Williams. It is also based on part of a Ph.D. thesis submitted to the University of the Witwatersrand, Johannesburg, under the supervision of H. H. Weinert and A. B. A. Brink. Most of the soil testing was carried out by D. Ventura and the late T. E. O'Connor. The Geological Survey kindly carried out most of the determinations of CO_2, FeO, and organic carbon, and P. Paige-Green assisted with most of the X-ray diffraction analyses.

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Publication of this paper sponsored by Committee on Soil and Rock Properties.

Laboratory Evaluation of Materials and Design Characteristics of PennDOT Underdrain System

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Results of an investigation of the adequacy of Pennsylvania's current design for highway underdrains and of specific materials used in that design are reported. Fine aggregate filter media, types A and B, were examined for their functional capabilities under relatively low hydraulic pressure gradients. Woven and nonwoven synthetic fabrics were investigated to determine the feasibility of using them as a filter medium in the underdrain system. Perforated underdrain pipe was investigated to determine the minimum cross-sectional area of perforation and minimum cross-sectional area of pipe to allow adequate outflow of anticipated inflow. Filter fabric materials appear to have a practical use in drainage systems. Recommendations include (a) further testing to evaluate the optimal combination of filterability versus permeability, the long-range effects on the permeability of filter fabric of contact with fine silt subgrade soils, and the most practical and effective installation procedures; (b) a minimum perforation area and a minimum pipe diameter; and (c) further investigation into changing subbase gradation specifications to make the material more permeable and eliminating fine aggregate backfill as a filter medium where heads of <0.3 m (<1 ft) are anticipated.

Many kilometers of Pennsylvania's highway drainage systems are being replaced annually because of premature failure, and the functional condition of much of the length of similar systems remains questionable. As a result, some aspects of the Pennsylvania Department of Transportation (PennDOT) highway drainage system design have already been revised. The addition or revision of other system characteristics is still under consideration. An in-house laboratory testing program was initiated by the Bureau of Materials, Testing, and Research to accumulate data that would influence these design change decisions. This report summarizes the data and conclusions that evolved from the testing program.

OBJECTIVE

The objective of this testing program was to evaluate the adequacy of the Pennsylvania highway drainage system design and of specified materials used in it. The following lists of system components were evaluated in the program to achieve this objective: (a) typical subbase material and fine aggregate backfill media, (b) woven and nonwoven synthetic filter fabrics, (c) ranges of typical quantities of trench infiltration, (d) capacities of drainage pipe products, and (e) tests of a full-scale model of an underdrain trench section.

Fine aggregate gradations were investigated to determine the adequacy of these materials as filter media. Types A and B gradation "bands," currently specified in PennDOT 408, were tested and are shown in Figure 1. Type A material is a well or nonuniformly graded coarse to fine sand; type B material is a nonuniformly graded sand with up to 15 percent silt. The permeabilities, stabilities, and functional capabilities under relative low pressure gradients of both types A and B fine aggregates were scrutinized. Tests were also done on typical subbase gradations (Figure 2) to determine the range of anticipated permeabilities.

Woven and nonwoven synthetic fabrics were evaluated to determine the feasibility of using them as a filter medium in the underdrain system. Both initial and short-term permeability characteristics were considered. The reduction in filter material permeabilities resulting from fabric "clogging" was used as an indicator of filterability.

Theoretical calculations were made by using anticipated field hydraulic conditions to predict ranges of typical trench infiltration. These infiltration quantities were used along with laboratory testing of infiltration and exfiltration rates of the pipes to establish pipe product specifications. Tests on perforated underdrain pipe were made to determine the minimum total intake area of perforations and the minimum pipe cross-sectional area to allow outflow of anticipated total inflow.

TEST PROCEDURES

Initially, tests on both types A and B fine aggregate backfill media were performed to compare the permeability and stability of typical stockpile samples. The fine aggregates were placed in molds at 95 percent of their maximum density (AASHTO T-99) and between layers of 1B crushed limestone on the top and bottom to simulate a "double filter" situation. Figure 3 shows the specified gradation band for 1B crushed limestone. Compaction was obtained with standard drop-hammer equipment. Fluctuations in permeability rates were monitored over a 2- to 3-d period of continuous flow. The degree of migration of fines through the filter medium was determined by obtaining initial particle-size distribution curves and comparing them with the particle-size distribution curves of material taken from the top, middle, and bottom layers of the sample after permeability testing was completed. Samples of the outflow water were also collected to compare the relative amounts of suspended soil that were carried through the fine aggregate filter.

Tests on the fine aggregates were made with a standard constant-head [112 cm (44 in)] permeability apparatus (AASHTO T-215) and in a "large" permeameter cell that was adapted to existing equipment in the foundation laboratory. These apparatuses are shown in Figures 4 and 5. The large cell was 45.7 cm (18

Figure 1. Specified gradation bands for types A and B fine aggregates.

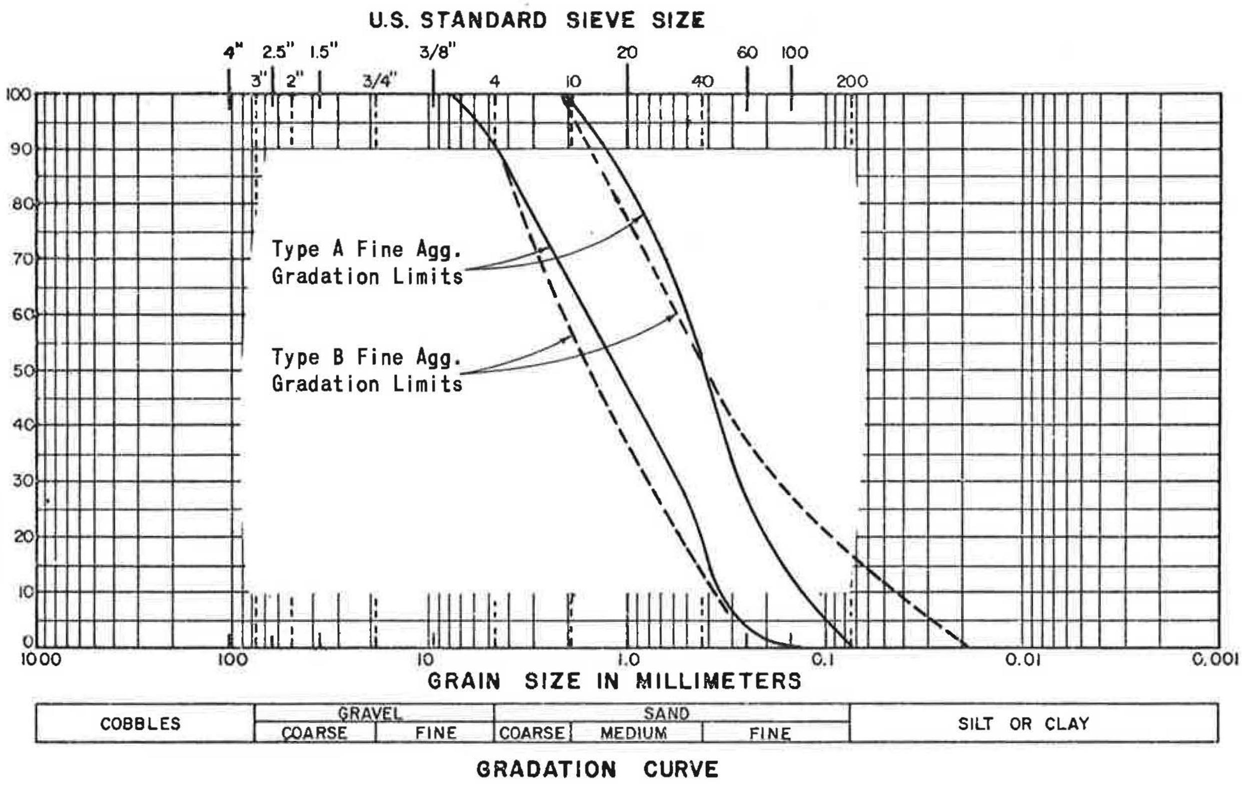


Figure 2. Specified gradation band for subbase material.

