SUMMARY

In summary, it should be stressed again that the majority of specifications in place today and the concepts on which they were developed were formulated in the late 1960s and early 1970s. Currently, a rapidly growing body of information demands that these older concepts be modified to accommodate an increased understanding of how fabrics and systems function. Current understanding will change further in this decade. Nevertheless, what is known today must be used as the basis for guidelines and practice. This is the continuing dilemma of working with a dynamic, essential technology.

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Permeability Tests of Selected Filter Fabrics for Use with a Loess-Derived Alluvium

G.T. WADE, F.W. KLAIBER, AND R.A. LOHNES

Permeability tests on six nonwoven and two woven geotextiles with a silty-clay alluvium indicate that all of the fabrics tested will prevent piping of the soil, regardless of the state of compaction. When a discontinuity (such as a hole) was introduced into the soil, some soils were observed to pipe. The range of permeabilities of soil-fabric systems was observed to be narrow, even though the range of fabric permeability was wide and the soil compaction varied. A theoretical analysis shows that the permeability of the soil is the controlling factor in permeability testing of the soil-fabric system. A piping test similar to the test for dispersive clays is suggested as an alternative to permeability testing of soils and filter fabrics.

Drainage problems have traditionally been solved by using aggregate filters. Loess-derived silty soils (like those in western Iowa) require multilayer filters, which are both expensive to produce and labor intensive to construct. The need for more economical methods of filter construction with silts resulted in a study of geotextile filters for use with these soils. There are currently more than 100 (1) different geotextiles available in the United States, which consist of both woven and nonwoven fabrics.

Several weaving techniques are used, but the products are essentially the same: a relatively thin cloth that has a rectilinear pattern of openings. The sizes of the openings differ, depending on the thickness of the filament and the number of picks per inch, but for any given fabric there is only slight variability in the size of the openings.

Nonwoven fabrics are produced by several techniques, depending on the manufacturer, and may be thin or more than a centimeter thick. Regardless of thickness, the irregular filament pattern produces various pore sizes through the fabric. Thicker nonwoven fabrics are often arbitrarily classified as mats.

LITERATURE REVIEW

Cotton cloth was first used in North Carolina in 1926 to improve subgrade strength, and the U.S. Army Corps of Engineers began using fabrics in the early 1950s to control shore erosion. Increased construction costs and the development of synthetics resulted in the expanded use of geotextiles, including embankment stabilization, grade stabilization for highways and railroads, retaining walls, consolidation of soils, drainage, and silt fences for erosion control. The product technology and availability of geotextiles have progressed ahead of published research results.

The Corps of Engineers used research conducted at the Waterways Experiment Station to develop guidelines for the use of plastic filter cloth (2). Six woven and one nonwoven filter cloths were tested for various chemical and physical properties. Two characterization tests of particular interest for drainage applications are the equivalent size of the openings and the percentage of openings in the fabric. Rounded sand of known gradation was sieved through the fabric, and the percentage retained was used to determine an equivalent opening size (EOS). The percent open area (%OA) was determined by projecting an image of the cloth on a grid and measuring the amount of open area at randomly selected points on the grid.

Filtration and clogging tests were conducted with several gap-graded soils that exhibited a suscepti-

Table 1. Fabric properties.

Fabric	Type[a]	Thickness (mm)	EOS[b]	%OA	k (cm/sec)
A	N	1.27	140	NA	0.05
B	N	0.76	80-100	NA	0.07
C	N	0.38	70-100[c]	NA	0.02
D	N	1.27	80-100	4-6	0.02-0.3
E	N	2.80	80-100	NA	0.3
F	W	0.43[d]	100	4-5	0.05
G	N	0.762	80-100	NA	0.10
H	W	0.61[d]	40	21-26	∞

Note: NA = not available.
[a]N= nonwoven and W = woven.
[b]U.S. sieve sizes.
[c]Pore-size distribution available.
[d]Measurements conducted on specimens.

