Draft Final Report

Geocomposite Capillary Barrier Drain for Limiting Moisture Changes in Pavement Subgrades and Bases

For the period March/2000 through June/2001

Contract No. NCHRP-68

Prepared for the IDEA Program
Transportation Research Board
National Research Council

Karen S. Henry, Ph.D., P.E.
Research Civil Engineer
U.S.A.C.R.R.E.L.
72 Lyme Rd.
Hanover, NH 03755-1290

John C. Stormont, Ph.D., P.E., Professor
Shelley Ramos
Department of Civil Engineering
University of New Mexico
Albuquerque, NM 87131

Lynette Barna
Research Civil Engineer
U.S.A.C.R.R.E.L.
72 Lyme Rd.
Hanover, NH 03755-1290

April, 2002

ACKNOWLEDGEMENTS

We are very grateful for the financial support and encouragement received from the NCHRP IDEA Program and our Program Manager, Mr. Inam Jawed. We have also received generous support from the New York State Department of Transportation, the New Hampshire Department of Transportation and the Vermont Agency of Transportation through a Regional Pooled Fund Study Program administered by the Federal Highways Administration. Mr. Robert Burnett of the New York Department of Transportation, Mr. Chris Benda of the Vermont Agency of Transportation, Mr. William Real of the New Hampshire Department of Transportation and Mr. Thomas Cleary of the New Hampshire Department of Transportation served on our Review Panel and provided guidance so that this work would serve the interests of transportation organizations. Because of their input, we conducted tests that simulated storms of several hours in duration and included cracked asphalt in our test section.

The engineering support staff at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) was critical to the success of this project. The individuals involved include Mr. Dennis Lambert, who designed the large test box and oversaw many modifications to the box during the program, and Mr. Paul Schwarz (welder extraordinaire) who built our test box and always seemed to have the right tools and supplies for what was needed thereafter. We also thank Mr. Chris Williams, who programmed the data logger and wired pressure transducers to it and Mr. Richard Roberts and Mr. Charles Schelewe, who provided valuable skilled labor in the placement and compaction of soil in the test box. Mr. Dean Kellogg and Mr. Jon Gelineau were very helpful in the deconstruction of the control section and reconstruction of soil layers with the inclusion of the Geocomposite Capillary Barrier Drain (GCBD); and, we thank them, too. Mr. Jack Bayer provided asphalt sealing and soil layer density readings. Mr. Troy Arnold helped us reconfigure the drainage system for the drainage geocomposite. Mr. Tom Tantillo provided advice, ideas and supplies in the completion of this work.

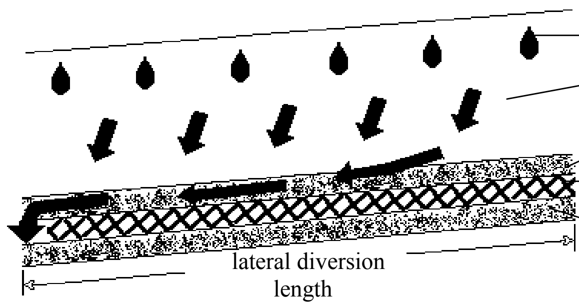
Mr. Robert Eaton of CRREL provided advice and guidance on the placement of asphalt, and we greatly appreciate Mr. Barry Betters and crew, of BBI asphalt, who paved the top of a box inside a building without setting off a fire alarm!

TABLE OF CONTENTS

EXECUTIVE SUMMARY

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) (Fig. 1). The transport layer removes infiltrating water, the capillary barrier stops upward and downward unsaturated flow of water from adjacent layers and the separator prevents underlying soil from intruding into the capillary barrier. The GCBD drains water from unsaturated overlying soil when placed at a slope, and it also cuts off capillary rise of water in the underlying soil.

Figure 1. Schematic of Geocomposite Capillary Barrier Drain (GCBD) with overlying soil.



Our test results indicate that when placed between a pavement base and subgrade, the GCBD will 1) accelerate the draining and drying of the base and 2) reduce subgrade wetting. We conducted experiments in two phases to obtain these results. In Phase 1, we selected a prototype transport layer from candidate textiles using capillary rise and moisture retention measurements and in-plane transmissivity tests. A drainage test in a 3-m-long box placed at a 2.5% gradient was then performed with the GCBD and the prototype transport layer. At an average long-term infiltration rate of 0.15 mm hr^{-1}, the GCBD drained all infiltrating water from the overlying soil at suctions of 120 mm and greater.

In Phase 2 we tested 1) a control pavement with a separator between the base and subgrade and 2) a pavement with a GCBD placed between the base and subgrade. The tests were conducted in a large, waterproof box that contained a 1.3-m-long lane of pavement structure from the centerline, across an unpaved shoulder and through the bottom of a ditch (0.71 m of subgrade, 0.3 m of base gravel and 50 mm of asphalt). The asphalt contained a 2.5-mm-wide crack, 300-mm in length that reached the top of the base. The box was placed at a 5% gradient from east to west and south to north and outflow was collected from the northwest corner. Water was applied to simulate storms that occur in the Northeastern United States. Outflow and soil moisture tension were monitored after each storm. At long-term steady-state infiltration rates of 0.1 to 0.15 mm hr^{-1}, the GCBD prevented all infiltrating water from reaching the subgrade. Three tests simulated a four-year design storm in northern New England of 6 hours duration, and two tests were approximately equivalent to a 10-year design storm of 1 hour.[1] The transport layer drained infiltrating water from overlying base at a minimum of 100 mm of suction head after water was applied. After one of the 6-hour storms, a small amount of water broke through into the subgrade; however, the GCBD recovered its function and protected the subgrade in a subsequent test that simulated a 1-hour storm.

The geonet and separator of the GCBD are commercially available. However, the transport layer should be further developed to drain more water at lower cost. The transport layer that we tested is a specialty fabric for industrial insulation applications. Development of a more economical transport layer (and thus GCBD) may involve partnering with a manufacturer that has experience bringing new products to market as well as with a textile or geotextile manufacturer willing to work with new polymer fibers such as fiberglass.

[1] In northern New England, a 10-year design storm of 1 hr. duration is about 37 mm, determined according to the Steel Formula.

1.0 IDEA PRODUCT: GEOCOMPOSITE CAPILLARY BARRIER DRAIN

The geocomposite capillary barrier drain (GCBD) drains water from overlying soil that is partially saturated and cuts off capillary rise of water in the underlying soil (*1*). When the GCBD is placed at an angle from the horizontal between the base and the subgrade, infiltrating water drains down slope either to daylight in a ditch or to a sub-surface drain. The GCBD thus reduces the amount of water and length of time that it persists in the base and reduces the amount of water that reaches the subgrade. The potential impact on the transportation infrastructure is quite large, as the lifetime of pavements may be significantly extended. We placed a GCBD between the base and the subgrade of a pavement test section that had cracked asphalt and an unpaved shoulder and ditch and applied water. The GCBD drained water that infiltrated the partially saturated base and prevented most infiltrating water from reaching the subgrade. A pavement test section without a GCBD was also tested, and water reached the subgrade after every application. Thus, when placed in paved roads between the base and subgrade, the GCBD will 1) accelerate base drainage and drying after infiltration, 2) protect the subgrade from wetting and 3) reduce the capillary rise of water into the base.

2.0 CONCEPT AND INNOVATION

Pavement drainage is designed for saturated flow. However, the positive pore water pressures required for saturated flow reduce strength and lead to rutting, heaving, and failure. Open-graded bases are permeable and minimize the build up of pore water pressures in the base, but they do not prevent the subgrade from wetting. Thus, drainage of water from the base before pore water pressures become positive will improve the pavement's performance and longevity. The Geocomposite Capillary Barrier Drain (GCBD) is a method to drain water from soils while the water is subjected to negative pore water pressures—that is, while the soil is unsaturated. When placed between a base and subgrade, it can drain the unsaturated base and prevent water from reaching the subgrade. Furthermore, even though the GCBD operates under unsaturated conditions, it will also provide drainage of saturated soils—because the capillary barrier (geonet) is permeable to saturated flow.

Lateral drainage in unsaturated soils occurs when downward moving water encounters dipping layers of underlying coarse-pored soil (a capillary barrier). Water accumulates near the fine/coarse interface and drainage is concentrated here because the hydraulic conductivity increases with water content (Fig. 2a). The soil moisture content continually increases down dip, and the horizontal distance at which breakthrough into the lower layer occurs (at near-saturated conditions) is called the lateral diversion length. Using a 'transport layer,' such as fine sand, between the two layers significantly increases the amount of unsaturated drainage (Fig. 2b). The transport layer has hydraulic properties intermediate between the fine and coarse soil. It drains water and yet remains unsaturated for a considerable distance so as to preserve the capillary barrier.

Experimental and numerical investigations indicate that effective unsaturated soil drainage is obtained using fine sand as the transport layer and gravel as the capillary barrier *(*2). However, transport layer and capillary barrier soils may not be available at the site and thus are costly. The soil is also difficult to place on many slopes and locations.

A soil drainage system made of geosynthetics has a number of advantages compared to a soil only, including:

1. properties can be optimized by design and controlled by manufacture,
2. drainage can be combined with other functions such as reinforcement and soil retention,
3. geosynthetics are thinner than soils (on the order of only a few cm), minimizing pavement structure thickness, and
4. geosynthetics are commercially available.

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) (Fig. 1). The transport layer removes infiltrating water, the capillary barrier stops upward and downward unsaturated flow of water from adjacent layers and the separator prevents underlying soil from intruding into the capillary barrier. The GCBD drains water from unsaturated overlying soil when placed at a slope, and it also cuts off capillary rise of water in the underlying soil. The GDBD resembles a drainage geocomposite; however, the transport layer is designed to transmit water under negative water pressures. The unsaturated hydraulic properties of the transport layer are critical to the proper functioning of the GCBD.

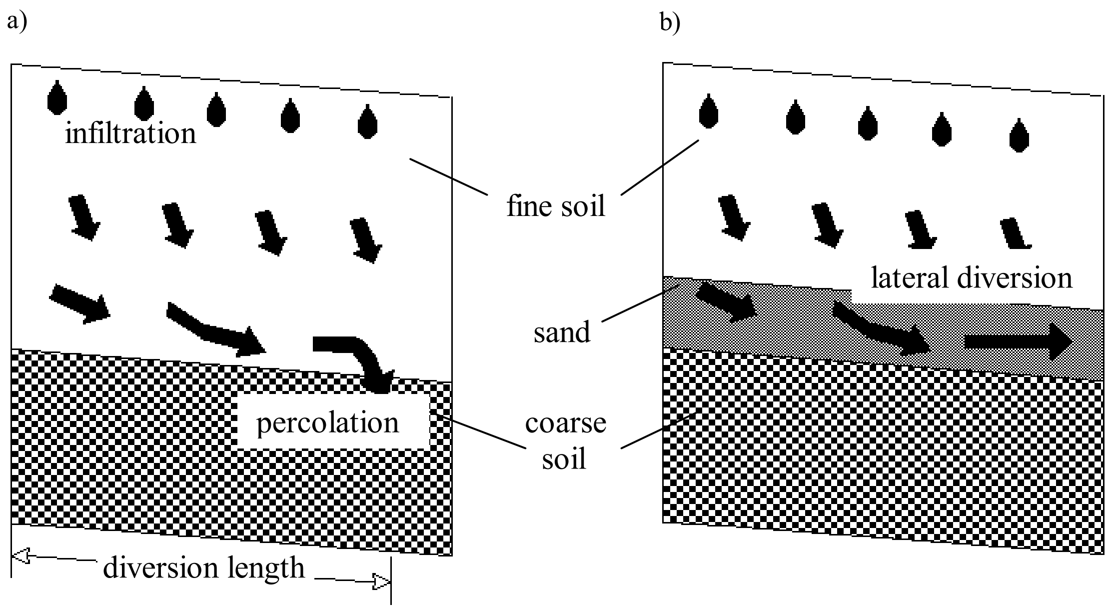


Figure 2. Lateral drainage in unsaturated soil with: a) a simple capillary barrier and b) capillary barrier with an overlying transport layer

3.0 INVESTIGATION

We conducted tests in two phases. In Phase 1 we measured capillary rise, soil moisture retention curves and unsaturated hydraulic conductivities for various transport layer candidates. We also tested a GCBD with a candidate transport layer in small-scale laboratory tests. In Phase 2 we evaluated the performance of a GCBD that utilized the top-performing transport layer from Phase 1 in a large-scale pavement test section and compared the performance to a pavement test section without a GCBD.