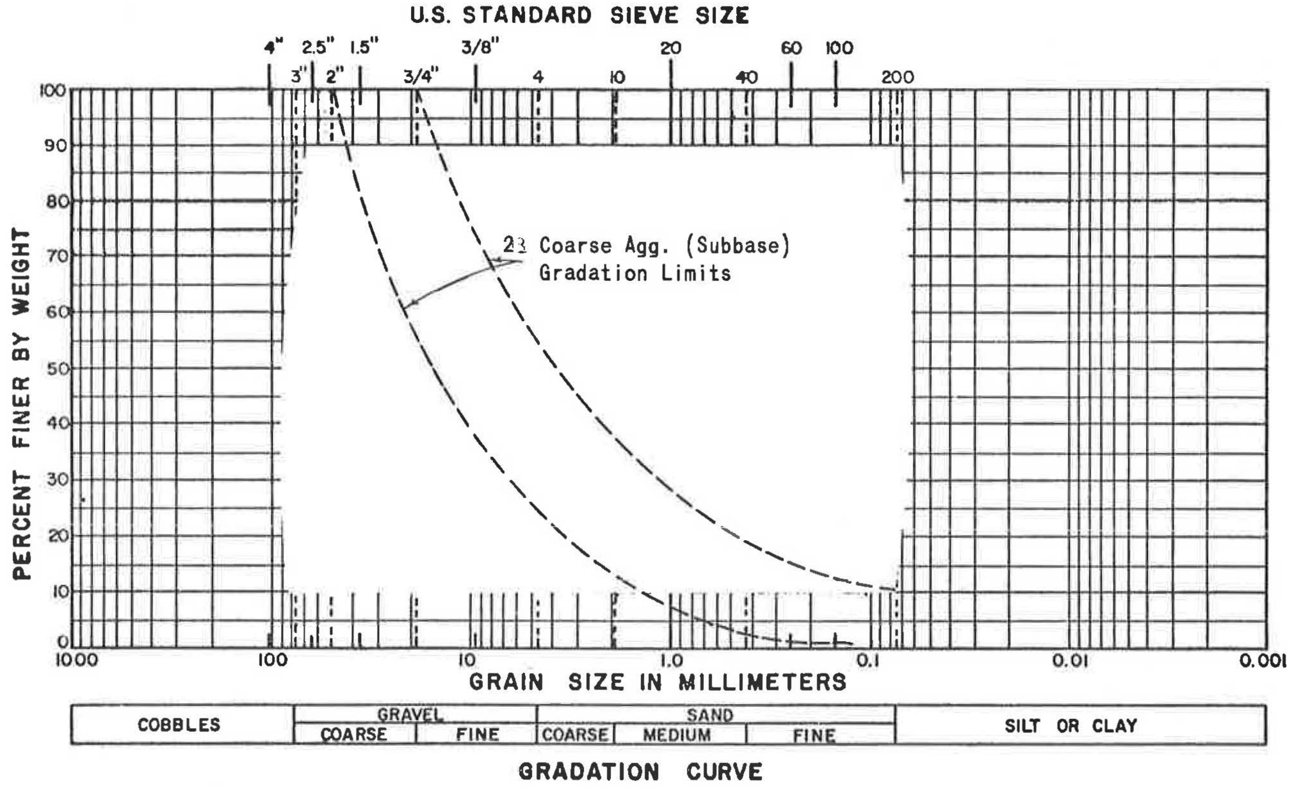
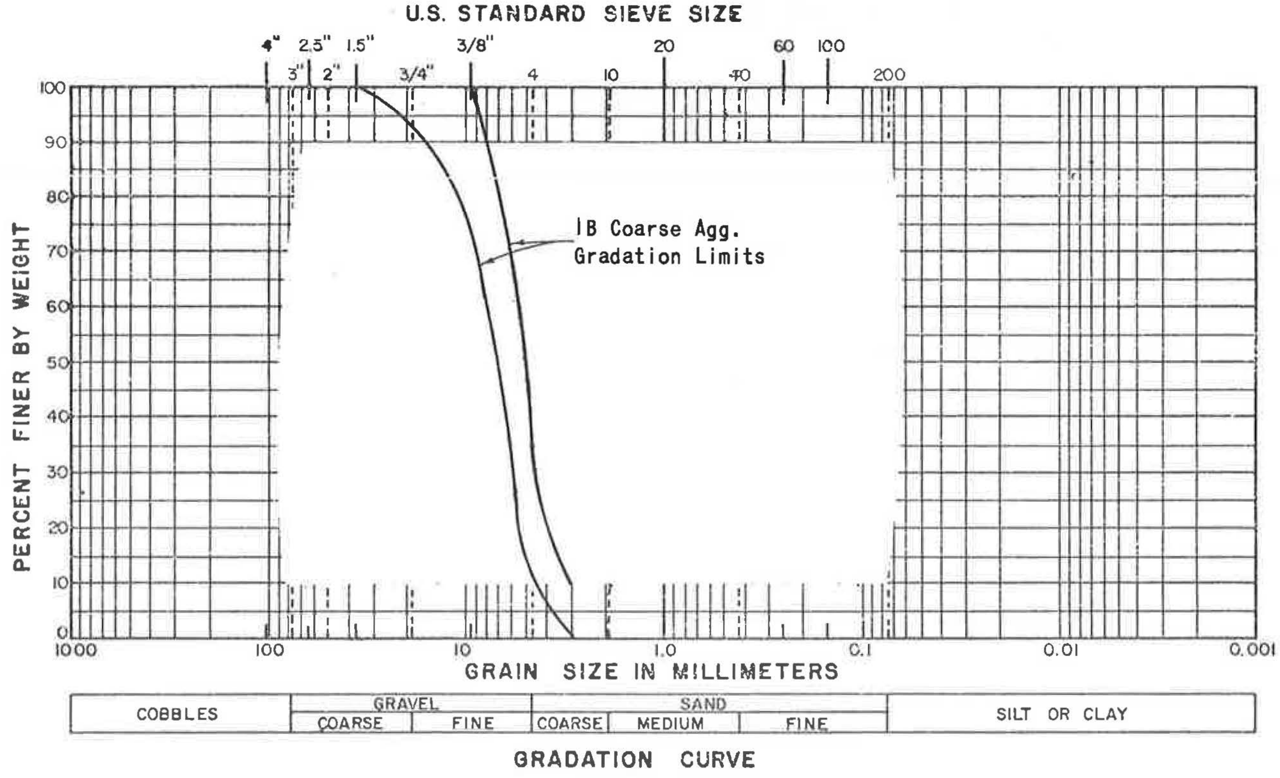


Figure 3. Specified gradation band for aggregate.



in) high and 15 cm (6 in) in diameter. The pneumatic pressure system used with the large cell was capable of applying pressure drops of from 0 to 690 kPa (0 to 100 lbf/in^2). A pressure differential, from top to bottom of the sample, of 13.8 kPa (2 lbf/in^2) was used in the permeability testing to provide approximately a 140-cm (55-in) pressure head. The use of this larger soil specimen had the advantage of averaging the effects of material nonhomogeneity.

Permeability tests on six different materials that met the subbase gradation specifications were also performed according to AASHTO T-215. These materials were blended in the laboratory to provide specific gradations that occurred at the extremes and the middle of the specified gradation band.

Next, four types of nonwoven and one woven synthetic filter fabric were tested to determine filterability and permeability characteristics. The five tested fabrics and their manufacturers are given in the following table:

Figure 4. Standard constant head permeability apparatus.