bility to piping. Silty soils were omitted because permeability was so low that no useful data could be obtained. By using EOS and %OA, the following guidelines for filter fabric selection were accepted. For granular soils that contain less than 50 percent silt, the EOS of the filter fabric should be smaller than the 85 percent size of the protected soil. Filter fabrics should not be used with soils that have more than 50 percent of their particles smaller than the No. 200 sieve (3). These specifications are now frequently used. There is no problem with the specifications as long as a granular material with less than 50 percent fines is being protected with a woven fabric. No additional guidelines are available for silty soils or nonwoven fabrics.

Ogink (4) studied both woven and nonwoven fabrics with sands and proposed that the ratio (O_{90} of the geotextile/D_{90} of the soil) be $\leq$ 1.0 for woven and $\leq$ 1.8 for nonwoven products, where O_{90} and D_{90} are the 90 percent opening and the particle size, respectively. Zitscher (5) recommends that the O_{50} of the geotextile equal (25 - 37) x D_{50} for silty soils, where O_{50} and D_{50} are the average pore and particle size. ICI Fibres in Great Britain give elaborate design procedures for "terram," a nonwoven geotextile they manufacture, and include the recommendation that $O_{50}/D_{85} \cong 1$. Rankilor (6) summarized these methods and concluded that more research is needed in this field, especially on cohesive soils.

Rosen and Marks (7) evaluated 12 soils against 1 nonwoven fabric (Mirafi 140) by using static head permeability tests of 300-hr duration. They used a conventional aggregate filter as a standard and noted a decrease in permeability with time for all tests. They concluded that, for well-graded soils, a filter cake develops behind the fabric. The fabric then acts as a boundary for the formation of an internal filter cake. Results of their tests also revealed that well-graded soils that possess higher plasticity and cohesion exhibit less piping before complete filter-cake formation. They concluded that Mirafi 140 was acceptable for all the soils tested, including those that contain up to 70 percent silt.

McKeand (8) performed similar permeability tests with several fabrics and testing durations to 3,000 hr. He concluded that filter-cake formation is a function of the pore-size distribution, percent open area, and thickness of the fabric; however, no quantitative relations were given. He also stated that the three nonwoven fabrics tested performed satisfactorily for the wide range of soils, including soils that possess liquid limits up to 40 percent and plasticity indices less than 15 percent.

The data in Table 1 summarize the physical properties provided for drainage geotextiles produced by several manufacturers and illustrates another problem currently faced by the engineer: inadequate product information that is nonstandardized. This results from the various manufacturing techniques; differing filament composition, texture, and fabric thickness; differing laboratory equipment; and lack of ASTM standards.

The EOS, as measured by Calhoun (2), is generally accepted for woven fabrics; however, values given for nonwoven fabrics, with their wide range of opening sizes, cannot be measured by sieving techniques. The sand is either entrapped in the fabric matrix or passes through the larger openings, thereby yielding an EOS value near the largest size openings. The EOS for nonwoven fabrics is generally equated to the 95 percent opening size.

The %OA is also not directly applicable to nonwoven fabrics, especially mats, because the openings are neither normal to the surface nor lead directly through the fabric.

Permeability, the most often published parameter for geotextile filters, is usually in the range of a fine to coarse sand. This range is sufficiently high enough to avoid flow restriction in silty soils. Permeability appears to be the most popular characteristic for evaluating geotextile acceptability for drainage and erosion control; however, it has been noted that improved tests and a better understanding of this property are needed (9).

PERMEABILITY AND GEOTEXTILE FILTERS

It is a common observation in permeability testing of soils alone, and in testing of soils in conjunction with filter fabrics, that the permeability of the system being tested decreases with increasing time after initiation of the test. Several interpretations have been offered to explain this phenomenon, including exsolution of dissolved air, bacterial growth, and, in the case of soil and filter fabric systems, formation of a filter cake at the fabric-soil interface.

