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Draft Final Report

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

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EXECUTIVE SUMMARY

The geocomposite capillary barrier drain (GCBD) is a new invention that drains water from overlying soil that is partially saturated and prevents the capillary flow of water from underlying soil to the soil overlying it. The GCBD comprises three layers that are, from top to bottom: a *transport* layer, a *capillary barrier* layer, and a *separator* layer (Fig. 1). Some non-woven textiles can be used as transport layers, while a geonet with relatively large, open pores functions as a capillary break. The separator layer (e.g., a non-woven geotextile) prevents underlying soil from intruding into the pores of the capillary barrier layer.

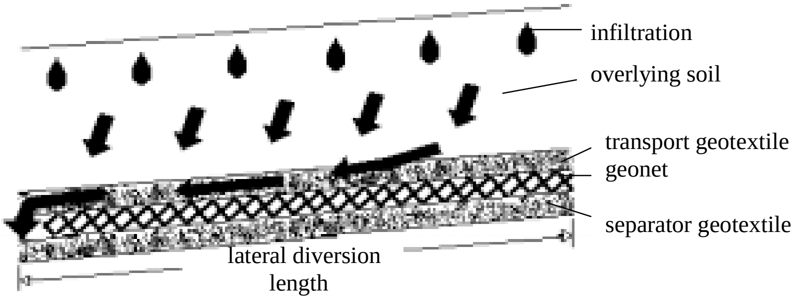


Figure 1. Schematic of Geocomposite Capillary Barrier Drain (GCBD) with overlying soil.

We developed the GCBD by selecting a candidate transport layer and then tested the concept of using a GCBD to limit moisture changes in the bases and subgrades of pavements. We placed the GCBD between the base and the subgrade of a pavement system placed in a large test box, and it drained water from the base when it was not saturated and the GCBD prevented most infiltrating water from reaching the subgrade. When placed in paved roads between the base and subgrade, the GCBD should 1) accelerate the drainage and drying of the base after infiltration, 2) protect the subgrade from wetting and 3) reduce the upward unsaturated flow of water into the base course induced by freezing.

We conducted experiments with a GCBD in two phases. In Phase 1, we selected the best available transport layer from among 16 candidates using capillary rise measurements, soil moisture retention tests and, finally, in-plane transmissivity tests conducted with water under negative pressure. We then tested the GCBD, constructed with the best performing transport layer, in a laboratory drainage test in which the GCBD was placed between 100 mm of clayey sand and 150 mm of overlying silty gravel (the test configuration was not paved in Phase 1 tests). In long-term infiltration tests in which the average rate of infiltration was 0.15 mm hr^{-1}, the GCBD transport layer drained water at suctions of 120 mm and greater.

In Phase 2 testing, 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. The box contained a pavement section, comprising a 1.3-m- (four-foot) 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.

In the specific GCBD that we tested, water drained in the transport layer from overlying base soil when the water was subjected to 100 mm to 500 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 that was performed subsequent to 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 explicitly designed and manufacture 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.

1.0 IDEA PRODUCT: GEOCOMPOSITE CAPILLARY BARRIER DRAIN

The geocomposite capillary barrier drain (GCBD) drains water from overlying soil that is partially saturated and prevents the capillary flow of water from underlying soil to overlying soil (*1*). We placed the GCBD between the base and the subgrade of a pavement, and it drained water from the base when it was not saturated and the GCBD prevented most infiltrating water from reaching the subgrade. When placed in paved roads between the base and subgrade, the GCBD should 1) accelerate the drainage and drying of the base after infiltration, 2) protect the subgrade from wetting and 3) reduce the upward unsaturated flow of water into the base course. The problems associated with excessive moisture in pavement base courses and subgrades include pumping, cracking, frost action and potholes. The GCBD reduces the total amount of water and length of time that water persists in the base and reduces the total amount of water in pavement subgrades in order to prevent related problems. When the GCBD is placed between the base and the subgrade, and dips at an angle from the horizontal, water drains down slope either to daylight in a drainage ditch or to a sub-surface drainage system.

The potential impact on transportation practice is quite large. If drainage can be improved through such a method, we expect that the lifetime of pavements will be considerably extended.

2.0 CONCEPT AND INNOVATION

Drainage of water from pavement layers prior to saturation will probably improve the pavement's performance and longevity. Soil water drainage is usually considered to occur by saturated flow. However, it would be beneficial in many circumstances if water could be drained from soil before it becomes saturated--that is, while the soil pore water pressures remain negative. For example, positive water pressures in the base of a pavement can reduce its strength and lead to rutting, heaving, and failure. Open-graded bases, which are very permeable and minimize the build up of positive pore water pressures in the base, do not prevent the subgrade from becoming moist. Moisture content changes in the subgrade soil can cause changes in volume and strength, which can affect pavement performance.

The Geocomposite Capillary Barrier Drain (GCBD) is a method to drain water from soils while the water is subjected to negative pore water pressures, i.e., prior to the development of positive pore water pressures. In contrast to conventional drainage systems, this drainage system is designed to operate under negative water pressures associated with unsaturated conditions.

Lateral water movement (drainage) in unsaturated soils occurs when downward moving water encounters dipping layers of underlying coarse-pored soil and a capillary barrier is formed. In this case water accumulates near the fine-coarse interface, and because hydraulic conductivity of the overlying unsaturated soil increases with water content, lateral drainage is concentrated in this region (Fig. 2a). The soil moisture content increases in the down dip direction due to the lateral diversion of the downward moving water at the interface. The horizontal length along the fine-coarse interface that water is diverted before the soil moisture content increases before appreciable breakthrough into the underlying soil occurs is called the lateral diversion length.

The unsaturated drainage of soils can be increased substantially by placing an intermediate transport layer such as a fine-grained sand between the overlying soil and the underlying coarse material (Figure 2b). The intermediate material should be conductive enough to laterally divert or drain downward moving water, yet remain unsaturated so as to preserve the capillary break with the underlying coarse material.

Experimental and numerical investigations indicate that for specific materials and conditions, unsaturated soil drainage using fine-sands as the transport layer with gravel as the capillary break layer can be effective *(*2). However, this approach shortcomings, including the fact that the transport layer and capillary barrier soils may not be readily available at the site and thus can be costly; and, the materials can be difficult to place on many slopes and locations.

An unsaturated soil drainage system fabricated from geosynthetics has a number of advantages compared to a soil-based system, including:

1. desirable properties can be optimized by design and controlled by manufacture,
2. drainage functions can be combined with other functions such as reinforcement and soil retention,
3. a geosynthetic system will be thinner (on the order of only a few cm), minimizing its impact on the overall project design, and
4. geosynthetics can be readily delivered throughout much of the world.

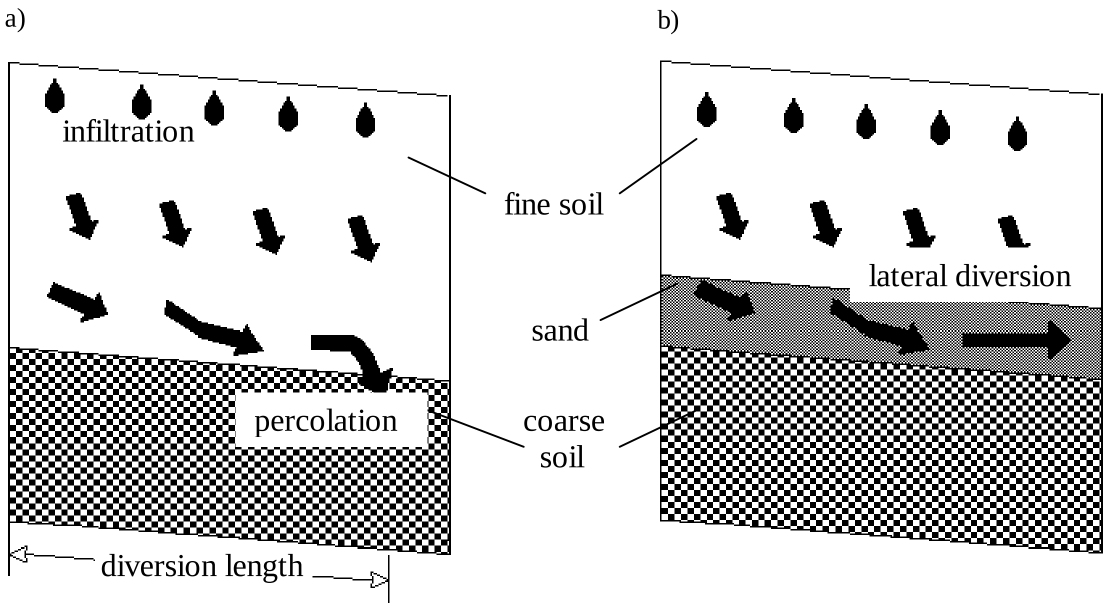


Figure 2. Lateral drainage in unsaturated soil with: a) a simple capillary barrier and b) capillary barrier with an overlying transport layer

The GCBD system comprises three layers that are, from top to bottom: a *transport* layer, a *capillary barrier* layer, and a *separator* layer (Fig. 1). Some non-woven geotextiles can be used as transport layers, while a geonet with relatively large, open pores can function as a capillary break—i.e., taking the place of the underlying coarse layer in the systems shown in Figure 2. The separator layer prevents underlying soil from intruding into the pore spaces of the capillary barrier layer. A non-woven geotextile is envisioned for this function. This configuration can also laterally drain upward moving water. In this case, the lower layer would serve as the transport layer.