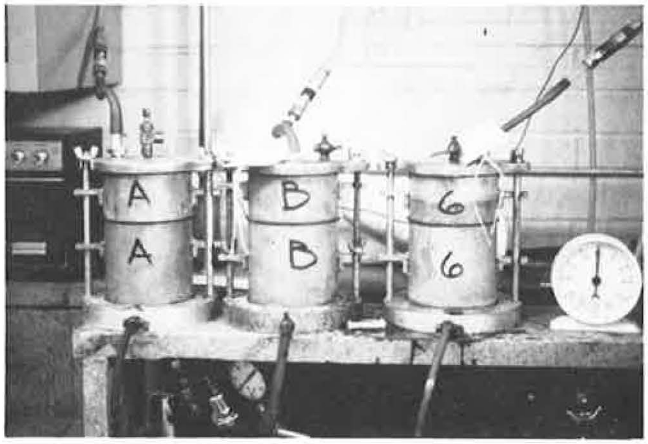
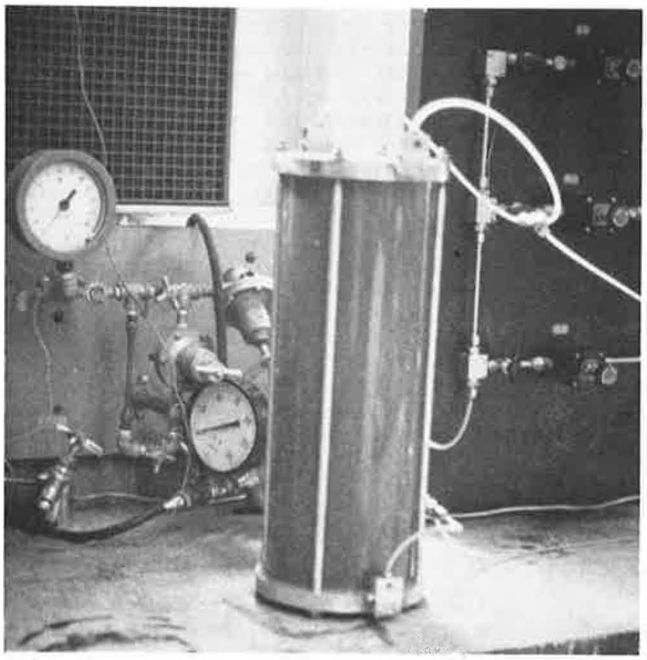


Figure 5. Large permeameter cell assembled in PennDOT laboratory.



Cloth Design	Trade Name	Manufacturer
A	Poly Filter X	Carthage Mills, Cincinnati, Ohio
B	Mirafi 140	Celanese Fiber Corporation, Charlotte, North Carolina
C	Bidim	Monsanto Textile, St. Louis, Missouri
D	Typar	Dupont Corporation, Wilmington, Delaware
E	Duon	Phillips Fiber Corporation, Greensville, South Carolina

Since the standard laboratory test equipment was incapable of measuring the high permeabilities of the cloths, a test apparatus fabricated by the Celanese Fiber Corporation (Figure 6) was used in determining the actual permeability rates of the cloths themselves. The actual head losses over multilayered fabric specimens were measured with manometers, and the fabric thicknesses were determined by a test procedure typically used in the garment industry (ASTM D 1777).

These five fabric types were also tested in combination with Ottawa sand, York Haven type A sand, and 1B crushed limestone in the standard constant-head permeameter (AASHTO T-215). A schematic of this test setup with the type A York Haven sand is shown in Figure 7. The filter cloths were tested with the Ottawa and York Haven sands under continuous flow for at least 2 d. The soiled cloths from the tests with the York Haven sand were then tested with the more permeable 1B crushed limestone aggregate. The permeabilities of these soiled cloths were then compared with the permeabilities of the clean cloths tested in

Figure 6. Filter fabric permeameter fabricated by Celanese Fiber Corporation.

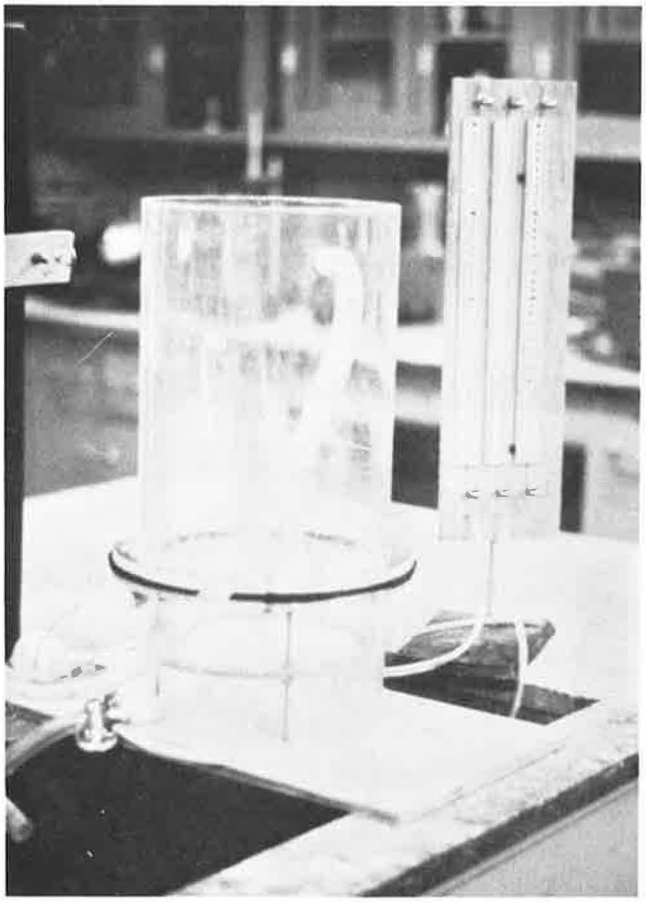


Figure 7. Standard permeameter test setup.

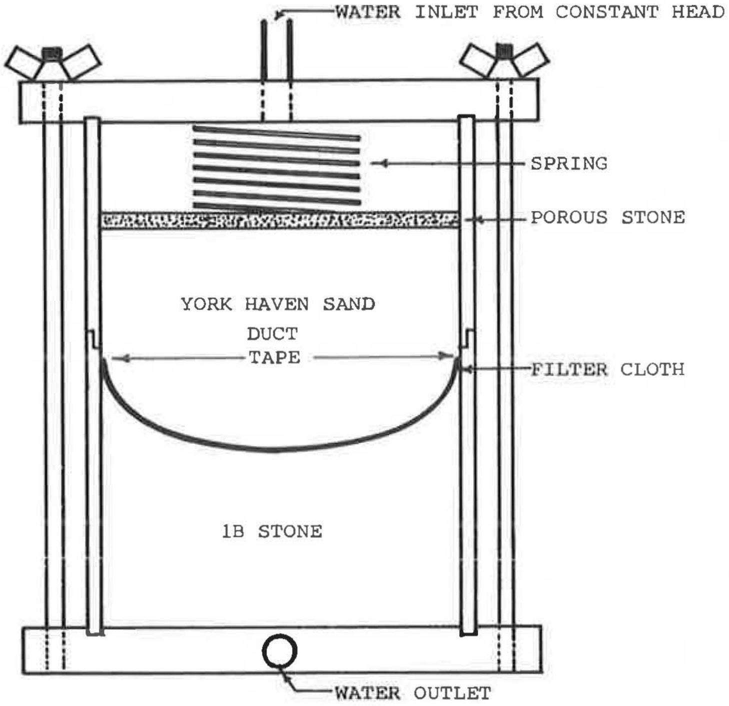
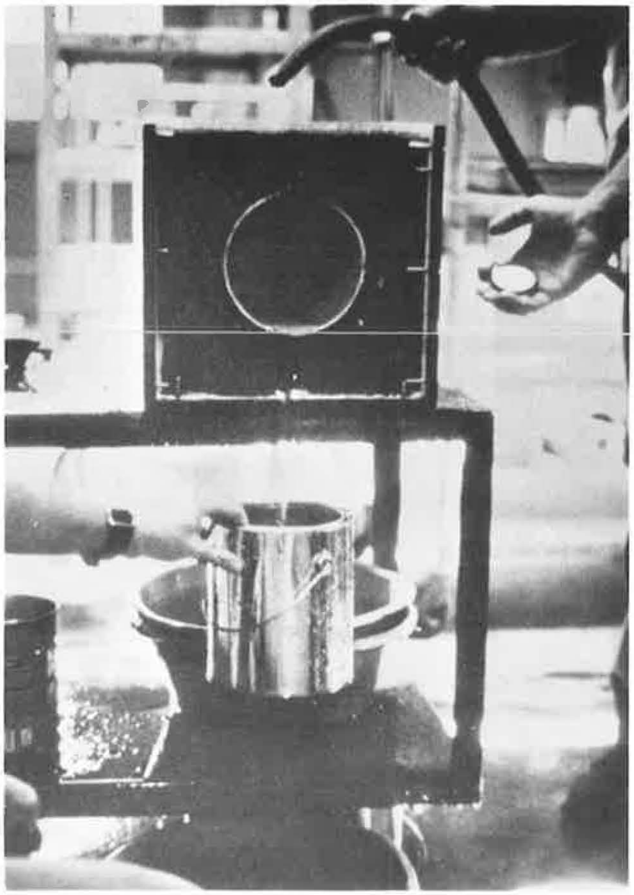