Bertram (10) conducted tests on sand filters and noted a decrease in permeability with time. He concluded that air in the distilled water was being exsolved, thereby creating an air filter that impeded the flow of water. Subsequent tests with de-aired water demonstrated no further decreases in permeability. Note that de-airing the water also removed the mechanism for organism growth and subsequent permeability decrease; therefore, de-airing the water may have a two-fold effect.

Permeability tests conducted on loess at several degrees of compaction revealed a similar decrease in permeability with increasing time after the initial test (11). Bacterial growth was observed after 7 days on all samples tested. Badger (11) hypothesized that the presence of those organisms decreased the permeability. He reported that his samples showed a 75 percent reduction in permeability after 2 days. Chen and others (12) noted a similar permeability decrease when using a permeant that contained 1 to 2 parts per million (ppm) residual chlorine. They concluded that a small amount of residual chlorine was ineffective in retarding bacterial growth during long-term tests. Subsequent tests performed by using 10 ppm residual chlorine revealed no substantial permeability decrease with time, which suggested that higher chlorine concentrations were effective in retarding the bacterial growth that caused the permeability decrease.

Fabric clogging has not been shown to be a direct factor in permeability reduction. Rosen and Marks (7) demonstrated that less than 0.05 percent of the soil particles are entrapped within the fabric; however, they concluded that a filter cake develops for gap-graded soils next to the geotextile. This filter cake has a lower permeability than either the geotextile or soil matrix and is increased by the restriction on fine particles within the soil. Chen and others (12) concluded that well-graded soils are natural filters and that no migration of fines occurs.

TEST PROCEDURE

To test the acceptability of fabrics that might be used with silty soils, a permeameter was constructed as shown in Figure 1. A constant head of 3 m was applied to induce a continuous flow through the specimen. The soil specimens were placed in 7-cm-diameter Lucite cylinders; the fabric was secured to the bottom of the cylinder; and the samples were allowed to capillary saturate. The 3-m head was then applied to induce flow through the sample. The head was removed periodically and the permeability measured by using the falling-head equation; the static head was then reapplied.

The soil used in the tests was a loess-derived alluvial material characterized as a silty clay. The soil properties and Atterburg limits are shown in Figure 2. Test conditions were designed to resemble possible field conditions of the soil, including field unit weight, nonuniform compaction, originally saturated unconsolidated soils, and soils with no compaction. Field densities were produced by dynamically compacting air-dried soil in uniform lifts until a density of 1.36 g/cm^3 was obtained. These samples were capillary saturated before application of the hydraulic head. The nonuniformly compacted samples were obtained by dynamic compaction of the soil; however, the soil was placed in one layer, and compaction was restricted to the center of the sample. Originally, saturated soils were produced by affixing the geotextile and then pouring a soil-water slurry into the Lucite cylinder. A low density was obtained by pouring the air-dried soil into the cylinders with no mechanical compaction before application of the hydraulic head. Where the aggregate filter was used, approximately 2.5 cm of fine sand was placed in the cylinder below the soil. Where the soil was compacted, the geotextiles were placed after compaction to minimize fabric clogging. Test conditions are summarized in the table below:

Test	Specimen Thickness (cm)	Filters	Soil Condition
1	5.5	A, B, C, D, F, G, pea gravel, sand	Natural dry unit weight; uniform compaction
2	1.8	A, B, D, G	Soil slurry
3	6.0	E, F, H	No compaction
4	4.0	C, E, F, pea gravel	Nonuniform compaction

Soil specimens in test 4 were intentionally disturbed by placing a 1.5-mm-diameter hole through the soil to the top of the filter. The head was then reapplied and the effect on permeability noted.

The filters selected consisted of one aggregate and eight geotextiles. The fine sand aggregate approximated Terzaghi's (13) piping criteria as a filter for the silty clay. The pea gravel at the base of the apparatus was coarse enough so that negligible head was lost in it. Curves identified as pea gravel reflect the properties of the soil alone. The geotextiles evaluated--two woven and six nonwoven fabrics--are given in Table 1.