Although this geocomposite outwardly resembles a conventional geocomposite drain, a GCBD is designed to drain water in the geotextile transport layer (not the geonet) under negative water pressures (not positive water pressures). Further, it does not require the underlying impermeable layer that a conventional drain requires. In the GCBD configuration, it is the unsaturated hydraulic properties of the geosynthetic materials that are of principal importance.

3.0 INVESTIGATION

We conducted the investigation in two phases. In Phase 1 we measured capillary rise, soil moisture retention curves and unsaturated hydraulic conductivities for various transport layer candidates for GCBDs. In an additional Phase 1 effort (in addition to what we promised in the proposal), we tested a candidate GCBD in small-scale laboratory tests. In Phase 2 we evaluated the performance of a drainage system that utilized the top-performing GCBD candidate from Phase 1.

3.1 PHASE 1 TESTS

3.1.1 Evaluation of candidate transport layers

Candidate materials were selected based on discussions and recommendations from manufacturers, engineers that utilize geotextiles, and research scientists in the textile field. Our basic requirements for these materials are (1) they are as "wettable" as possible, and (2) they have reasonable longevity when placed in a sub-surface environment. The motivation for the wettable requirement is that our previous work has suggested that the GCBD performance can be increased if the transport layer becomes conductive at as great of suction head values as possible.

We obtained 16 textile samples for evaluation (Table 1). They included nonwoven, woven, multifilament and multilayer materials. Selecting the best transport layer material from these candidate materials involved three steps: (1) measuring capillary rise (all specimens), (2) determining moisture retention functions (six specimens), and (3) measuring transmissivity (four specimens). Results of these tests are given in the Stage 1 report, and are only summarized here.

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	Amatek
9	TGLASS	Thermally treated fiberglass	Amatek
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.

3.1.1.2 Capillary rise

Capillary rise above a free water surface provides a measure of the wetting behavior of a porous material. The capillary rise, or capillary depression in the case of a hydrophobic material, is a function of the contact angle of the material as well as the pore structure. The capillary rise of water in geotextiles was measured in 16 materials (Fig. 3)

The F300 and TG1000 specimens are conventional geotextiles and have been used in prototype GCBD systems, yet they have the lowest capillary rise of all the materials tested. These results indicate that there are materials that are more suitable than F300 and TG1000 to serve as the transport layer of a GCBD. We selected 4 materials, based on the capillary rise measurement, to determine 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 determined to be too thin to serve as a transport layer. The FGWK material was only available as a rope, and thus was not further evaluated.

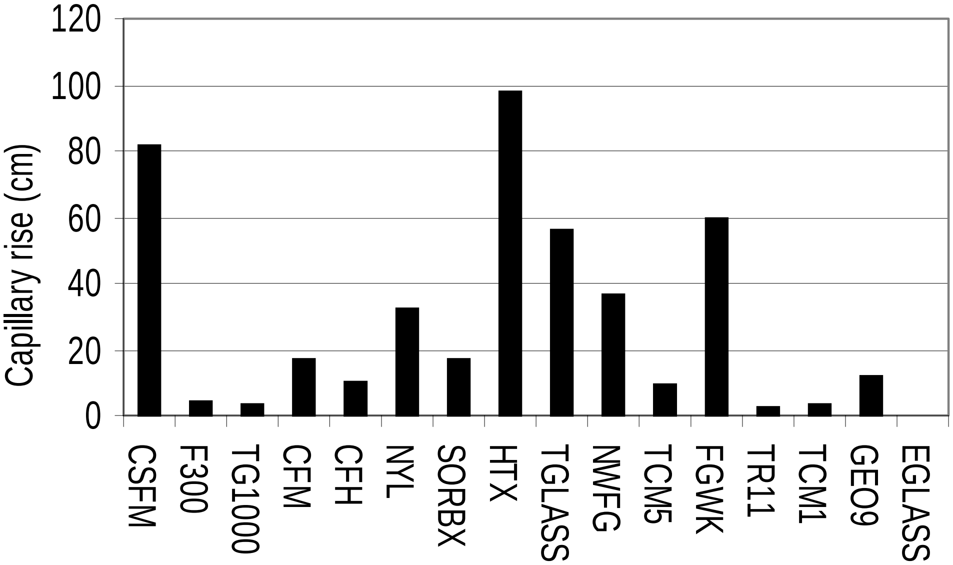


Figure 3. Forty-eight-hour capillary rise data on various textiles.

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, which is described elsewhere *(5).*

Wetting and drying paths for six materials are shown in Figure 4. In addition to the most wettable materials as determined by the capillary rise testing (NYL, TGLASS, HTX and CSFM), the moisture retention functions curves from the two conventional geotextiles (F300 and TG1000) are given. All of the moisture retention functions are hysteretic, indicating that 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. (Caution should be used in interpreting these results, especially when saturations greater than 1 are reported. This result is believed to be a consequence of the change in sample thickness when the surcharge was placed and removed.)

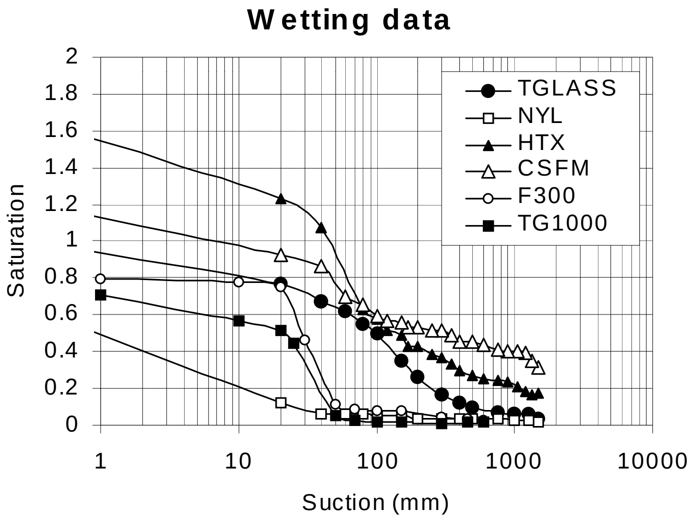
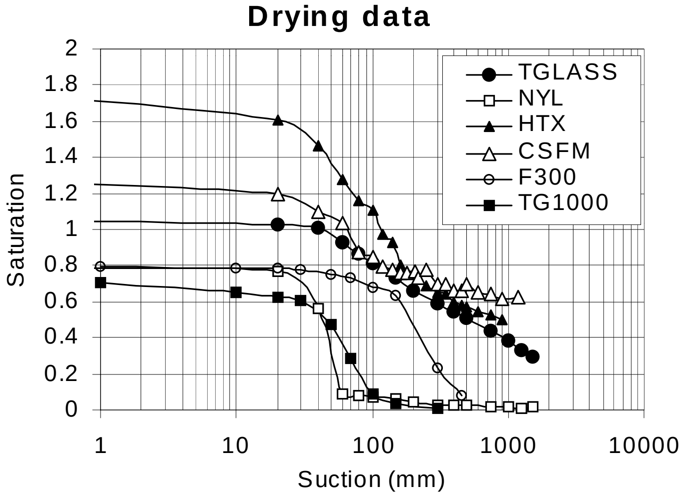


Figure 4. Moisture retention functions obtained from hanging column method for six candidate transport layer materials during wetting and drying.



3.1.1.4 Transmissivity

The ability of the transport layer to transmit water in-plane (transmissivity) under suction is its most important characteristic. A key factor in the ability of a geotextile to serve as a transport layer is the range of suctions over which it is transmissive. Previous tests on polyester and polypropylene geotextiles reveal that these materials do not become transmissive until about 50 mm suction head during wetting, and are not transmissive beyond about 100 mm suction head in drying. An improved transport layer material should be transmissive over a greater range of suctions, corresponding to lower degrees of saturation in the overlying soil.

A siphon test was used to indicate the ability of a geotextile to transmit water in-plane under suction. The HTX (silica) material was not transmissive at any value of suction. Thus, although this material is very wetting, it does not have the pore structure required to be transmissive under suction. The other three materials did not become transmissive in wetting until 13 cm of suction. At this suction, the TGLASS material conveyed about an order of magnitude more water than the NYL and CSFM materials. As the suctions were increased (drying), only the TGLASS remained transmissive.

Because of its high transmissivity in the siphon tests, the TGLASS was tested in a permeameter that has been designed for measuring in-plane transmissivity of geotextiles under suction *(7)*. Results using this method are given in Figure 5 for both a wetting path (beginning dry and progressively decreasing the suction) and a drying path (beginning at zero suction and progressively increasing the suction). The first measurable transmissivity during wetting occurred at 100 mm. As the suction was decreased to zero, the measured transmissivity increased by more than two orders of magnitude. During subsequent drying, the TGLASS was much more conductive at the same value of suction compared to wetting, and remained measurably transmissive to 600 mm. In contrast, the transmissivity under suction for a nonwoven polypropylene (TG1000) geotextile, previously used as a transport layer, is also given. Compared to the polypropylene, the TGLASS was transmissive over a greater range of suctions during both wetting and drying.