Figure 8. Testing with simulated trench section model fabricated in PennDOT laboratory.



Ottawa sand. The degree of reduction in permeability of the soiled cloths was considered to be an indication of the relative clogging and filterability characteristics.

A 0.3-m (1-ft) cube trench section (Figure 8) was constructed to obtain laboratory measurements of outflow capabilities of various underdrain systems. Pipe intake areas, types of filter cloths, and filter media were varied to observe the effects on the total outflow under a relatively small constant head. Circular plastic pipe 15 cm (6 in) in diameter that met the requirements of ASTM D 3033 was used in this test sequence. One set of data was obtained by using 0.45-cm (3/16-in) diameter perforations, and 0.95-cm (3/8-in) diameter perforations were used in a second data set. The test sequence included initial base (no fabrics) measurements for the plastic pipe with only 1B aggregate or type A fine aggregate backfill medium. The plastic pipe was next wrapped with the five different filter fabrics, and individual measurements were made with each of the fabrics in conjunction with 1B aggregate and type A fine aggregate backfill media. When the type A fine aggregate backfill was used in the system, the duration of the test was a minimum of 1 h so that the clogging tendency of each of the fabrics could be observed. After the tests in type A sand, the soiled filter fabrics were retested with 1B aggregate backfill to compare the changes in permeabilities between the "dirty" fabrics and the "clean" fabrics with the 1B aggregate. All tests in the trench section had an approximate 23-cm (9-in) head from the top of the section to the invert of the pipe. This small amount of hydraulic head is typical of the PennDOT pavement or base drain system where the bottom of the trench extends 30 cm (12 in) below the bottom of the subbase layer. Tests with this trench section showed that it was very difficult or impossible to establish flow through type B fine aggregate medium with this small hydraulic head.

RESULTS

Permeability test results for types A and B fine aggregate filter media are given in Table 1. The higher capabilities of the apparatuses themselves indicate that the apparatuses do not limit the permeability rates. These rates show no significant difference between permeabilities for types A and B fine aggregates under the substantial 112-cm (44-in) hydraulic head. Even though as much as 15 percent silt size particles are allowed by specification for the type B gradation, only 5 percent silt size particles existed in the two tested stockpile samples.

Significant migration of the coarse silt and fine sand fractions of both types A and B fine aggregates occurred during the 2-d continuous flow tests. As much as a 5 percent shift (by weight) of the particle-size distribution curve occurred in the direction of flow. Since a greater portion of type B gradation is in the coarse silt and fine sand range, greater percentages of shifts in the distribution curve were evident in the type B material.

Table 1. Permeability test results for types A and B fine aggregates.

Type of Fine Aggregate	Standard Constant Permeability[a] (cm/s)	Large Permeability[b] (cm/s)
Ottawa sand	0.002 5	0.0012
Type A sand		
Summit	0.000 16	0.0012
Hempt	0.001 7	0.0020
York Haven	0.001 2	0.0014
Type B sand		
Erie	0.000 94	0.0023
Edin	0.002 5	0.0012
Maximum equipment capability	0.025	0.010

Notes: 1 cm/s = 0.394 in/s.
See Figure 1 for gradation specifications. Permeability rates are average of a minimum of three tests.

[a] Constant pressure head = 112 cm (44 in).

[b] Constant pressure head = 140 cm (55 in).

Figures 9 and 10 show permeabilities for six laboratory-fabricated gradations of crushed limestone subbase aggregate. Five of these gradations fell within the specified gradation limits whereas sample 6 fell slightly above the fine end of the upper limit. The permeabilities ranged from approximately 0.000 01 cm/s (3.9 μin/s) at the lower limit to 0.0002 cm/s (0.000 08 in/s) at the upper limit. Sample 6, which fell outside the specified limits, had a permeability of 0.002 cm/s (0.0008 in/s). These subbase permeabilities, which were low to very low and were coincident with the expected permeability range for typical A-4 subgrade soil, are given below (1 cm/s = 0.394 in/s):

Relative Permeability	Subbase Permeability K (cm/s)	Typical Soil
High	>0.1	Coarse gravel
Medium	0.1-0.01	Sand, fine sand
Low	0.001-0.000 01	Silty sand, dirty sand
Very low	0.000 01-0.000 000 1	Silt
Impervious	<0.000 000 1	Clay

Silty sand and nonplastic silt (A-4) soils exist in most subgrade conditions in Pennsylvania.

The filter fabric permeabilities are given in Table 2. Data on the permeabilities of the fabrics in the Celanese apparatus indicated that all the fabrics except Typar had very similar initial permeabilities. The permeability of the Typar was about 10 times slower than that of the other fabrics. The results of the 2-d tests with the cloths in contact with type A York Haven sand and in a standard permeameter are also given in Table 2. These permeabilities, except for Typar, were all significantly faster than the permeabilities of the York Haven sand by itself. The permeabilities of the soiled cloths, given in the last column of Table 2, were about 10 times slower than the permeabilities of the clean cloths tested with Ottawa sand.

Figure 9. Permeability test results for four subbase gradations.