Figure 1. Permeameter used for hydraulic testing.

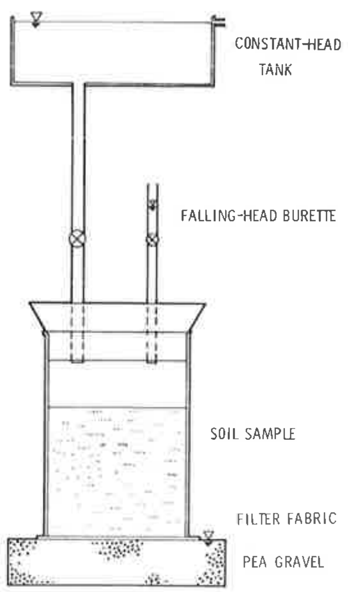
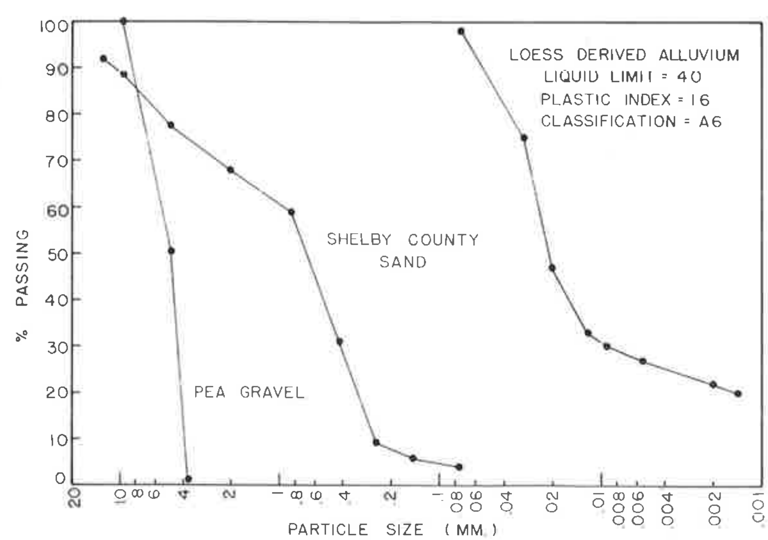


Figure 2. Sieve analysis for aggregate filters and loess-derived alluvium.



TEST RESULTS

Test 1 (Figure 3) demonstrated that a wide variety of geotextiles all behaved in essentially the same manner. Each had a decrease in permeability between 35 and 45 percent over the 340-hr test period, and none piped. There was an unexpected 40 percent decrease in the soil alone, whereas the sample with the sand filter had a decrease of only about one-half that experienced by the other samples. The 24-hr permeability of each sample is given in the table below (note that all 24-hr permeabilities are multiplied by 10^{-6} cm/sec, and NA signifies that the test was not conducted with this filter):

	24-hr Permeability		
Filter	Test 1	Test 2	Test 3
A	159	162	NA
B	155	372	NA
C	149	NA	75
D	139	107	NA
E	161	NA	103
F	161	NA	102
G	NA	87	NA
Sand	197	NA	NA
Pea gravel	195	NA	40

In test 2 (Figure 4), all permeabilities decreased from the initial values listed in the table above and appeared to stabilize at approximately 30×10^{-6} cm/sec. During testing, the soil samples with fabric G showed transverse cracking, thereby giving a nonuniform flow through the samples.

The pattern of decreasing permeability with increasing time was also apparent in test 3. Although the initial permeabilities vary from the other tests, the behavior of these systems is the same as in the other tests.

The results of test 4 (Figure 5) demonstrated that the variation of permeability with time was more erratic than in the previous tests. Fabric E and pea gravel behaved the most erratically in the early portions of the test, whereas fabrics C and F behaved in a manner similar to the previous tests.