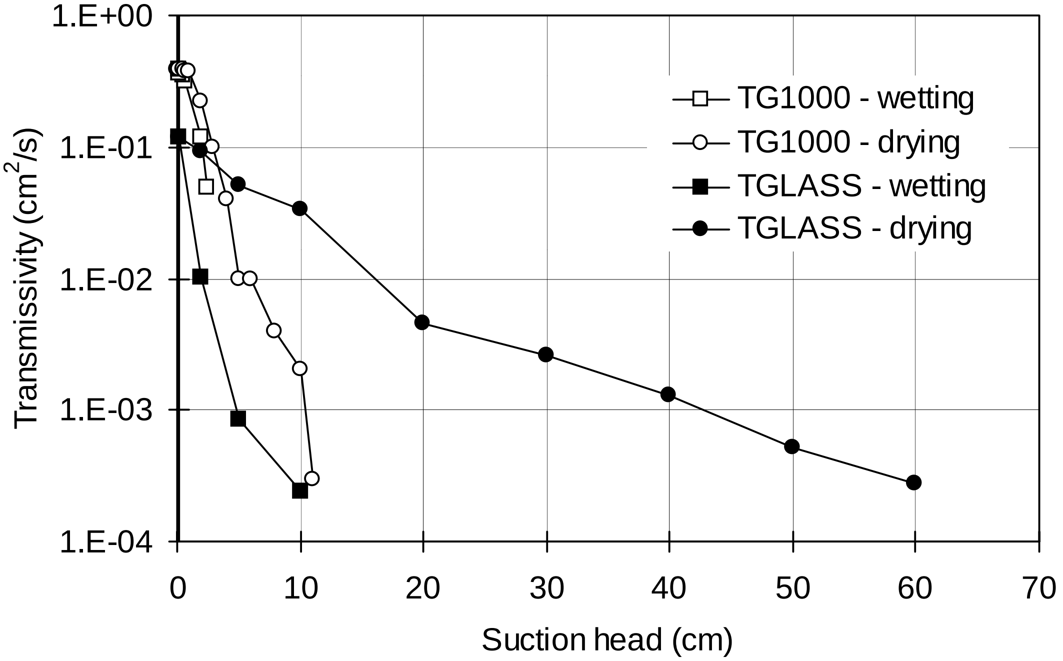


Figure 5. Transmissivity of TGLASS and polypropylene (TG1000) geotextiles using constant suction permeameter.

3.1.1.5 Transport layer selection

We selected the TGLASS as the best transport layer from the original 16 materials tested based largely on its large range of suctions over which it is transmissive. 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 evaluated in this test consisted of a geonet sandwiched between fiberglass geotextiles (TGLASS) as the transport layers. The standard HDPE geonet has a thickness of 5.9 mm. For the transport layer on top of the geonet, two layers of this geotextile were used to double its lateral flow capacity. One layer of the geotextile was used for the underlying separator layer.

Two soils were used in the lateral diversion apparatus. The underlying soil was a clayey sand (designated SC by the USCS classification method). This soil, which is representative of much of the near-surface soils in New Mexico, had 35% fines, a plasticity index of 8, and a saturated hydraulic conductivity of 1.4×10^{-4} cm s^{-1}. The overlying soil was a poorly-graded silty gravel (designated GP-GW). The GP-GW is commonly used as a base material in New Mexico and was obtained locally. The GP-GW soil had 7% fines, no measurable plasticity, and a saturated hydraulic conductivity of 1.3×10^{-2} cm s^{-1}.

The drainage capacity of the GCBD was tested in a 3-m-long box (Fig. 6). The profile tested was 100 mm of the SC soil, the GCBD, and 150 mm of the GP-GW soil. The underlying and overlying soil layers are also referred to as the subgrade and base course soils, respectively, in reference to the possible location of a GCBD within a pavement section. Measurements were made of water infiltrated onto the top of the soil profile, water drained out of the GCBD, water laterally drained in the overlying soil and water produced out of the bottom of the sub-grade soil. Measurements were also made of soil suction above and below the GCBD. Details regarding the lateral drainage test apparatus can be found elsewhere *(8).*

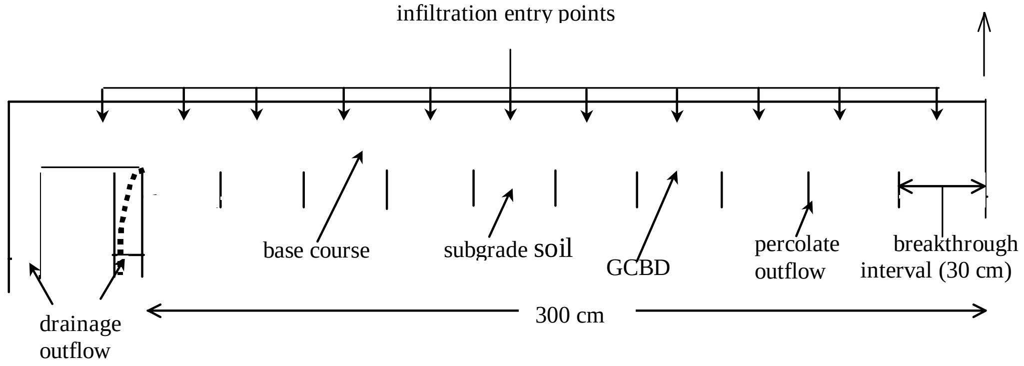


Figure 6. Lateral diversion test apparatus.

The GCBD performance was evaluated during three test phases: (1) constant rate infiltration, (2) subsequent drainage with no infiltration, and (3) transient infiltration corresponding to a design storm. During the constant rate infiltration portion of the test, water was added to the top of the base course with a manifold-type distribution system. Water was added 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 over this 7 days 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 was continued until the rate of laterally drained water was steady and was greater than 90% of the infiltration rate. Collection of drained water continued for 14 days after infiltration was stopped until the drainage production was very small.

The transient infiltration consisted of manually distributing 9 mm of water in a 1 hour period onto the top of the base course. This transient event corresponds to 50% of the 1-hr duration , 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.

3.1.2.2 Results and discussion

Infiltration and drainage histories for the entire test are given in Figure 7a. The suction history of the tensiometers immediately above the GCBD is reported in Figure 7b. The average suction is given because the tensiometers all had similar responses. The soil above the GCBD remained in tension during the entire test as water laterally drained from the base course 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 the average suction in the first 50 hrs is due to de-airing of the tensiometers. Water first drained from the GCBD system at an average suction value of 260 mm. With continuing infiltration, the suctions were further reduced and the GCBD produced increasing amounts of water. The suctions 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 was successful in not only draining water while the upper soil remained in tension, but also appeared to allow little if any breakthrough into the underlying sub-grade soil. No water was produced from any of the breakthrough intervals and most suctions measured in the sub-grade soil immediately below the GCBD remained nearly constant during the tests, typically at values of about 3500 mm. Planned water content measurements of the sub-grade soil during eventual disassembly of the lateral drainage test apparatus will allow a more definite answer to the question of whether any water made it through the GCBD and into the sub-grade.

The post-infiltration drainage rate as a function of time is given in Figure 8, along with the average suction from the ten tensiometers above the GCBD. The rate of drainage from both the GCBD and the overlying base course soil decreases with time as the suctions increase. 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 over about 4 days laterally drained from the overlying soil. The GCBD was still draining a small amount of water when this test phase was terminated at an average suction in excess of 600 mm. The tensiometers indicated that the overlying soil remains in tension during the transient infiltration event. In other words, its storage capacity was sufficient to accommodate the added water without reaching saturation.

The drainage from the GCBD reached its peak value about 3 hours after the infiltration event, and occurred at an average suction of 120 mm. The suctions in the overlying soil continued to increase as water was drained at a decreasing rate from the base course through the GCBD. Water was still draining through the GCBD 14 days after the transient infiltration event when the test was terminated.

Some comparisons are possible between these test results and those reported by Stormont and Stockton (*10*) from tests on GCBD systems with both a polypropylene and a polyester geotextile as the transport layer. For this test, the GCBD began producing water at a suction 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 can be 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, the flow capacities of the GCBDs can be increased by using more than one layer of geotextile for the transport layer. Finally, the GCBD with the fiberglass transport layer drained water at much greater suctions (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 sufficient water under suction to prevent positive pore water pressures from developing in the base course and limit 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}). At no time during these tests did the base reach saturation.

The fiberglass transport layer exhibited a substantial increase in the range of suctions in which the GCBD drained water compared to polypropylene and polyester transport layers. 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.

