Figure 3.14, 3.15, 3.40, 3.41, 3.48, and 3.49).
Figure 3.6 – Saturations of base course and subgrade for case with and without GCBD. Conditions: conventional base course 15 cm thick, 400 cm width, clay subgrade, and Minneapolis climate.

Figure 3.7 – Annual water balance results. Conditions: conventional base course 15 cm thick, 400 cm width, clay subgrade, and Minneapolis climate.
Figure 3.8 – Saturations of base course and subgrade for case with and without GCBD. Conditions: conventional base course 15 cm thick, 400 cm width, clay loam subgrade, and Minneapolis climate.

Figure 3.9 – Annual water balance results. Conditions: conventional base course 15 cm thick, 400 cm width, clay loam subgrade, and Minneapolis climate.
Figure 3.10 – Saturations of base course and subgrade for case with and without GCBD. Conditions: conventional base course 15 cm thick, 40 cm width, silt subgrade, and Minneapolis climate.

Figure 3.11 – Annual water balance results. Conditions: conventional base course 15 cm thick, 400 cm width, silt subgrade, and Minneapolis climate.
Figure 3.12 – Saturations of base course and subgrade for case with and without GCBD. Conditions: dense graded base course 15 cm thick, 400 cm width, clay subgrade, and Minneapolis climate.

Figure 3.13 – Annual water balance results. Conditions: dense graded base course 15 cm thick, 400 cm width, clay subgrade, and Minneapolis climate.
Figure 3.14 – Saturations of base course and subgrade for case with and without GCBD. Conditions: dense graded base course 15 cm thick, 400 cm width, clay loam subgrade, and Minneapolis climate.

Figure 3.15 – Annual water balance results. Conditions: dense graded base course 15 cm thick, 400 cm width, clay loam subgrade, and Minneapolis climate.
Figure 3.16 – Saturations of base course and subgrade for case with and without GCBD. Conditions: dense graded base course 15 cm thick, 400 cm width, silt subgrade, and Minneapolis climate.

Figure 3.17 – Annual water balance results. Conditions: dense graded base course 15 cm thick, 400 cm width, silt subgrade, and Minneapolis climate.
Figure 3.18 – Saturations of base course and subgrade for case with and without GCBD. Conditions: permeable base course 15 cm thick, 400 cm width, clay subgrade, and Minneapolis climate.

Figure 3.19 – Annual water balance results. Conditions: permeable base course 15 cm thick, 400 cm width, clay subgrade, and Minneapolis climate.
Figure 3.20 – Saturations of base course and subgrade for case with and without GCBD. Conditions: permeable base course 15 cm thick, 400 cm width, clay loam subgrade, and Minneapolis climate.

Figure 3.21 – Annual water balance results. Conditions: permeable base course 15 cm thick, 400 cm width, clay loam subgrade, and Minneapolis climate.
Figure 3.22 – Saturations of base course and subgrade for case with and without GCBD. Conditions: permeable base course 15 cm thick, 400 cm width, silt subgrade, and Minneapolis climate.

Figure 3.23 – Annual water balance results. Conditions: permeable base course 15 cm thick, 400 cm width, silt subgrade, and Minneapolis climate.
Figure 3.24 – Saturations of base course and subgrade for case with and without GCBD. Conditions: stone base course 15 cm thick, 40 cm width, clay subgrade, and Minneapolis climate.

Figure 3.25 – Annual water balance results. Conditions: stone base course 15 cm thick, 400 cm width, clay subgrade, and Minneapolis climate.
Figure 3.26 – Saturations of base course and subgrade for case with and without GCBD. Conditions: stone base course 15 cm thick, 400 cm width, clay loam subgrade, and Minneapolis climate.

Figure 3.27 – Annual water balance results. Conditions: stone base course 15 cm thick, 400 cm width, clay loam subgrade, and Minneapolis climate.
Figure 3.28 – Saturations of base course and subgrade for case with and without GCBD. Conditions: stone base course 15 cm thick, 400 cm width, silt subgrade, and Minneapolis climate.

Figure 3.29 – Annual water balance results. Conditions: stone base course 15 cm thick, 400 cm width, silt subgrade, and Minneapolis climate.
Figure 3.30 – Saturations of base course and subgrade for case with and without GCBD. Conditions: dense graded base course 15 cm thick, 800 cm width, clay loam subgrade, and Minneapolis climate.