The permeabilities of each soil-fabric system decreased with time, regardless of soil preparation or filter type. Also, none of the soils piped, including test 3 where piping was anticipated. However, when a 1-mm hole was punched through the soil, progressive soil piping followed with several of the geotextiles.

DISCUSSION OF RESULTS

The data on initial permeabilities reveal that for each test there is little variation in the permeabilities of the soil-fabric systems. The quantity

Figure 3. Permeability versus time for test 1.

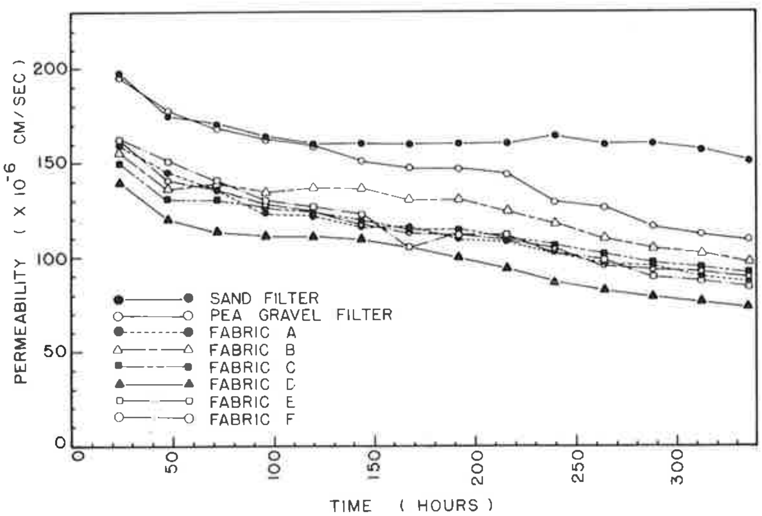


Figure 4. Permeability versus time for test 2.

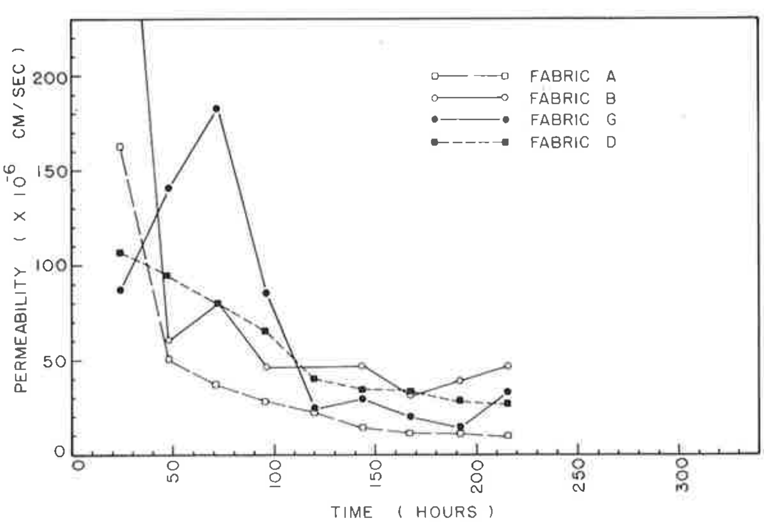
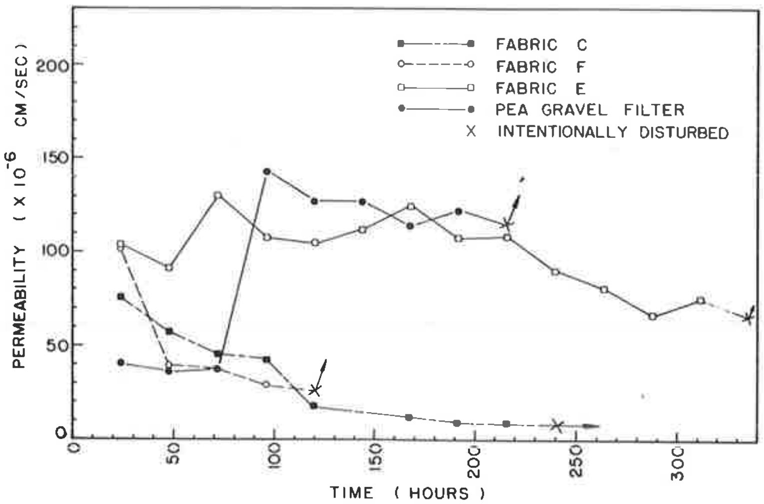