3.1 PHASE 1 TESTS

3.1.1 Evaluation of candidate transport layers

The hydraulic requirements for a transport layer are that (1) it wets and transmits water easily, and (2) it has longevity in a sub-surface environment. Theory and previous work indicates that the GCBD performance is optimized when the transport layer is hydraulically conductive at relatively high suction heads.

We obtained 16 textile samples for evaluation (Table 1). They included nonwoven, woven, multifilament and multi-layer materials. Three types of measurements were used to select the best transport layer from these candidates: (1) capillary rise (all specimens), (2) moisture retention function determinations (four specimens), and (3) transmissivity (four specimens). Results are given in the Stage 1 report, and are summarized below.

3.1.1.2 Capillary rise

Capillary rise above a free water surface provides a measure of the wetting and unsaturated transmitting behavior of a porous material. The capillary rise of water was measured in 16 materials (Fig. 3). We selected 4 materials for further evaluation based on the results, and determined their moisture retention functions: CSFM, NYL, HTX and TGLASS. Even though it had a relatively great capillary rise, the NWFG specimen was not tested further because it was too thin to serve as a transport layer. The FGWK material was only available as a rope, and thus was not further evaluated.

Table 1. Candidate transport layer materials evaluated in Phase 1.

Number	Designation	Description	Manufacturer
1	CSFM	Chopped strand fiberglass	PPG Industries
2	F300	Polyester	Texel, Inc.
3	TG1000	Polypropylene	Evergreen Technologies
4	CFM	Fiberglass and cellulose	PPG Industries
5	CFH	Fiberglass and cellulose	PPG Industries
6	NYL	Nylon	Troy Mill, Inc.
7	SORBX	Polypropylene and cellulose	Matarah Industries, Inc.
8	HTX-1000	Silica cloth	Amatex
9	TGLASS	Thermally treated fiberglass	Amatex
10	NWFG	Nonwoven fiberglass	PPG Industries
11	TCM5	NonwovenProprietary	TC Mirafi
12	FGWK	Fiberglass yarn	Pepperell Braiding Co.
13	TR11	Nonwoven Polyester	Hoescht Celanese
14	TCM1	Nonwoven Proprietary	TC Mirafi
15	GEO9	Nonwoven polypropylene	Texel, Inc
16	EGLASS	Nonwoven e-glass	BGF Inc.

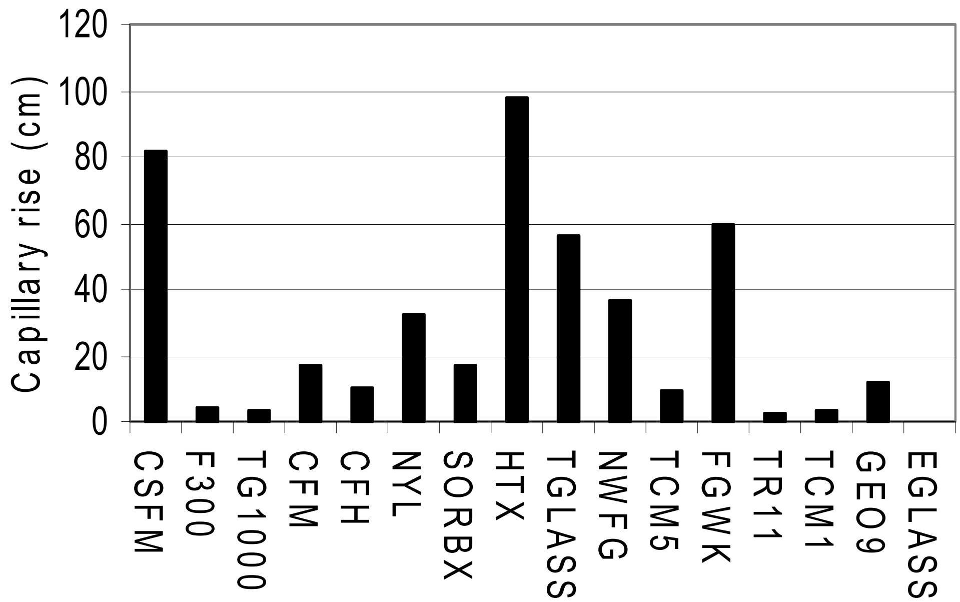
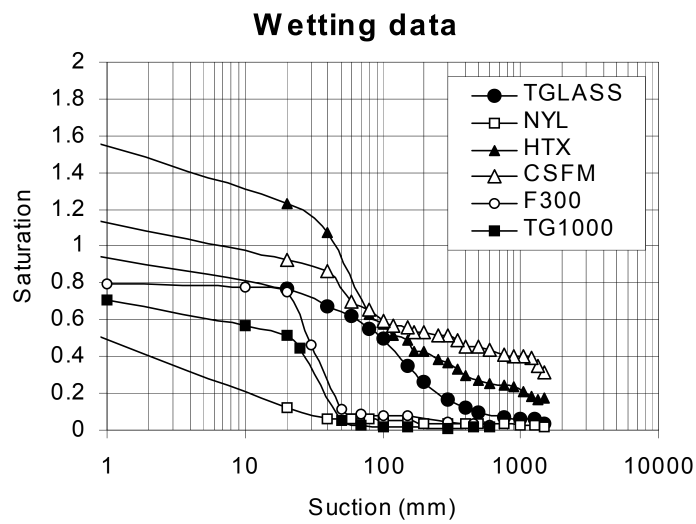


Figure 3. Forty-eight-hour capillary rise measurements.

3.1.1.3 Moisture retention functions

The moisture retention function (or, moisture characteristic curve) describes the relationship between negative water pressures (or suctions) and water content (or saturation) of a material. We used the hanging column method to obtain these data *(5)*. Wetting and drying paths for six materials are shown in Figure 4. In addition to the most easily wetting materials as determined by the capillary rise testing (NYL, TGLASS, HTX and CSFM), the moisture retention functions curves from two conventional geotextiles (F300 and TG1000) are given. All of the moisture retention functions are hysteretic--the materials contain more water during drying compared to wetting at the same suction.

There is a considerable difference in the moisture retention functions among the various materials. The HTX, CSFM and TGLASS materials all contained more water than the other materials at comparable suctions, whether following a wetting or drying path. (Saturations greater than 1 are believed to be a consequence of the change in sample thickness when the surcharge was placed and removed.)



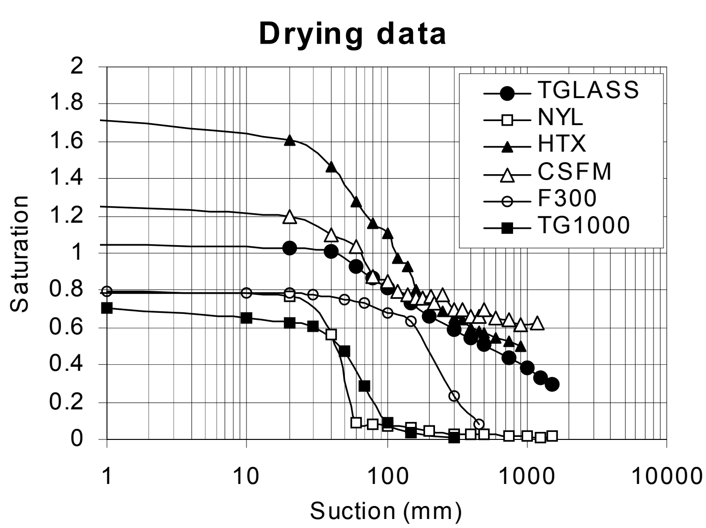


Figure 4. Moisture retention functions obtained from hanging column method for six candidate transport layer materials during wetting and drying.

3.1.1.4 Transmissivity

A siphon test was used to measure the ability of a geotextile to transmit water in-plane under suction. The HTX (silica) material was not transmissive at any suction, and thus was eliminated as a candidate transport layer. The other three materials did not become transmissive in wetting until 130 mm of suction head. At this suction, the TGLASS material conveyed approximately one order of magnitude more water than the NYL and CSFM materials. As the suctions were increased (drying), only the TGLASS remained transmissive above suction heads of 400 mm.

The TGLASS was further tested in a permeameter designed for measuring in-plane transmissivity of geotextiles under suction (Fig. 5) *(7)*. The first measurable transmissivity during wetting occurred at 100 mm; and as the suction decreased to zero, the measured transmissivity increased by more than two orders of magnitude. During drying, the TGLASS was much more conductive at the same suction head compared to wetting, and remained measurably transmissive to 600 mm. The transmissivity under suction for a nonwoven polypropylene (TG1000) geotextile is also given. Compared to TG1000, TGLASS is significantly more transmissive over a greater range of suctions during both wetting and drying.

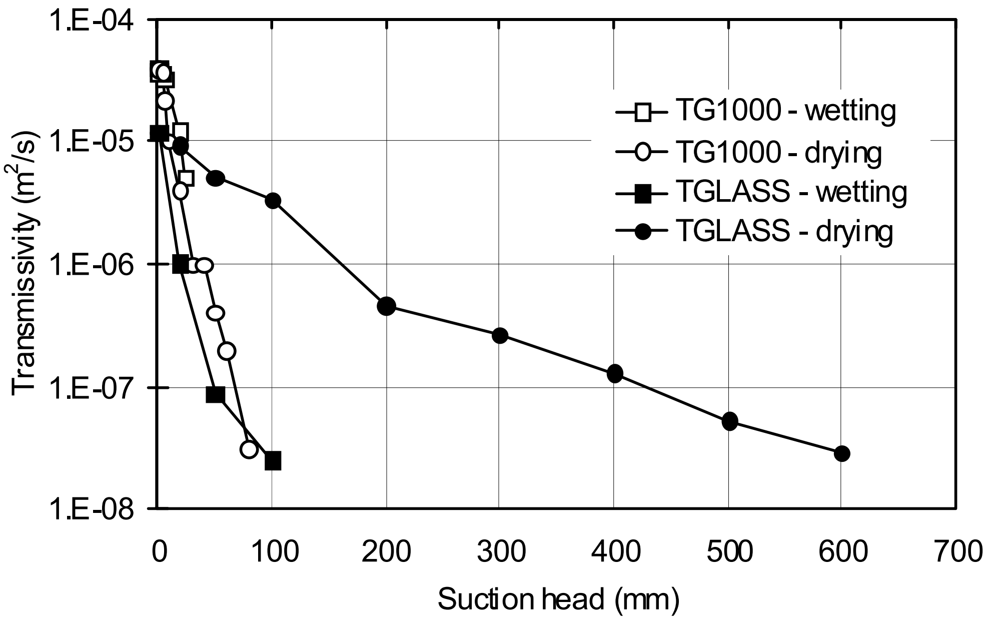


Figure 5. Transmissivity of TGLASS and polypropylene (TG1000) geotextiles using constant suction permeameter.

3.1.1.5 Transport layer

We selected the TGLASS as the best transport layer from the original 16 materials tested because it is transmissive over a large range of suctions. It is a very heavy, woven, multifilament material with a mass per unit area of 2370 g m^{-2}, a thickness of 3.2 mm, and an O_{95} size of 0.075 mm.