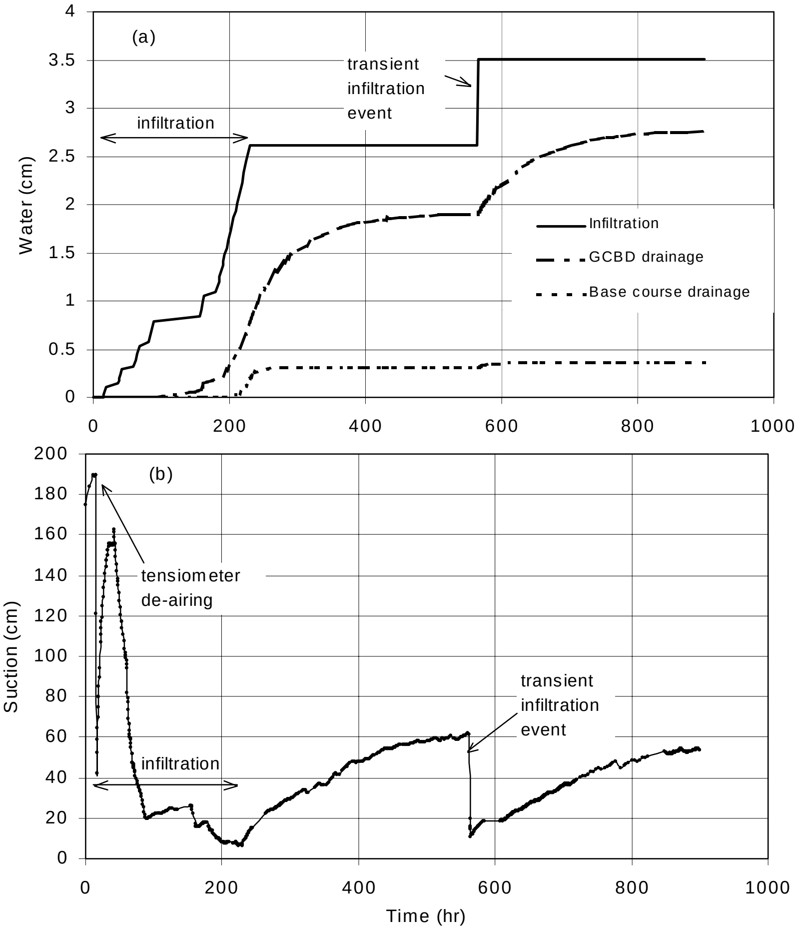


Figure 7. Summary of test results. (a) History of infiltration, drainage from GCBD and drainage from overlying soil, and (b) average suction history immediately above GCBD.

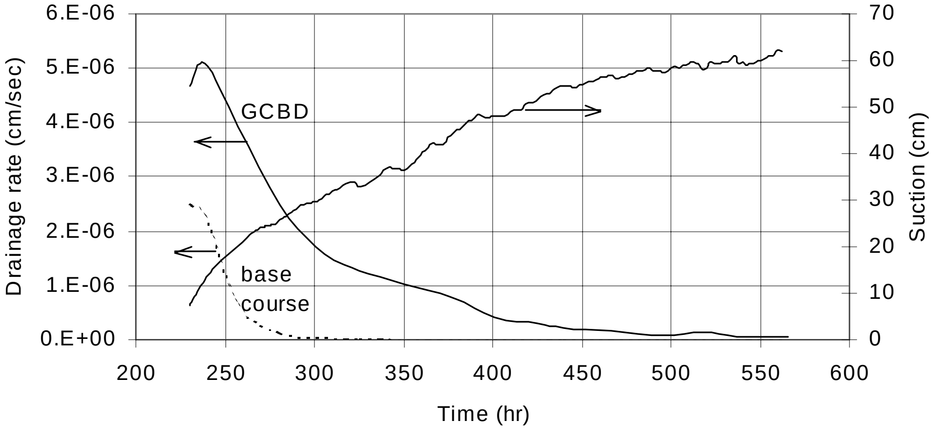


Figure 8. Drainage rate from GCBD and overlying soil during period between constant rate infiltration and transient infiltration. The average suction in the overlying soil immediately above the GCBD is also shown.

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- (four-foot) 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 to the tilt of the box, 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).

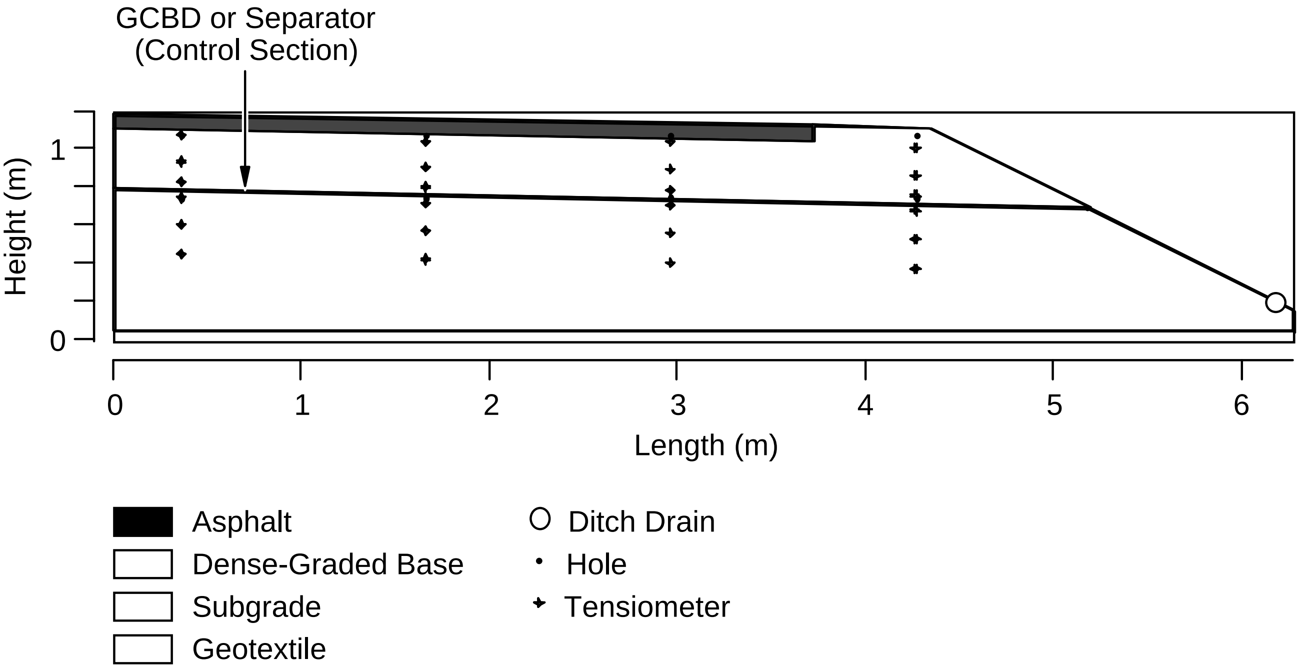


Figure 9. Cross-section of the pavement configuration tested, with the GCBD included between the base and subgrade.

3.2.1.2 Placement of control section

The control section consisted of an average thickness of 0.71 m (28 in) of subgrade, a geotextile separator, 0.3 m (12 in) of base gravel and 50 mm (2 in) of asphalt pavement. A 50 mm (2 in) 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 10. Photograph of test box with tensiometer tubes connected to pressure transducers exiting the side of the box.

During the original placement of soil, the subgrade material, lean clay, classified as A-4 according to AASHTO, was placed in the box in five layers, approximately 150-mm (6 in) thick. Each layer was compacted and tested for the moisture content and density values (Table 2). The target density value was 1.64 Mg m^{-3}, or 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 (12 ft) from the east end of the box, so that there is a 0.61 m (2 ft) gravel shoulder area. In addition, one 6.5-mm-(0.25-in) wide and 610-mm-(24-in) 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. Density and moisture content readings taken during construction of the control section.

Layer	**Average Density ($Mg\ m^{-3}$/ $lb\ ft^{-3}$)**	**Average Moisture Content (% by weight)**
Nuclear Gage		
Subgrade 1st lift	1.65 / 103.0	16.6
Subgrade 2nd lift	1.65 / 103.0	17.9
Subgrade 3rd lift	1.62 / 101.1	16.9
Subgrade 4th lift	1.61 / 100.5	18.0
Subgrade 5th lift	1.62 / 101.1	17.1
Base 1st lift	1.98 / 123.6	3.3
Base 2nd lift	2.01 / 125.5	3.2
Drive Cylinders (Second lift of subgrade)	1.60 / 99.6	19.09

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 (4 in) in diameter and cut down to the surface of the base course. The thickness of the asphalt specimens ranged from 64-89 mm (2.5-3.5 in).

After removing the asphalt, two drive cylinders were collected from the base course 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).

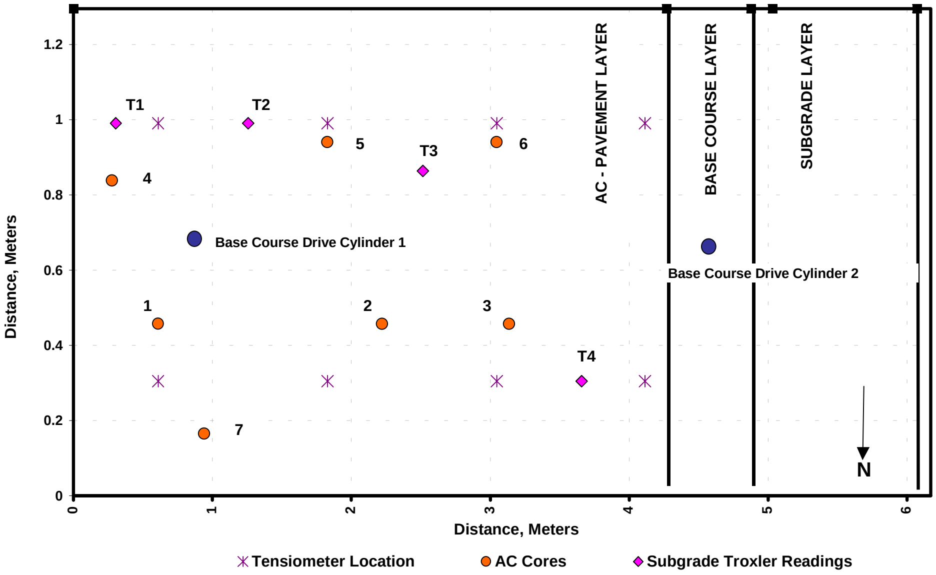


Figure 12. Plan view of test section showing locations of soil testing during deconstruction.