Figure 5. Permeability versus time for test 4.



of water per unit time (Q) flowing through the soil and fabric is described by Darcy's law:

$$Q = Aki = Ak(H/t) \text{ or } H = (Qt/Ak) \quad (1)$$

where

A = cross-sectional area,
k = permeability of soil-fabric system,
i = hydraulic gradient,
t = combined thickness of fabric and soil, and
H = head loss in system.

The head loss in the entire system is

$$H = H_s + H_f \text{ or } H_f + H - H_s \quad (2)$$

where H_s is the head loss in the soil and H_f is the head loss in the fabric. Substituting Equation 1 into Equation 2 gives

$$H_f = (Qt/Ak) - H_s \quad (3)$$

Because the quantity of flow through the soil and the fabric is the same, and because the cross-sectional areas of both soil and fabric are equal,

$$k_s(H_s/t_s) = k_f(H_f/t_f) = k_f\,[(Qt/kA - H_s)/t_f] \quad (4)$$

where

k_s, k_f = permeabilities of soil and fabric, respectively;
t_s = thickness of soil; and
t_f = thickness of fabric.

Therefore, because

$$Q = k_s\,(H_s/t_s)\,A \quad (5)$$

then

$$k_s(H_s/t_s) = (k_f/t_f)\left\{[k_s\,(H_s/t_s)\,t/k] - H_s\right\} \quad (6)$$

Equation 6 can be manipulated algebraically, such that H_s cancels out and

$$k = k_f k_s t/(k_s t_f + k_f t_s)$$

Because the product of the permeability of the soil times the thickness of the fabric is very small and the thickness of the fabric is small (relative to the thickness of the total system), the apparent permeability of the soil-fabric system is approximately equal to the permeability of the soil alone; or by using the symbols above, because $k_s \rightarrow 0$ and $t \sim t_s$, then, $k \sim k_s$.

If Equation 3 (for apparent permeability) is used with the data from Table 1, and a permeability for soil of 0.0002 cm/sec and a thickness of soil at 5.5 cm are also used, then all of the fabrics tested (except fabric A) give a theoretical apparent permeability of about 0.0002 cm/sec. The apparent permeability of fabric A was calculated to be 0.000 14 cm/sec. This analysis indicates that the results of permeability tests on soil-fabric systems are of questionable value because they reflect mainly the permeability of the soil, not the soil-fabric system.

All permeability versus time curves show a decrease with time. The nonuniformly compacted samples have the most erratic behavior. This behavior is interpreted to be the result of particle migration as the soil structure is rearranged. Permeabilities of the slurry samples drop to 20 percent of their original value with fabrics A and B, whereas fabrics D and G have less-dramatic decreases. The uniformly compacted samples have a decrease of less than 40 percent. Phenomena that have been used to explain the decrease in permeability with time are consolidation, bacterial growth, fabric clogging, and air entrapment. As discussed in a previous section, evidence exists that clogging of fabric pores is not responsible for a reduction of permeability with time (7,12) with well-graded soils.

The possibility for permeability reduction as a result of consolidation can be evaluated by the following analysis. The flow through the soil creates a seepage force per unit volume (j):

$$j = i \cdot \gamma_w \quad (7)$$

where i is the hydraulic gradient and γ_w is the unit weight of water.

