

FINAL  
CONTRACT REPORT

**EVALUATION  
OF WICK DRAIN PERFORMANCE  
IN VIRGINIA SOILS**

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<p>16. Abstract</p> <p>Prefabricated vertical drains (PVD), also known as wick drains, are commonly used to accelerate the consolidation of fine-grained soils in order to reduce future settlements and increase shear strength. Various drain designs are currently on the market, with significant variations in price. This variability of designs makes the performance highly product specific.</p> <p>Tests were carried out to assess the behavior of several wick drains in Virginia soils. Drains were subjected to crimping, lateral pressure, and consolidation, with the resulting impact on the flow rate. All tests were performed in the laboratory to ensure controlled boundary and initial conditions.</p> <p>Significant differences in the performance of wick drains were evaluated. The performance was quantified based on the percentage reduction in flow capacity during flow in a crimped position, percentage reduction in flow capacity under lateral stress, and percentage reduction in the consolidation time. Test results identified the Ameridrain AD607 and Mebra-Drain MD-88 as the most effective drains among those studied.</p>			
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## ABSTRACT

The use of prefabricated vertical drains (PVDs), also known as wick drains, to hasten the consolidation of fine-grained compressible soils is a well-established practice in the field. PVDs consist of a core designed to transmit water vertically or horizontally to freely draining layers and a geotextile filter jacket designed to allow rapid flow of water into the core while preventing the migration of soil particles into the drain. A variety of drain designs, with different core and filter jacket configurations, are available, with significant variations in price. Because the drain cores can take a variety of configurations, including fin channels, corrugated cores, and dimple cores, and because the filter fabrics can be made from geotextiles with differing strengths, the performance of the drains is product specific. This study assessed the behavior of six PVDs in Virginia soils under a variety of laboratory conditions.

Three laboratory tests were performed to assess the behavior of the PVDs in four Virginia soil types. The index tests included crimp testing, lateral pressure testing, and large-scale consolidation testing. All tests were performed in a laboratory setting in order to ensure controlled boundary and initial conditions.

Significant differences in behavior of the PVDs were quantified in this study. Performance was quantified based on the % reduction in flow capacity during flow through the drains in a crimped position, % reduction in flow capacity under lateral stress, and % reduction in the measured  $t_{90}$  value compared to  $t_{90}$  for a control test. Based on the results of the laboratory tests performed, the Amerdrain AD607 consistently exhibited superior performance when compared to other drains through the largest average reduction in  $t_{90}$  ( $t_{90}$  with the drain  $\approx 9\%$   $t_{90}$  of control) during consolidation testing and through one of the lowest reductions in flow capacity in the crimp test (20%). However, the Mebra-Drain MD-88 also performed well with the least reduction in flow capacity in the crimp test (17%) and with good performance in the consolidation tests ( $t_{90}$  with the drain  $\approx 17\%$   $t_{90}$  of control). It is important to note that the year 2003 cost per foot of AD607 is \$0.14 compared to \$0.11 for the MD-88, a price difference that could be significant on a large-scale project. The remaining drains (AD407, AD407F, AD417, and MD-7407) demonstrated varying levels of performance in these index tests, which might eliminate them from consideration in a field application. Of most concern was the significant effect of lateral pressure on AD417, although this did not translate into significantly reduced performance in the consolidation test. From a purely cost basis, the Mebra-Drain MD-88 yielded the best results, giving superior performance in two out of three tests and having one of the lowest year 2003 costs per foot (\$0.11) of the drains tested.

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## **INTRODUCTION**

The use of prefabricated vertical drains (PVDs), also known as wick drains, to hasten the consolidation of fine-grained compressible soils is a well-established practice in the field. PVDs consist of a core designed to transmit water vertically or horizontally to freely draining layers and a geotextile filter jacket designed to allow rapid flow of water into the core while preventing the migration of soil particles into the drain. A variety of drain designs, with different core and filter jacket configurations, are available, with significant variations in price. Because the drain cores can take a variety of configurations, including fin channels, corrugated cores, and dimple cores, and because the filter fabrics can be made from geotextiles with differing strengths, the performance of the drains is product specific. This study assessed the behavior of six PVDs in Virginia soils under a variety of laboratory conditions.

## **PURPOSE AND SCOPE**

The objective of this project was to compare the performance of a variety of commercially available PVDs in four soil types commonly encountered throughout Virginia in order to determine if lower cost drains perform to an acceptable standard and can be used in place of more expensive drains.

The primary objective of the study was to assess the performance of the drains under the different laboratory controlled conditions and compare performance based on cost per foot of drains.

## MATERIALS AND METHODS

To achieve the objectives of the study, six different tasks were performed:

1. Review of literature to assess the current state of knowledge on PVD testing in the laboratory.
2. Acquisition of soils and PVDs for the test program.
3. Laboratory characterization of the soils used in testing.
4. Quantification of the flowrate through the PVDs with the drains in the vertical position and with a 90° bend.
5. Quantification of the flowrate through the PVDs as a function of applied lateral stress after the drains were compacted in each of the soil types studied.
6. Quantification of the consolidation properties of four soils with and without the presence of the PVDs.

### Task 1: Literature Review

PVDs are an ideal solution to decrease the time required for primary consolidation settlement in fine-grained inorganic soils with a high water content and low strength (Holtz et al., 1991); however, PVDs are not often successful in peat soils because they do not reduce secondary settlements (Holtz, 2000). Consequently, PVDs are commonly used in highly compressible clay soils in order to hasten settlement due to the primary consolidation of these soils. Due to the complex boundary and initial conditions commonly encountered in field testing, testing performed in the laboratory is often desirable in order to quantify the performance of PVDs under controlled settings. These tests can be characterized as index tests, which quantify the effect of the PVD on the consolidation characteristics of the soil and the effect of lateral pressure and crimping on the discharge capacity of the drains that have been investigated.

#### *Laboratory Scale Consolidation Testing*

Guido and Ludewig (1986) performed a laboratory-based study to compare the performance of five wick drains consolidated in a kaolinite soil in a consolidometer with an inside diameter of 30.2 cm (11.9 in). The drains were manufactured by Mebra-Drain and Geodrain (filter jacket wrapped around core with longitudinal grooves), Castleboard (non-woven jacket, heat bonded to the core), Franki-Kjellman (thick filter fabric, glued to both sides of core), and Alidrain (filter jacket, wrapped around studded core). The investigators inserted the 38.1 cm (15.0 in) long wick drains into a kaolinite soil at a water content of 50%, which was equal to the liquid limit of the soil. The soil was compacted around the clay soil as it was placed in the consolidometer. After the consolidometer was filled, the clay was consolidated to 86.2 kPa (12.5 psi) and allowed to drain for two to three days. For all of the drains tested, the results

demonstrated that drainage was faster than in the control case with no wick. The tests performed with the Alidrain wick had the fastest rate of compression, with the Castleboard, Geodrain, and Mebra-Drain demonstrating intermediate performance and the Franki-Kjellman the slowest rate of compression. As anticipated, the amount of water released from the drains was closely correlated with the total amount of compression. The consolidation tests were performed with a sand layer at the base of the clay layer. The control test with no wick present drained the largest quantity of water into the sand layer; however, when the wicks were in place, horizontal drainage became dominant and the bulk of the water drained through the clay soil. The authors concluded that the longitudinal drainage channels in the Geodrain and Mebra-Drain were susceptible to closure, and reduction of available volume for flow, when the lateral pressure forced the filter jacket into the channels, but the studded Alidrain core was thicker and less sensitive to this intrusion, and so performed better.

Ali (1991) performed laboratory tests to quantify the influence of consolidation on the deformation of wick drains. The drains were confined in a large consolidation cell with dimensions of 0.5 m (19.7 in) in diameter by 1.2 m (47.2 in) tall, with sand drainage layers above and below a 0.5 m (19.7 in) thick layer of clay that was consolidating. The author studied six types of drains, with a range of cores and filter jacket types. For all six drain types, the discharge capacity decreased as the relative compression increased to 35%, which reflected a consolidation pressure of 300 kPa (43.5 psi). The reductions in discharge ranged from 75% to 100%. Four of the drains tested had their discharge reduced to almost zero. The drain with the highest discharge at 35% consolidation was described as having an open three-dimensional structure with interconnected flow paths and demonstrated a pattern of gentle folding as compared to the sharp kinking of some of the other drains. The drains with the lowest discharge after consolidation tended to accommodate the settlement in sharp kinks. Comparison of two drains with the same core but different filter jackets demonstrated that the stiffer filter jacket provided bridging over the channels of the core and yielded a higher discharge capacity. In drains with studded cores, the studs punched through the filter jacket, which decreased the volume of channel available for flow. The drain with the most compressible core and filter jacket produced the lowest discharge at all levels of compression.

Holtz et al. (1989) embedded PVDs in a clay slurry, confined them in a consolidometer, and subjected them to 20% vertical deformation. The flow capacity for two of the drains tested was reduced to 20% to 25% of the straight flow capacity, although not all of the drains tested were as sensitive to the settlement. The authors concluded that some drains could experience significant reductions in flow capacity if the vertical consolidation at the site was greater than 15% to 20%.

Suits et al. (1986) confined fifteen different PVDs in two or three soils types in a test cylinder with dimensions of 25.4 cm (10 in) in diameter by 55.9 cm (22 in) high. The soils were remolded and compacted around the PVDs, and a wax seal was placed over the top of the soil to prevent vertical drainage. A sand blanket was then placed over the wax seal, and the soil/PVD was loaded to 96.5 kPa (14 psi). The researchers allowed the soil to consolidate for about 7 days. The results demonstrated that the PVDs were effective in reducing the time for consolidation in the soils tested. The authors also determined equivalent diameters for sand

drains based on the results of the consolidation tests and found that the PVDs had equivalent dimensions of 25 mm to 76 mm (1 to 3 in).

#### *Drain Performance Under Increasing Lateral Pressure*

Holtz et al. (1989) conducted three series of tests on PVDs embedded in soil as straight drains, bent drains, and drains subject to 20% consolidation. The testing apparatus was 30 cm (11.8 in) in diameter and 50 cm (19.7 in) to 300 cm (118 in) high, with a lateral stress capacity of 600 kPa (87 psi). The tests were performed under a hydraulic gradient of one, at increasing levels of lateral stress. Multiple drains were tested, and most yielded flow capacities on the order of several hundred cubic meters/year, even at the highest level of lateral stress, with deviations of  $\pm 10\%$  to 15% for repetitions performed on the same drain.

Ali (1991) tested the Colbond CX1000 drain (width of 5 cm, or 2 in) in a pressure vessel with an inside diameter of 0.3 m (11.8 in). The discharge capacity of the drain was tested by sealing it in plastic sheeting and filling the vessel with water or air to apply lateral pressure. The researcher also tested the filter function and discharge capacity of the drain, with it embedded in soil. In both cases the confining pressure was increased incrementally to 300 kPa (43.5 psi). The Colbond CX1000 showed a decrease of roughly 30% when the lateral pressure was increased from 100 kPa (14.5 psi) to 300 kPa (43.5 psi). The author found that the rate of particle infiltrations into the drain was highest just after the drain had been placed, which corresponded with the highest level of flow. Once a filter cake formed around the drain, the quantity of fines flowing out of the drain decreased.

Bergado et al. (1996) performed modified triaxial and ASTM-based discharge tests. The modified triaxial tests confined the PVD in a rubber membrane, which was then placed in a triaxial testing cell. The PVDs were tested in the straight, free bending, and twisted conditions under varying hydraulic gradients and lateral pressures. The ASTM-based discharge tests were performed by wrapping the drains in a rubber membrane, confining the wrapped drains in sand, and applying lateral pressure to the drains using hydraulic pressure. Ten drains were tested in the investigations: Alidrain, Amerdrain 408, Castle Board, Colbond CX-1000, Desol, Fibredrain, Flodrain FD4-EX, Geodrain L-type, Hongplast GD75, and Mebra-Drain MD-7007. Lateral pressures up to 200 kPa (29 psi) were applied to the drains. Bergado et al. (1996) found that the discharge from the drains decreased as lateral pressure, time, and hydraulic gradient were all increased. They concluded that lateral pressure forced the filter jacket into the flow channels, restricting the volume available to transmit water.

Suits et al. (1986) assessed the effect of lateral pressure on the performance of 13 PVDs. The drains were placed in heat shrink plastic, encased in sand, and subjected to lateral pressures ranging from 0 kPa (0 psi) to 55.6 kPa (8 psi). Based on their results, the researchers estimated that the flow capacity of the soft core drains would be reduced to zero under the high lateral stresses encountered in the field.

#### *Drain Performance Under Crimped Conditions*

Lawrence and Koerner (1988) tested the flow behavior of the following PVDs that had been subjected to kinking: rigid, straight channeled: Bando, Castle Board, and Desol; semi-rigid, straight channeled: Aliwick, Ameridrain, Mebra-Drain, Vinyles; flexible, studded two-sided:

Alidrain; flexible, studded one-sided: Alidrain "B"; flexible, entangled web: Colband CX 1000; flexible, waffle two-sided: Hitek Flodrain. All drains tested were 10 cm (3.9 in) in width. The authors encased 66 cm (26 in) long sections of wick drains in heat shrinkable window insulation and clamped the encased drain in a kink testing device similar to that used by Suits et al. (1986). The kinking mechanism had either a 90° wedge or a 1.3 cm (0.5 in) cylinder that could be screwed into a mating fitting to produce the desired degree of bend in the drain. All testing was performed at a gradient of 1, and all drains were tested in the uncrimped position before kinking began. The flowrate through the wicks decreased in all cases; however, the pattern for reduction was variable, with reductions produced by the 90° wedge ranging from 38% to 100% at the largest level of applied load and reductions by the 1.3 cm (0.5 in) cylinder ranging from 38% to 100% at the largest level of applied load. However, at moderate loads, all drains transmitted some quantity of flow. The authors concluded that the performance of the wick drains could not be correlated to any specific material properties of the individual PVDs and required individual testing.

Holtz et al. (1989) conducted a series of tests on drains bent in a gentle S-shaped curve, although the method of drain confinement was not discussed. The authors concluded that the drains in the bent condition had discharges as low as 10% of that in the unbent position; however, the reduction was largely dependent on the stiffness and geometry of the drain and its resistance to bending.

Suits et al. (1986) tested the effects of a crimp on drain flow capacity by wrapping 13 PVDs in heat shrink plastic and screwing a wedge into the drain, which forced a 90° bend into the drains. The average flowrates through the drains in the crimped and uncrimped positions were then quantified. Results demonstrated that crimping alone did not affect the PVD performance. It reduced the flow capacity to between 15% and 67% of the uncrimped flow capacity for the PVDs tested, but the PVDs contained two orders of magnitude greater capacity than required for consolidation.

#### *Drain Flow Capacity Under Vacuum Conditions in the Laboratory*

Quaranta and Gabr (2000) performed a laboratory study of the behavior of prefabricated vertical drains under vacuum conditions. Drains with corrugated and fin cores were sealed in plastic sheeting and immersed in a constant head reservoir at their base, with a variable vacuum applied at the top of the drain. The tests demonstrated that the fin type core provided over three times the flowrate of the corrugated core, due to its larger nominal hydraulic radius. Flow velocity was linear and Darcy's law was valid below a gradient of 0.5. Finally, the transmissivity of the fin type core was roughly 3 times that of the corrugated core.