Figure 3.31 – Annual water balance results. Conditions: dense graded base course 15 cm thick, 800 cm width, clay loam subgrade, and Minneapolis climate.
Figure 3.32 – Saturations of base course and subgrade for case with and without GCBD. Conditions: dense graded base course 30 cm thick, 800 cm width, clay loam subgrade, and Minneapolis climate.

Figure 3.33 – Annual water balance results. Conditions: dense graded base course 30 cm thick, 800 cm width, clay loam subgrade, and Minneapolis climate.
Figure 3.34 – Saturations of base course and subgrade for case with and without GCBD. Conditions: permeable base course 15 cm thick, 800 cm width, clay loam subgrade, and Minneapolis climate.

Figure 3.35 – Annual water balance results. Conditions: permeable base course 15 cm thick, 800 cm width, clay loam subgrade, and Minneapolis climate.
Figure 3.36 – Saturations of base course and subgrade for case with and without GCBD. Conditions: permeable base course 30 cm thick, 800 cm width, clay loam subgrade, and Minneapolis climate.

Figure 3.37 – Annual water balance results. Conditions: permeable base course 30 cm thick, 800 cm width, clay loam subgrade, and Minneapolis climate.
Figure 3.38 – Saturations of base course and subgrade for case with and without GCBD. Conditions: conventional base course 15 cm thick, 400 cm width, clay loam subgrade, and Albuquerque climate.

Figure 3.39 – Annual water balance results. Conditions: conventional base course 15 cm thick, 400 cm width, clay loam subgrade, and Albuquerque climate.
Figure 3.40 – Saturations of base course and subgrade for case with and without GCBD. Conditions: dense graded base course 15 cm thick, 400 cm width, clay loam subgrade, and Albuquerque climate.

Figure 3.41 – Annual water balance results. Conditions: dense graded base course 15 cm thick, 400 cm width, clay loam subgrade, and Albuquerque climate.
Figure 3.42 – Saturations of base course and subgrade for case with and without GCBD. Conditions: permeable base course 15 cm thick, 400 cm width, clay loam subgrade, and Albuquerque climate.

Figure 3.43– Annual water balance results. Conditions: permeable base course 15 cm thick, 400 cm width, clay loam subgrade, and Albuquerque climate.
Figure 3.44 – Saturations of base course and subgrade for case with and without GCBD. Conditions: stone base course 15 cm thick, 400 cm width, clay loam subgrade, and Albuquerque climate.

Figure 3.45 – Annual water balance results. Conditions: stone base course 15 cm thick, 400 cm width, clay loam subgrade, and Albuquerque climate.
Figure 3.46 – Saturations of base course and subgrade for case with and without GCBD. Conditions: conventional base course 15 cm thick, 400 cm width, clay loam subgrade, and Albany climate.

Figure 3.47 – Annual water balance results. Conditions: conventional base course 15 cm thick, 400 cm width, clay loam subgrade, and Albany climate.
Figure 3.48 – Saturations of base course and subgrade for case with and without GCBD. Conditions: dense graded base course 15 cm thick, 400 cm width, clay loam subgrade, and Albany climate.

Figure 3.49 – Annual water balance results. Conditions: dense graded base course 15 cm thick, 400 cm width, clay loam subgrade, and Albany climate.
Figure 3.50  – Saturations of stone base course and subgrade for case with and without GCBD. Conditions: permeable base course 15 cm thick, 400 cm width, clay loam subgrade, and Albany climate.

Figure 3.51 – Annual water balance results. Conditions: permeable base course 15 cm thick, 400 cm width, clay loam subgrade, and Albany climate.
Figure 3.52 – Saturations of base course and subgrade for case with and without GCBD. Conditions: stone base course 15 cm thick, 400 cm width, clay loam subgrade, and Albany climate.

Figure 3.53 – Annual water balance results. Conditions: stone base course 15 cm thick, 400 cm width, clay loam subgrade, and Albany climate.
3.3 Upward and lateral flow

Upward flow

The GCBD serves as a capillary break, interrupting upward or lateral flow from the subgrade into the base course. Consequently, a base course that has a GCBD beneath it may have a lower saturation than a comparable configuration without a GCBD. The significance of the GCBD in terms of limiting upward flow is expected to be greatest in the presence of a shallow water table.

For the case with no GCBD, the amount of water in the base course is calculated assuming the base course is in hydraulic equilibrium with a water table. Assuming equilibrium allows the suction head to be determined - it is simply the distance above the water table. From its moisture characteristic curve, the water content and saturation of the base course can be estimated.