3.1.2 Laboratory-scale testing of GCBD

Although not part of the required scope of work, a laboratory drainage test of a GCBD system that utilized the TGLASS material as the transport layer was conducted in order to validate and confirm its performance. This work has been published separately *(8)*, and is summarized here.

3.1.2.1 Materials and methods

The GCBD comprised a geonet sandwiched between TGLASS (two layers on the top and one layer on the bottom). The HDPE extruded tri-planar geonet is 5.9 mm thick with a minimum aperture size of 6 mm. Two soils were used in a lateral diversion apparatus (described below). The underlying soil is designated SC by the USCS classification method, and is representative of near-surface soils in a much of New Mexico. It has 35% fines, a plasticity index of 8, and a saturated hydraulic conductivity of 1.4 x 10^{-4} cm s^{-1}. The overlying soil is GP-GW, commonly used as a base material in New Mexico and was obtained locally. The GP-GW soil has 7% fines, no measurable plasticity, and a saturated hydraulic conductivity of 1.3 x 10^{-2} cm s^{-1}.

The drainage capacity of the GCBD was tested in a 3-m-long box (Fig. 6) *(8)*. The profile was 100 mm of SC subgrade, the GCBD, and 150 mm of GP-GW on the surface. The GCBD performance was evaluated during three phases: (1) constant rate infiltration, (2) subsequent drainage with no infiltration, and (3) transient infiltration. Measurements were made of water infiltrated onto the surface, water drained out of the GCBD, water laterally drained in the overlying soil and water produced out of the bottom of the subgrade. Soil suction above and below the GCBD was also monitored.

For constant rate infiltration, water was added to the top of the base with a manifold-type distribution system for about 8 hours per day for 4 consecutive days, followed by 2 days with no infiltration, and then another day with about 8 hours of infiltration. After drainage from the GCBD was observed the following day, water was added continually over the next 2 days. Water was added for a total of 88 hours, with a total input of 26 mm. The average infiltration rate was 1.5 mm hr^{-1}. The soil located past the end of the GCBD collection interval was infiltrated with water to minimize the influence of this soil on suction gradients and subsequent flow in the GCBD. Infiltration continued until the rate of laterally drained water was steady and was greater than 90% of the infiltration rate. Drained water was measured for 14 days after infiltration was stopped. The transient infiltration consisted of manually distributing 9 mm of water in one hour on the surface. This is 50% of the 1-hr, 1-yr return period storm for Albuquerque, NM, and is consistent with the infiltration rate suggested by Cedergren *(9)* for design of pavement subsurface drainage systems.

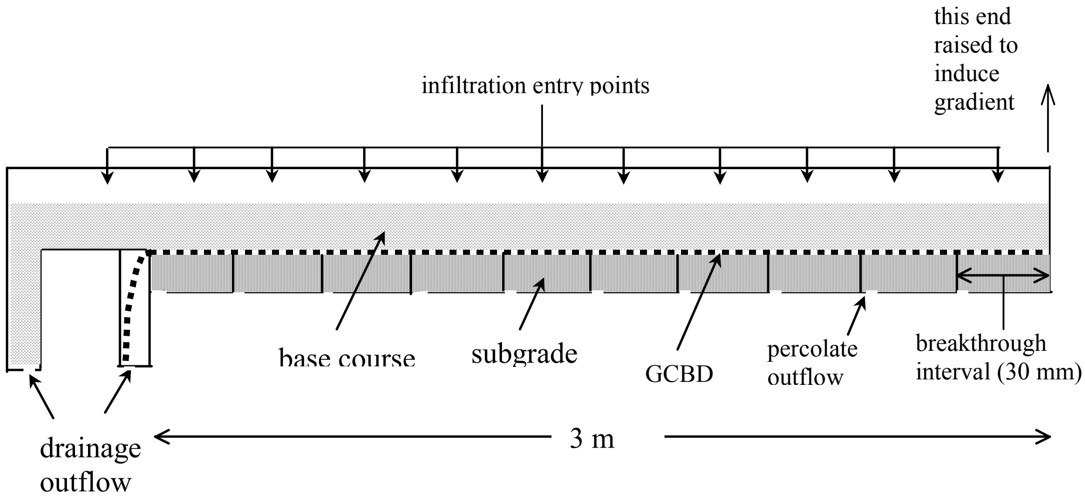


Figure 6. Lateral diversion test apparatus.

3.1.2.2 Results and discussion

Infiltration and drainage histories for the test are given in Figure 7a. The suction heads measured by the tensiometers immediately above the GCBD are reported in Figure 7b. The average suction head is given because the tensiometers all had similar responses. The water in the soil above the GCBD remained in tension as water laterally drained from the base through the GCBD. Water also drained from the overlying soil while the water pressures remained negative.

The suctions in the soil immediately above the GCBD decreased rapidly in response to infiltration from a pre-infiltration value of more than 1500 mm. The very sharp decline and recovery of suction head in the first 50 hrs is due to de-airing of the tensiometers. Water first drained from the GCBD system at an average suction head value of 260 mm. With continuing infiltration, suction heads decreased further and the GCBD produced increasing amounts of water. The suction heads reached a minimum value of about 70 mm when steady state was achieved and the constant rate infiltration portion of the test was terminated. The overlying soil also laterally drained some water while the water pressures remained negative. At no time during the infiltration did any of the tensiometers above the GCBD indicate that the overlying soil reached saturation.

The GCBD drained water while the upper soil remained in tension, and also prevented breakthrough into the underlying soil. No water was produced from any of the breakthrough intervals and most suction heads measured in the subgrade soil immediately below the GCBD remained nearly constant, typically at values of about 3500 mm.

The post-infiltration drainage rate as a function of time is given in Figure 8 along with the average suction head from the ten tensiometers above the GCBD. The rate of drainage from both the GCBD and the overlying base soil decreased with time as suction increased. A total of 126 mm of water was collected during this test phase: the GCBD drained 11.3 mm of water over 14 days and 1.3 mm of water drained from the overlying soil for about 4 days. The GCBD was still draining a small amount of water at suction heads in excess of 600 mm when this test phase was terminated. The overlying soil remained in tension during transient infiltration, indicating that its storage capacity was sufficient to accommodate the added water without reaching saturation.

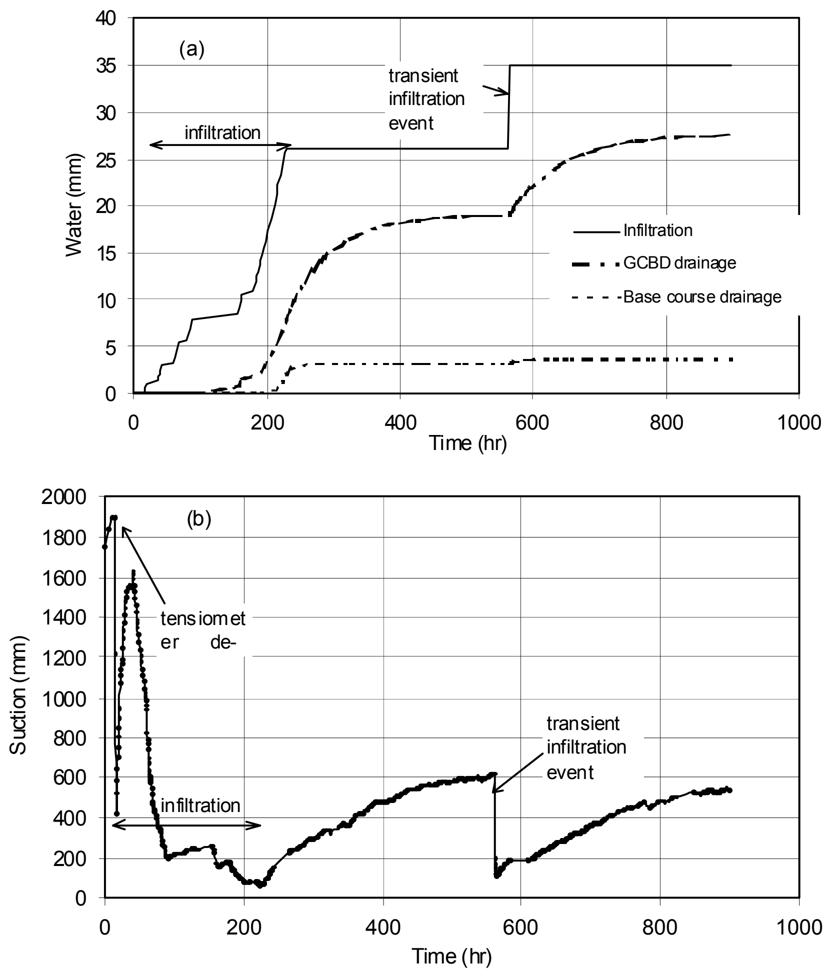


Figure 7. Summary of test results. (a) History of infiltration, drainage from GCBD and drainage from overlying soil, and (b) average suction history immediately above GCBD.

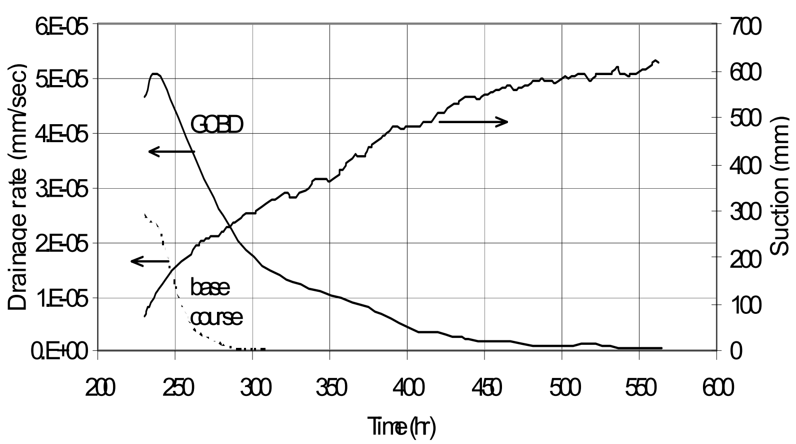


Figure 8. Drainage rate from GCBD and overlying soil during period between constant rate infiltration and transient infiltration. The average suction in the overlying soil immediately above the GCBD is also shown.

The drainage from the GCBD reached its peak value about 3 hours after transient infiltration, and occurred at an average suction head of 120 mm. The suctions in the overlying soil continued to increase as water drained from the base through the GCBD. Water was still draining through the GCBD 14 days after transient infiltration. Some comparisons are possible between these test results and those reported by Stormont and Stockton (*10*) from tests on GCBD systems using either a polypropylene or a polyester geotextile as the transport layer. For this test, the GCBD began producing water at a suction head of 260 mm, whereas the previously tested GCBDs first drained water in the 2 to 50 mm range. The peak drainage capacities of the GCBDs are different, and are related to the maximum (saturated) transmissivity of the geotextile (6). The saturated transmissivities of the polypropylene, polyester and fiberglass geotextiles are 0.39, 0.07 and 0.12 $cm^2 s^{-1}$, respectively. Thus, the polypropylene has the greatest drainage capacity. However, using more than one layer increases the flow capacity of the GCBD. Finally, the GCBD with the fiberglass transport layer drained water at much greater suction heads (more than 600 mm) compared to the GCBD with the polypropylene and polyester transport layers (about 100 mm). These results are consistent with the differences in the measured transmissivities of the different materials.

3.1.3 Phase 1 test conclusions

The GCBD was successful in draining water under suction and prevented positive pore water pressures from developing in the base. At no time during these tests did the base reach saturation. The GCBD also prevented water movement into the underlying subgrade during both constant rate (1 hr storm of 9 mm) and transient infiltration tests (average intensity of 0.15 mm hr^{-1}). The GCBD drained water from the overlying base to suctions greater than 600 mm. This drainage under suction resulted in the base becoming drier and having an increased capacity to accommodate infiltration events without reaching saturation.