#### *Summary*

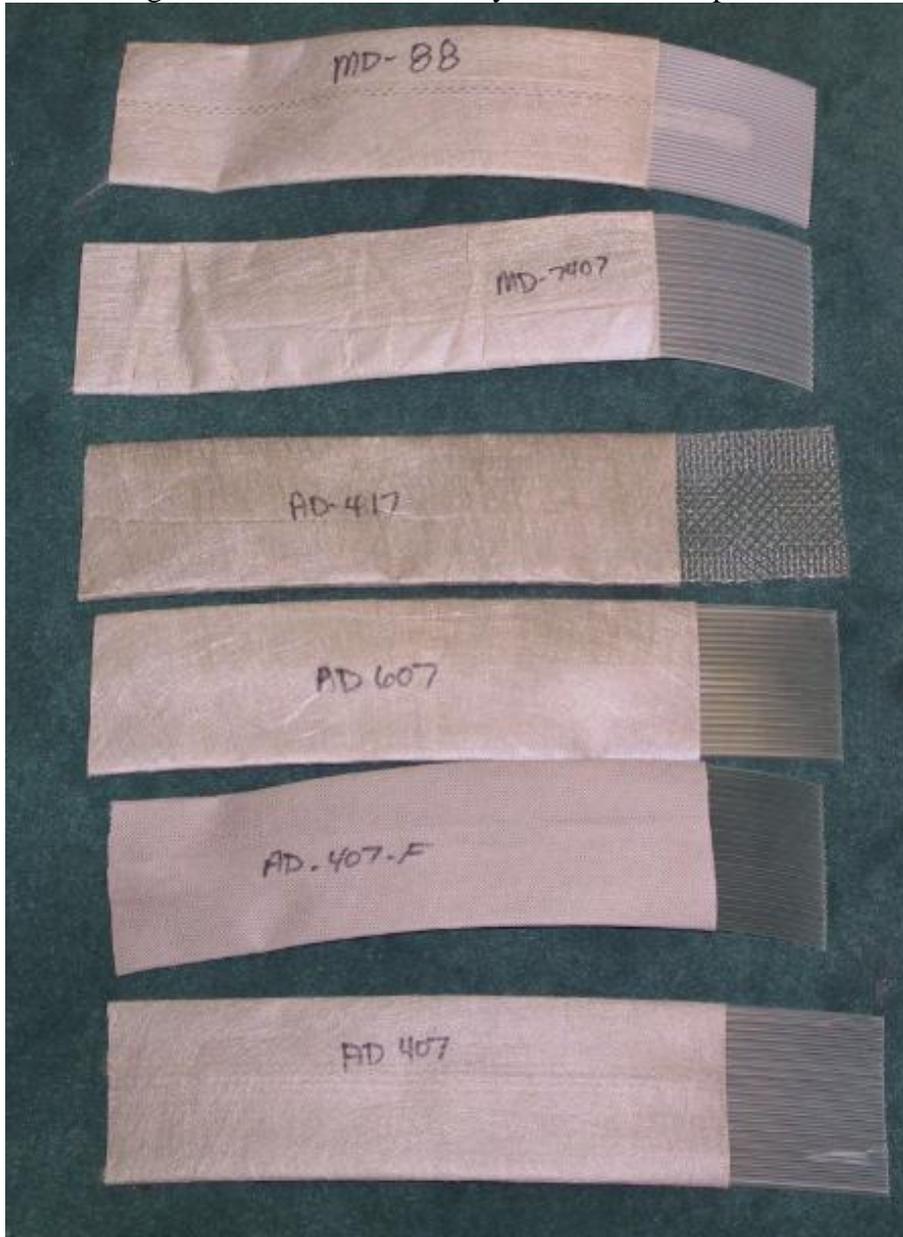
PVDs have been tested under a variety of laboratory conditions, and significant differences in performance have been quantified. However, the behavior of an individual PVD is material specific and its behavior must be quantified by specific drain and soil variables.

It is important to note that the laboratory tests did not consider factors that are important in the behavior of drains in the field, including installation effects, smear, partial saturation, and well resistance in long drains.

## Task 2: Acquisition of PVDs and Soils for Test Program.

### *Drains*

Six commercially available PVDs were used in the testing program: Amerdrain 407, Amerdrain 407F, Amerdrain 417, Amerdrain 607, Mebra-Drain MD-88, and Mebra-Drain MD-7407 Typar 3407-1. After discussion with personnel from the Virginia Department of Transportation (VDOT), the tested drains were chosen to represent a range of core designs including corrugated (AD407, AD407F, AD607, and MD-7407), dimpled (AD417), and fin (MD-88), as well as a variety of geotextile jackets with differences in fabric weight and construction (Figure 1). Table 1 lists the relevant properties of the drains tested. The tested drains represent the designs that are most commonly encountered in practice.



**Figure 1. Six Prefabricated Vertical Drains Tested in Virginia Soils.**

**Table 1. Properties of Prefabricated Vertical Drains Tested**

<b>Property</b>	<b>Amerdrain 407</b>	<b>Amerdrain 407F</b>	<b>Amerdrain 417</b>	<b>Amerdrain 607</b>	<b>Mebra- Drain MD-7407</b>	<b>Mebra- Drain MD-88</b>
Core*	Corrugated	Corrugated	Dimple	Corrugated	Corrugated	Fin
Weight (oz/yd <sup>2</sup> )	4	2.5	4	6	4	3.9
Grab Tensile Strength (lb)	145	65	145	250	130	130
Puncture Strength (lb)	50	50	50	80	40	40
Trapezoidal Tear (lb)	70	70	70	100	60	56
AOS (US Sieve)	80	>200	80	70	100	120
Core Tensile Strength (lb)**	200	200	200	200	180	180
Discharge Capacity (gpm)***	1.6	1.6	1.6	1.6	1.7	1.9
2003 Cost per foot (\$)	0.10	0.10	0.12-0.13	0.14	0.10	0.11

\*All fabric and cores made from polypropylene.

\*\*Amerdrain – ASTM D 4632; Mebra-Drain – ASTM D 638.

\*\*\* ASTM D4716.

### *Soil*

Four soils were used in the testing program. Clay samples were obtained from current VDOT work sites at the Route 1/I-95 Interchange in Alexandria, Virginia, and West Point, Virginia, and soil from Craney Island, Virginia, was obtained from Virginia Geotechnical Services. A silt soil with a larger grain size than the clay samples was obtained from the region surrounding Charlottesville, Virginia. The soils were chosen from representative current work sites that are likely candidates for consolidation using PVDs. Each of the clay soils tested would be a good candidate for PVD installation.

### **Task 3: Laboratory Characterization of Soils Used in Testing**

Characterization tests for the silt soil included a grain size analysis that was performed according to ASTM D422, standard Proctor compaction test performed according to ASTM D698, and determination of the Atterberg limits according to ASTM D4318. Characterization of the clay soil samples included determination of the Atterberg limits for each homogenized soil sample. Tests were performed according to ASTM D4318. Consolidation on the remolded clay soils were performed according to ASTM D2435.

### **Task 4: Quantification of Flowrate Through PVDs with Drains in Vertical Position and with a 90° Bend**

The rate of flow of water through each PVD was quantified with the drain in the straight position and with a 90° crimp in the drain. A 38.1 cm (14 in) section of drain was encased in heat shrink tubing. During the course of testing, it was found that uniform shrinkage of the heat shrink around the PVD was essential to obtaining repeatable test results. In order to shrink the tubing uniformly and to prevent bubbles surrounding the drain, the drain and the heat shrink tubing were encased between two aluminum plates (Figure 2). The plates were bolted together, with spacers separating them at a distance equal to the width of the PVD plus the heat shrink tubing, and the aluminum plates were then heated with a heat gun. This application of heat across the aluminum plates created a uniform and repeatable impermeable jacket surrounding the PVD. After the heat shrink jacket cooled, the PVD was placed under a constant head reservoir at a gradient of 1.0 and water was allowed to flow through the drain (Figure 3). After repeated trials with the PVD in the vertical position, the drain was crimped at 90° (Figure 4), and the flowrate through the crimped drain at a gradient of 1.0 was again quantified.

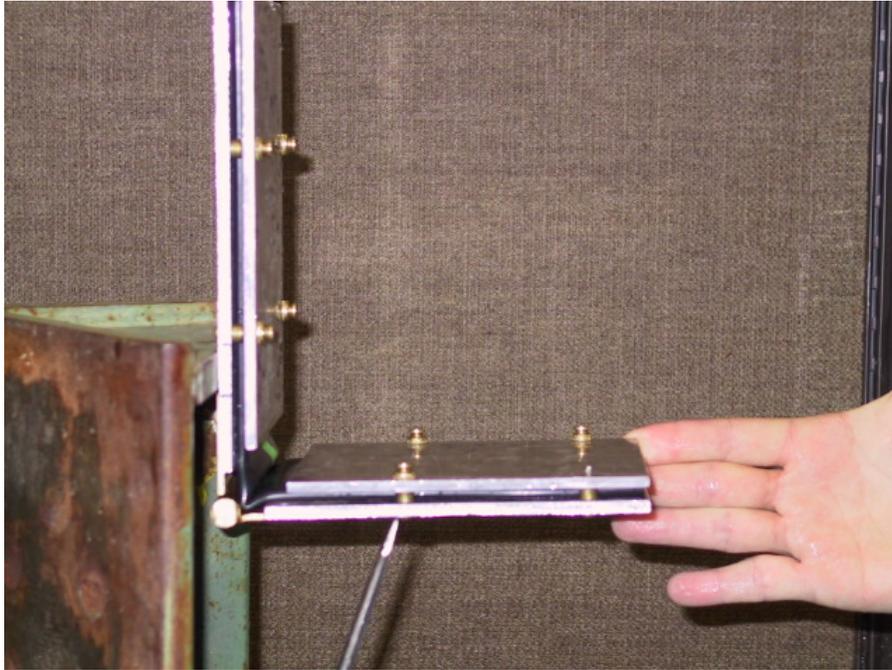
Tests were performed to compare the flowrate through the drain when water flowed from the top of the PVD to the bottom of the PVD to the flowrate through the drain when water flowed from the bottom of the PVD to the top. No significant differences in flowrate were measured, so all testing was performed with flow from top to bottom.



**Figure 2. PVD Encased in Heat Shrink and Aluminum Plates.**



**Figure 3. PVD in the Uncrimped Position Before Testing.**



**Figure 4. PVD in the Crimped Position Before Testing.**

**Task 5: Quantification of Flowrate Through PVDs as Function of Applied Lateral Stress, After Drains Were Compacted in Each Soil Type**

The influence of lateral stress on the flow capacity was quantified by compacting each of the four soils around each of the six PVDs that were partially encased in heat shrink tubing. The test cell had dimensions of 20 cm (8 in) by 61 cm (24 in) by 14 cm (5.5 in); the ends of the PVD were sealed in heat shrink tubing, while an 18 cm (7 in) section of heat shrink tubing was left exposed for loading (Figure 5 and Figure 6). The four soils were compacted to optimum water content surrounding the PVD, taking care not to damage the drain during installation. When the test cell was filled with soil, the PVD was 5 cm (2 in) below the top of the soil profile (Figure 7 and Figure 8). A loading plate with counter stress of 9.6 kPa (1.4 psi) was placed on the soil to resist hydraulic uplift pressure, while a loading plate of 193.5 cm<sup>2</sup> (30 in<sup>2</sup>) was placed on the soil above the section of drain that was not encased in heat shrink (Figure 9). A constant head reservoir applied a gradient of 1.0 to the flow through the PVD, and lateral stresses up to 276 kPa (40 psi) were applied through a hydraulic load frame. The flowrate through the PVD was measured as a function of lateral stress.



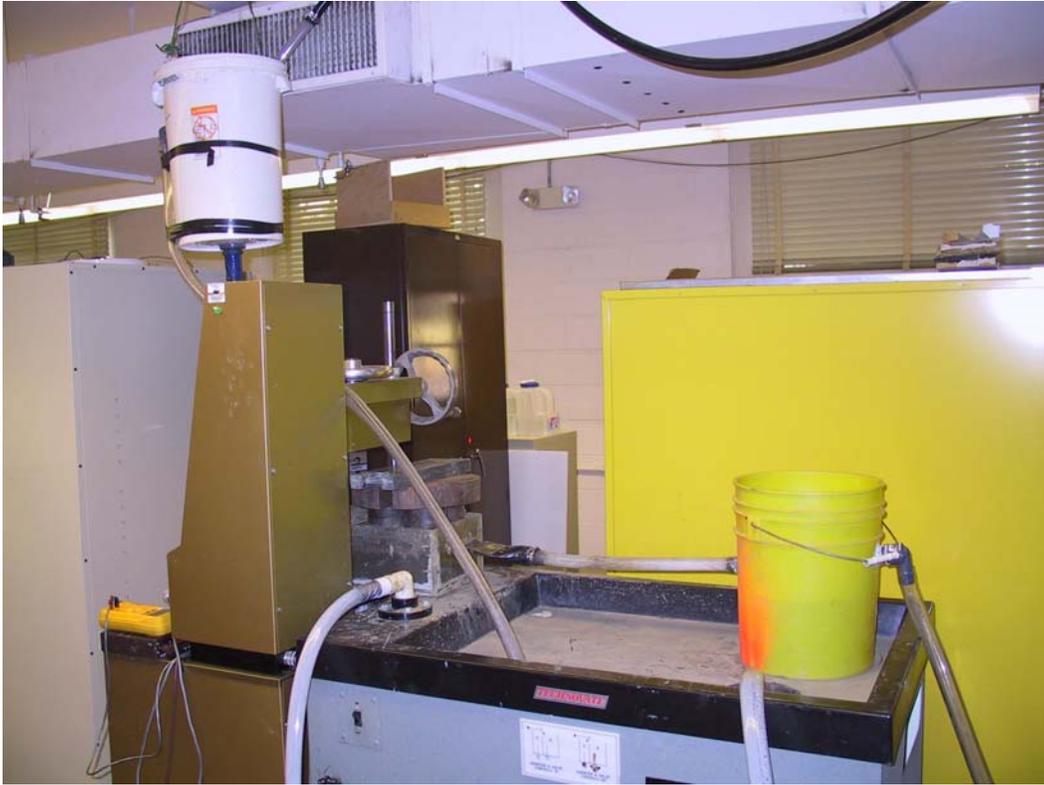
**Figure 5. Chamber for Lateral Pressure Testing.**



**Figure 6. Top View of Lateral Pressure Test Chamber.**



**Figure 7. Ongoing Lateral Pressure Test.**



**Figure 8. Outflow from Lateral Pressure Test.**



**Figure 9. Counterweight for Lateral Pressure Testing.**

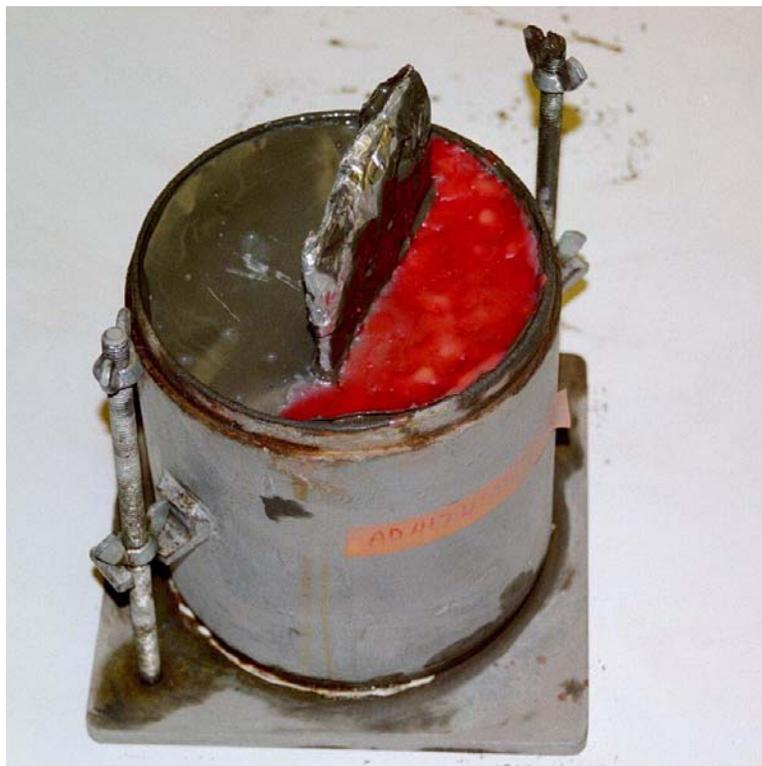
## **Task 6: Quantification of Consolidation Properties of Soils with and without PVDs**

Consolidation tests were performed in each of the soils with five PVDs (AD407F, 417, 607, MD-7407, and MD-88), and one control test was performed with no PVD present. For the silt soil, a 20 cm (8 in) long section of PVD was placed inside a steel mold with a diameter of 15 cm (6 in), and the soil was compacted to optimum water content (12%) using standard Proctor techniques. The inside of the mold was coated with silicon spray in order to reduce friction. After compaction, the silt samples were inundated with water for forty-eight hours in order to completely saturate the soil. For the clay soils, the soil was placed as a slurry in order to ensure complete saturation of the sample; preliminary tests that placed the clay using Proctor compaction techniques, followed by soaking, demonstrated that full saturation of the clay samples did not occur in a reasonable time frame for the soils tested. Consequently, the clay samples were prepared by mixing to an initial water content approximately equal to the liquid limit of the soil. A 20 cm (8 in) long section of drain was placed inside the steel mold, and the soil slurry was poured into the mold surrounding the drain (Figure 10). In all cases, the top of the drain was sealed during sample preparation in order to prevent soil intrusion into the interior portion of the drain. Once the mold was filled to a height of 16.5 cm (6.5 in), a layer of parafilm wax paper was placed on top of the soil, and the soil was sealed with a heavy layer of wax to force drainage through the drain by preventing vertical drainage through the soil (Figure 11 and Figure 12). Once the wax cover was placed on the soil, the collar was added to the mold and a sand drainage blanket was placed directly on top of the wax seal (Figure 13), and the seal to prevent soil intrusion into the drain was removed (Figure 14). A Plexiglas plate was placed on top of the sand drainage blanket (Figure 15), and the sample was placed into the load frame for testing (Figure 16 and Figure 17).