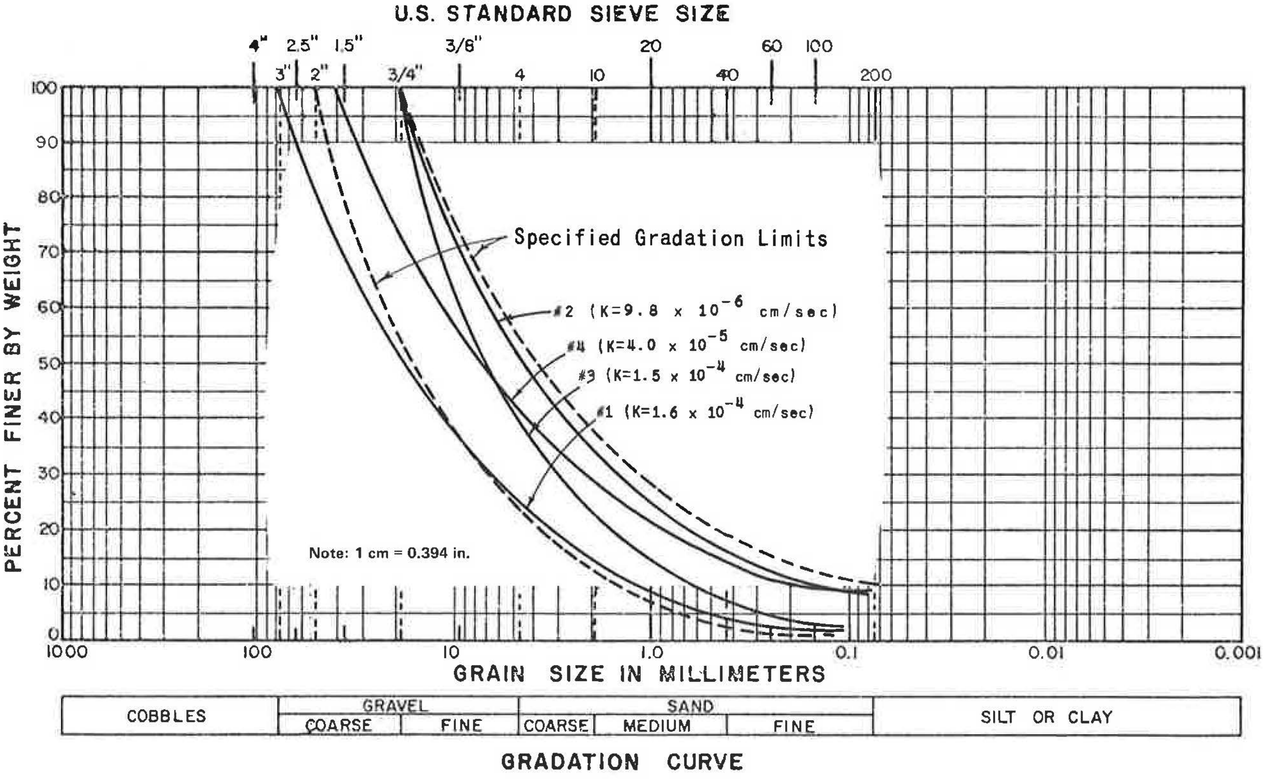


Figure 10. Permeability test results for three subbase gradations.

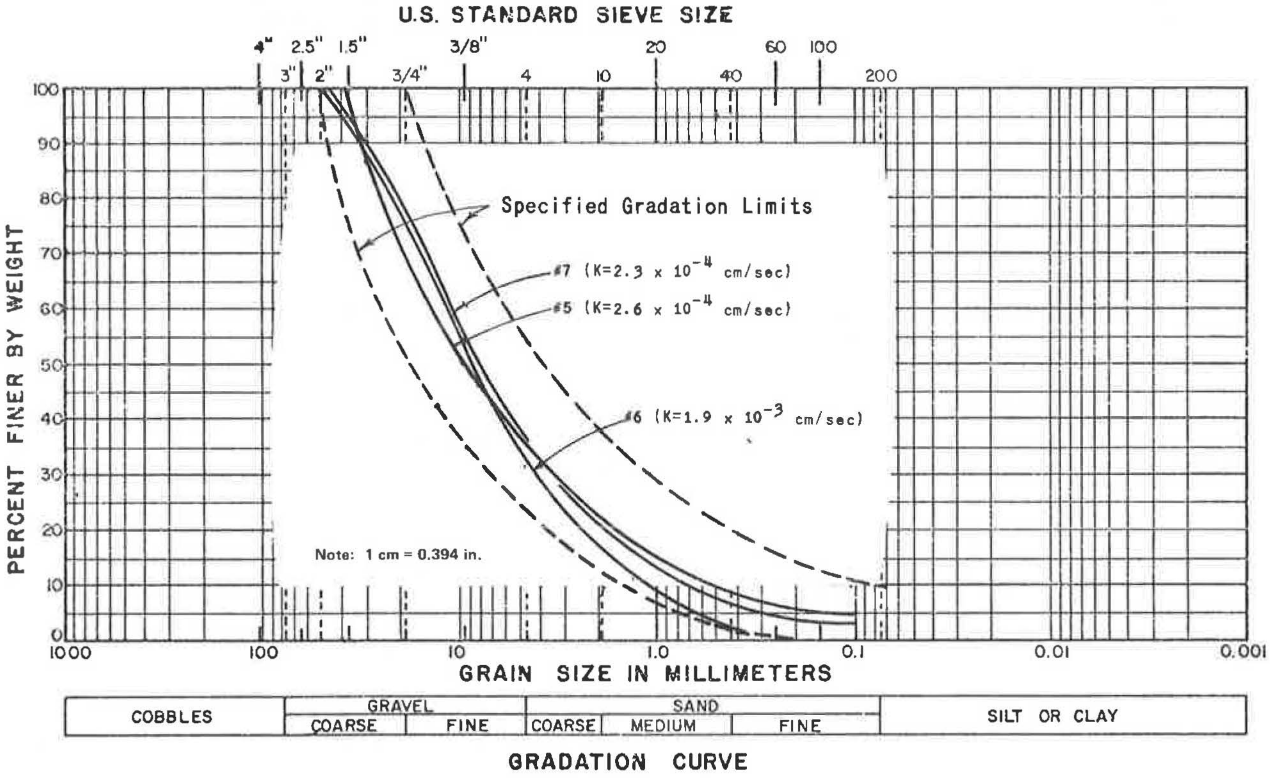


Table 2. Permeability test results for soil-filter fabric system in standard permeameter.

	Permeability (cm/s)			
		Standard Constant Head Permeameter		
Fabric	Celanese Permeameter[a]	Cloth With Ottawa Sand	Cloth With York Haven Sand	Soiled Cloth With 1B Stone[b]
Poly Filter X	0.015	0.023	0.013	0.003 7
Mirafi 140	0.041	0.023	0.012	0.002 5
Bidim	0.05	0.0095	0.0074	0.002 8
Typar	0.0046	0.0063	0.0017	0.000 60
Duon	0.078	0.012	0.0065	0.002 1

Note: 1 cm/s = 0.394 in/s.

[a] Cloth only. [b] Tests made by using soiled cloth from tests with York Haven sand.

The change in the rate of permeability with time for each of the fabrics in contact with York Haven sand in the standard permeameter is shown in Figure 11. Notice that the Poly Filter X fabric (the only woven tested) not only had the fastest permeability but also had the lowest rate of decrease and stabilized faster at a minimum permeability. The Bidim and Typar fabrics showed the greatest rate of decrease. Admittedly, the test time should have been extended until all systems had stabilized at a minimum permeability. Laboratory tests by others have shown that nonwoven fabric systems do stabilize within approximately 1 week of continuous flow (1).

Table 3 and Figure 12 present data accumulated from tests performed in the trench section model rather than in standard laboratory equipment. The flow rates for A sand with no cloth were obtained with only the compacted York Haven sand and a 15-cm (6-in) diameter plastic pipe in the trench section. The flow rates for both A sand with no cloth and with soiled cloth were obtained by wrapping the 15-cm-diameter plastic pipe with the respective filter fabrics and backfilling with the compacted York Haven sand.

The woven Poly Filter X fabric was the only cloth that increased the flow rate over the rate in the soil alone. The increased flow rate occurred from "piping" because the Poly Filter X fabric allowed the coarse silt- and fine sand-sized particles to pass into the pipe, changing the characteristics of the York Haven sand matrix. Again, the Duon fabric produced the slowest rate. All the soil-fabric systems resulted in significant flow reductions after 1 h of continuous flow; the Typar showed the least percentage reduction, and the Bidim and Duon showed the largest percentage reduction. Even with a 13 percent reduction in flow rate after 1 h, the flow rate in the soil-Poly Filter X system was still greater than the flow rate in the soil alone.

The changes in flow with time over the 1-h period are shown in a graph in Figure 9. The Poly Filter X and Duon fabrics clearly demonstrated the fastest and slowest flows respectively, and the Bidim and Duon fabrics had the highest rates of decrease in flow. The flow rates for 1B stone with soiled cloth were unexpectedly higher than the flow rates for 1B stone with clean cloth (Table 3). One explanation for these increased flow rates was the possibility that the fabric opening size increased because of stretching during handling. The fabric samples were used in three test sequences by the time the rates for 1B stone with soiled cloth were obtained.