It is useful to compare the saturation of the base course with and without a GCBD. With a GCBD, the base course will be isolated from the water table, and the amount of water will be independent of the water table. The amount of water in the base course is estimated from the infiltration model. No precipitation is applied to the base course, rather, the base course and the GCBD are allowed to equilibrate for one year. In this way, any excess construction or initial water drains from the base course.

The difference in saturation with and without a GCBD for 3 base course materials is given in Figure 3.54. The base course layers are assumed to be 15 cm thick. Because a stone base course forms a capillary barrier comparable to that of the GCBD, no benefit is gained with a GCBD for this situation and thus the stone base course was not included in the calculations.

The capillary barrier effect of a GCBD for upward flow is significant when the water table is within 1 m. The increase in base saturation increases greatly as the depth to the water table decreases. When the water table is less than 50 cm, large differences in saturation are expected. Because the difference in saturation is principally a result of the moisture characteristic curve of the base course material, each base course material should be evaluated individually.
Lateral flow

The capillary barrier effect also applies to limiting lateral flow into the base course. This scenario could be envisioned in response to a precipitation event where there is considerable infiltration in the adjacent native soils (Figure 3.55). Such infiltration may be increased from the contribution of pavement run-off. The protection the GCBD offers depends on the details of the infiltration event. The extreme case would be a large precipitation event in which the ground adjacent to the pavement gets very wet and approaches saturation. In this case, the difference in saturation of the base course due to the presence of the GCBD would correspond to the case of zero suction or zero water table depth.
Figure 3.55 – Schematic illustration of wetting of soil adjacent to pavement section in response to precipitation and pavement run-off.

Although these results are based on very idealized and approximate conditions, they suggest that the GCBD may have a very significant impact on the saturation within a base course when the adjacent soil wets. With no barrier to unsaturated water movement, the base course will nearly saturate if it is exposed to and equilibrates with fully wetted soil. A GCBD will isolate the base course from the surrounding wet soil.
3.4 Summary

The design calculations indicate that less of the water that infiltrates through the pavement will reach the underlying subgrade soil if the pavement includes a GCBD at the bottom of the base course. This result is true for any base course, for all climates, and for all subgrade soils. The significance of this result depends on the strength and modulus reduction that the subgrade will experience due to an increased saturation.

For base course materials that are not good drainage materials, the GCBD will provide a drainage mechanism that can substantially limit the saturation of the base course. In this way, materials that are desirable for cost or availability considerations but do not drain well can be used in conjunction with a GCBD with a substantially increased performance as inferred by a lower saturation.

The GCBD limits base course saturation of the base course when there is a shallow water table. For water tables within 1 m of the base course, there is always less water in the base course with a GCBD compared to the case without a GCBD. This effect is diminished with the coarseness of the base course material. A base course may also be isolated from adjacent soil that wets due to infiltration. Including a GCBD in a pavement system will always result in less water in the base course compared to the case of without it.

A schematic that summarizes the applicability of the GCBD for different design conditions is shown in Figure 3.56.

![Figure 3.56 – Schematic of benefits of GCBD in pavement configuration as a function of the drainage characteristics of the base course.]

Base course material

Infiltration

Upward flow from shallow water table and lateral flow

Poorly draining

Reduces saturation of both base course and subgrade

Excellent draining

Reduces saturation of subgrade

Little effect

Reduces saturation of base course
Chapter 4
Recommendations

The results of this project have demonstrated that the GCBD performs as expected, that is, it has provided the following benefits in laboratory and field demonstrations:

- Reduced equilibrium water content in base
- Prevent positive pressures in base
- Prevent wetting of underlying subgrade due to infiltration
- Prevent capillary rise of water from subgrade into base

Further, practical issues related to the constructability of the GCBD have been resolved, including how to tie the GCBD into a conventional edgedrain system.

The following efforts are recommended to continue the development of the GCBD toward full-scale commercial deployment:

- Continued monitoring of the MnROAD test cells will provide water content data that will allow ongoing evaluation of the GCBD performance to be estimated.

- Numerical modeling of GCBD performance. To date, sophisticated numerical models to predict the detailed response of the GCBD have not produced useful results due to numerical stability issues.

- Development of additional applications. There are other applications for use of the GCBD that can be developed, including retaining wall and foundation drainage.

- Presentation of results of laboratory, field and numerical studies at conferences.

- Pursue commercial development with manufacturers and distributions of geosynthetic products. There is serious interest in the technology, especially if a less costly alternative to the transport layer can be found.
References