A seating load of 34 kPa (5 psi) was applied to each sample for twenty-four hours. The samples were then loaded to 145 kPa (21 psi) for a period of five to seven days, and deformation readings were taken periodically throughout the duration of the load. The manner in which the load was applied (using a static loadframe) deviated from the original proposal of using pneumatic loading, and the mold used in testing was of smaller diameter than that originally proposed. Primarily, the changes in loading method and mold size were made in order to obtain a high stress that was representative of likely field conditions. The stress used in testing approximated an embankment on the order of 8.2 m (27 feet) high, which is in the range of heights commonly encountered in practice. This relatively high stress would not have been achievable with a larger mold using pneumatic pressure. While the change allowed a higher stress to be applied to the sample, it also created a problem with drift in the stress. As the sample consolidated, the load released gradually over time, resulting in a small decrease in the applied stress. This was compensated for by frequently adjusting the load to ensure that the stress did not drop below 138 kPa (20 psi). Consequently, the applied load actually delivered to the soil sample ranged from 138 kPa to 145 kPa (20 psi to 21 psi).



**Figure 10. Placement of Soil in Mold.**



**Figure 11. Sample with Parafilm Cover and Partial Wax Cover.**



**Figure 12. Partial Wax Cover Over Sample.**



**Figure 13. Sand Drainage Blanket.**



**Figure 14. Completed Specimen Before Testing.**



**Figure 15. Specimen with Loading Plate in Place.**



**Figure 16. Specimen in Load Frame Ready for Testing.**

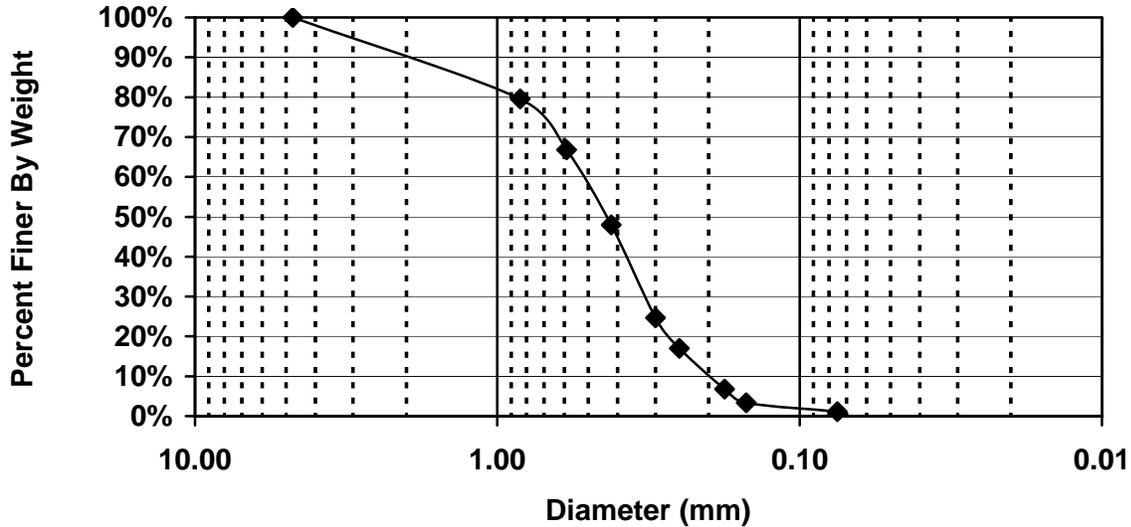


**Figure 17. Close Up Photo of Specimen Before Testing.**

## RESULTS

### Soil Characterization

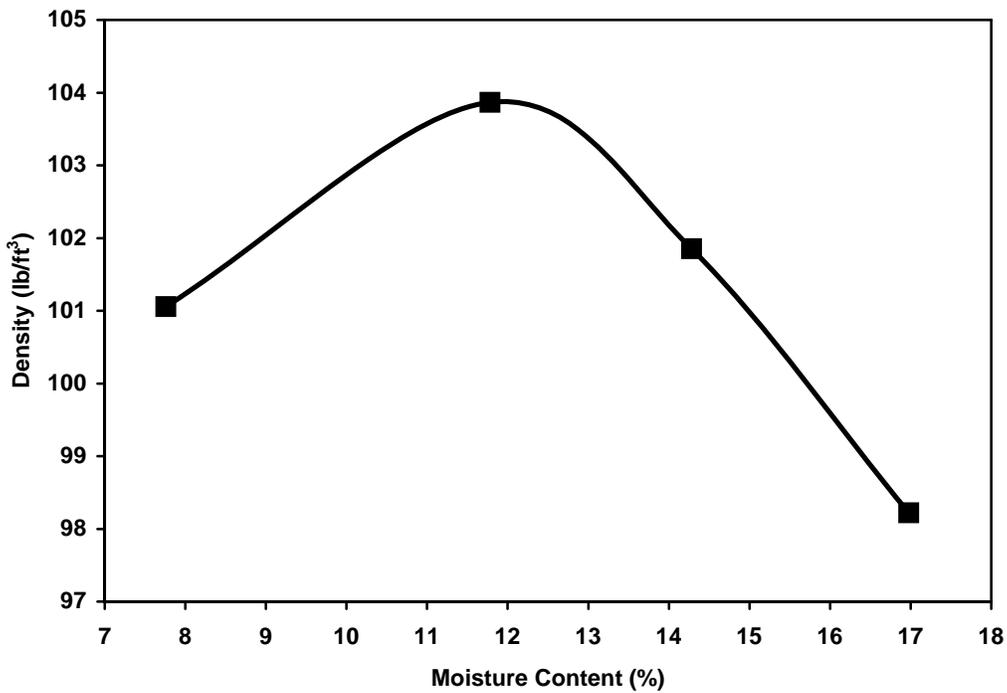
The grain size distribution for the silt sample is given in Figure 18 and Table 2.  $D_{10}$  for the soil was 0.2 mm (0.008 in), and  $D_{60}$  for the soil was 0.51 mm (0.02 in). Standard Proctor compaction results for the silt are given in Figure 19 and show a maximum dry density of 16.3 kN/m<sup>3</sup> (104 lb/ft<sup>3</sup>) at an optimum water content of 12%.



**Figure 18. Grain Size Analysis for the Virginia Silt.**

**Table 2. Soil Grain Sizes for the Virginia Silt**

Sieve Number	Sieve Opening (mm)	% Finer
4	4.75	100.0%
20	0.840	79.6%
30	0.590	66.8%
40	0.420	47.9%
50	0.300	24.7%
60	0.250	17.0%
80	0.177	6.8%
100	0.150	3.3%
200	0.075	1.1%
Pan	-	0.1%



**Figure 19. Standard Proctor Compaction Test Results for the Virginia Silt.**

Measured Atterberg limits for the three clay samples are shown in Table 3. Results for the consolidation tests performed on remolded specimens of the three clay soils are given in Figure 20 through Figure 22, with compression indices shown in Table 4.

**Table 3. Atterberg Limits for Clay Soil Samples**

<b>Soil</b>	<b>Liquid Limit</b>	<b>Plastic Limit</b>	<b>Plasticity Index</b>
Woodrow Wilson Bridge	90	43	47
Craney Island	123	38	85
West Point	71	49	22

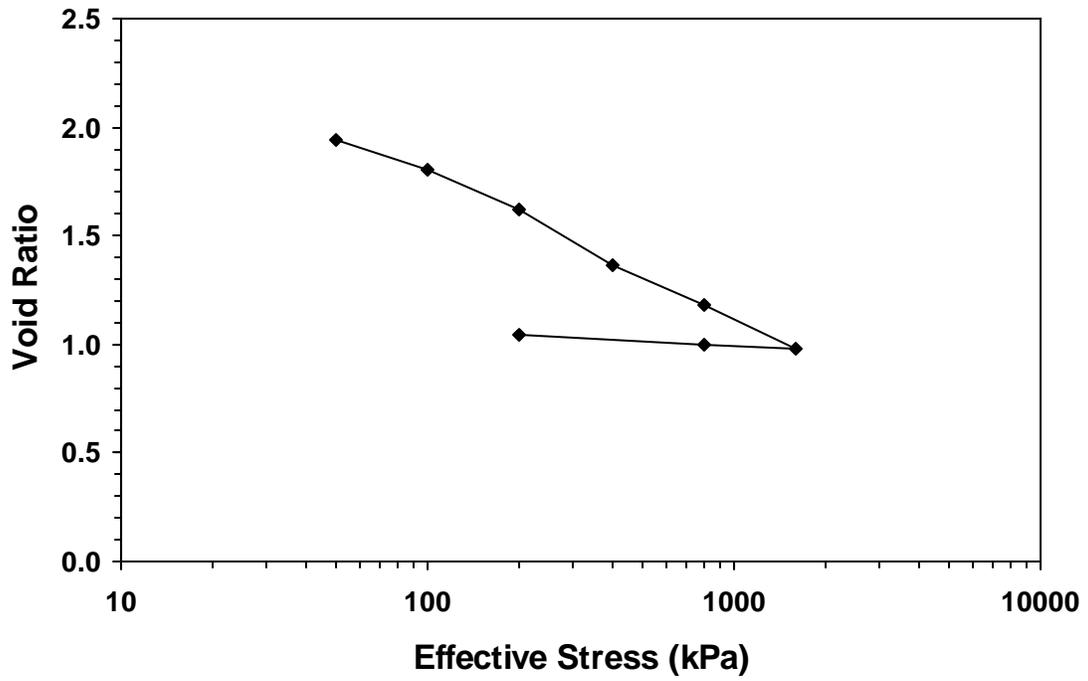


Figure 20. Consolidation Test Results for Woodrow Wilson Bridge Soil.

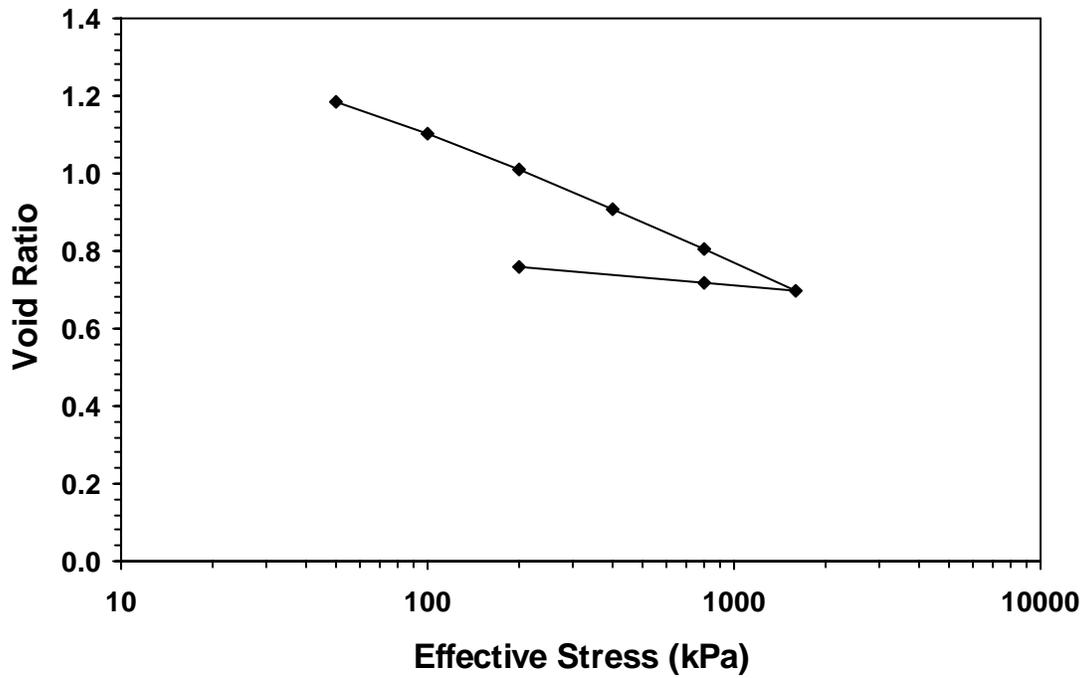
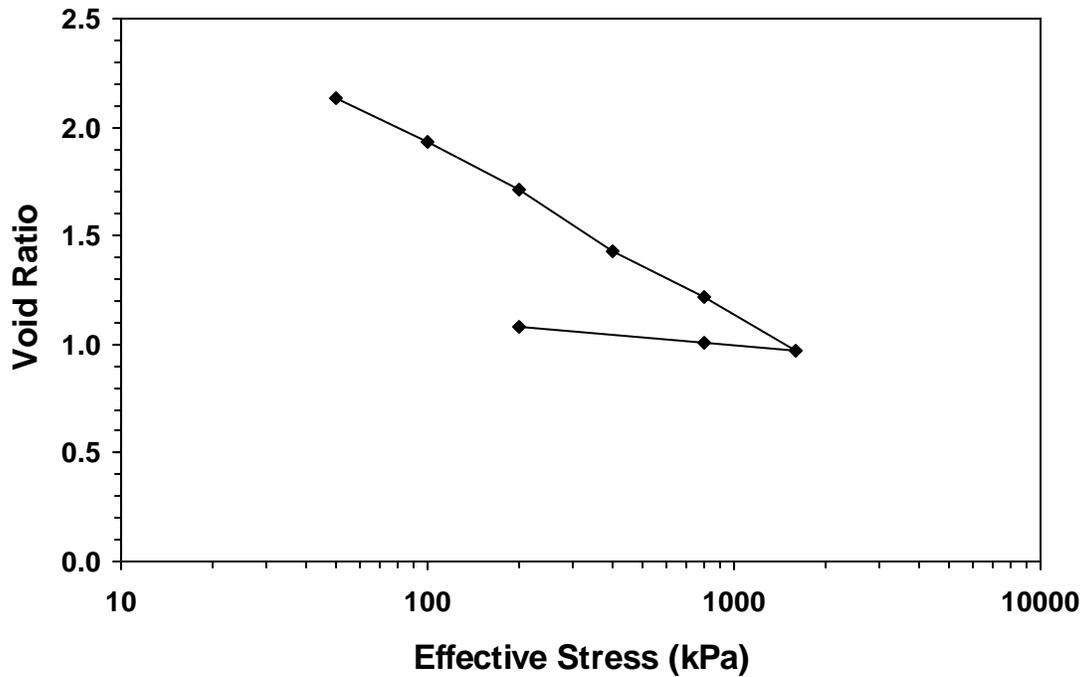


Figure 21. Consolidation Test Results for Craney Island Soil.