Relative ratings of the five filter fabrics are given below:

Fabric	Relative Permeability	Relative Filterability
Poly Filter X	High	Low
Marafi 140	Moderate	Moderate
Bidim	Moderate	Moderate to high
Typar	Moderate to low	Moderate to high
Duon	Moderate to low	Moderate

These permeability ratings were based on tests of the soil-filter fabric systems in both the standard permeameter and the trench section model. The filterability ratings were based on the amount of reduction in the flow rates as an indication of clogging or formation of a "tighter" soil matrix adjacent to the cloth or both and also on the amount of fines that entered the pipe in the trench section model. A photograph of fine sand-sized and coarse silt-sized (noncolloidal) particles that entered the pipe wrapped with Poly Filter X fabric is shown in Figure 13.

Basic calculations shown in Figure 14 were made (in U.S. customary units) to obtain an order of magnitude for anticipated flow into the underdrain system. By using a realistically high permeability for typical fine or silty sand subgrade and compacted subbase of 0.001 cm/s (0.000 39 in/s), a trench infiltration rate of a few tenths of a gallon per minute per foot of trench was predicted. This order of magnitude is substantiated by model test results reported by the Federal Highway Administration (2) and by the trench section test results previously presented here.

Next, exfiltration rates on currently accepted drainage pipe products were compared with this anticipated flow into the trench. Figure 15 shows a linear relation between perforation areas and exfiltration-infiltration rates per linear meter of pipe as established during previous testing in the PennDOT laboratory (3). Porous concrete pipe 15 cm (6 in) in diameter has the lowest exfiltration rate [37 L/min (10 gal/min)] of currently accepted pipe products. If one extrapolates the linear relation, this rate cor-

Figure 11. Change of permeability rate with time for York Haven sand-filter fabric systems in standard permeameter.

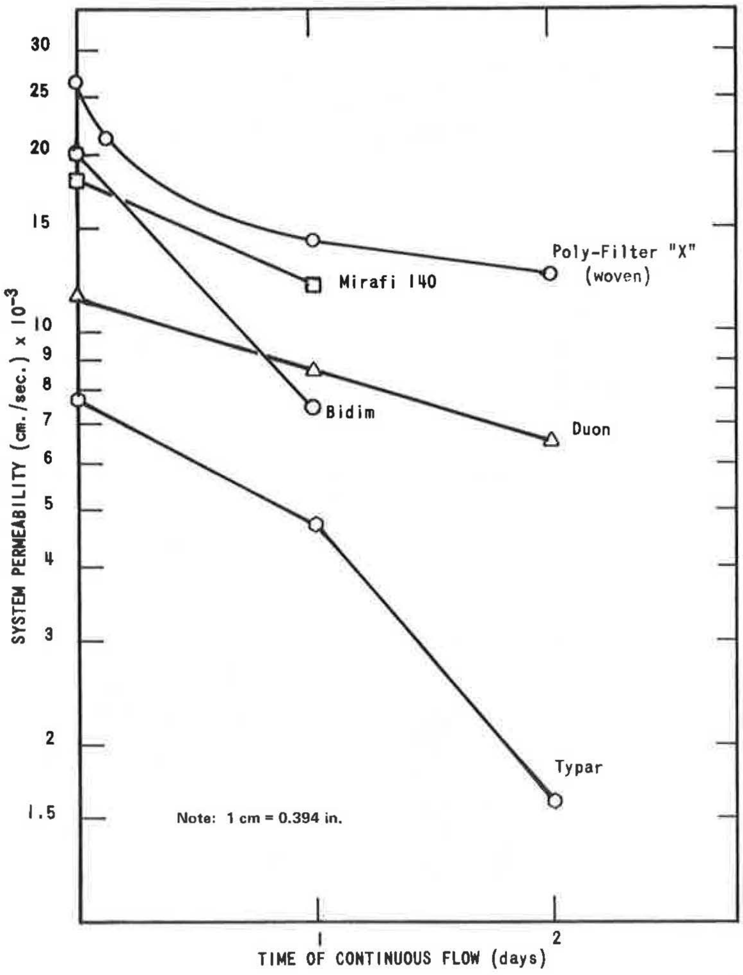


Table 3. Flow rates obtained by using trench section model.

	Flow Rate[a] (L/min)						
	1B Stone			A Sand			
Fabric	No Cloth	With Clean Cloth	With Soiled Cloth[b]	No Cloth	With Clean Cloth[c]	With Soiled Cloth[d]	Decrease[e] (%)
Poly Filter X	30.5	22.26	22.86	2.27	2.95	2.57	13
Mirafi 140	30.5	14.27	11.24	2.27	2.01	1.74	13
Bidim	30.5	14.31	15.56	2.27	2.23	1.78	20
Typar	30.5	18.51	18.7	2.27	1.85	1.66	10
Duon	30.5	6.66	7	2.27	1.55	1.25	20

Note: 1 L = 0.264 gal.

[a] Averages of three tests.

[b] Tests made using soiled cloth from tests with York Haven sand.

[c] Initial flow measurements.

[d] Measurements after 1 h of continuous flow.

[e] Inflow rate over 1-h test cycle using York Haven sand.

Figure 12. Change in flow rate with time in trench section model.

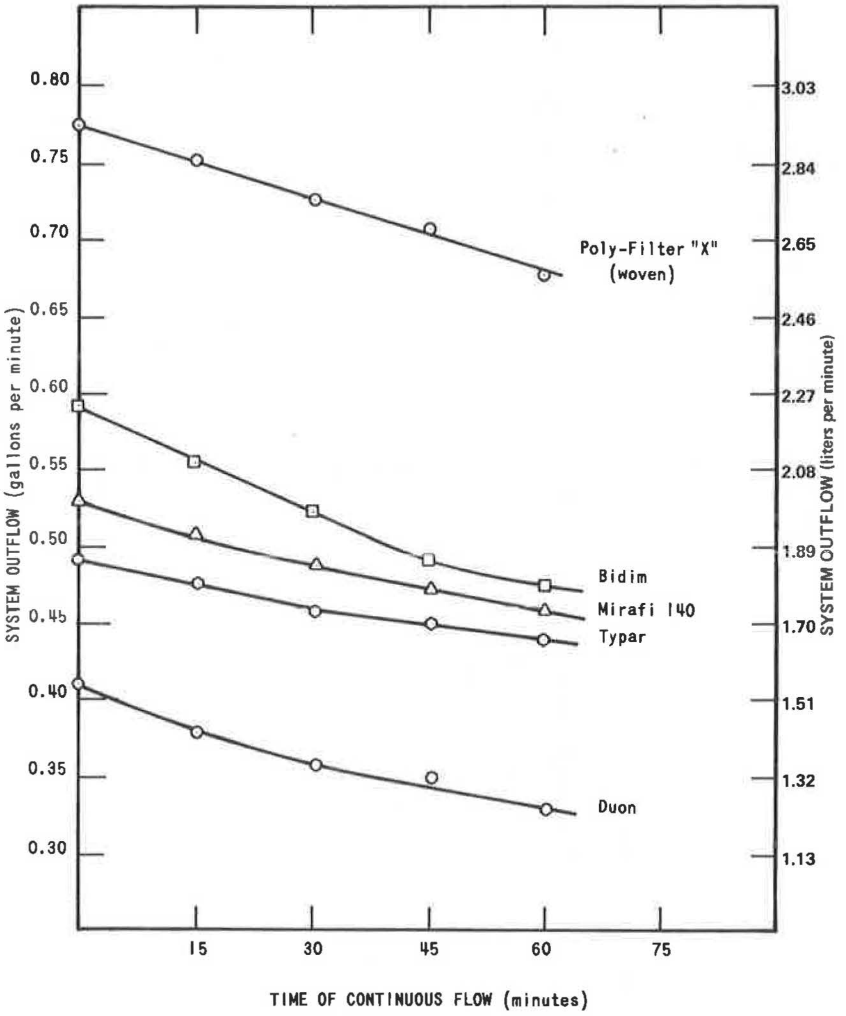
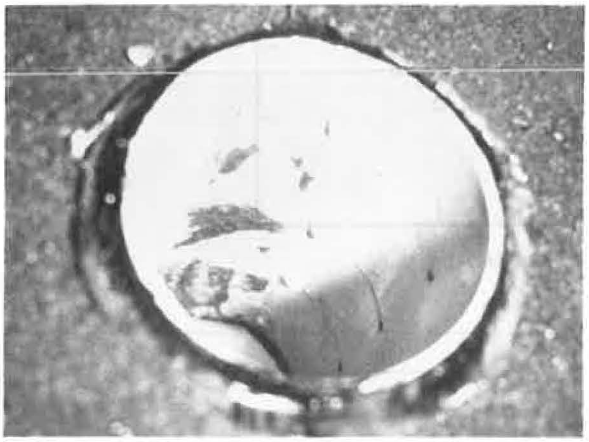


Figure 13. Siltation that occurred in 15-cm (6-in) diameter pipe during testing with trench section model.