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

Location	Dry Density Reading ($Mg\ m^{-3}$/ $lb\ ft^{-3}$)	Moisture Content (% by weight)
Nuclear gage readings		
1	2.02/ 126.0	4.2
2	2.01/ 125.7	4.1
3	1.93/ 120.3	4.7
4	1.98/ 123.7	3.4
5	1.96/ 122.5	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 ($Mg\ m^{-3}$/ $lb\ ft^{-3}$)	Moisture Content (% by weight)
1	1.59/ 99.0	17.8
2	1.59/ 99.2	18.6
3	1.69/ 105.3	17.4
4	1.74/ 108.6	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 course 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 thermocouple nodes, spaced in increments of 152 mm (6 in). Eight rods were also placed in the base course layer directly above the ones in the subgrade. The base thermocouple rods were 305 mm (12 in) long with three nodes vertically spaced 152 mm (6 in) 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 (3 ft) wide. The width of the test box is 1.3 m (4 ft), so we cut an additional strip of geotextile and overlapped it by 152 mm (6 in) toward the south side of the box to ensure complete coverage of the subgrade (Fig. 14).

Figure 14. Separator layer 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 upper layer of the GCBD, the transport layer, was placed on top of the geonet. This layer consisted of two layers of the same geotextile used as the separator. As with the separator layer, each layer was 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 layer 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 course 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.

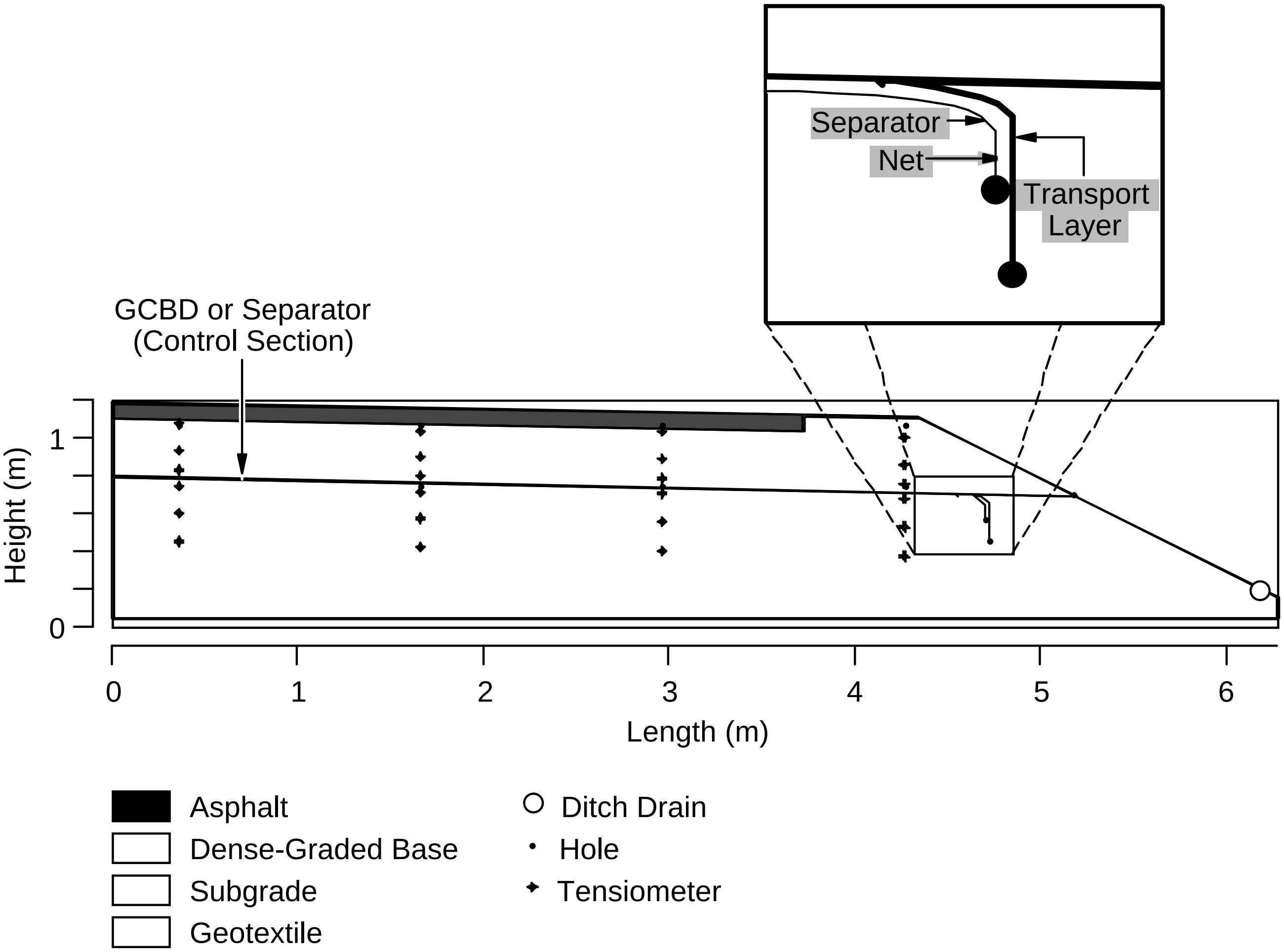


Figure 16. Cross-section of the GCBD test section with vertical drop for water collection.

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). The subgrade tensiometers were located 0.3 m from each edge of the box (horizontally) at depths of 330, 179 and 25 mm (13, 7 and 2 in.) below the base/ subgrade interface, respectively. The tensiometers in the base layer were located at 13, 127 and 279 mm (1/2, 5 and 11 in) above the base/ subgrade interface. The lowest layer of tensiometers was 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.

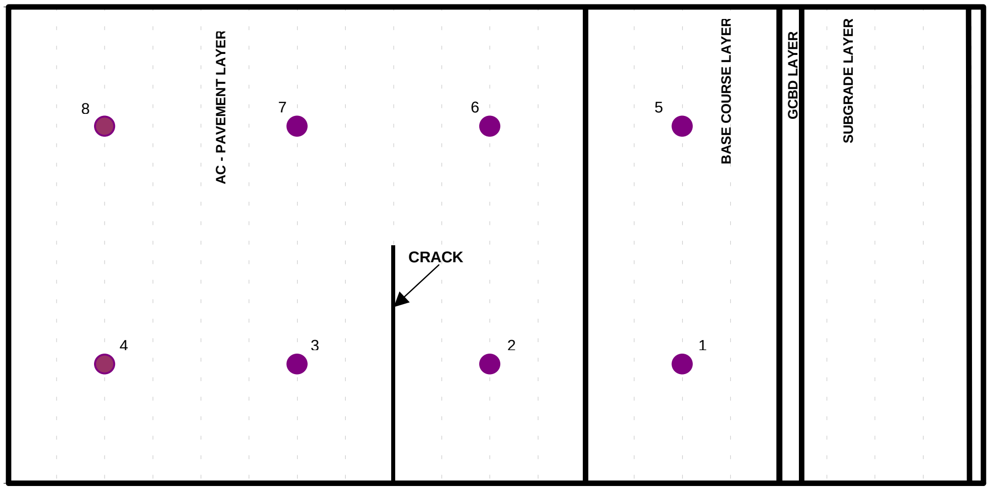


Figure 16. Plan view of the GCBD test section showing instrumentation layout.

The tensiometers comprise a ceramic tip, nylon tubing, and a pressure transducer connected to a data acquisition system. The ceramic tips were purchased from Soil Moisture Equipment Corporation and were round-bottomed and straight walled (28.6 mm in length and 1.6 mm thickness). The ceramic 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

The projects' expert review panel advised us that they are interested in storms of duration of 3 or more hours. The tests applied are described in Table 5. Tests 1 through 4 were conducted on the control section without a GCBD. The remaining tests were conducted on a test section containing a GCBD.

Tests 4, 6 and 8 were designed to simulate a four-year design storm in northern New England of 6 hours duration. The intensity of this storm, determined according to the Steel Formula *(11)*, is 6.6 mm hr^{-1} (0.26 in hr^{-1}) for a total of 39 mm of water (1.55 in). Tests 3 and 9 were approximately equivalent to a 10-year design storm of 1 hour.[1]

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.

For the control tests, the separator geotextile and the last 15 mm (3 in) of base course 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.

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[1] In northern New England, a 10-year design storm of 1 hr. duration is about 37 mm (1.46 in), determined according to the Steel Formula.

In addition to applying storms on the test section that contains the GCBD, we conducted long-term infiltration tests at a rate of infiltration similar to the Phase 1 tests. 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 5. Rates and amounts of water applied during tests. The box surface area is assumed to be 7.996 m^2.