**Figure 22. Consolidation Test Results for West Point Soil.**

**Table 4. Compression Index from Remolded Consolidation Tests**

Soil	$C_c$
Woodrow Wilson Bridge	0.64
Craney Island	0.32
West Point	0.77

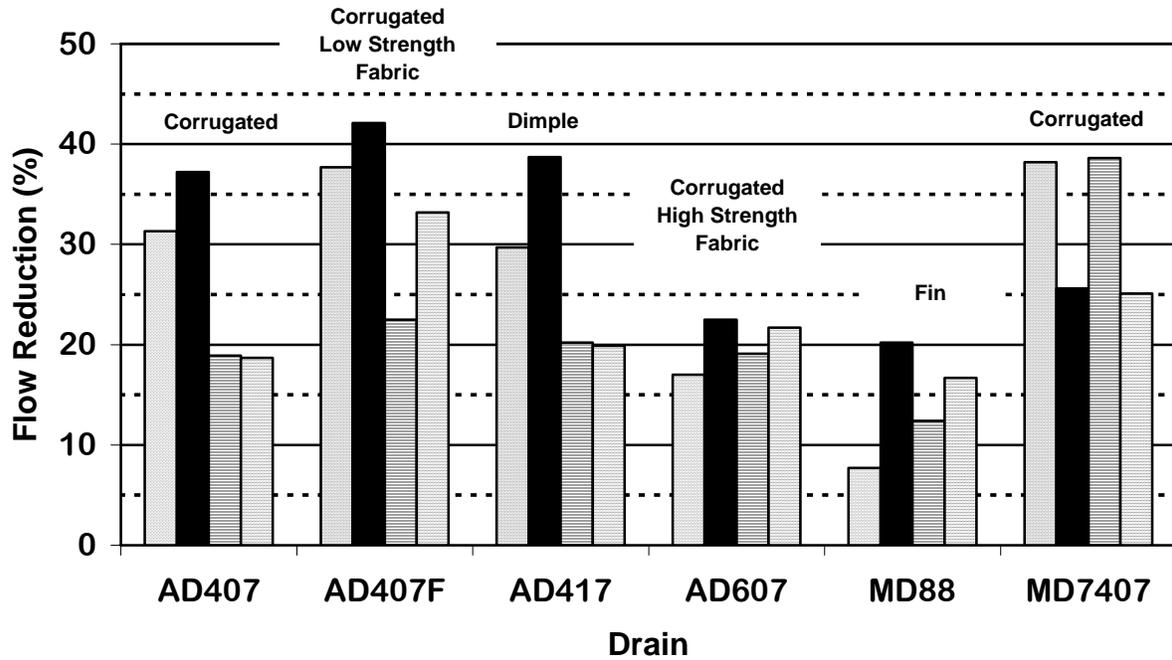
### *Crimp Testing*

Each of the six PVDs was subjected to eight test runs; four with direct flow through the drain in the vertical position, and four with flow through a 90° crimp in the drain. The flow rates through the drains in the uncrimped position and the average percent reduction in flow in the crimped position are given in Table 5. The data show that the average flowrates through the uncrimped drains ranged from a low of 237 mL/s for the Amerdrain AD407F to a high of 412 mL/s for the Mebra-Drain MD-88. Two drains, AD607 and MD-88, performed significantly better than the other four in the crimped flow position, with only a 17% and 20% average reduction in flow, respectively (Figure 23). Standard deviations for these drains in the crimped position were low as well, with only a 3% standard deviation. The four remaining drains demonstrated a flow reduction ranging from 27% to 34%, with standard deviations of 8% to 9%. Interestingly, the drain with the highest flowrate, MD-88, had the lowest reduction in flow in the

crimped position at 17%, while the drain with the lowest flowrate, AD407F, had the highest reduction in flow in the crimped position at 34%.

**Table 5. Test Results for Flow Through Six PVDs in the Crimped and Uncrimped Positions.**

	<b>Test 1 (mL/s)</b>	<b>Test 2 (mL/s)</b>	<b>Test 3 (mL/s)</b>	<b>Test 4 (mL/s)</b>	<b>Avg Flow Rate (mL/s) [Stan Dev]</b>	<b>Avg Flow Reduction in Crimped Position (%) [Stan Dev]</b>
Amerdrain 407	240	249	244	223	<b>239</b> [10]	27 [9]
Amerdrain 407F	260	220	229	240	<b>237</b> [15]	34 [8]
Amerdrain 417	310	255	247	262	<b>269</b> [25]	27 [9]
Amerdrain 607	287	290	311	281	<b>292</b> [11]	20 [3]
Mebra-Drain MD-88	447	345	404	451	<b>412</b> [43]	17 [3]
Mebra-Drain MD-7407	371	290	263	316	<b>310</b> [40]	32 [8]
Blank No Drain	692	692	457	-	<b>614</b> [111]	No flow



**Figure 23. Flow Reductions for Six PVDs in the Crimped Position.**

*Lateral Pressure Testing*

Lateral pressure testing was performed using each of the six PVDs encased in each of the four test soils (24 tests total). Figure 24 through Figure 27 demonstrate the dependence of the flowrate through the PVDs on the lateral stress that is applied to soil in which the drains are compacted. Because different initial magnitudes of flow through the drains resulted from the compaction of each drain in the soil in the test chamber, the data were normalized to the initial magnitude of flow at zero lateral applied stress in each test case. Data are presented as the ratio of flowrate at a given applied lateral stress divided by the flowrate at zero applied lateral stress. The four drains with the corrugated cores (AD407, AD407F, AD607, and MD7407) and the drain with the fin core (MD88) show essentially no dependence of flowrate through the drain up to the applied maximum lateral stress of 276 kPa (40 psi); however, the dimple core drain (AD417) consistently demonstrated a significant dependence on the applied lateral stress, with the flowrate through the drain decreasing as the lateral stress was increased in all soils tested. In summary, no significant effects of applied lateral pressure were detectable, except for the dimpled core drain, which showed consistently decreasing flowrates of 25% to 50% of the flowrate measured at zero applied lateral stress.

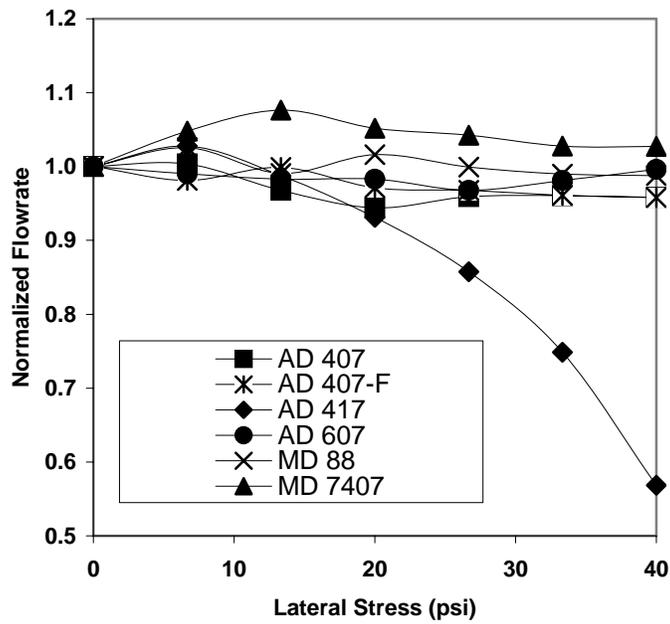


Figure 24. Lateral Pressure Test Results for Six PVDs in Craney Island Soil.

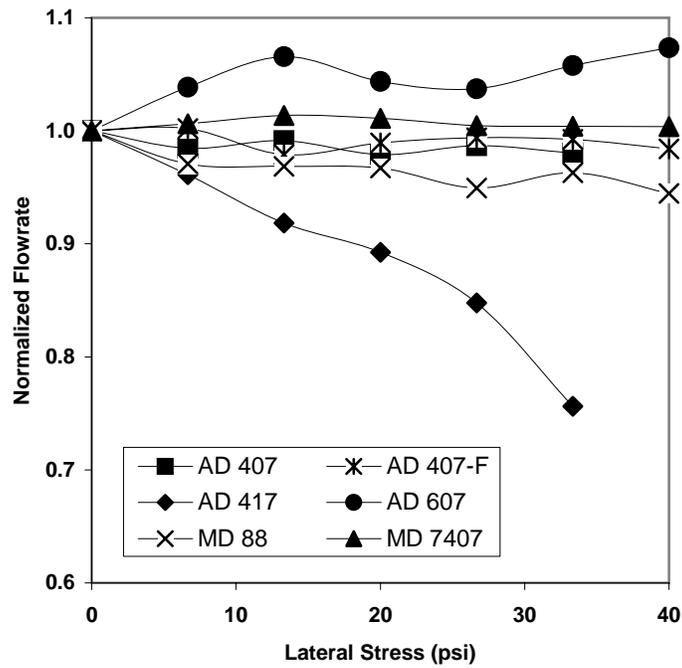


Figure 25. Lateral Pressure Test Results for Six PVDs in West Point Soil.

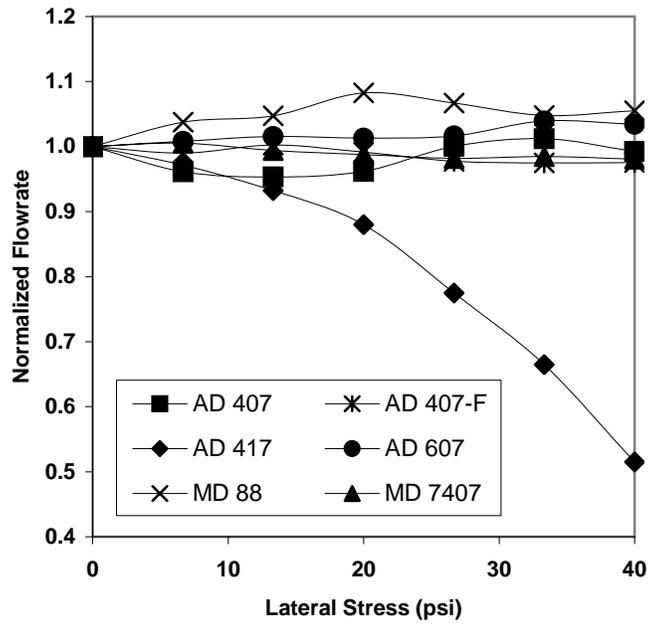


Figure 26. Lateral Pressure Test Results for Six PVDs in Woodrow Wilson Bridge Soil.

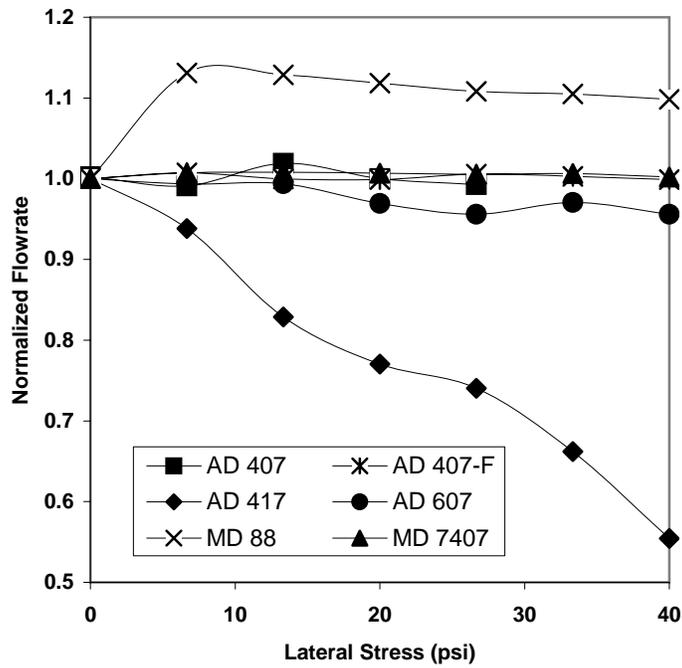
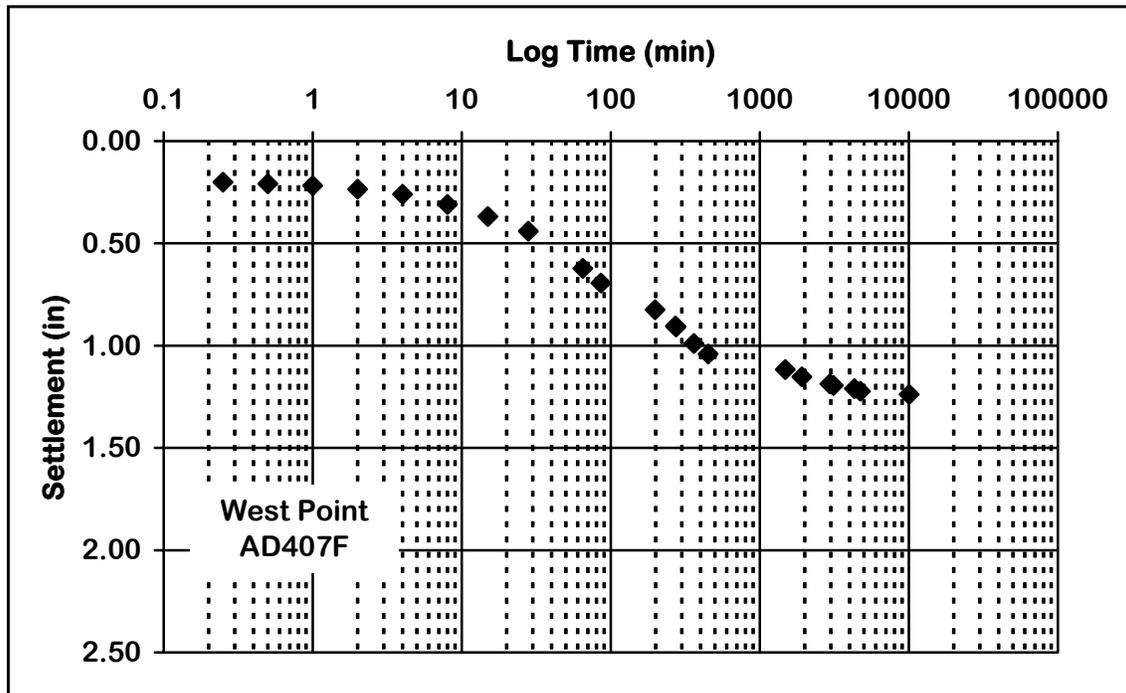


Figure 27. Lateral Pressure Test Results for Six PVDs in Silt.

*Consolidation Testing*

Six consolidation tests (five with PVDs and one control) were run in each soil type (twenty-four tests total). The results for the consolidation tests are given in Figure 28 through Figure 48 and clearly demonstrate the increase in speed of consolidation in the tests with PVDs in clay soils as compared to the control tests. As was anticipated, the silt soil showed little effect of the PVD, due to the lack of consolidation in the compacted silt.



**Figure 28. Consolidation Test Results for AD407F in West Point Soil.**

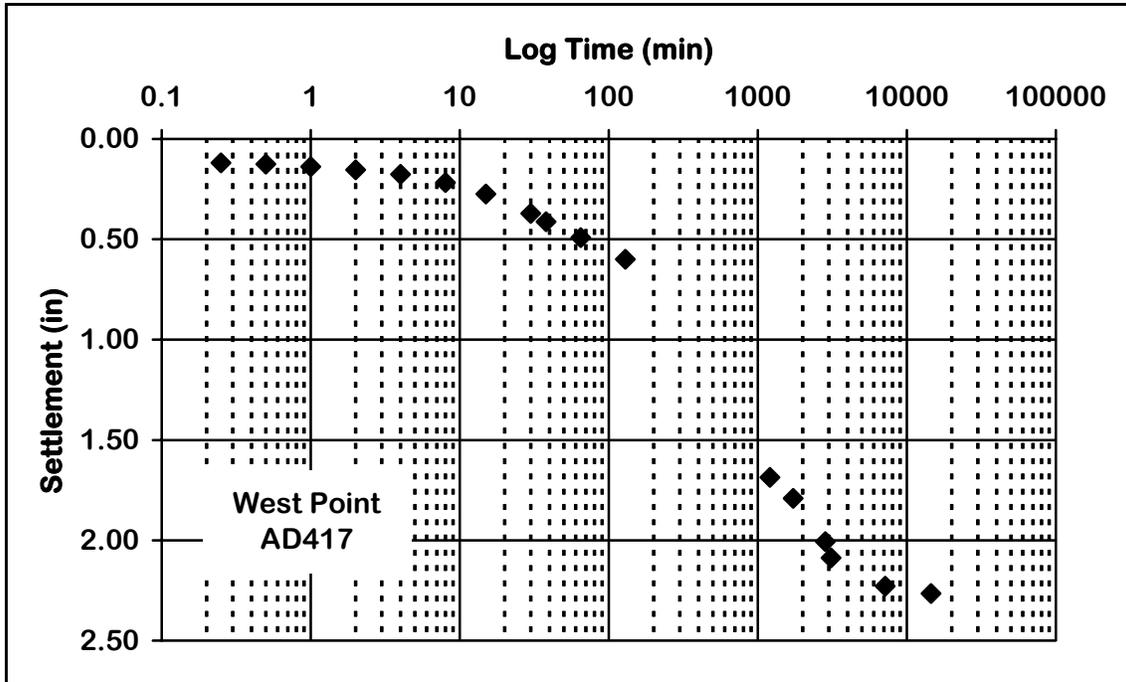


Figure 29. Consolidation Test Results for AD417 in West Point Soil.