3.2 PHASE 2 TESTS

In the second phase we constructed a large test box for testing the performance of 1) a control section and 2) the GCBD. The box was filled with subgrade overlain by a separator (control section) or the GCBD that was, in turn, overlain by the base and then paved (Fig. 9). The box contained a pavement section, comprising a 1.3-m-long lane of pavement from the centerline through the bottom of a ditch. Tests were performed by applying water, measuring outflow and monitoring soil moisture tension. Water was applied to simulate typical storms that occur in the Northeastern United States. For initial GCBD tests, we performed steady-state infiltration to simulate conditions in Phase 1 tests.

3.2.1 Experimental method

3.2.1.1 Construction of test box

The test box for performing large-scale tests of the GCBD was constructed of welded steel plates and is 6.2 m in length, 1.2 m high and 1.3 m wide (Fig. 9). The interior of the box is painted with primer for water tightness and to resist rusting. In order to facilitate internal water flow and drainage, the box is tilted by 2% from south to north and from east to west. In addition, the soil layers were emplaced at a 2% grade from east to west. The ditch, at the west end of the box, has a slope of 2:1, and there is an outlet drain at the bottom. On the long sides of the box, waterproof outlets are located for tensiometers, thermocouples and drains (Fig. 10).

3.2.1.2 Placement of control section

The control section consisted of an average thickness of 0.71 m of subgrade, a geotextile separator, 0.3 m of base gravel and 50 mm of asphalt pavement. A 50 mm layer of gravel topped with a geotextile separator was placed under the subgrade to help insure uniform water distribution when a water table is present. The test section containing the GCBD is identical to the control section, except that the GCBD is located between the base and subgrade. When the test section was reconstructed for placement of the GCBD, only the asphalt, base and geotextile separator were removed, the GCBD was placed on the subgrade, the base was replaced and compacted and the test section was repaved.

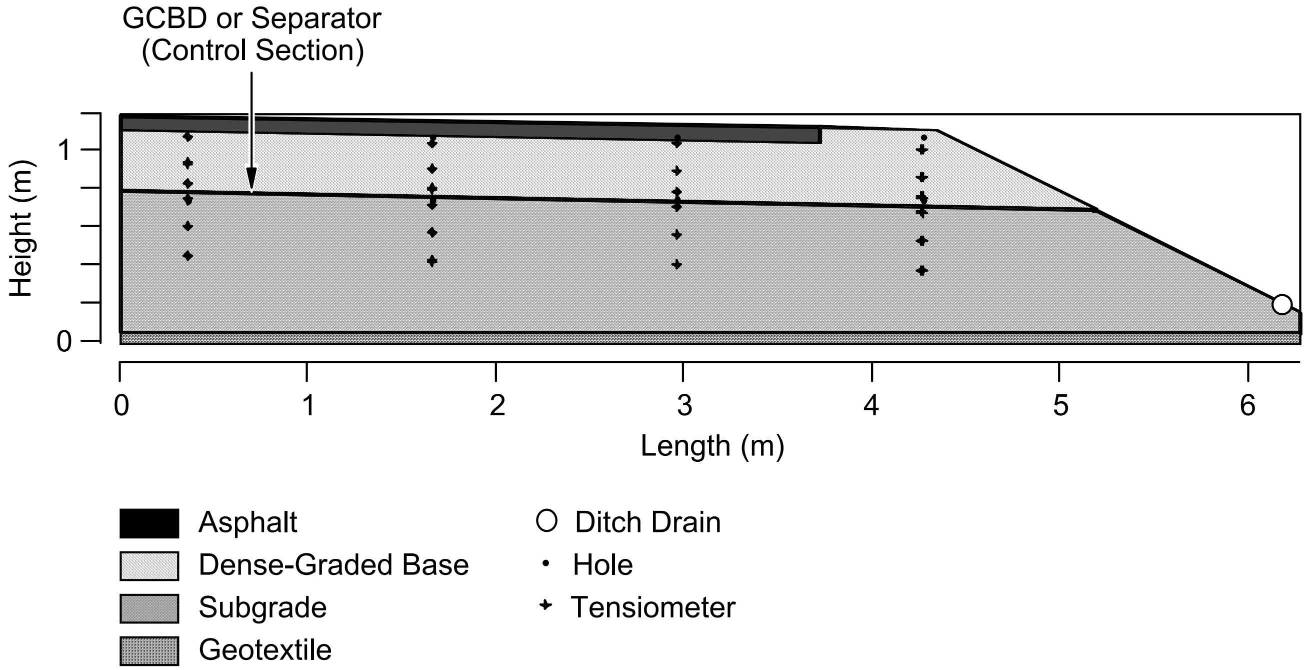


Figure 9. Cross-section of the pavement configuration tested, with the GCBD included between the base and subgrade.

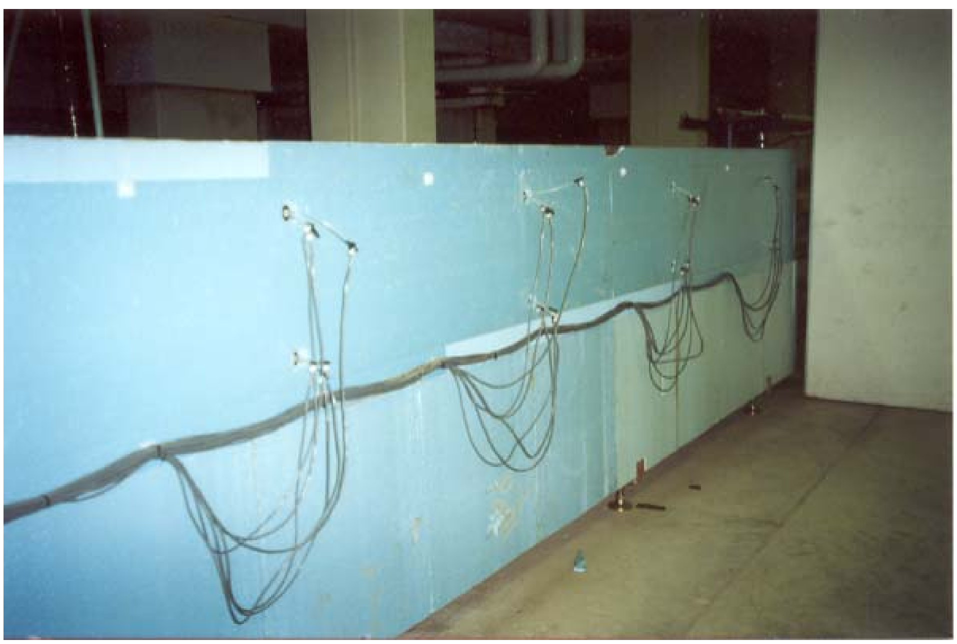


Figure 10. Photograph of test box with tensiometer tubes connected to pressure transducers exiting the side of the box.

During soil placement, the subgrade material, lean clay (A-4 according to AASHTO) was placed in the box in five layers, approximately 150 mm thick. Each layer was compacted and tested for moisture content and density (Table 2). The target density value was 1.64 Mg m^{-3}, 90% of the maximum as determined by standard proctor tests. Each soil layer was compacted with three passes of a vibratory plate compactor. We hand tamped the soil near the edge of the box to achieve uniform density and near the water wells and the instrumentation to avoid causing damage with the larger compactor. The same procedure was used to place the base, a bank run gravel approved by the State of New Hampshire for use as a dense graded aggregate base. Density and moisture content measurements were taken with the Troxler nuclear gage (model #3440) and a drive cylinder.

Hot mix asphalt, using a State of New Hampshire Type E mix specification, was spread and compacted with a vibratory compactor and hand tamper. The asphalt was placed for a distance of 3.66 m from the east end of the box, so that there is a 0.61 m gravel shoulder area. In addition, one 6.5-mm-wide and 610-mm-long crack, located at 2.44 m from the from the east edge of the box, extended from the north edge to the center of the box. The crack reached through the asphalt to the base material (Fig. 11).

Table 2. Dry density and moisture content readings taken during construction of the control section.

Layer	Average Dry Density ($Mg\ m^{-3}$)	Average Moisture Content (% by weight)
Nuclear Gage		
Subgrade 1st lift	1.65	16.6
Subgrade 2nd lift	1.65	17.9
Subgrade 3rd lift	1.62	16.9
Subgrade 4th lift	1.61	18.0
Subgrade 5th lift	1.62	17.1
Base 1st lift	1.98	3.3
Base 2nd lift	2.01	3.2
Drive Cylinders (Second lift of subgrade)	1.60	19.1

Note: Six nuclear gage readings were taken per lift and three drive cylinders were taken in the second lift.

Figure 11. Photograph of crack sawn into the asphalt. The crack is 6 mm wide.

3.2.1.3 Deconstruction of control section

After the control tests were completed and prior to removing the asphalt for reconstruction with the GCBD, seven asphalt specimens were cored for permeability and density testing in the future (Fig. 12). One core was sampled in the northeast section to check for variability in density or permeability since water ponded at this location during testing and a leak occurred from tensiometer holes that were located closest to this area. The specimens were 102 mm in diameter and cut down to the surface of the base. The thickness of the asphalt specimens ranged from 64-89 mm.

After removing the asphalt, two drive cylinders were collected from the base to test for the soil moisture (Fig. 12). Nuclear gage readings for dry density and moisture content were recorded for the base (Table 3). The density readings are comparable to the readings taken during the construction of the control section. We also recorded nuclear gage readings for the subgrade (Fig. 12, Table 4).

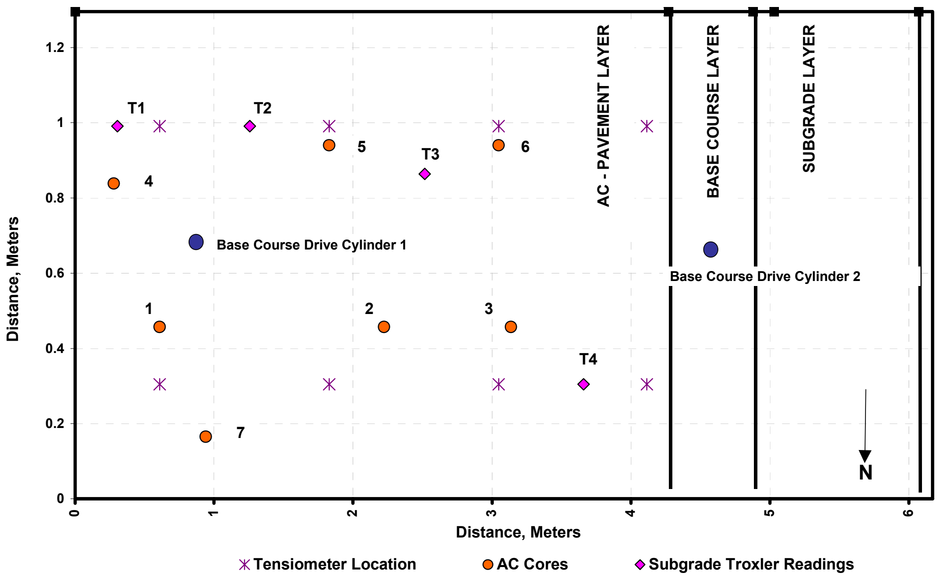


Figure 12. Plan view of test section showing locations of soil testing during deconstruction.

Table 3. Dry density and moisture in the base layer after completion of control section testing.

Nuclear gage readings		
Location	**Dry Density Reading ($Mg\ m^{-3}$)**	**Moisture Content (% by weight)**
1	2.020	4.2
2	2.01	4.1
3	1.93	4.7
4	1.98	3.4
5	1.96	4.5
Drive cylinders		
1 (under pavement)	------	5.9
2 (shoulder)	------	4.4

Table 4. Dry density and moisture from nuclear density tests of the subgrade after completion of control section testing.