The average effective stress ($\bar{s}$) created by the seepage force can be shown as

$$\bar{s} = j \cdot t_s \quad (8)$$

where t_s is the soil sample thickness. Combining Equation 8 with Equation 7 gives

$$\bar{s} = i \cdot \gamma_w \cdot t_s \quad (9)$$

or, because $i = H_s/t_s$, where H_s is the head loss,

$$\bar{s} = H_s \cdot \gamma_w \qquad (10)$$

In the tests performed in this study, the average effective stress is 29 kN/m^2. Void ratio versus pressure curves for loess-derived alluvium (14) indicate that a stress increase of this magnitude is negligible; therefore little decrease in permeability can be attributed to consolidation. From the foregoing analyses it appears that the reduction in permeability is the result of bacterial growth, or exsolution of air from the water, or both.

Recognizing that permeability tests on soil-fabric systems may be of limited value, the following analysis suggests an alternate test that may be more useful in evaluating geotextiles for use with various soils.

Hjulström (15) demonstrated that a critical velocity exists below which stream erosion will not occur, and that a minimum velocity of 18 cm/sec is required for erosion, regardless of particle size. Sherard and others (16) have found that nondispersive clays withstand velocities of 300 cm/sec through 1-mm pinholes without erosion. The Corps of Engineers, after performing piping tests with sand filters, concluded that the D_{15} of the sand filter may be as large as 0.4 mm when protecting medium to highly plastic soils with or without silt partings. Therefore, a critical velocity must exist for erosion through, as well as over, the soil.

Darcy's law states that

$$Q = kiA \qquad (11)$$

and because

$$Q = AV - A_v V_s \qquad (12)$$

and

$$n = e/(1 + e) = A_v/A \qquad (13)$$

then the seepage velocity can be expressed as

$$v_s = [(1 + e)/e]\ ki \qquad (14)$$

where

n = porosity,
e = void ratio,
V = approach velocity,
V_s = seepage velocity, and
A_v = area of voids in the cross section.

Typical values for loess-derived alluvium are 0.8 for void ratio (10^{-5} cm/sec for permeability). If a minimum velocity for erosion is 18 cm/sec, the minimum hydraulic gradient required of flow through loess-derived alluvium would be more than 800,000. This indicates that the critical velocity will occur only if macrovoids are available.

As reported by Sherard and others (16), the pipe flow relations, which assume that all head is lost in creating fluid flow, are

$$H = (V^2/2g)\ [K_1 + f(L/d) + K_2] \qquad (15)$$

where

V = velocity through pipe;
K_1,K_2 = entrance and exit losses, respectively;
L = pipe length;
d = pipe diameter;
$f = 64/N_R$ (assuming laminar flow);
N_R = Reynolds number; and
H = net head loss.

By using values for H, L, and d; values for d of 5 cm, 2.5 cm, and 1 mm, respectively; and values of $K_1 = 0.5$ and $K_2 = 1.0$, the velocity (V) will equal 43 cm/sec. Sherard and others (16), while conducting pinhole tests for dispersing soils (by using these values for H, L, and d), obtained velocities of 38 cm/sec, which support the theory.

Theoretically, uniform loess-derived alluvium will not pipe and filters are not required; however, in practice, nonuniformities as small as 1 mm in diameter may exist, which result from incomplete compaction, differential settlement, tunneling of insects or animals, or plant roots. Thus filters are required to avoid piping.

The pinhole test, as explained in detail by Sherard and others (16) for dispersive soils, requires placing a 1-mm-diameter horizontal hole through a 2.5-cm soil sample. After the introduction of a 5-cm hydraulic head, the hole will rapidly erode to 2 or 3 mm in diameter if the soil is dispersive. If the soil is not dispersive, the head can be increased to 100 cm without erosion. This test could be modified to evaluate geotextile performance with dispersive silty soils by placing down a geotextile gradient of a soil that had been previously perforated. The acceptable geotextile would either restrict soil particles, thereby decreasing velocities below critical levels, or sufficiently restrict flow to reduce velocities below critical levels. This test can be conducted rapidly and, if used for other cohesive soils, can also be used to check for dispersive soils.