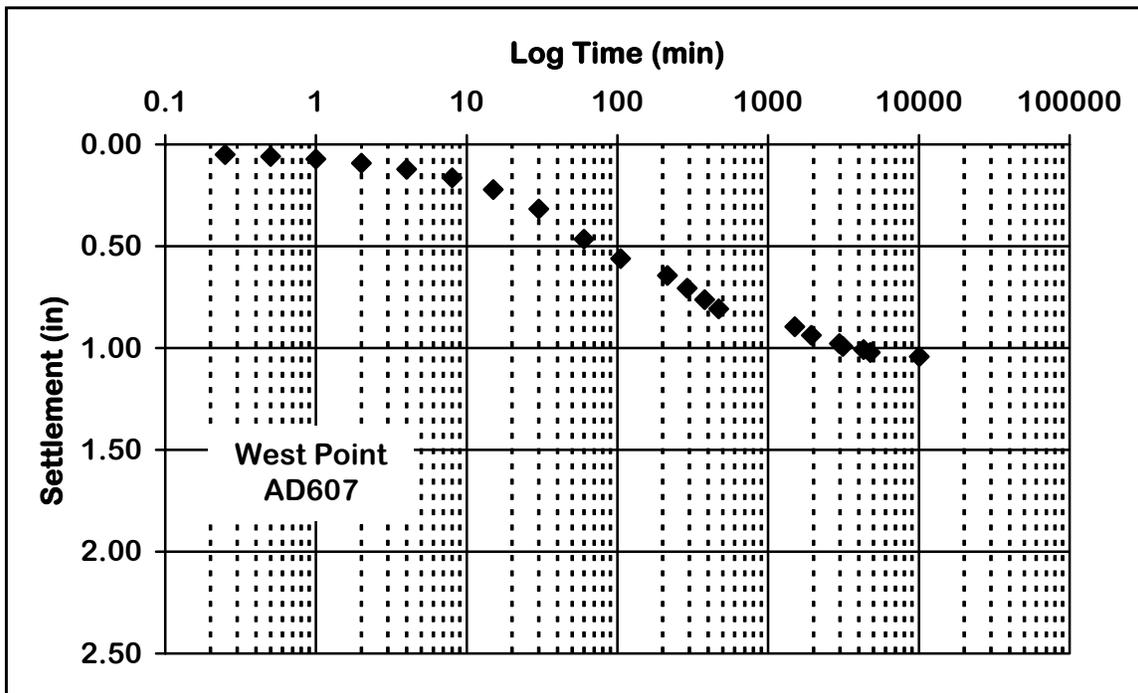


Figure 30. Consolidation Test Results for AD607 in West Point Soil.

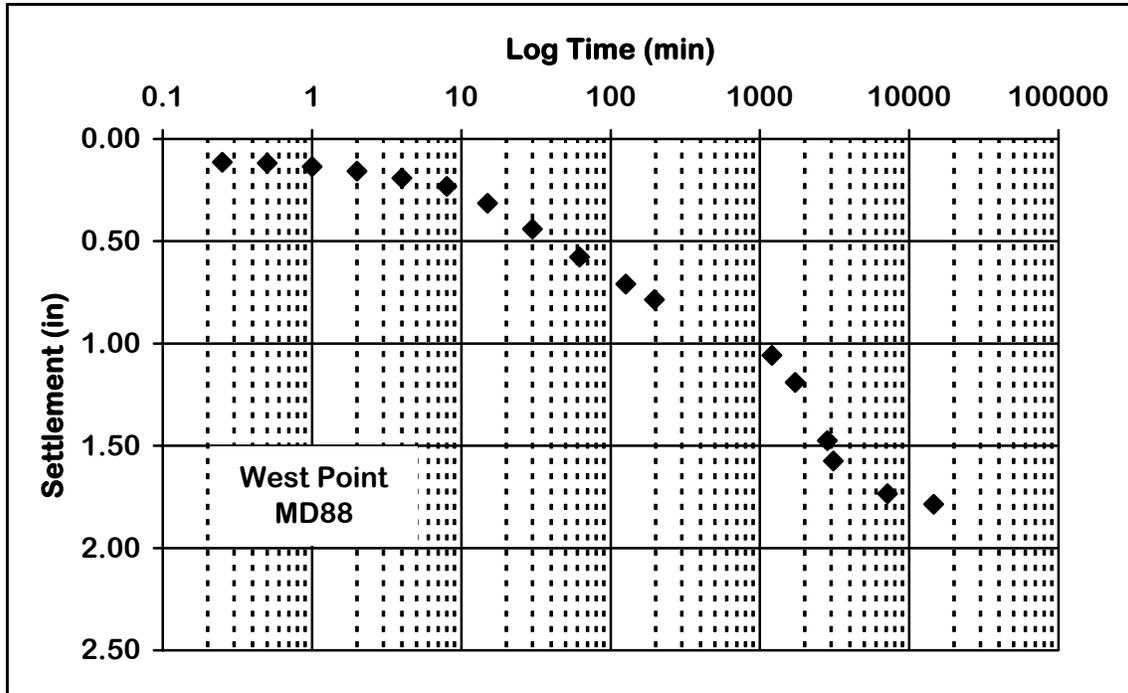


Figure 31. Consolidation Test Results for MD88 in West Point Soil.

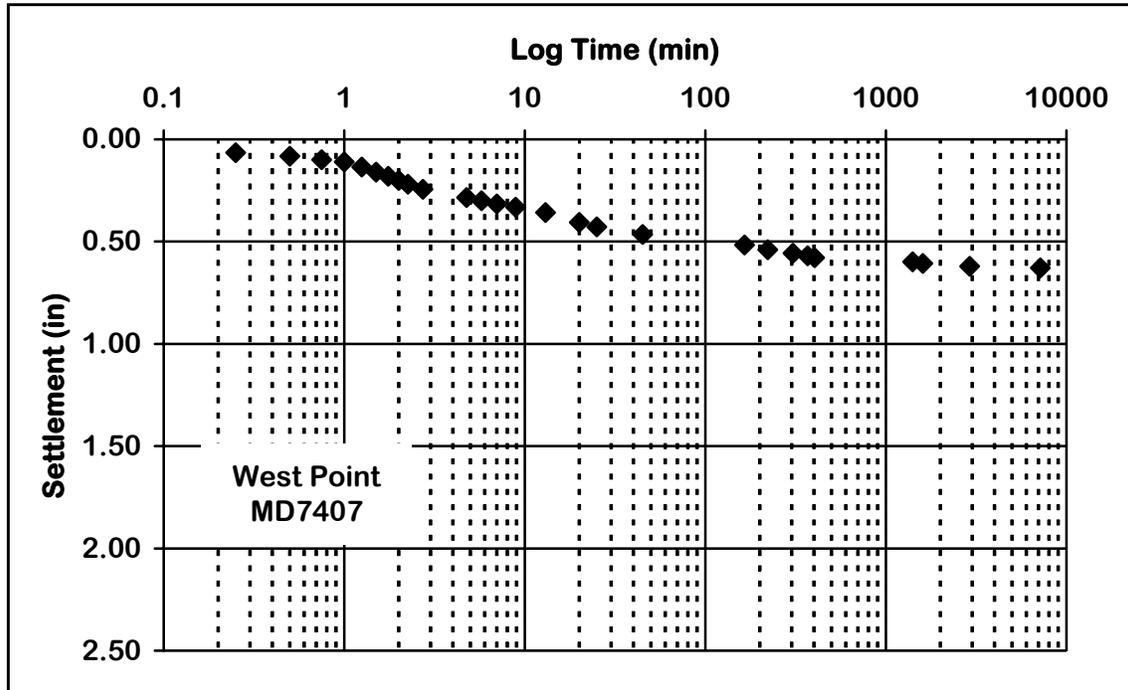


Figure 32. Consolidation Test Results for MD7407 in West Point Soil.

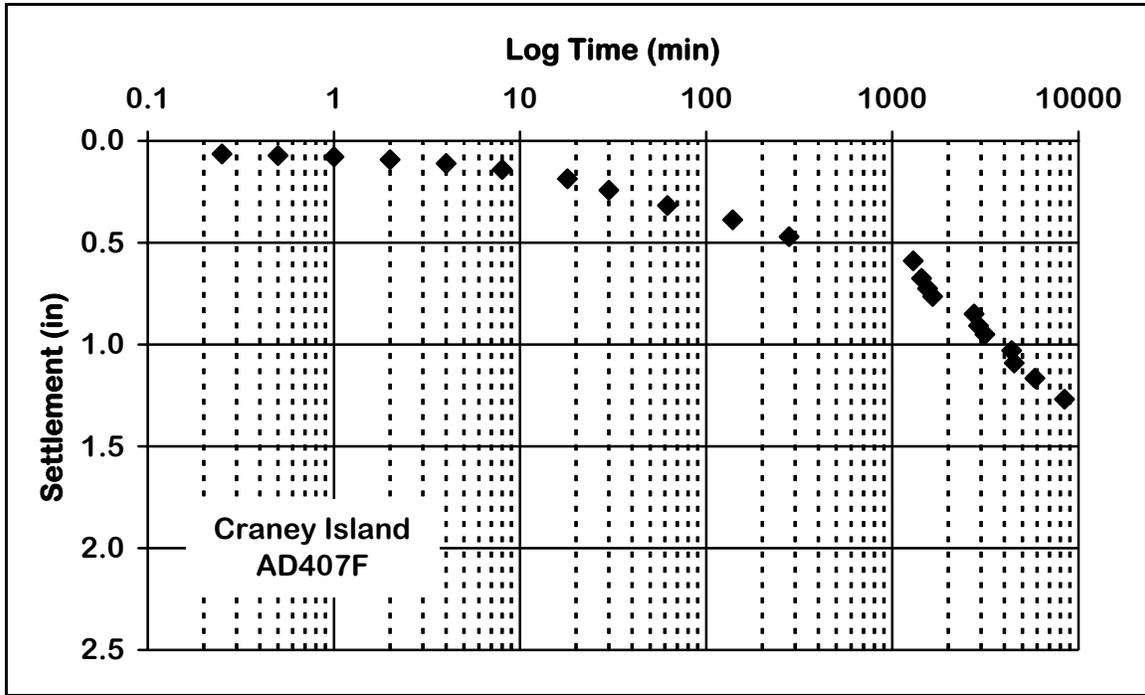


Figure 33. Consolidation Test Results for AD407F in Craney Island Soil.

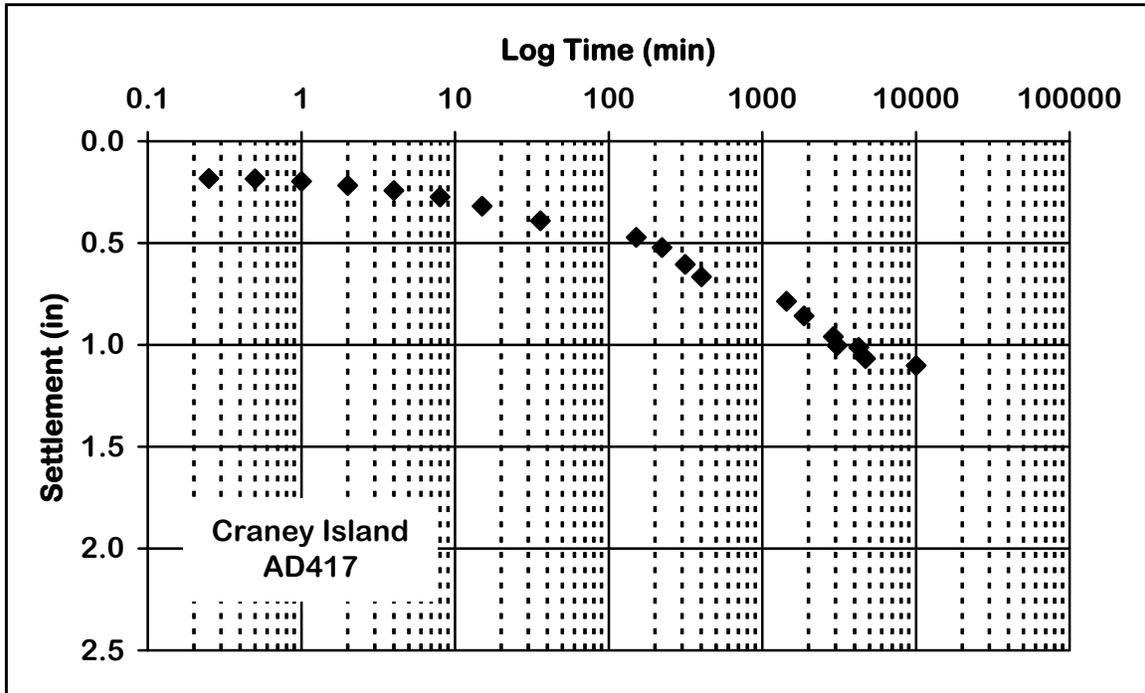


Figure 34. Consolidation Test Results for AD417 in Craney Island Soil.

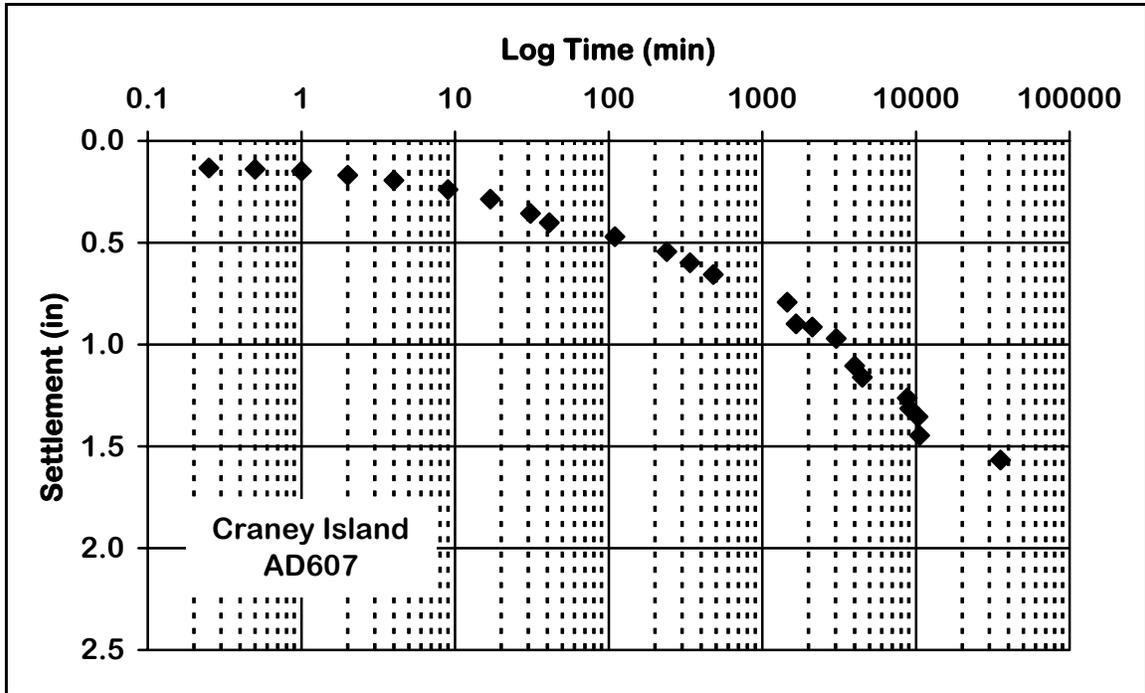


Figure 35. Consolidation Test Results for AD607 in Craney Island Soil.

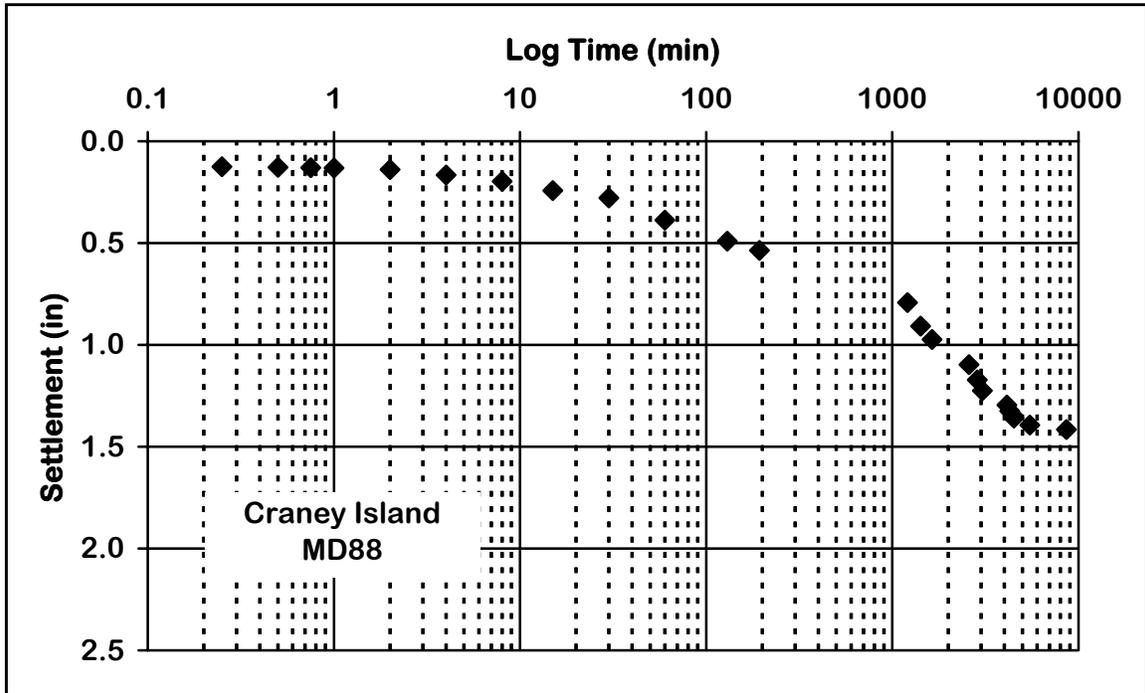


Figure 36. Consolidation Test Results for MD88 in Craney Island Soil.