Test	Date	Storm intensity ($mm\ hr^{-1}$/$in\ hr^{-1}$)	Storm duration (hr)	Amount of water (m^3/ gallons)
Phase 2 control tests				
1	9/21/00	11.08/ 1.52	6	0.532 / 140.4
2	10/11/00	6.44/ 0.25	6	0.309 / 81.6
3	10/26/00	9.47/ 0.37	1	0.076 / 20.0
4	11/2/00	1.62/ 0.06	5.42	0.070 / 18.4
Phase 2 tests with GCBD intersecting the ditch				
5	2/05/01-3/08/01	0.1 / 0.004*	Not applicable	Not applicable
6	3/08/01	1.56/ 0.06	6	0.076/ 20.0
Phase 2 tests with GCBD outflow measurements				
7	3/23/01-4/05/01	0.1 / 0.004*	Not applicable	Not applicable
8	4/05/01	1.56/ 0.06	6	0.076/ 20.0
9	4/13/01	9.47 / 0.37	1	0.076/ 20.0

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

3.2.2 Experimental results

We present results in this section that demonstrate benefit of the GCBD, including suction head measurements from 13 mm below the interface and 25 mm above the interface for certain test. The other suction measurements recorded and tests conducted are consistent with the data presented here. 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.

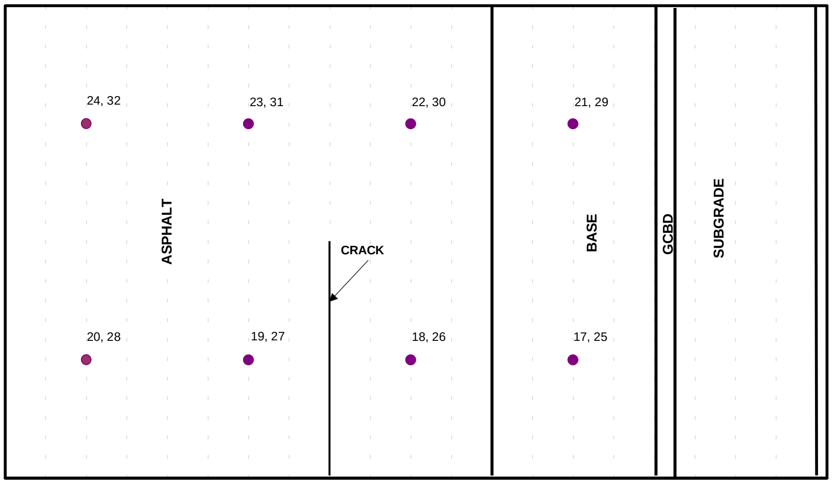

Figure 17. Plan view of tensiometers located 25 mm below the separator or GCBD (17-24) and 13 mm above the separator or GCBD (25-32). The box, as depicted, tilts from left to right and top to bottom by 2%. The soil layers also slope 2% from left to right.

3.2.2.1 Long-term infiltration: Test 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.

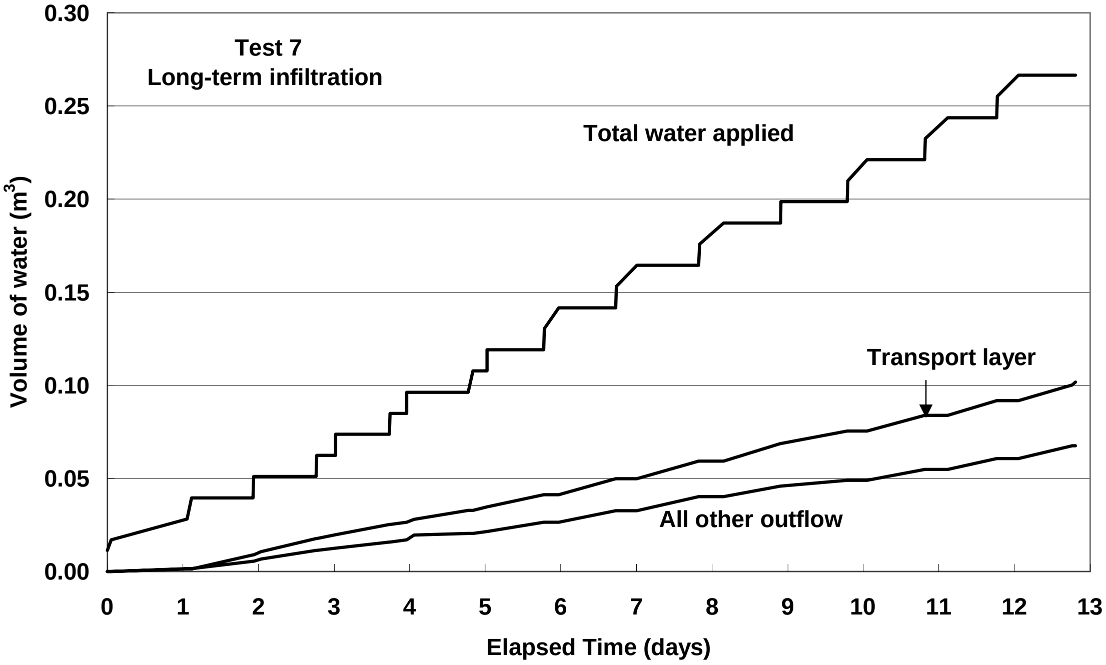

Figure 18. Outflow from long-term infiltration test 7.

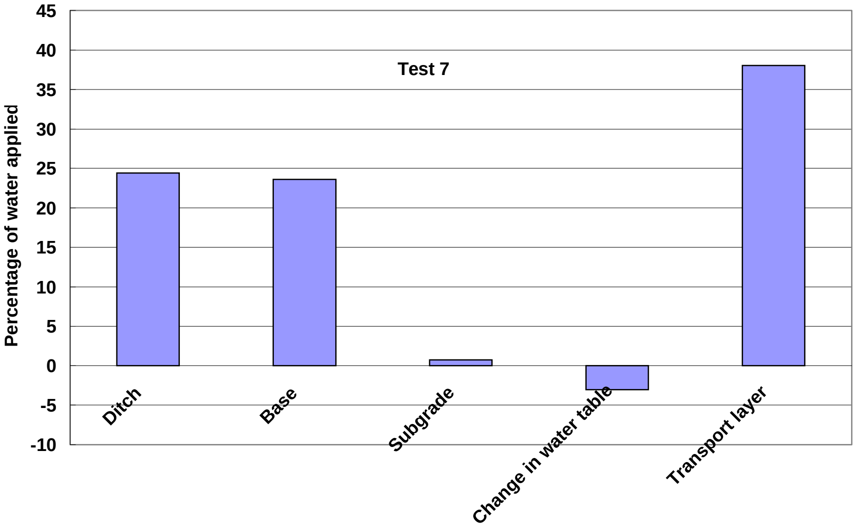

Figure 19. Percentage of water applied that was drained from the ditch, stored in the base, subgrade and in changing the elevation of the water table and drained from the transport layer in long-term infiltration Test 7.

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 (above the GCBD) and remain nearly constant in the subgrade (below the GCBD) (Figs. 20, 21). All the tensiometers, except 31 and 32, in the base layer immediately above the GCBD, 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, probably at least partially due to the fact that the subgrade was subjected to infiltration where it intersected the ditch.

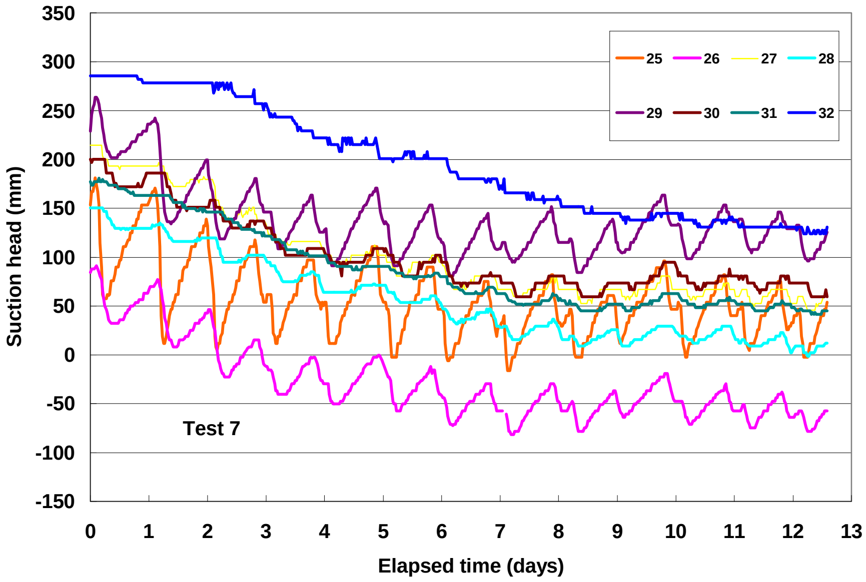

Figure 20. Soil suction heads in the base, 13 mm above the GCBD in Test 7, a long-term infiltration test.