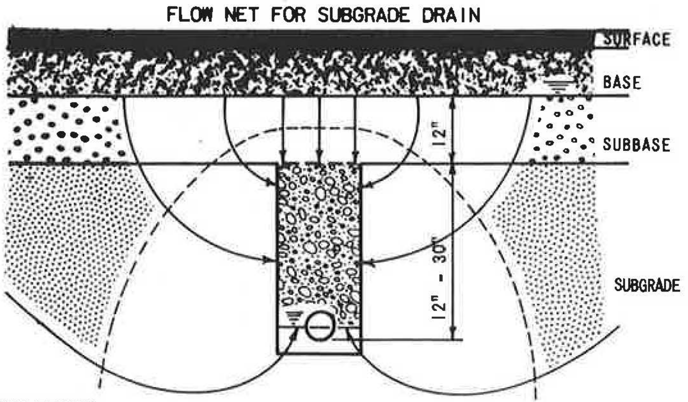
responds to a perforation area of 32 cm^2/linear m (1.5 in^2/linear ft) of pipe. The comparison of the anticipated rate of groundwater infiltration into the trench with the infiltration capabilities of existing pipe products indicated that even the minimum pipe infiltration capability is more than adequate in most cases to transmit anticipated groundwater infiltration.

Hydraulic pipe flow calculations for 10-cm (4-in) diameter corrugated polyethylene pipe are shown in Figure 16 (because the calculations were formulated in U.S. customary units, no SI units are given in the figure). This particular pipe was selected for consideration because of its more critical flow resistance characteristics. Turbulent pipe flow and a high friction coefficient of 0.075 were used in these calculations. The head loss calculations indicated that, at the minimum specified slope of 0.5 percent, gravity flow would more than adequately transmit anticipated inflow and would transmit as much as 178 and 125 L/min (47 and 33 gal/min) flowing full and half full respectively. Additional calculations not shown here on 7.6-cm (3-in) diameter pipe indicated that the performance of this size of pipe may be marginal or inadequate in some instances.

CONCLUSIONS AND RECOMMENDATIONS

Satisfactorily high permeability rates for both types A and B fine aggregate of approximately 0.001 cm/s (0.000 39 in/s) were obtained from the standard 112-cm (44-in) constant-head test. However, in the simulated trench section test, where the effective head at the pipe was only about 23 cm (9 in), both fine aggregate gradations showed relatively slow flow rates that were initially difficult to establish. At this lesser head, the type B material showed a significantly slower flow rate than the type A fine aggregate. The permeability of both gradations decreased with time

Figure 14. Calculations to predict an order of magnitude of anticipated flow in underdrain system.



ASSUMPTIONS:

(1) Initially the water table is at the interface of the base and subbase layers before drawdown occurs.

(2) The filter medium in the trench has a significantly higher permeability than the adjacent subbase and subgrade material thus causing a free boundary at the trench wall.

(3) The subbase and subgrade have a reasonably high (for Pennsylvania's conditions) permeability of 1×10^{-3}cm/sec.

(4) Darcy's Law Applies.

CALCULATIONS:

no. of flow paths, $n_f = 9$, and no. of equipotential drops, $n_d = 2$

therefore; $n_f/n_d = 9/2 = 4.5$

now, $Q/L = KHn_f/n_d = (2 \times 10^{-3}\text{ft./min.}) (\frac{42\text{in.}}{12\text{in./ft.}})\ 4.5 = 0.03\text{ft.}^3\text{/min./ft.}$

therefore; $Q/L = 0.24$ gal./min./linear foot of trench

Figure 15. Regression relation between perforation areas and infiltration quantities.

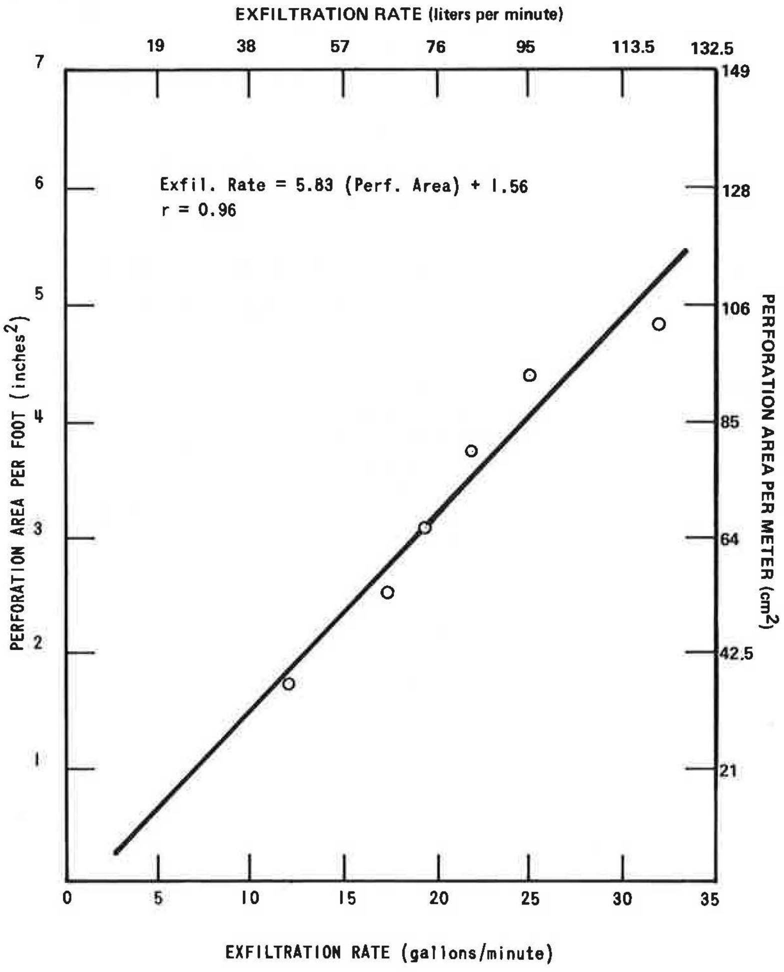
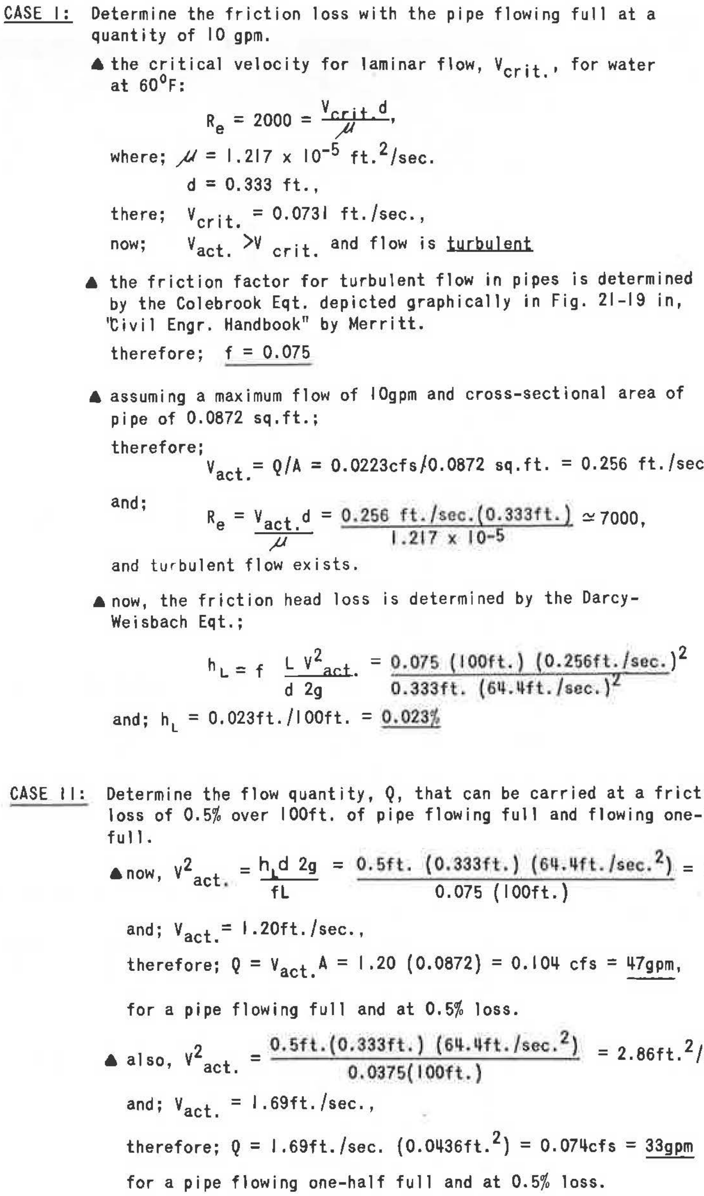