Location	**Dry Density Reading ($Mg\ m^{-3}$)**	**Moisture Content (% by weight)**
1	1.59	17.8
2	1.592	18.6
3	1.69	17.4
4	1.74	17.7

The control section geotextile separator was removed and the locations of the crack and shoulder were drawn onto it. Certain areas of the geotextile contained large amounts of soil fines, suggesting that a significant amount of water had passed through. In particular, the rather large zone of influence from the asphalt crack was evident (Fig. 14). The effects of water movement related to leaks that occurred during testing could also be seen.

Figure 13. Photograph of the top of the geotextile separator removed from the control section. Staining with soil fines appears to indicate where significant amounts of water flowed through. The location of the crack in the asphalt is highlighted with the chalk line. The black edge suggests that no water migrated across the edges of the separator.

3.2.1.4 Construction of GCBD section

Before replacing the base and asphalt over the GCBD, tensiometers in the uppermost subgrade layer were checked and three were replaced due to damage that occurred during excavation. In the event that future testing might include freezing the test box, 8 thermocouple rods were installed in the subgrade. The bottom node was located on the top of the bottom geotextile—just above the bottom gravel layer. Each rod consists of 5 thermocouples, spaced in increments of 152 mm. Eight rods were also placed in the base layer directly above the ones in the subgrade. The base thermocouple rods were 305 mm long with three nodes vertically spaced 152 mm apart.

We raked the subgrade surface then installed the geotextile separator--the bottom layer of the GCBD. The separator is one thickness of the transport layer material, and is 1 m wide. The width of the test box is 1.3 m, so we cut an additional strip of geotextile and overlapped it by 152 mm toward the south side of the box to ensure complete coverage of the subgrade (Fig. 14).

Figure 14. Separator of GCBD after placement on the subgrade. Note overlap of the geotextile towards the right side of the box.

The capillary barrier (drainage net) is a 5.8 mm-thick, extruded tri-planar geonet (Fig. 15). It was placed and trimmed to fit around the water wells. The ends toward the ditch of both the geotextile and the geonet were trimmed and inserted into slotted drainage pipe that exited through a 25.4 mm drain in the side of the test box. The transport layer of the GCBD (two layers of TGLASS), was placed on top of the geonet. The layers were overlapped to completely cover the width of the test box. There was opposing overlap for each layer. The transport layer was inserted into a slotted drainage pipe that exited the side of the box. A bead of RTV was put around each of the water wells and all along the edge of the transport layer as a seal to reduce any water migration along the edge of the box and the GCBD.

Figure 15. Separator of GCBD overlain by the geonet (capillary barrier).

The base material was replaced in three lifts and the tensiometers were installed. Five nuclear gage readings were taken approximately 0.7 m (28 in) apart from the east end to the end of the base at the west end of the box (Table 5). The asphalt was a similar mix to that used during the construction of the control section, and it was placed and compacted similarly. As with the control section, the edge of the asphalt was cut back to create a 0.61 m (2 ft) gravel shoulder and an identical crack, located approximately 2.43 m from the East side, 654-mm-long and 10-mm-wide, was saw cut through the full depth of the asphalt surface.

Table 5. Base layer nuclear gage readings during re-construction.

Location	Dry Density Reading ($Mg\ m^{-3}$/ $lb\ ft^{-3}$)	Moisture Content (% by weight)
1	2.06	6.4
2	2.06	5.8
3	2.03	6.8
4	2.02	6.2
5	1.98	6.8

After some initial tests with the GCBD we realized that we would not be able to measure the amount of water flowing in the transport layer unless the downslope edge was lowered about 300 mm. Thus, the GCBD was reshaped near the west end, under the shoulder area, to drop vertically downward, so that water flowing at 300 mm suction head would saturate the bottom of the transport layer and thus flow out of the box (Fig. 16). Two 25.4-mm (1in)-diameter drainage holes (the pipe centers are located 32 mm apart) were drilled in the side of the box to collect the water, and the original drain holes were capped. We inserted the ends of the transport layer and the combined net and separator into slotted drain pipes, installed with a 2% slope from south to north. To maintain separation between the transport and net layers, a section of 0.15 mm black plastic was placed between them for the vertical section.

3.2.1.5 Instrumentation

We placed three layers of eight tensiometers in the subgrade and base, for a total of 48 tensiometers. They were located in vertical columns at increasing depths (Figs. 9, 16, 17). The subgrade tensiometers were located 0.3 m from each edge of the box (horizontally) at depths of 330, 179 and 25 mm below the base/ subgrade interface, respectively. The tensiometers in the base were located at 13, 127 and 279 mm above the base/ subgrade interface. The tensiometers in the lowest layer were labeled 1 through 8. One through four were on the north side of the box from west to east and 5-8 were on the south side of the box from west to east, and so forth for each layer. It is noted that the westernmost tensiometers were not located beneath asphalt, but below the shoulder area.

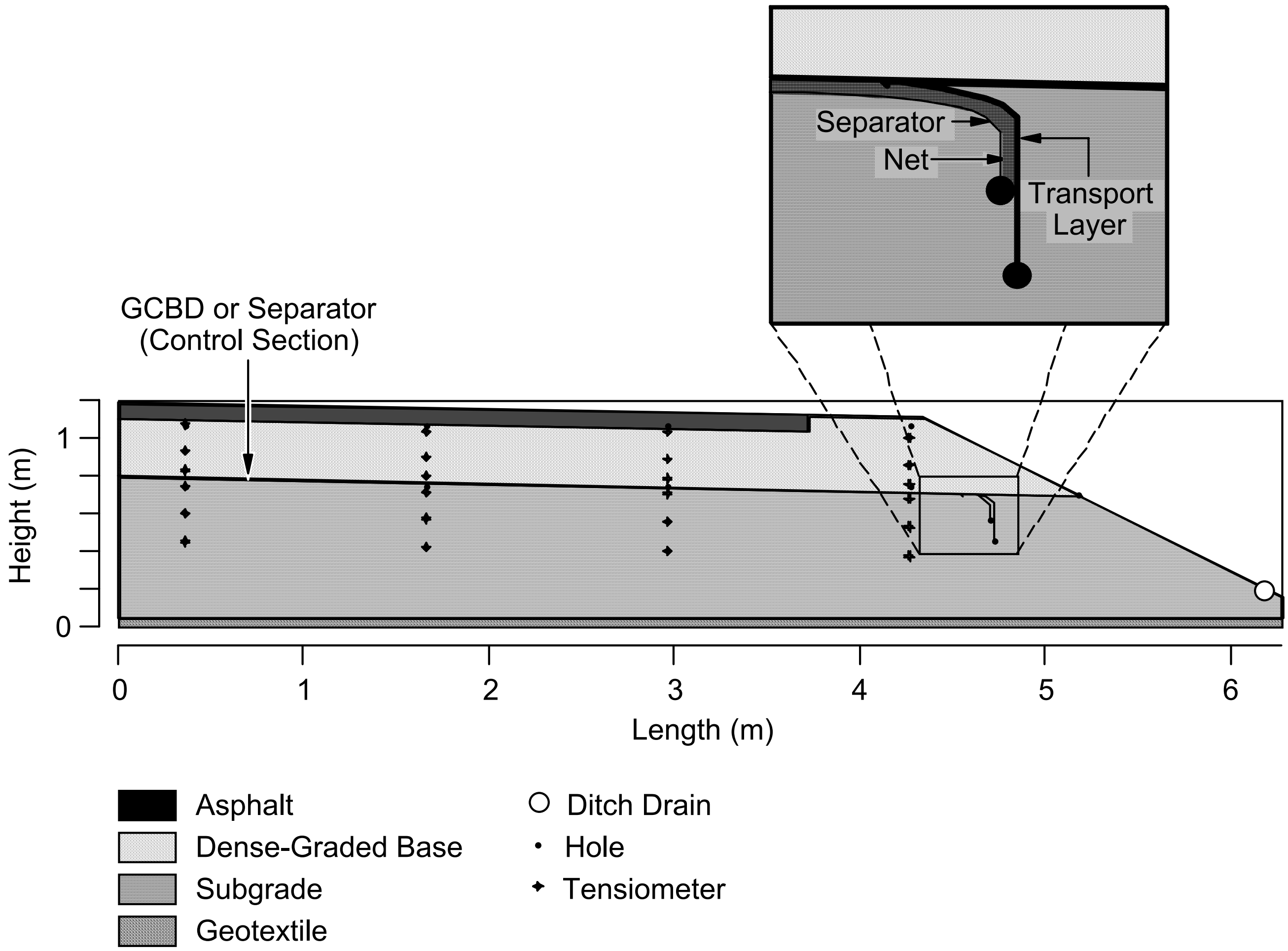


Figure 16. Cross-section of the GCBD test section with vertical drop for water collection.

The tensiometers comprise a ceramic tip, nylon tubing, and a pressure transducer connected to a data acquisition system. The round-bottomed, straight walled ceramic tips (28.6 mm in length and 1.6 mm thick) were purchased from Soil Moisture Equipment Corporation. The tips were affixed with epoxy to nylon tubing that was rated up to 1.72 MPa. The pressure transducers, from Omega Engineering, Inc., are wet/wet differential. Two transducer pressure ranges were selected for use, 0.21 MPa and 0.10 MPa.

The transducers from the tensiometers are wired into a data acquisition box, mounted on the end of the test box. A Campbell Scientific CR10X datalogger storage module collects the data for downloading and processing. Readings on all 48 tensiometers are taken every 30 minutes.

3.2.1.6 Tests conducted

Tests 1 through 4 were conducted on the control section without a GCBD (Table 6). The remaining tests were conducted on a test section containing a GCBD. Tests 4, 6 and 8 simulated a four-year design storm in northern New England of 6 hours duration. Storm intensity was determined according to the Steel Formula *(11)*, and is 6.6 mm hr^{-1} for a total of 39 mm of water. Tests 3 and 9 simulated a 10-year design storm of 1 hour.[2]

The first storm was very large and served to moisten the soil layers and place a 0.2 m-high water table into the test box. In tests 1 and 4 we applied the water by hand with sprinkling cans, and in tests 2 and 3 we applied water with a sprinkler hose suspended above the test section. We found that applying the water by hand allowed for the best control the infiltration rate. Thus, for tests with the GCBD we applied the water by hand.

[2] In northern New England, a 10-year design storm of 1 hr. duration is about 37 mm, determined according to the Steel Formula.

For the control tests, the separator geotextile and the last 15 mm of base fed into a metal angle that was connected to a drain. The water collected here was negligible, indicating that there was no significant lateral flow along the base/ subgrade interface. Generally, water in the base flowed downward through the separator into the subgrade.

We conducted long-term infiltration tests at a rate of infiltration similar to the Phase 1 tests on the GCBD test section prior to the design storm applications. Because of the large volume of water that was applied in very small increments during the infiltration tests, the soils of the GCBD test section were significantly wetter than those of the control section prior to the application of each storm (transient event).

Table 6. Rates and amounts of water applied during tests. The box surface area is 7.996 m^2.

Test	Date	Storm intensity ($mm\ hr^{-1}$)	Storm duration (hr)	Amount of water (m^3)
Phase 2 control tests				
1	9/21/00	11.08	6	0.532
2	10/11/00	6.44	6	0.309
3	10/26/00	9.47	1	0.076
4	11/2/00	1.62	5.42	0.070
Phase 2 tests with GCBD intersecting the ditch				
5	2/05/01-3/08/01	0.1*	Not applicable	Not applicable
6	3/08/01	1.56	6	0.076
Phase 2 tests with GCBD outflow measurements				
7	3/23/01-4/05/01	0.1*	Not applicable	Not applicable
8	4/05/01	1.56	6	0.076
9	4/13/01	9.47	1	0.076

*Long term infiltration tests. The water was applied two times per day: 0.073 m^3 each time.