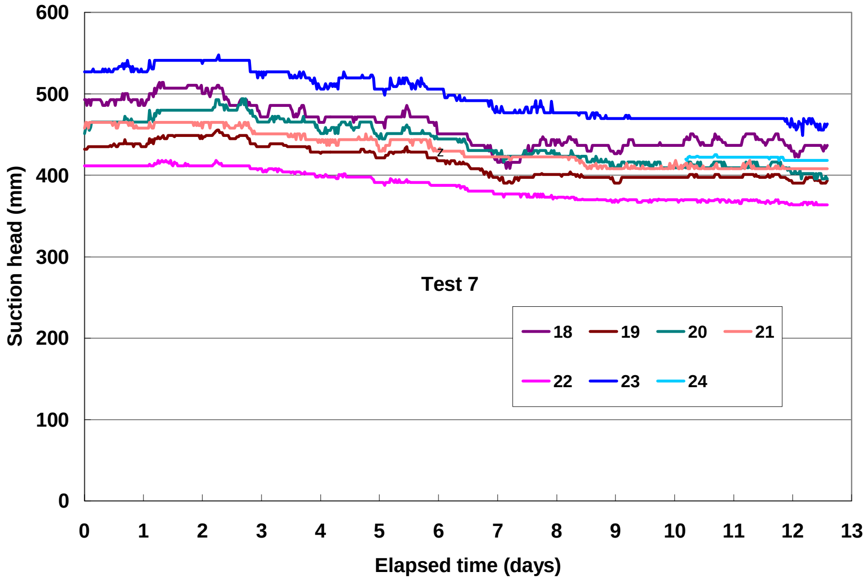

Figure 21. Soil suction heads in the base, 25 mm below the GCBD in Test 7, a long-term infiltration test.

3.2.2.2 Six hour storm: Tests 4 and 8

Tests 4 and 8 represent the type of infiltration event of most interest to the technical review committee—a rain of several hours (6) 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. Furthermore, the transport layer drained water 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).

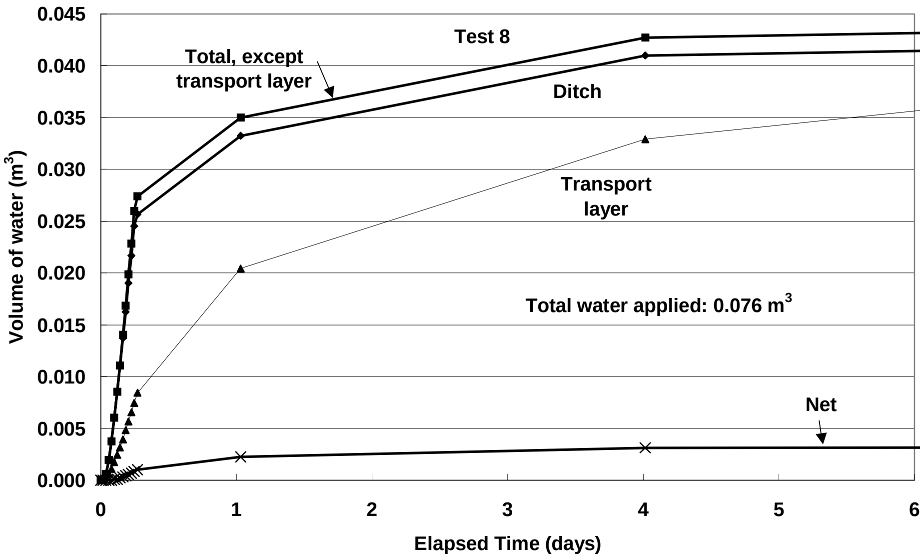

Figure 22. Outflow for test 8.

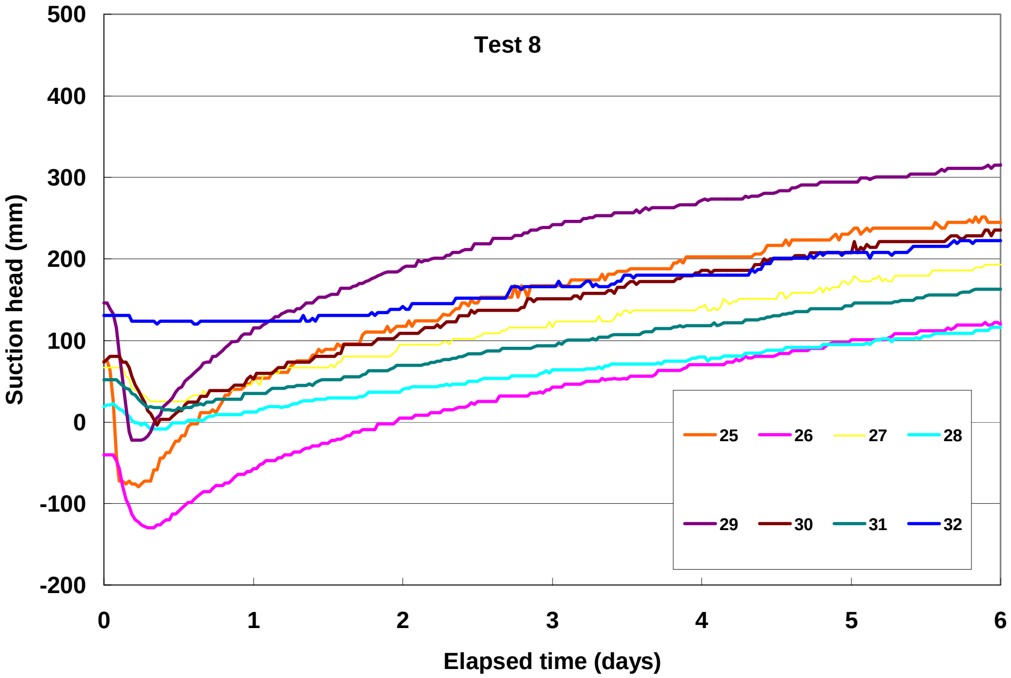

Figure 23. Soil suction heads in the base at 13 mm above GCBD for Test 8.

The GCBD protected the subgrade (Figs. 24 and 25). The suction heads below the interface decreased in test 4, whereas the suction heads below the GCBD remained approximately constant except for the section located under the shoulder. Only tensiometers 17 and 21 indicate water breakthrough within one day of the water application in test 8 with the GCBD.

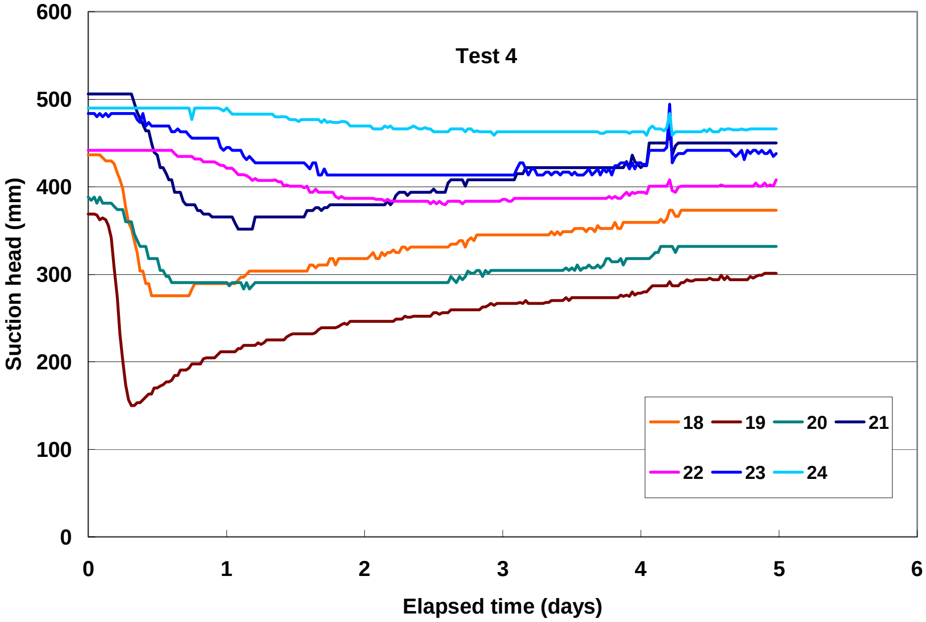

Figure 24. Soil suction heads in the base at 25 mm below the geotextile separator in the control section for Test 4.

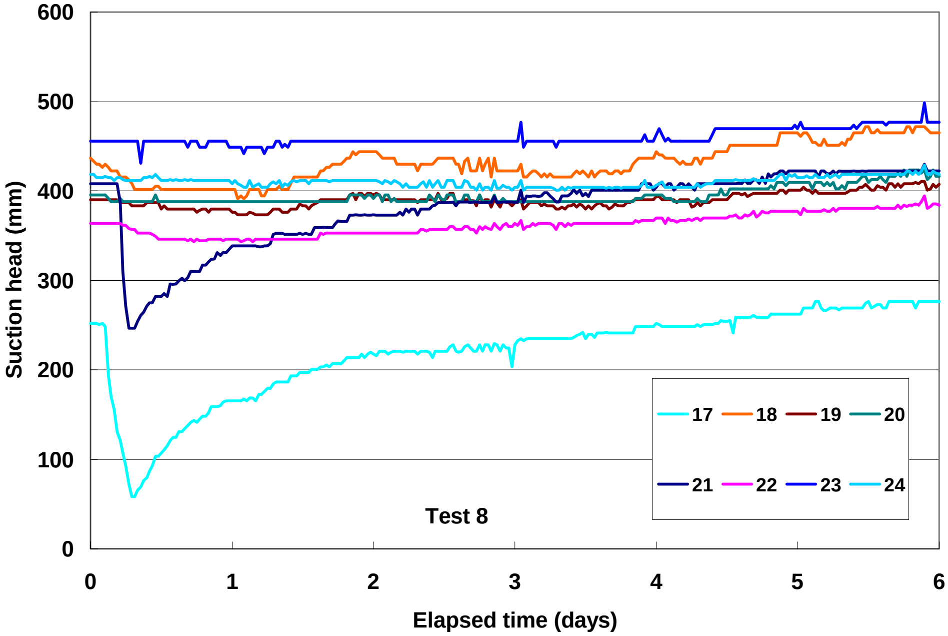

Figure 25. Soil suction heads in the base at 25 mm below the GCBD for Test 8.