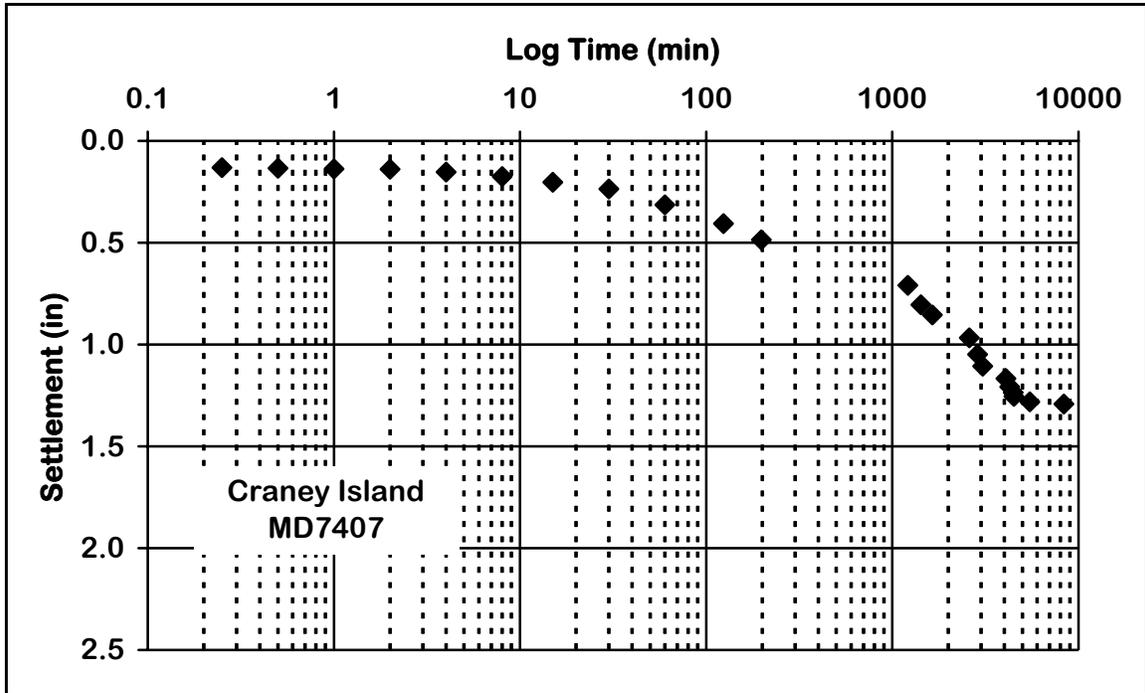


Figure 37. Consolidation Test Results for MD7407 in Craney Island Soil.

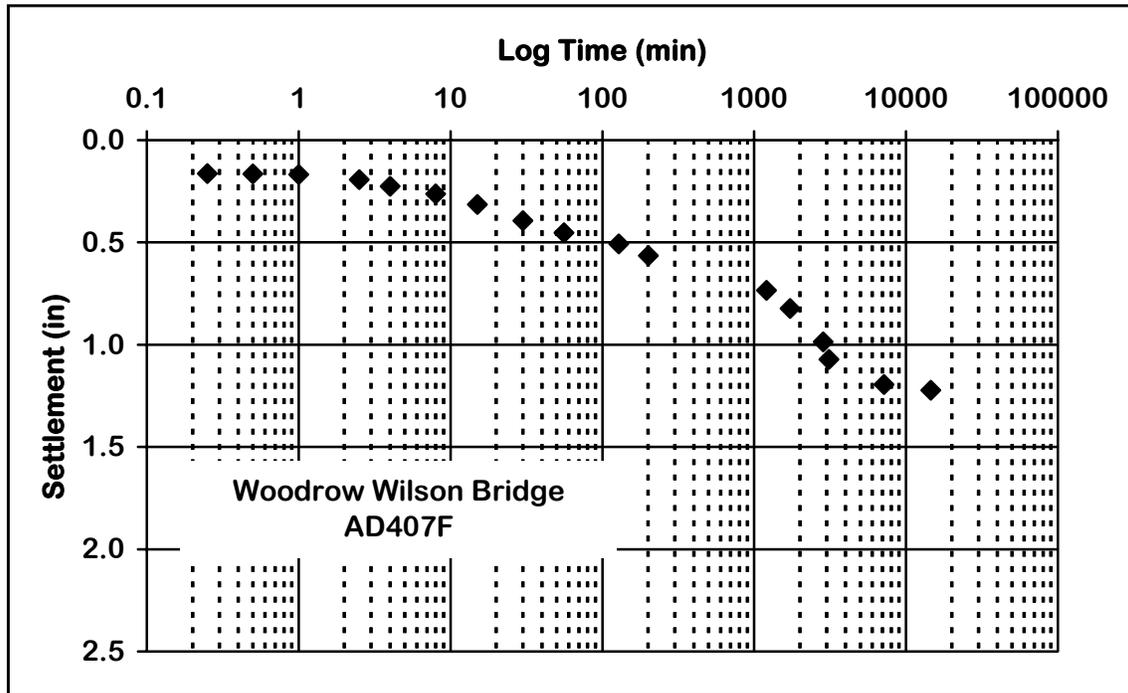


Figure 38. Consolidation Test Results for AD407F in Woodrow Wilson Bridge Soil.

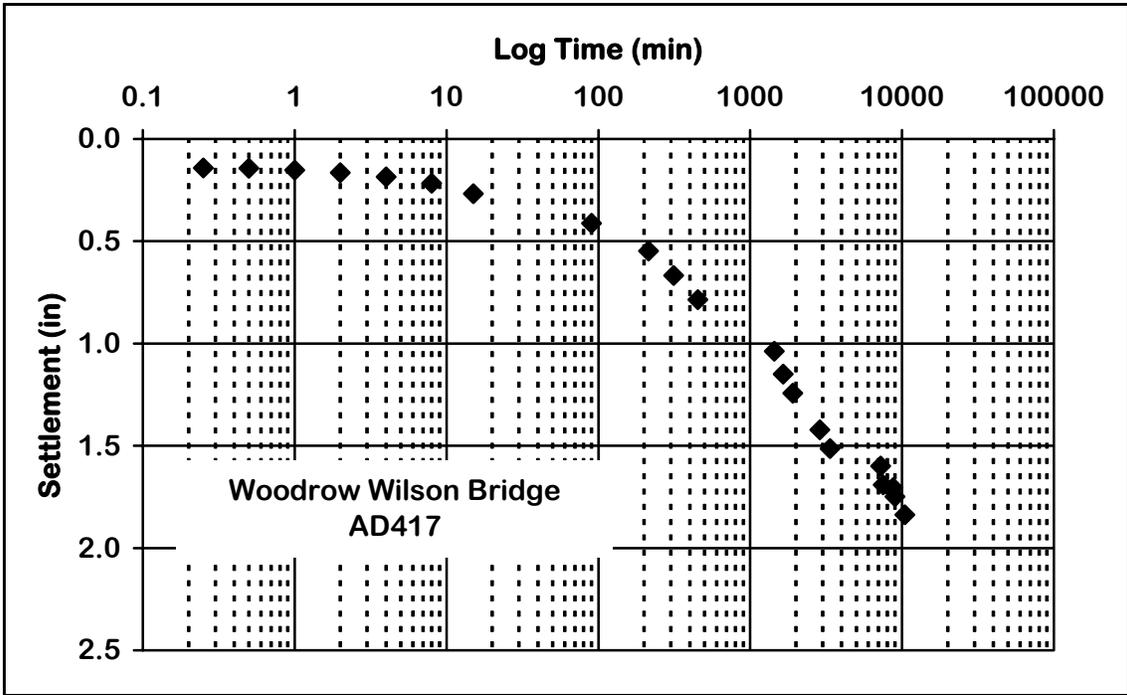


Figure 39. Consolidation Test Results for AD417 in Woodrow Wilson Bridge Soil.

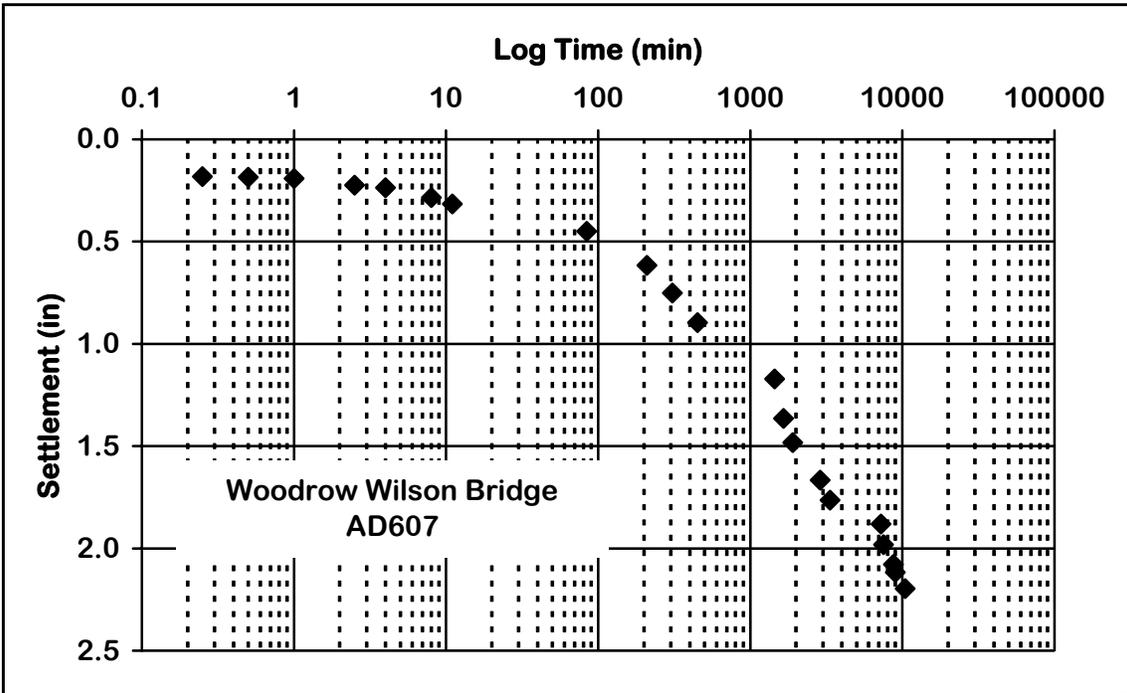


Figure 40. Consolidation Test Results for AD607 in Woodrow Wilson Bridge Soil.

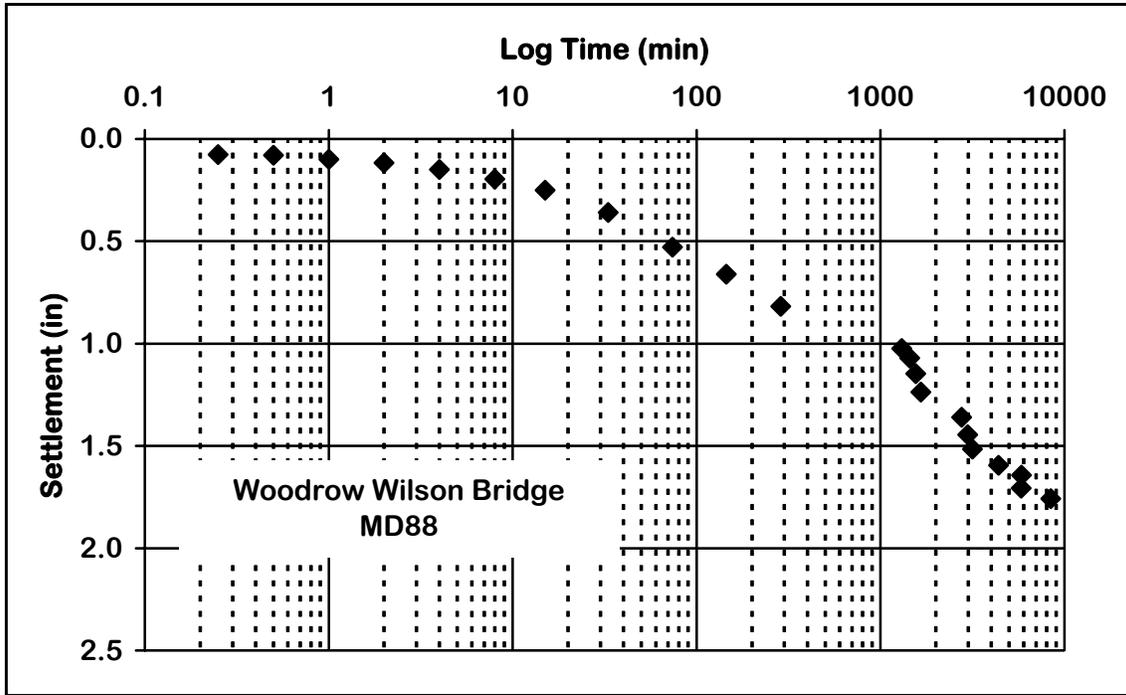


Figure 41. Consolidation Test Results for MD88 in Woodrow Wilson Bridge Soil.

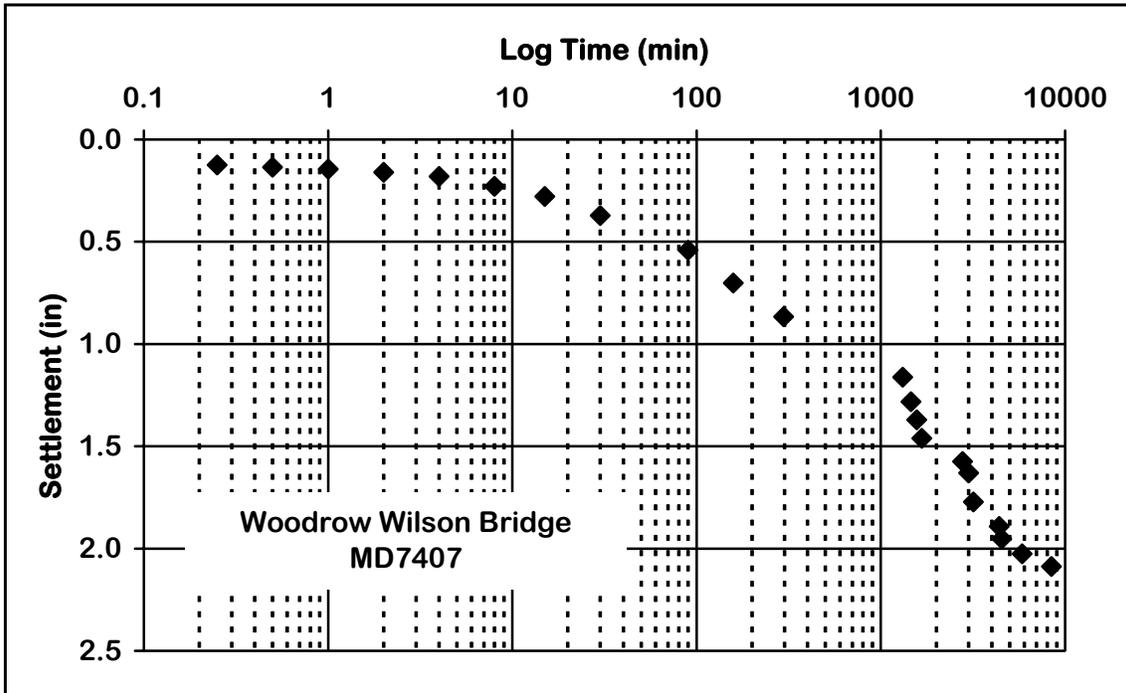


Figure 42. Consolidation Test Results for MD7407 in Woodrow Wilson Bridge Soil.