3.2.2 Experimental results

We present results that demonstrate the benefit of the GCBD in this section. Because an extremely large amount of data was generated, only tests 3, 4 and 7 through 9 with suction head measurements from 13 mm below the interface and 25 mm above the interface are included. The other suction measurements recorded and tests conducted are consistent with the data presented.

Figure 17 depicts the layout of tensiometers located 13 mm above and 25 mm below the separator geotextile or the GCBD. Due to the slope of the box, the tensiometer with the lowest elevation is located in the lower-right-hand corner (i.e., tensiometers 17 and 25). This is helpful in interpreting suction head measurements recorded during the tests and discussed below.

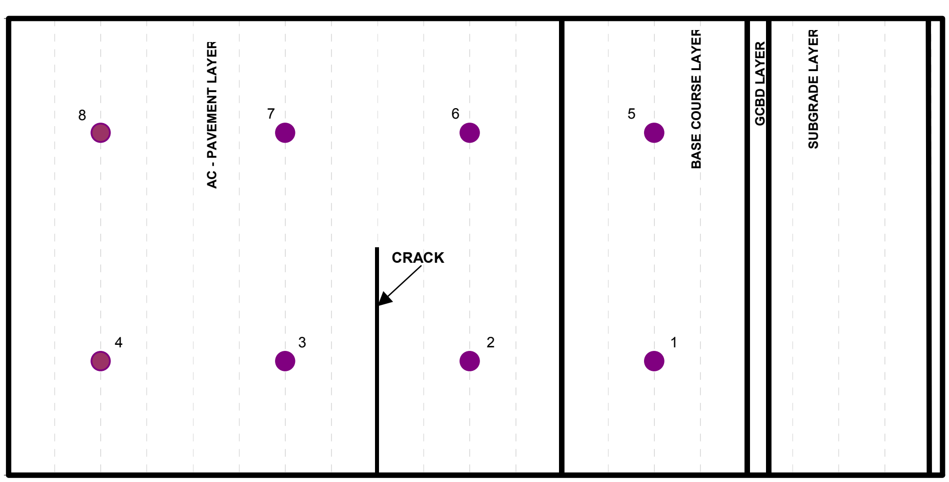


Figure 17. Plan view of tensiometers located 25 mm below the separator or GCBD (17-24) and 13 mm above the separator or GCBD (25-32). The box, as depicted, tilts from left to right and top to bottom by 2%. The soil layers also slope 2% from left to right.

3.2.2.1 Long-term infiltration test with GCBD (Test 7):

For the long-term infiltration test in which we applied approximately 0.1 mm day^{-1} in two daily applications, the transport layer drained more water than the ditch (Figs. 18, 19). The GCBD also protected the subgrade—the water table actually decreased in elevation during this test, and only a small percentage of the water applied was stored in the subgrade.

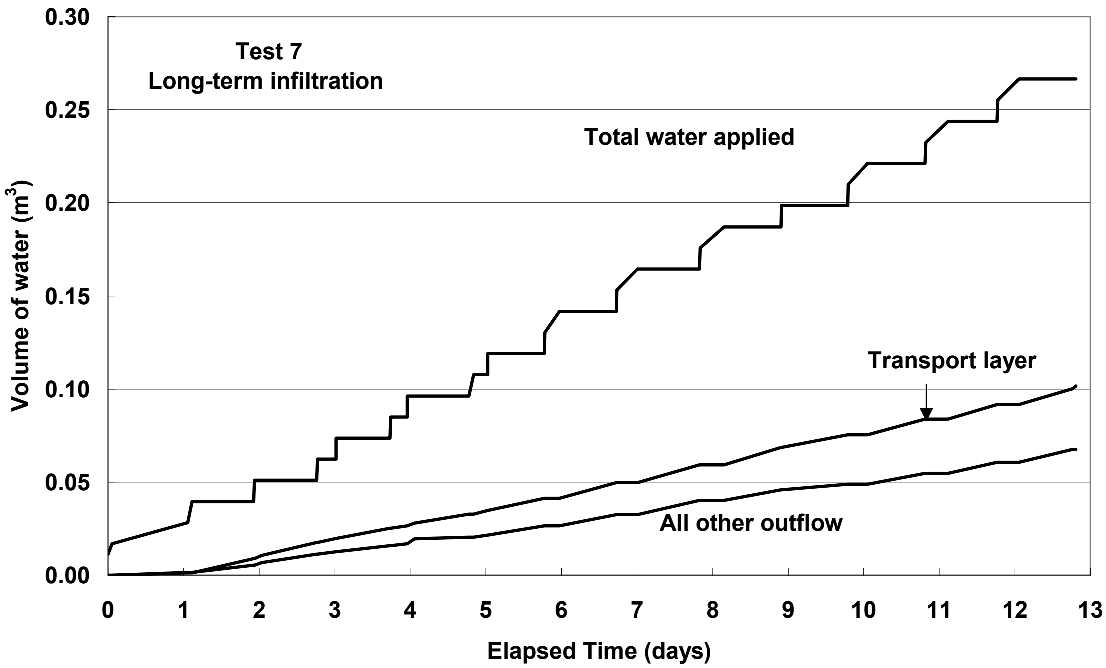


Figure 18. Outflow from long-term infiltration test with GCBD (Test 7).

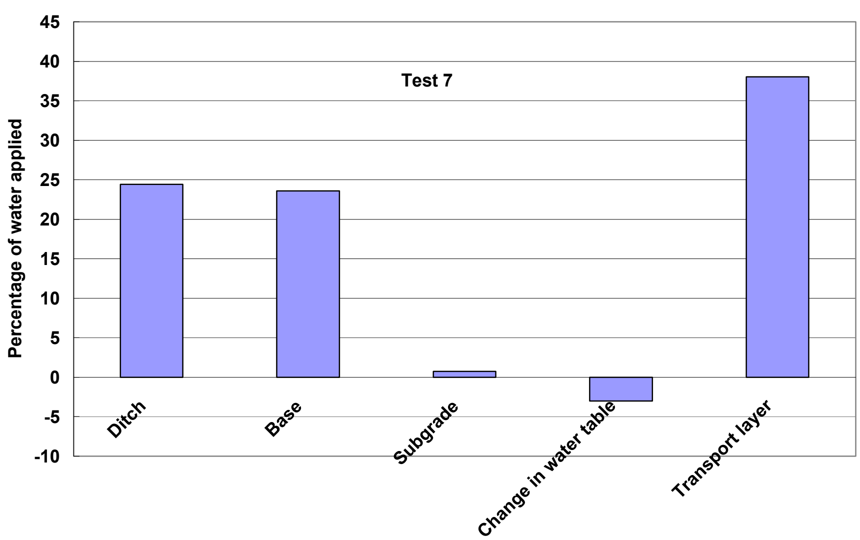


Figure 19. Percentage of water applied that was drained from the ditch, stored in the base and subgrade, in changing the elevation of the water table and drained from the transport layer in long-term infiltration with GCBD (Test 7).

The water content of the base layer increased significantly during this test; but the water content of the subgrade increased only slightly. This is reflected in the tensiometer readings, which decrease in the base and remain nearly constant in the subgrade (Figs. 20, 21). All the tensiometers in the base layer immediately above the GCBD, except 31 and 32, responded to the daily application of water, whereas those immediately below the GCBD in the subgrade did not—indicating that the transport layer was draining water from the base while the subgrade was being protected from wetting. The subgrade did moisten somewhat, due at least in part to the fact that the subgrade was subjected to infiltration where it intersected the ditch.

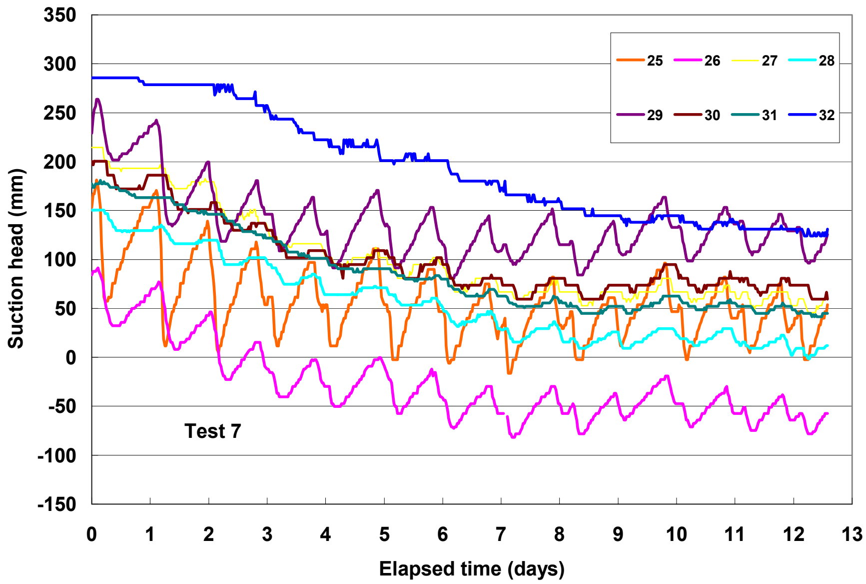


Figure 20. Soil suction heads in the base, 13 mm above the GCBD in a long-term infiltration test (Test 7).

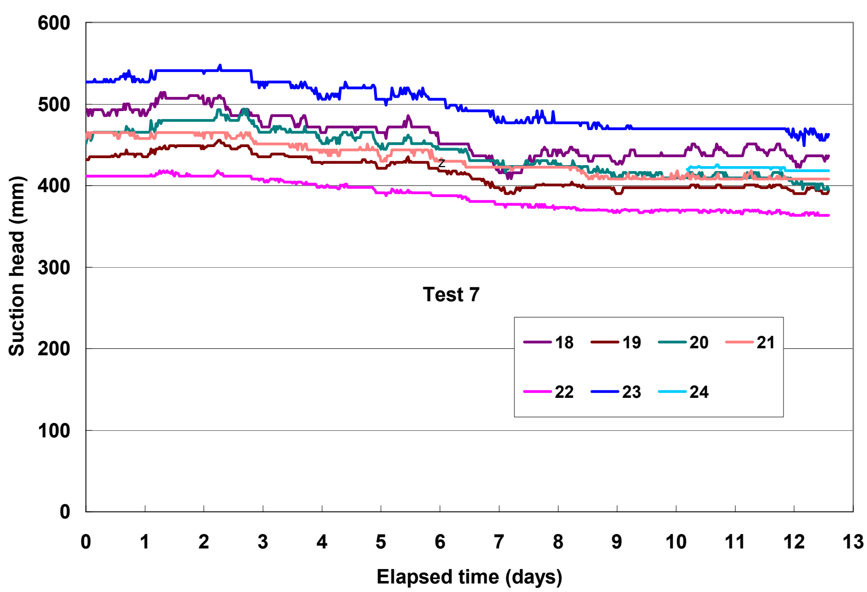


Figure 21. Soil suction heads in the base, 25 mm below the GCBD in a long-term infiltration test (Test 7).

3.2.2.2 Six hour storm in control section and in section with GCBD (Tests 4 and 8):

Tests 4 and 8 represent a rain of six hours in duration. After we stopped applying water in test 8 (at day 0.25), the transport layer drained water at a greater rate than the ditch; and it did so while the water was under suction. (Fig. 22). While the transport layer was producing water, the water in the base overlying the transport layer was in tension. Six days after the storm, the minimum suction head of water in the base was 100 mm (Fig. 23).