3.2.2.3 One hour storm: Tests 3 and 9

There was a larger volume of runoff for tests 3 and 9 (one-hour storm) compared to tests 4 and 8 (Fig. 26). As with test 8, in test 9 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. On day 5 The transport layer drained water at suction heads ranging from 175 to 360 mm (Fig. 27).

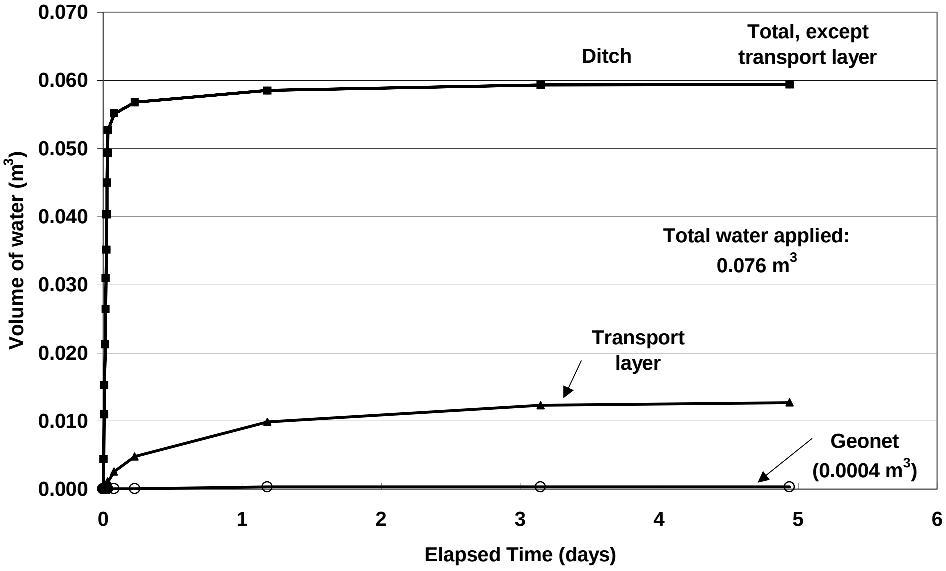

Figure 26. Outflow for test 9.

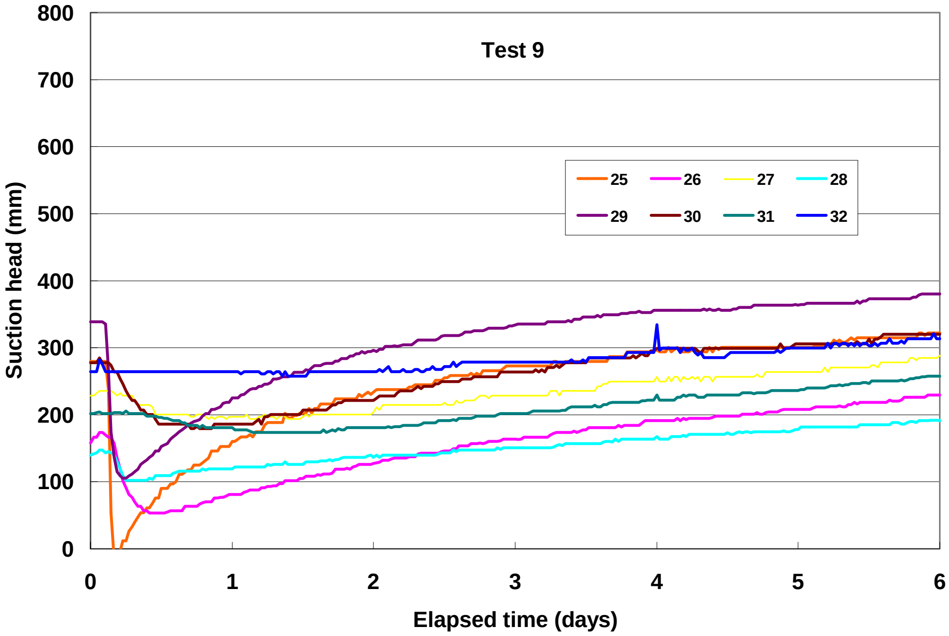

Figure 27. Soil suction heads in the base at 13 mm above the GCBD in Test 9.

The subgrade of test 9 was completely protected from changes in moisture content due to this storm whereas the subgrade of test 3 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 test 3 started out slightly drier than test 9, the separator did not prevent water from the overlying section from reaching it. However, the GCBD protected the subgrade in test 9 after it had allowed some water to pass through in test 8. This means that once allowed to “dry,” the GCBD also functioned well after it once ‘failed,’ meaning that water broke through the GCBD into the subgrade in test 8.

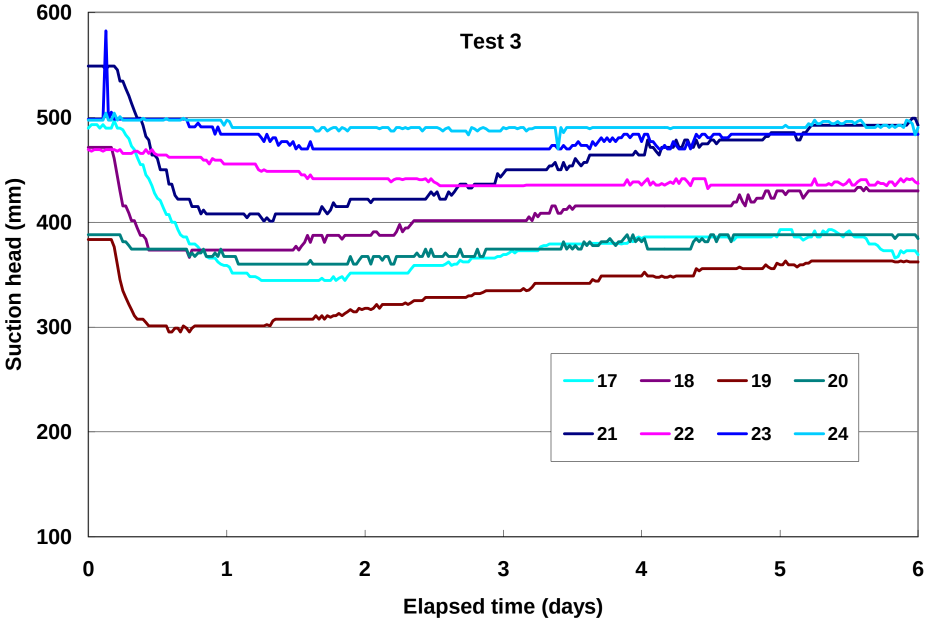

Figure 28. Soil suction heads in subgrade, 25 mm below the geotextile separator in the control section in Test 3.

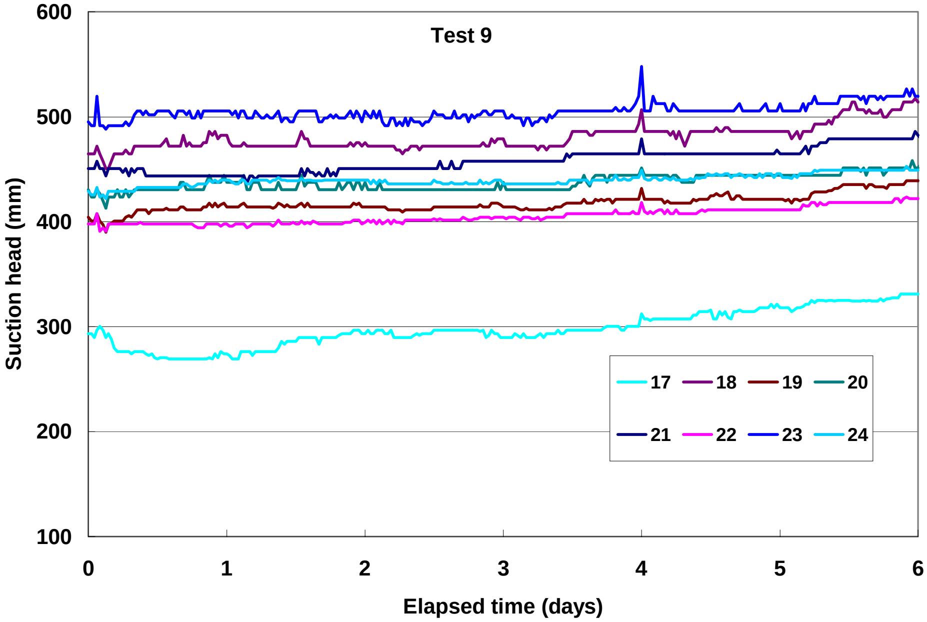

Figure 29. Soil suction heads in subgrade, 25 mm below the GCBD in Test 9.

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}) 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, 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 conducted subsequent to the 6-hour storm, 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 (again) 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 can drain water at even higher suctions than it already does 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 soil 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 explicitly designed and manufacture 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

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