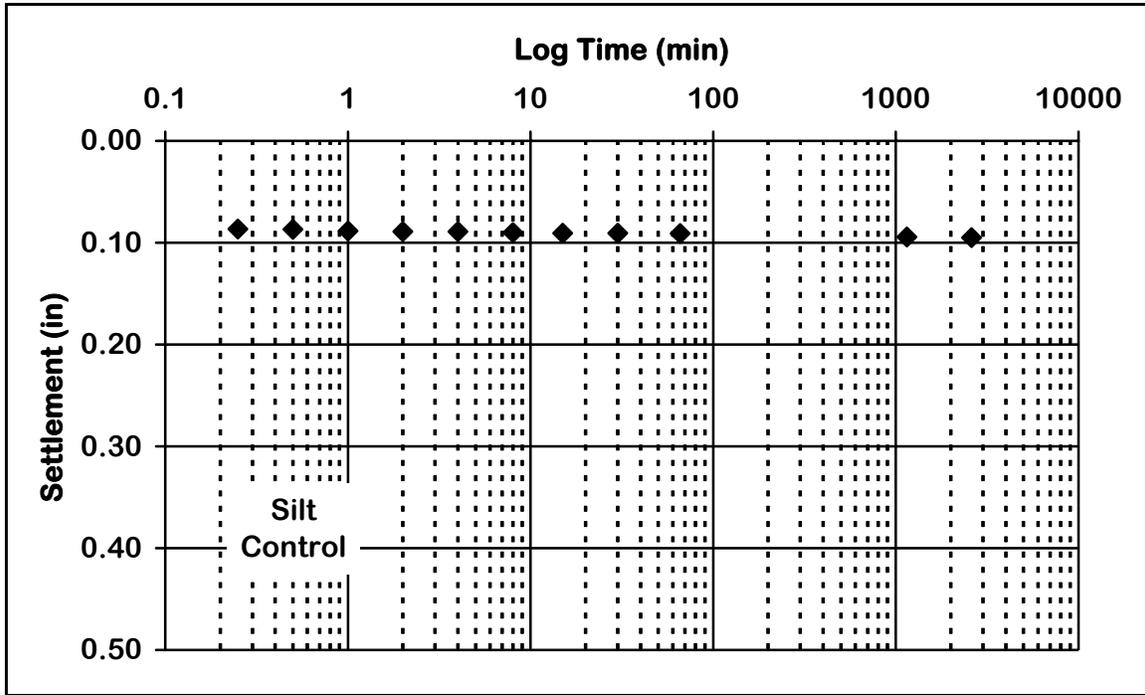


Figure 43. Consolidation Test Results for the Control Test in Silt.

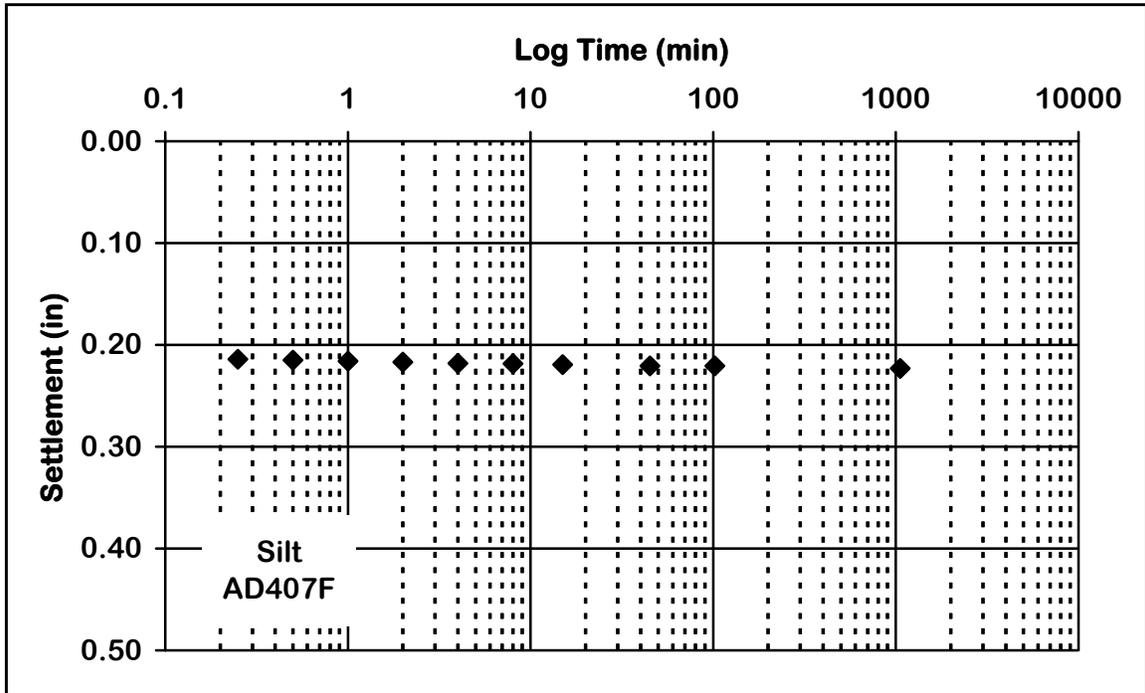


Figure 44. Consolidation Test Results for AD407F in Silt.

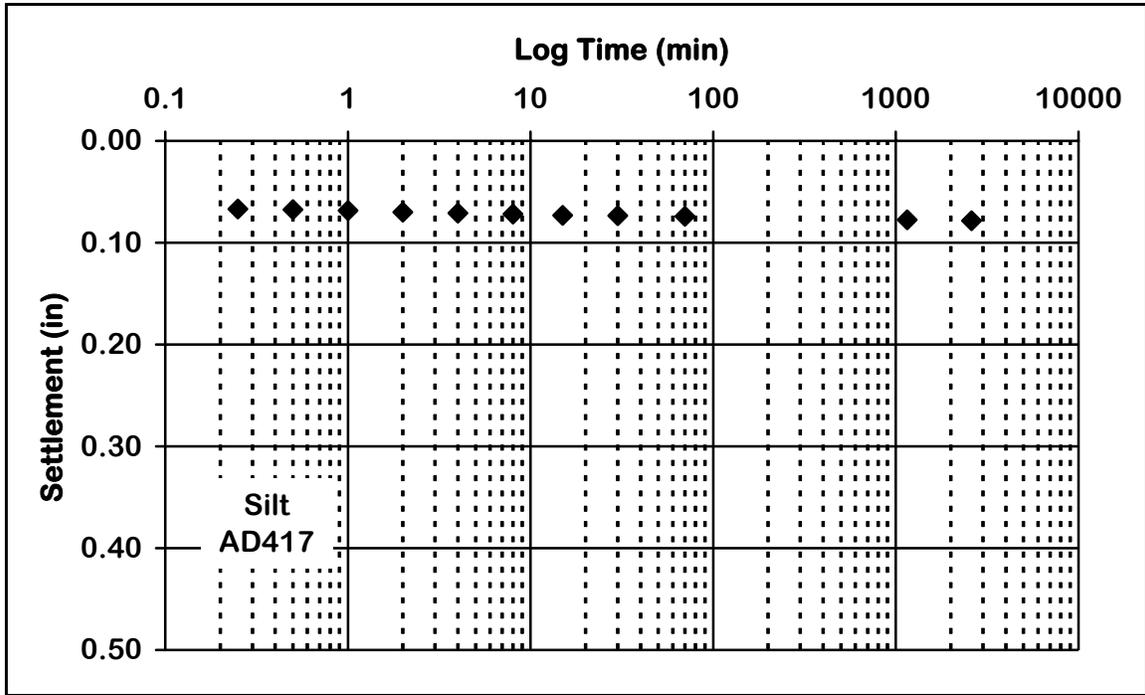


Figure 45. Consolidation Test Results for AD417 in Silt.

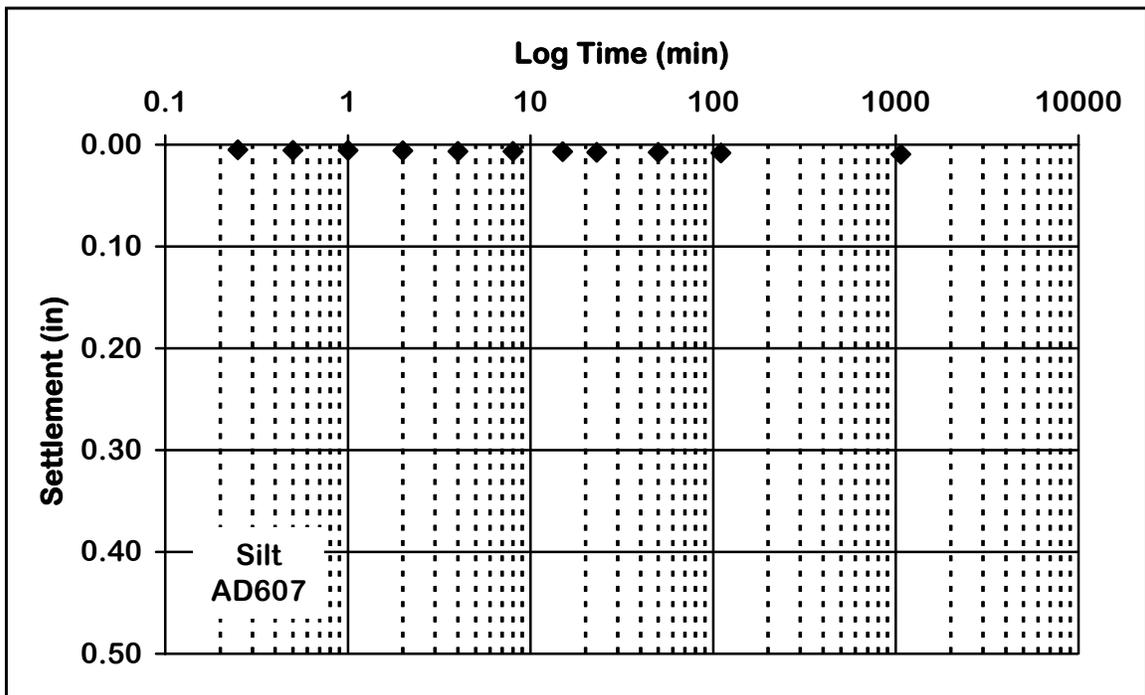


Figure 46. Consolidation Test Results for AD607 in Silt.

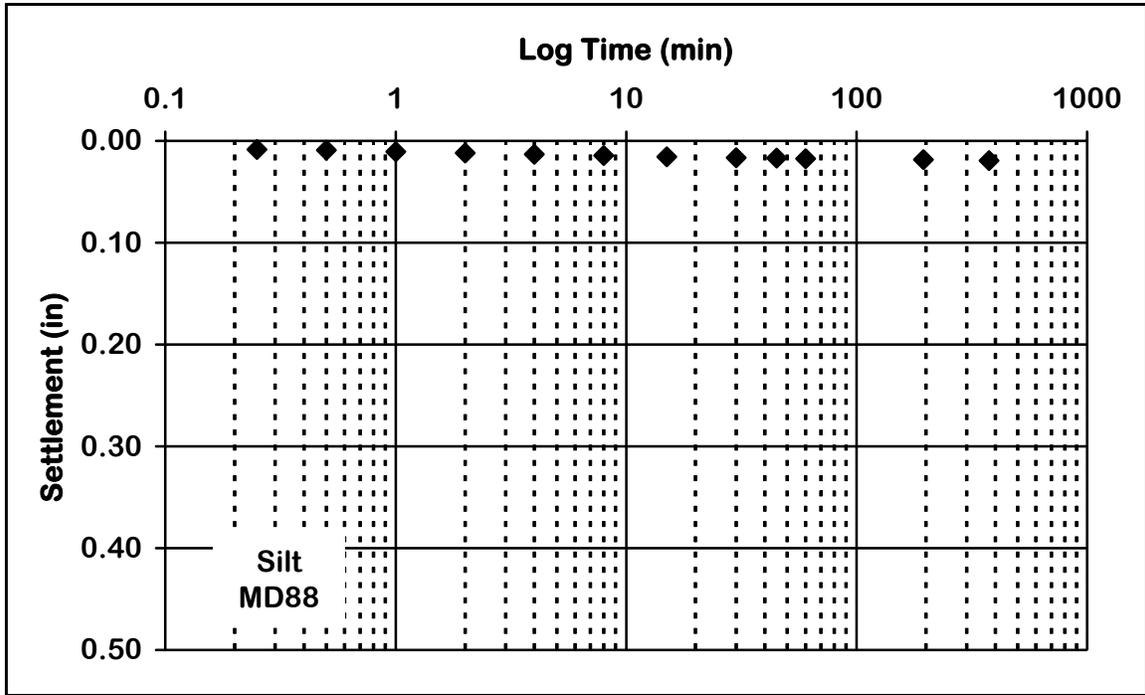


Figure 47. Consolidation Test Results for MD88 in Silt.

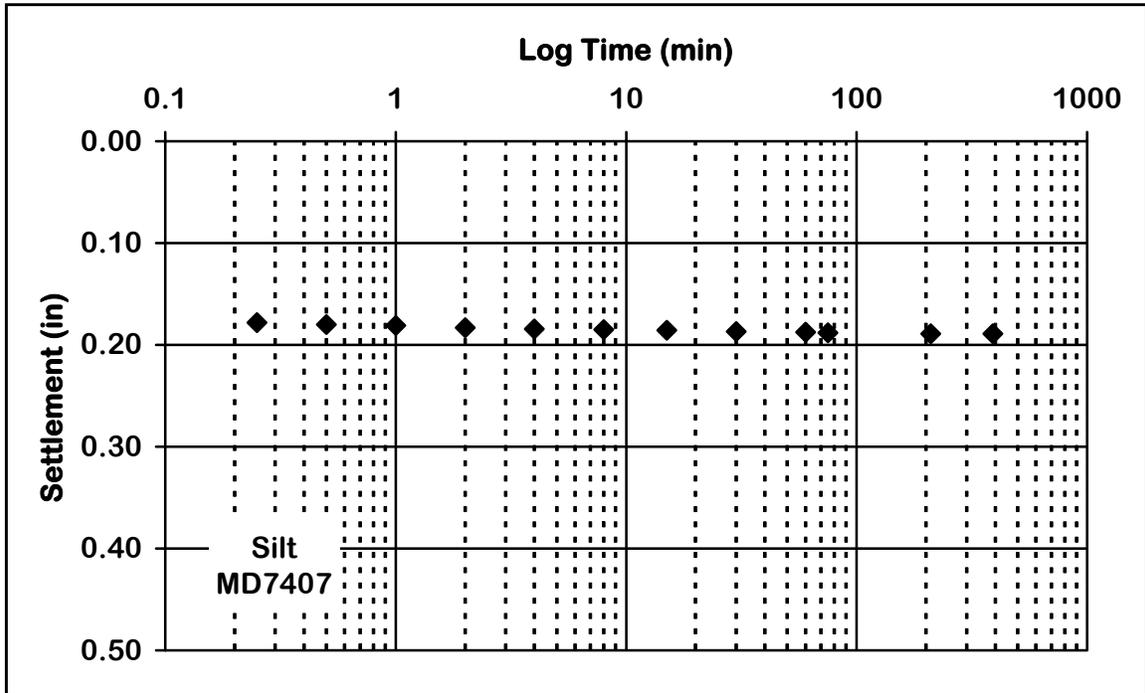


Figure 48. Consolidation Test Results for MD7407 in Silt.