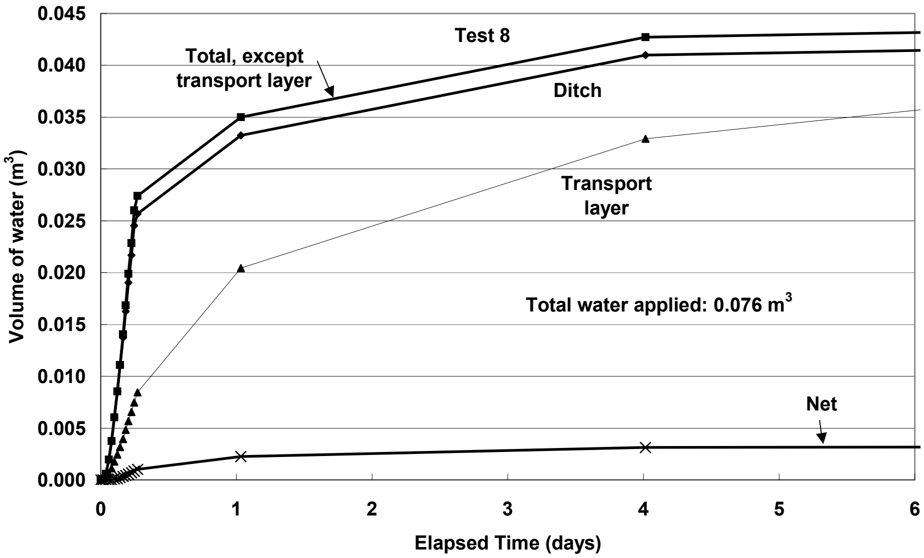


Figure 22. Outflow for six- hour storm in test section with GCBD (Test 8).

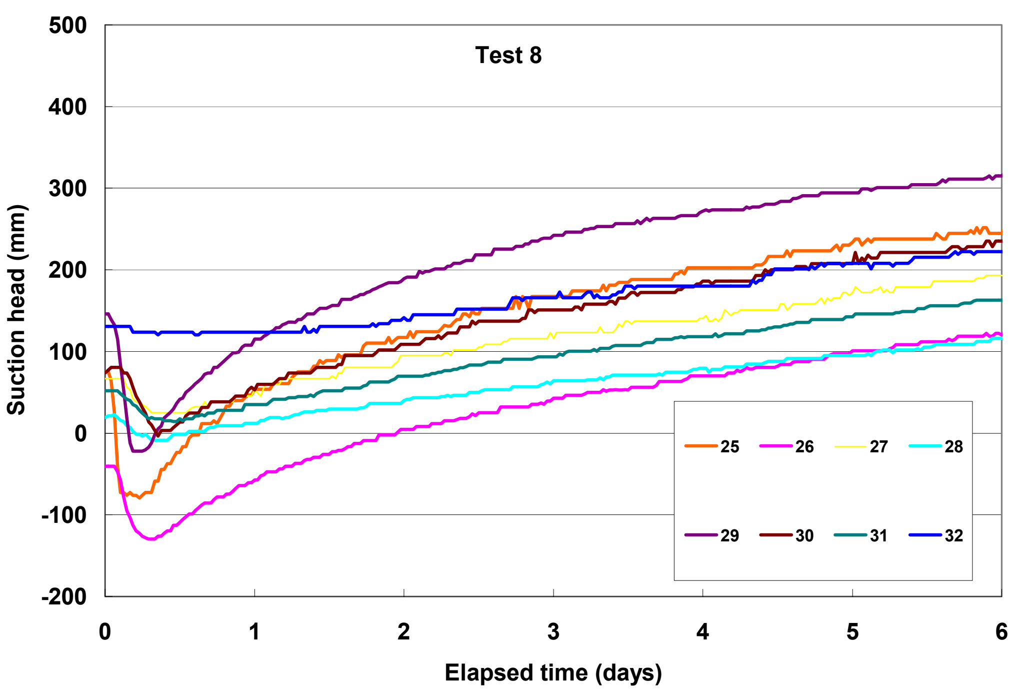


Figure 23. Soil suction heads in the base at 13 mm above GCBD for Test 8.

The GCBD protected the subgrade for the six-hour storm (Figs. 24 and 25). The suction heads below the interface decreased in the control section (test 4), whereas below the GCBD they remained approximately constant except for the subgrade located beneath the unpaved shoulder. In this region, tensiometers 17 and 21 indicate water breakthrough shortly after water was applied (Fig. 25).

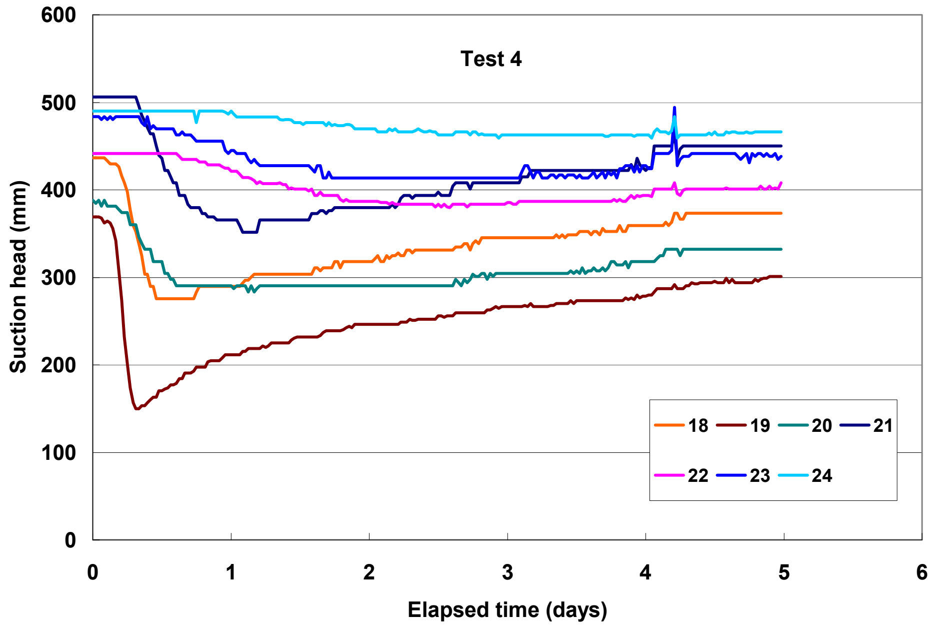


Figure 24. Soil suction heads in the subgrade at 25 mm below the geotextile separator in the control section for Test 4.

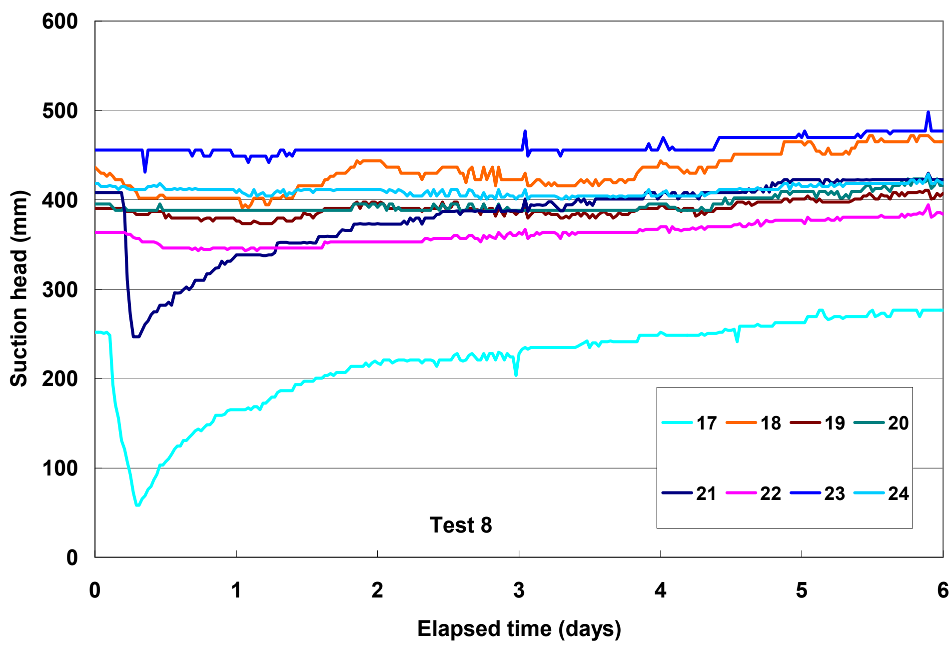


Figure 25. Soil suction heads in the base at 25 mm below the GCBD for Test 8.

3.2.2.3 One hour storm in control section and in section with GCBD (Tests 3 and 9):

There was a larger volume of runoff for the one-hour storm compared to the six-hour storm. The transport layer evacuated water at a greater rate than the rate of water flow from the ditch after we stopped applying water (at 0.04 days); however, the transport layer discharged a smaller percentage of the water applied due to the high runoff rate (Fig. 26). On day 5 the transport layer drained water at suction heads ranging from 175 to 360 mm (Fig. 27).

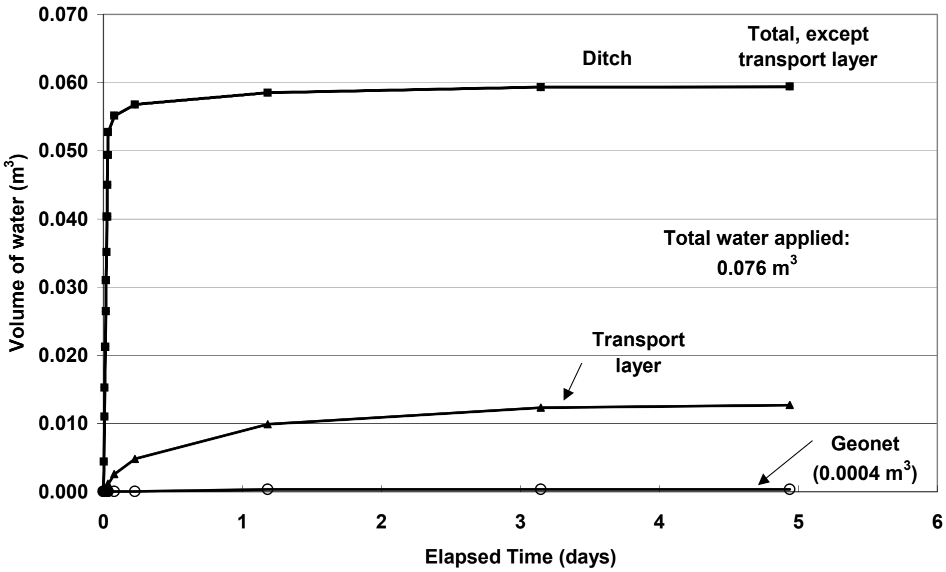


Figure 26. Outflow for one-hour storm with GCBD (Test 9).

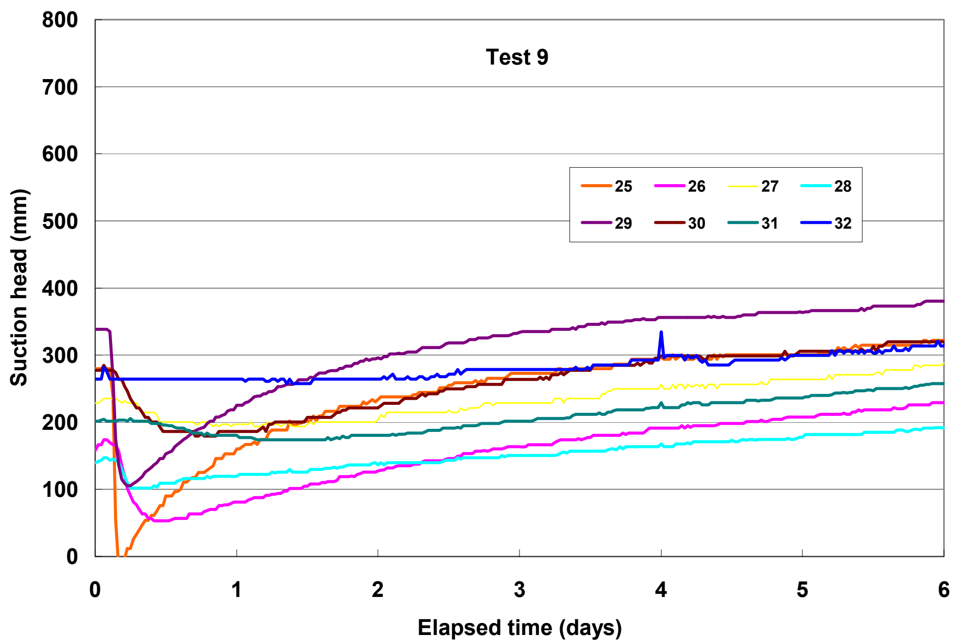


Figure 27. Soil suction heads in the base at 13 mm above the GCBD in Test 9.