Figure 16. Hydraulic flow calculations in 10-cm (4-in) corrugated polyethylene pipe.



CASE I: Determine the friction loss with the pipe flowing full at a quantity of 10 gpm.

▲ the critical velocity for laminar flow, $V_{crit.}$, for water at 60°F:

$$R_e = 2000 = \frac{V_{crit.} d}{\mu},$$

where; $\mu = 1.217 \times 10^{-5}$ ft.^{2}/sec.

$d = 0.333$ ft.,

there; $V_{crit.} = 0.0731$ ft./sec.,

now; $V_{act.} > V_{crit.}$ and flow is turbulent

▲ the friction factor for turbulent flow in pipes is determined by the Colebrook Eqt. depicted graphically in Fig. 21-19 in, "Civil Engr. Handbook" by Merritt.

therefore; $f = 0.075$

▲ assuming a maximum flow of 10gpm and cross-sectional area of pipe of 0.0872 sq.ft.;

therefore;

$$V_{act.} = Q/A = 0.0223\text{cfs}/0.0872 \text{ sq.ft.} = 0.256 \text{ ft./sec.},$$

and;

$$R_e = \frac{V_{act.} d}{\mu} = \frac{0.256 \text{ ft./sec.} (0.333\text{ft.})}{1.217 \times 10^{-5}} \simeq 7000,$$

and turbulent flow exists.

▲ now, the friction head loss is determined by the Darcy-Weisbach Eqt.;

$$h_L = f \frac{L V^2_{act.}}{d\ 2g} = \frac{0.075\ (100\text{ft.})\ (0.256\text{ft./sec.})^2}{0.333\text{ft.}\ (64.4\text{ft./sec.})^2}$$

and; $h_L = 0.023$ft./100ft. = 0.023%

CASE II: Determine the flow quantity, Q, that can be carried at a friction loss of 0.5% over 100ft. of pipe flowing full and flowing one-half full.

▲ now, $V^2_{act.} = \frac{h_L d\ 2g}{fL} = \frac{0.5\text{ft.}\ (0.333\text{ft.})\ (64.4\text{ft./sec.}^2)}{0.075\ (100\text{ft.})} = 1.43\text{ft}^2/\text{sec.}^2,$

and; $V_{act.} = 1.20$ft./sec.,

therefore; $Q = V_{act.} A = 1.20\ (0.0872) = 0.104$ cfs = 47gpm,

for a pipe flowing full and at 0.5% loss.

▲ also, $V^2_{act.} = \frac{0.5\text{ft.}(0.333\text{ft.})\ (64.4\text{ft./sec.}^2)}{0.0375(100\text{ft.})} = 2.86\text{ft.}^2/\text{sec.}^2,$

and; $V_{act.} = 1.69$ft./sec.,

therefore; $Q = 1.69\text{ft./sec.}\ (0.0436\text{ft.}^2) = 0.074$cfs = 33gpm

for a pipe flowing one-half full and at 0.5% loss.

because of the migration of as much as 5 percent of the finer particles within the material matrix. About 0.63 cm (0.25 in) of siltation occurred in the bottom of the pipe when the fine aggregate media were used without the filter fabrics. The 23-cm head test simulated the conditions anticipated to occur in the PennDOT pavement drain system in which the bottom of the drainage trench is 30.4 cm (12 in) below the bottom of the subbase layer, whereas the higher head tests were indicative of the anticipated situation in the PennDOT deeper subgrade drain system. Consequently, it is recommended that both types of fine aggregate be eliminated from the pavement drain system and only the type A material be considered useful in the deeper subgrade drains where higher hydraulic heads and finer adjacent subgrade soils generally exist compared with the more shallow pavement drain system.

The low to very low permeabilities of the specified subbase materials indicated that one of the primary purposes of this pavement layer--to effect lateral blanket drainage--was not necessarily being achieved. Subbase material specifications should be modified to provide aggregate products with a permeability range an order of magnitude higher than that revealed by the testing discussed here.

The filter fabrics appear to have a practical use in the PennDOT pavement drain and underdrain systems and as such warrant additional evaluation toward specification of their use. The performance of the fabrics in this work indicated that long-term permeability and filterability are inversely related and are basically functions of the average and range of fabric opening sizes. This suggests that both upper and lower limits should be established on an average opening size. The intent of these limits should be to retain the coarse silt and sand particles that compose the basic structure of the adjacent soil matrix and to transmit colloidal-size particles that cause clogging and significant reduction in system permeabilities. Some states, such as Illinois, have already adopted opening-size specification for filter fabrics. Based on this type of opening-size specification, the woven Poly Filter X fabric had openings that were too large. The four nonwoven fabrics were different in the amount of fines that were retained, as shown by the differences in the rate of permeability reduction with time. Because of the relatively short test periods, it would be difficult to conclude from the data given here that any of the nonwoven fabrics had opening sizes that were too small and would consequently not function adequately over the long term. It could be concluded, however, that some of the nonwoven fabrics would function better than others. Long-term, in situ testing for the purpose of developing the opening-size (primarily lower limit) concept is recommended.

Calculations, test data from this work, and results of model tests by others (2) indicate that currently specified PennDOT requirements for pipe cross section and intake area are unnecessarily high. It is recommended that the intake area requirements be reduced from 74.5 to 32 cm^2/linear m (3.5 to 1.5 in^2/linear ft) [the Federal Highway Administration uses 19.3 cm^2/linear m (1 in^2/linear ft)]. It is further recommended that minimum inside diameter for circular pipes be reduced from 15 to 10 cm (6 to 4 in).

Finally, it should be noted that these recommendations are made for what is assumed to be typical conditions in Pennsylvania for a pavement or subgrade drain system. The recommendations certainly do not apply to a situation where a spring or very permeable acquifer is being "tapped." The use of the data given here should not preclude an engineering evaluation on a site-to-site basis.

ACKNOWLEDGMENT

The contents of this report reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Pennsylvania Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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Publication of this paper sponsored by Committee on Subsurface Drainage.