In order to compare the different clays and each PVD tested, the value of  $t_{90}$  for each test in the clay soil was calculated using the square root of time method. While  $t_{90}$  is defined for the case of vertical drainage, the graphical construction technique provided a useful method to compare the different tests performed. At the applied stress of 145 kPa (21 psi), the control tests had  $t_{90}$  values of 1.0 day for the Craney Island soil and 0.9 days for the West Point and Woodrow Wilson Bridge soils (Table 6 and Figure 49). The presence of the PVDs in the soil consistently reduced the value of  $t_{90}$  to between 7% and 20% of the  $t_{90}$  values determined in the control tests. However, one out of fifteen of the tests had a  $t_{90}$  value of less than 5% of its control, while three of the fifteen tests had  $t_{90}$  values between 30% and 41% of the control values. Amerdrain 407F and 607 consistently provided the lowest  $t_{90}$  values, while the Mebra-Drain MD-7407 provided the highest values of  $t_{90}$ , even with the exceptionally low value measured for the MD-7407 in the West Point soil (Table 7 and Figure 50). Mebra-Drain MD-88 reduced the average  $t_{90}$  value to 17% that of the control, with a low standard deviation. Amerdrain AD417 demonstrated a similar average reduction when compared to the control (19%); however, the standard deviation for that drain was large.

**Table 6.  $t_{90}$  Values Determined for Each Consolidation Test**

Soil	Drain	$t_{90}$ (days)	$t_{90}/\text{Control } t_{90}$ (%)
Craney Island	Control	1.0	n/a
West Point	Control	0.90	n/a
Woodrow Wilson	Control	0.90	n/a
Craney Island	MD88	0.18	18
West Point	MD88	0.12	13
Woodrow Wilson	MD88	0.18	20
Craney Island	MD7407	0.31	31
West Point	MD7407	0.01	1
Woodrow Wilson	MD7407	0.37	41
Craney Island	AD407F	0.11	11
West Point	AD407F	0.13	14
Woodrow Wilson	AD407F	0.06	7
Craney Island	AD417	0.07	7
West Point	AD417	0.28	31
Woodrow Wilson	AD417	0.17	19
Craney Island	AD607	0.07	7
West Point	AD607	0.12	13
Woodrow Wilson	AD607	0.07	8

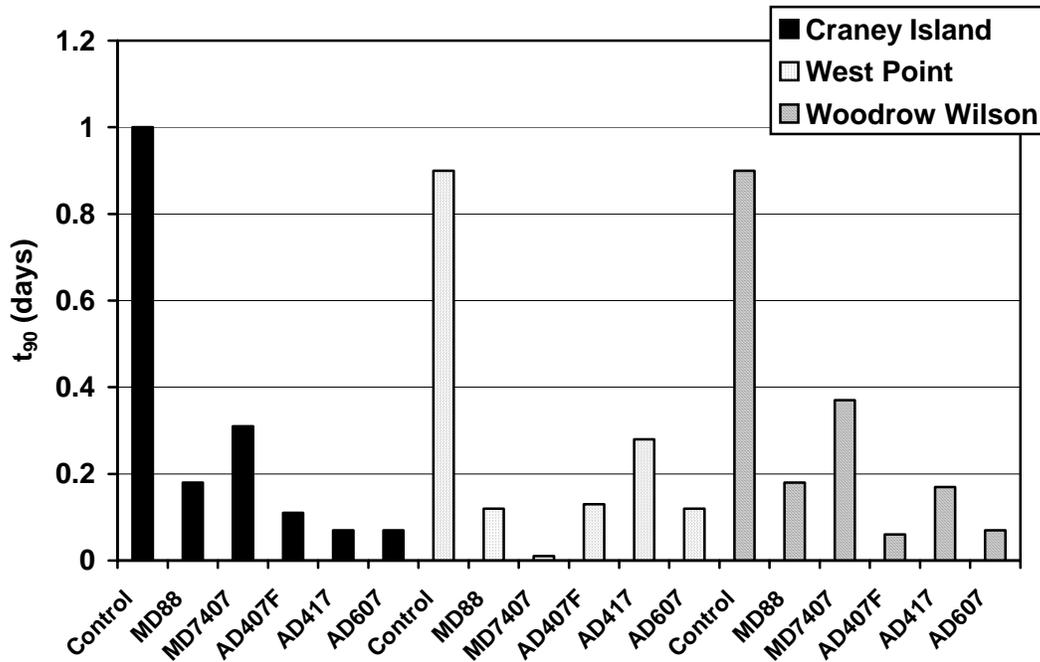
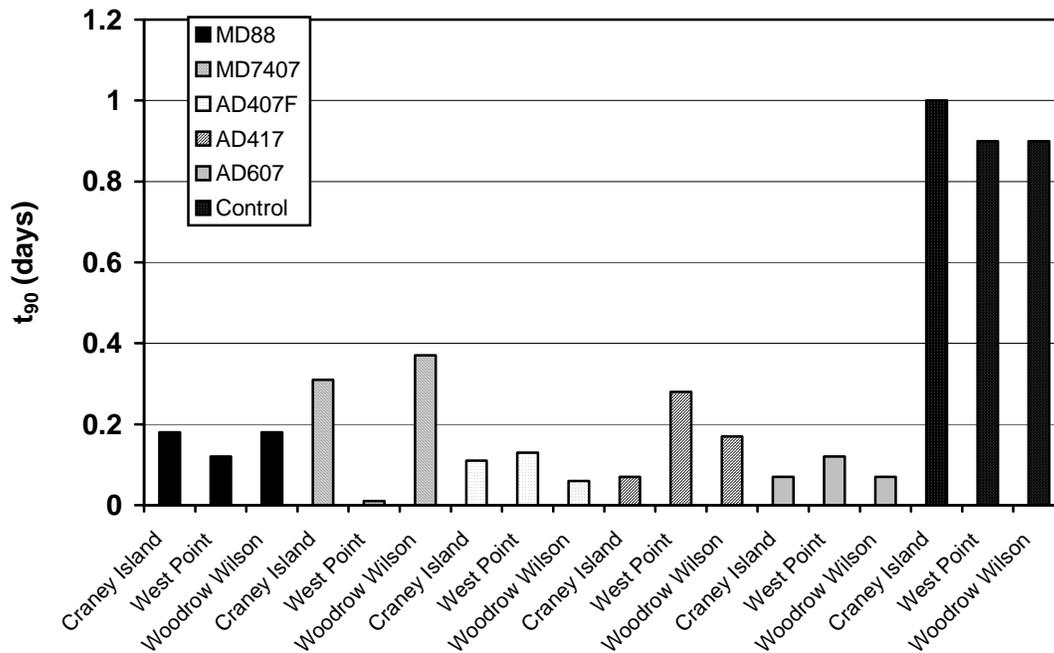


Figure 49.  $t_{90}$  Values by Soil Type.

Table 7. PVD Performance Data in Terms of  $t_{90}$

Drain	$t_{90}$ Average (days) (Standard Deviation)	Average $t_{90}$ in % of Control $t_{90}$ (Standard Deviation)
MD-88	0.16 (0.03)	17% (3%)
MD-7407	0.23 (0.19)	24% (21%)
AD407F	0.10 (0.04)	11% (4%)
AD417	0.17 (0.11)	19% (12%)
AD607	0.09 (0.03)	9% (3%)



**Figure 50.  $t_{90}$  Values by PVD Type.**

In summary, Amerdrain 407F and 607 produced the most consistent and the lowest values of  $t_{90}$  (averages of 11% and 9% of the control values, respectively); Mebra-Drain MD-88 and Amerdrain AD417 produced intermediate values (averages of 17% and 19% of the control values, respectively); and the Mebra-Drain MD-7407 produced the highest value of  $t_{90}$ , at an average of 24% of its control test value.

## DISCUSSION

### *Crimp Testing*

Significant differences in performance of the PVDs were quantifiable in the 90° crimp tests. In the uncrimped position, the flowrates through the drains were highest for the Mebra-Drain MD-88 and MD-7407 and were lowest for the AD407 and AD407F drains. However, the AD607 and MD-88 drains experienced a lower reduction in flowrate in the crimped position when compared to the other four drains, which resulted in AD607 and MD-88 having the highest flowrates through the drains in the crimped position. Additionally, the drain with the lowest flowrate in the uncrimped position (AD407F) also had the greatest percentage reduction and lowest flowrate in the crimped position.

The superior performance of AD607 and MD-88 in the crimp tests can be attributed to their construction. AD607 is constructed with the same corrugated core as AD407, AD407F, and AD417; however, it is made with a high-strength fabric filter jacket. It is believed that the high-strength fabric prevented jacket intrusion into the channels of the drain, which provided a larger volume for flow through the drain. In contrast, the drains constructed with the low-strength fabric did not have as large a volume available for fluid flow because the jackets intruded into the drain channels, which resulted in a lower flowrate in the crimped position. For the MD-88 drain, the core was constructed as a series of fins with distinct channels between them. This core configuration was very durable during testing and strongly resisted deformation. While the corrugated and dimpled cores deformed relatively easily, the fin configuration was difficult to bend. This resulted in less deformation of the flow channels and maintained flow volume better than other core configurations. Ali (1991) noted that the dimpled, or studded, cores on the drains were able to punch through the filter fabric in some instances, which significantly reduced flow through the drain; however, this was not observed during the crimp testing performed here.

### *Lateral Pressure Testing*

The lateral pressure tests demonstrated few differences between drain type or soil type, except in the case of AD417, the dimpled core drain. In all four test soils, AD417 exhibited a substantial decline in flow capacity as the lateral pressure was increased to 276 kPa (40 psi). The flowrate through AD417 declined to between 25% and 50% of the flowrate measured at zero applied lateral stress. The other five drains tested (AD407, AD407F, AD607, MD-88, and MD-7407) showed no dependence on lateral stress applied or on type of confining soil up to a stress of 276 kPa (40 psi). This finding is not consistent with previous studies (Ali, 1991; Bergado et al., 1996), which found decreasing flow capacity through all drains as lateral pressure was increased. The specific reasons for these differences are not known, although differences in testing methods and PVDs may account for the variations. In the present study, soils were compacted around the drains, which may have forced intrusion of the filter jacket into the drain channels, before lateral stress was applied, in a way that was not observed in other studies.

### *Consolidation Testing*

The relationship between the average degree of consolidation under equal vertical strain and the time factor for radial flow is given in Equations 1 through 5 (Holtz et al., 1991):

$$U_h = 1 - \exp\left[\frac{-8T_h}{F(n)}\right] \quad \text{Equation 1}$$

$$T_h = \frac{c_h t}{d_e^2} \quad \text{Equation 2}$$

$$F(n) = \frac{n^2}{(n^2 - 1)} \cdot \ln(n) - \frac{3n^2 - 1}{4n^2} \quad \text{Equation 3}$$

$$n = \frac{d_e}{d_w} \quad \text{Equation 4}$$

$$d_w = \frac{2(a + b)}{\pi} \quad \text{Equation 5}$$

where  $U_h$  = average degree of consolidation,  $T_h$  = time factor,  $n$  = drain spacing ratio,  $d_e$  = diameter of PVD drainage influence area,  $d_w$  = band-shaped drain equivalent diameter,  $a$  = drain width, and  $b$  = drain thickness. This analysis assumes that the PVDs function as ideal drains, with no smear or well resistance during drainage. Based on this assumption, the consolidation characteristics should be consistent within a given soil type and should vary only with the horizontal coefficient of consolidation of the soil  $c_h$ . For the most part in these experiments, the PVDs performed similarly in the different clay soils (Figure 50). With the exception of Mebra-Drain MD-7407, the standard deviations on the reduction in  $t_{90}$  when compared to the control  $t_{90}$  were quite low. The performance of the Mebra-Drain MD-7407 was strongly affected by anomalous performance in the West Point soil, which demonstrated a significantly lower value of  $t_{90}$  than observed for other soils or drains. It is believed that this data point is unrepresentative and should be ignored for analysis purposes. Subsequently, the performance of the MD-7407 in the Craney Island and Woodrow Wilson soils was consistent but demonstrated a higher  $t_{90}$  than observed for other soils.

A summary of the performance of the PVDs is given in Table 8.

**Table 8. PVD Performance Summary in Virginia Soils**

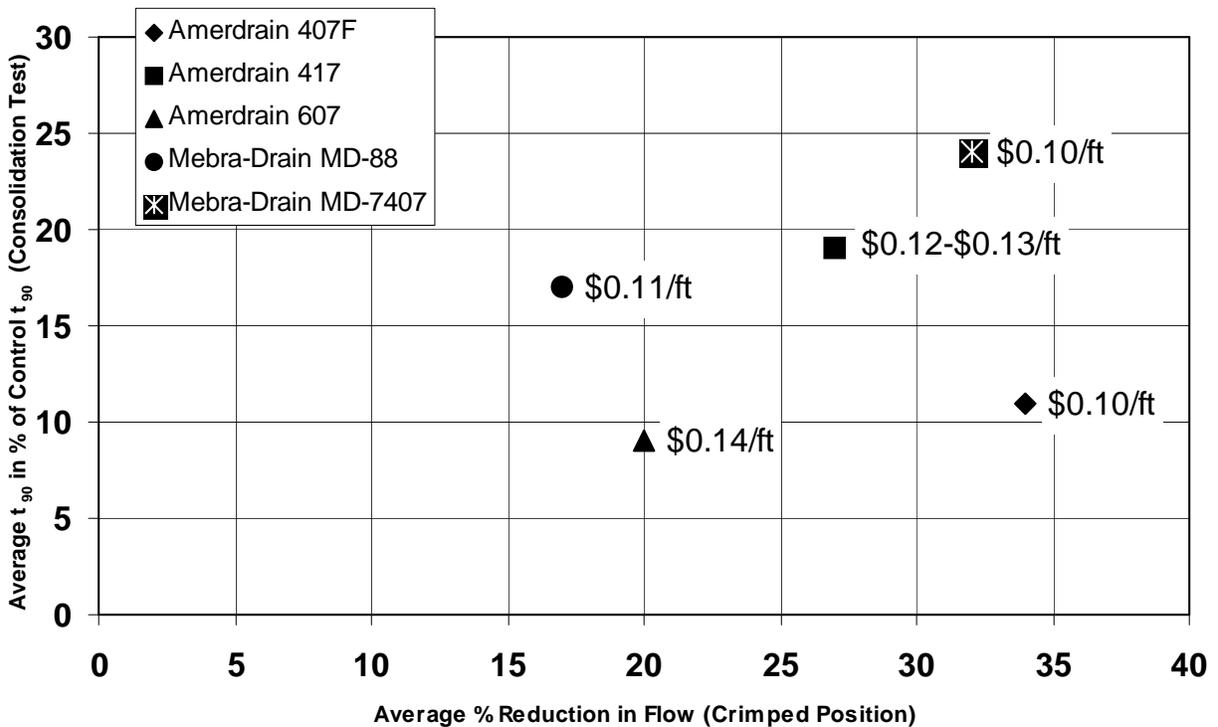
Test	Best performance	Worst performance
<b>Crimp</b>	AD607 (\$0.14)	AD407F (\$0.10)
	MD-88 (\$0.11)	
<b>Lateral Pressure</b>	AD407 (\$0.10)	AD417
	AD407F (\$0.10)	
	AD607 (\$0.14)	
	MD-88 (\$0.11)	
	MD-7407 (\$0.10)	
<b>Consolidation</b>	AD407F (\$0.10)	MD-7407 (\$0.10)
	AD607 (\$0.14)	

All costs are quoted for 2003.

## CONCLUSIONS AND RECOMMENDATIONS

Significant differences in performance of the prefabricated vertical drains were quantified in this study (see Figure 51). Performance was quantified based on the % reduction in flow capacity during flow through the drains in a crimped position, % reduction in flow capacity under lateral stress, and % reduction in the measured  $t_{90}$  value compared to  $t_{90}$  for a control test.

Based on the results of the laboratory tests performed here, the Amerdrain AD607 consistently exhibited superior performance when compared to other drains through the largest average reduction in  $t_{90}$  ( $t_{90}$  with the drain  $\approx 9\%$   $t_{90}$  of control) during consolidation testing and through one of the lowest reductions in flow capacity in the crimp test (20%). However, the Mebra-Drain MD-88 also performed well with the least reduction in flow capacity in the crimp test (17%), and with good performance in the consolidation tests ( $t_{90}$  with the drain  $\approx 17\%$   $t_{90}$  of control). It is important to note that the year 2003 cost per foot of AD607 is \$0.14 compared to \$0.11 for the MD-88, a price difference that could be significant on a large-scale project. The remaining drains (AD407, AD407F, AD417, and MD-7407) demonstrated varying levels of performance in these index tests, which might eliminate them from consideration in a field application. Of most concern was the significant effect of lateral pressure on AD417, although this did not translate into significantly reduced performance in the consolidation test. From a purely cost basis, the Mebra-Drain MD-88 yielded the best results, giving superior performance in two out of three tests and having one of the lowest year 2003 costs per foot (\$0.11) of the drains tested.



**Figure 51. Overall Performance of PVDs as a Function of Test Conditions.**

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