The GCBD completely protected the subgrade from changes in moisture content due to this storm whereas the subgrade of the control section was not (Figs. 28 and 29). The suction head readings in the subgrade immediately below the base/ subgrade interface were similar at the beginning of each test—468 and 420 mm average for tensiometers 25-32 in tests 3 and 9 respectively. Thus, even though the subgrade of the control test started out slightly drier than test 9, the separator allowed significantly wetting of the subgrade. However, the GCBD protected the subgrade in test 9 after it had allowed some water to pass through in the previous test. Thus, that once allowed to 'dry,' the GCBD functioned well after it 'failed.'

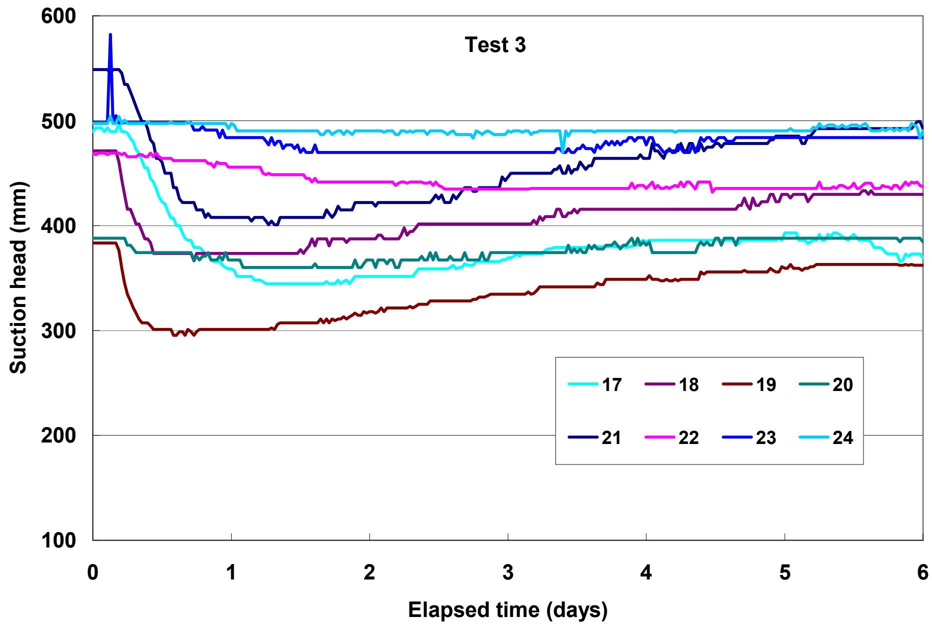


Figure 28. Soil suction heads in subgrade, 25 mm below the geotextile separator in the control section in Test 3.

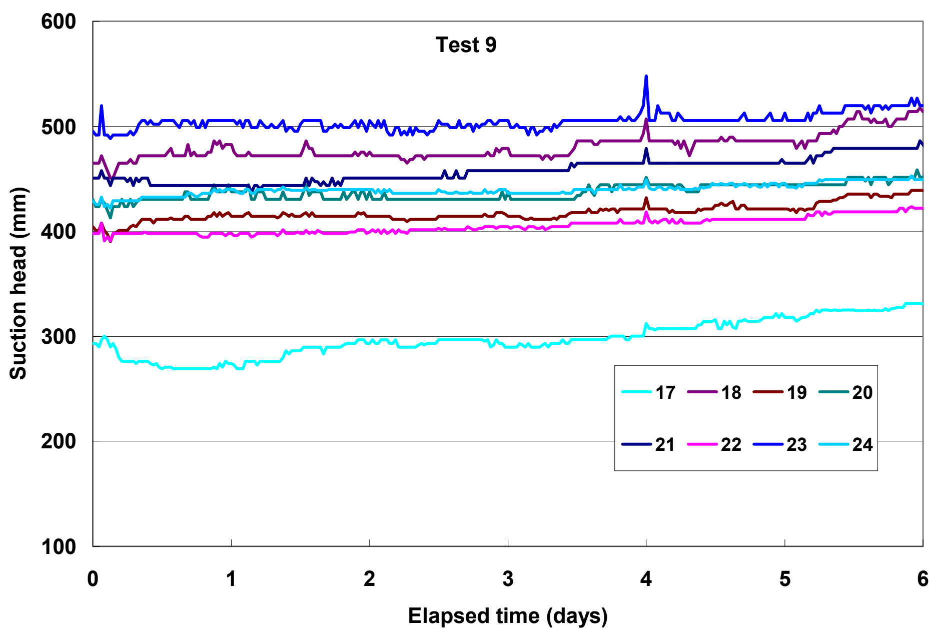


Figure 29. Soil suction heads in subgrade, 25 mm below the GCBD in Test 9.

3.2.3 Summary and conclusions, Phase 2 tests

For long-term steady rates of precipitation of about 0.1 mm hr^{-1} (2.4 mm day^{-1}) (test 7) the transport layer delivered more water than the amount of water that ran off or was stored in the base layer—approximately 37% vs. 24% and 23% of the total volume of water applied. Furthermore, the subgrade was protected from gaining water by the GCBD.

After the water was applied at a rate equivalent to a 6-hour-long, 4-year design storm (tests 3 and 9), the transport layer of the GCBD drained water at a greater rate than the ditch. The transport layer continued to produce water from the base at suction heads of 120-300 mm. Some water broke through the transport layer into the subgrade, but only under the portion of the base that was not protected by the asphalt. In the control section subjected to the same storm, all tensiometers indicated that the water reached the subgrade from the storm within one day of application.

For a one-hour storm (tests 4 and 8), there was a considerable amount of runoff related to the storm intensity (about 80% of the water applied ran off). However, the transport layer drained water from the unsaturated subgrade, and continued to do so at suction heads ranging from 175 to 360 mm. Finally, the GCBD protected the subgrade in this test and it did so following a test in which a small amount of water had broken through the GCBD into the subgrade--thus indicating that the GCBD recovers when subjected to drying conditions.

4.0 PLANS FOR IMPLEMENTATION

Further development is needed before this technology is implemented. A more economical transport layer than the one we tested would lower costs of the GCBD making it more affordable. More development of the transport layer so that it will drain water at even higher suctions than it does now would also be desirable; however, just making a product with the current hydraulic characteristics more economical would probably be enough to bring this technology into use.

Dr. Henry visited Tenax, Inc., of Baltimore, MD, during May 2001 to discuss the possibility of licensing this technology. Tenax indicated that they are very interested in this technology and we are currently discussing ways to partner to develop it.

5.0 CONCLUSIONS

The results of this investigation into the use of the GCBD to limit moisture changes in pavement subgrades and bases are very promising. At infiltration rates that occur in the field and are of concern to transportation agencies, the GCBD drained water from overlying base material that was not saturated—base aggregate that is used in New Mexico and in New Hampshire. Furthermore, the GCBD prevented the moistening of the subgrade at many of the infiltration rates tested. This introduces the revolutionary concept that we can design unsaturated soil drainage for the ultimate purpose of extending pavement lifetime by 1) limiting the time that bases are saturated and 2) diverting large volumes of water to a drainage system before it reaches the subgrade.

In the specific GCBD that we tested, we drained water from overlying base when the water was subjected to 100 mm of suction head and greater. Furthermore, at long-term infiltration rates of 0.1 to 0.15 mm hr^{-1}, the GCBD prevented infiltrating water from reaching the subgrade. Finally, the GCBD recovered its function and protected the subgrade in a test following a test in which a small amount of water had broken through the GCBD into the subgrade.

The transport layer that we tested was a commercially available specialty fabric for industrial insulation applications. The cost of this material is relatively great, which suggests that a material designed and manufactured as a transport layer may be substantially less expensive. Development of a more economical transport layer (and thus GCBD) may involve partnering with a geosynthetic manufacturer that has experience bringing new products to market as well as with a textile or geotextile manufacturer willing to work with new polymer fibers such as fiberglass.

6.0 RECOMMENDATIONS

We recommend that the information developed in this project be published in peer-reviewed articles to a broad transportation audience. This will disseminate the results to potential users as well as to help to attract partners for two purposes—1) to test this concept in the field and 2) to help develop the economic production of the transport layer. We also recommend that the concept that the capillary barrier will reduce or prevent frost heave by preventing upward flow during freezing be tested. The current test box is set up so that such tests can be conducted.

In the near future we will pursue the ability to produce a GCBD at a price that makes it a desirable product for limiting moisture in pavement bases and subgrades. This will require that interested manufacturers partner with the U.S. Government and Dr. Stormont (the owners of the patent rights) for the purpose of developing this technology.

7.0 REFERENCES

1. Henry, K.S. and J.C. Stormont. *Geocomposite capillary barrier drain* U.S. Patent Office, Patent No. 6,152,653, November 28, 2000.
2. J.C. Stormont. and C.E. Morris, "Unsaturated Drainage Layers for Diversion of Infiltrating Water," *Journal of Irrigation and Drainage Engineering*, Vol. 123, No. 5, 1997, pp.364-366.
3. K.S. Henry, and R.D. Holtz, "Capillary Rise of Water in Geotextiles." In S. Knutsson (Ed.), Proceedings, *International Symposium on Ground Freezing and Frost Action in Soils*, Luleå, Sweden, 15–17 April, 1997, 227–233.
4. K.S. Henry and S. Patton "Measurement of the Contact Angle of Water on Geotextile Fibers." *Geotechnical Testing Journal*, *21*(1), 1998, 11-17.
5. J.C. Stormont, K.S. Henry, and T.M. Evans, "Water retention functions of four non-woven polypropylene geotextiles," *Geosynthetics International,* Vol. 4, No. 6, 1997, pp. 661-672.
6. K.S. Henry. *The use of geosynthetics to mitigate frost heave in soils*. Ph. D. Dissertation, Civil Engineering Department, University of Washington, Seattle, 1998.
7. J.C. Stormont, C. Ray, and T.M. Evans, "Transmissivity of a Nonwoven Geotextile under Suction," *Geotechnical Testing Journal*, Vol. 24, No. 2, pp. 164-171, 2001.
8. J.C. Stormont, J.C., R. Ramos, and K.S. Henry, "A Geocomposite Capillary Barrier Drain with a Fiberglass Transport Layer," *Journal of the Transportation Research Board*, 2001 (in press).
9. H.R. Cedergren, K. H. O'Brien, and J. A. Arman. *Guidelines for Design of Subsurface Drainage Systems for Highway Structural Sections*. Final Report No. FHWA-RD-73-14. Federal Highway Administration, Washington, D.C., 1973.
10. J.C. Stormont and T. Stockton, "Preventing positive pore water pressures with a geocomposite capillary barrier drain", *Testing and Performance of Geosynthetics in Subsurface Drainage*, ASTM 1390, L.D. Suits, J. B. Goddard and J.S. Baldwin, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2000, pp. 15-31.
11. M.R. Lindburg, "Civil Engineering Reference Manual for the PE Exam," Sixth Edition, Professional Publications, Inc., Belmont, CA