CONCLUSIONS

Permeability tests on six nonwoven and two woven fabrics with a silty alluvium indicate that all fabrics tested will prevent piping, regardless of whether the soil was noncompacted, uniformly compacted, or in a slurry. However, when a pinhole was introduced, some of the soil-fabric systems were observed to pipe immediately after the disturbance.

Theoretical analyses and the narrow range of observed permeability with a wide range of fabrics tested and varied soil conditions suggest that permeability testing of the soil-fabric systems may be of little value because the data reflect the conditions of the soil, not the soil-fabric system. Theoretical analyses indicate that the ubiquitous reduction in permeability with time is the result of exsolution of air or bacterial growth that clogs the pores of the system. A piping test similar to the test for dispersive clays is suggested as an alternative to permeability testing for selecting geotextiles to be used as filter fabrics with cohesive soils.

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Geotextile Filter Criteria

R. G. CARROLL, JR.

In the past decade, drainage fabric performance has been the subject of numerous research projects. Two general conclusions can be drawn from the many research findings: (a) both woven and nonwoven fabrics can provide acceptable filtration performance in drainage applications, and (b) soil and hydraulic conditions influence fabric filter properties necessary for optimum performance. More specific observations are made in this paper concerning the relation between fabric and soil properties versus drain fabric performance. These observations include the following: (a) fabric equivalent opening size (EOS) and permeability coefficients do not indicate clogging potential, (b) fabric EOS provides an indirect indication of retention ability, (c) gap-graded soils and high hydraulic gradient conditions are conducive to soil piping and filter clogging, (d) well-graded soils and low hydraulic gradients are not conducive to soil piping, and (e) fabric clogging potential can be determined by testing soil-fabric systems in simulated drainage tests that model expected use conditions. The state of the art in drainage fabric technology is reviewed, and rational filter criteria for geotextiles based on three performance parameters—retention ability, permeability, and clogging resistance—are recommended.

Geotextiles are rapidly replacing graded aggregates as the approved filter medium in drainage systems. Engineers use the performance and cost benefits of geotextiles in their drain designs, but they are often confused in their efforts to select the appropriate fabric filter. Regardless of the filter medium chosen for drainage applications, it must meet two conflicting requirements to assure optimum performance:

1. Retention--the filter must have a pore structure fine enough to retain erodable soils, and
2. Permeability--the filter must maintain adequate permeability so that seepage can escape freely from the protected soil. (Note that clogging resistance is inherent to this requirement.)

Grain-size distribution of a graded aggregate filter creates its pore structure that, in turn, controls filtration performance. There are universally accepted criteria for specifying the grain-size distribution of aggregate filters that relate the particle size of a graded aggregate to that of the protected soil (1). These criteria, based on theoretical relations among particle size, pore size, and retention ability of granular materials, have proved adequate through decades of use.

There are no well-established filter criteria for geotextiles. Filtration performance of a geotextile is controlled by its fiber structure, which in turn determines pore sizes, pore distribution, and porosity--the major characteristics that control fabric retention ability and permeability. The ideal retention criteria for fabrics should specify the appropriate pore structure in order to eliminate piping through the fabric, provide an adequate fabric seepage rate, and to assure clogging resistance. But an accurate measure of pore structure in porous media is difficult to obtain. Although numerous tests have been developed, no method has been universally accepted. The next-best alternative to an accurate measure of filter pores is an index test(s) that relates pore characteristics to filtration performance. Such index values are the basis for filter media selection in most filtration applications.

Geotextile performance in filtration-drainage applications has been the scope of considerable research over the past 10 years. The state of the art in drain fabric technology contains sufficient information on performance mechanisms and pertinent