C.R. Coll. Int. Sols Textiles. Paris 1977

INGLES O.G.
University of New South Wales, Australia

The permeability of geotechnical fabrics, Its reduction, and modification to suit particular uses

La perméabilité des textiles géotechniques, Réduction et modification pour satisfaire des besoins particuliers

RÉSUMÉ

On discute d'abord les moyens de faire la mesure de la perméabilité (ou perméance) des textiles geotechniques. Ensuite, on considère des methodes dont on peut se servir, ou pour l'amélioration (abaissement) de la perméabilité d'un textile commercial, ou pour la préparation des nouveaux textiles qui auront une perméance choisie d'avance.

On indique le role important qu'un choix juste entre les diverses perméabilités peut jouer, et pour les barrages, les levées, les remblais de terre, et surtout en ce qui concerne les chaussées. Pour les zones désertiques et semi-désertiques on démontre un nouveau principe de construction avec ces textiles geotechniques qui assure la sécurité des chaussées soumises aux inondations peu fréquentes ou sporadiques.

The Permeability of Geotechnical Fabrics.

Because of their early usage as filter materials, values for the permeability of geotechnical fabrics are usually reported in conventional terms - that is, their ability to pass water under a simple hydraulic gradient according to Darcy's Law. The permeability coefficient,

$$k, = \frac{Q}{A} \frac{d\ell}{d\phi} ,$$

where Q is the volumetric rate of flow. A the cross-sectional area, ℓ the length of the flow path and ϕ the potential. Values so determined for commercial fabrics usually lie in the range of a coarse to fine sand ($1 \sim 10^{-2}$ cm sec^{-1}), (cf. Calhoun 1972, Bourdillon 1975, McGown 1976.)

This measurement method has two major deficiencies. First, it can only be an approximation for the ultrathin fabrics now available, and second - much more seriously - it is *not* the appropriate permeability for unsaturated soils. For such soils, Darcy's Law no longer holds.

A proper treatment of unsaturated soil water transmission is given by Richards (1974), but it is important to note also that in unsaturated soils the water films are often discontinuous and water movement can occur only by vapor phase transport or surface ion migration (Ingles & Grant, 1975). Vapor phase transmission across geotechnical fabrics can be measured, and the measurements recorded in terms of either the rate of water vapor transmission (grams day^{-1} m^{-2}) or the water vapor permeability (grams day^{-1} m^{-2} mm Hg^{-1} cm thickness) or best, as the water vapor permeance (grams day^{-1} m^{-2} $mmHg^{-1}$). The latter is called a metric perm, and standard methods of test are defined (ASTM, 1972).

The numerical values cited in this paper refer to the commercial fabric "Terra Firma" (Mirafi, Terram) whose Darcy permeability is 1.6×10^{-1} cm sec^{-1}. Its permeance has been measured by Ingles and Lawson (1976), and is 720 metric perms (or 47 perm cms as a water vapor permeability).

The substantial difference between saturated and unsaturated fabric permeabilities is thus obvious, and it remains only to consider in what circumstances either is the correct permeability to use in design.

For saturated soils, where saturation conditions apply on *both sides* of the membrane, the conventional (Darcy) permeability is appropriate. Such are the uses of fabric as a drainage blanket in earth dams or unsealed roads on a soft saturated subgrade. However, if both sides of the membrane abut *unsaturated* soil, the only correct measure of water transmission is the permeance. If one side abuts saturated soil and the other abuts unsaturated soil, the nature of the water transmission will depend on (a) the potential head across the membrane and (b) the wetting pressure of the membrane itself. Below the membrane wetting pressure permeance *is* the correct measure of transmission, whereas above the membrane wetting pressure permeability *may* be the appropriate measure depending on soil and hydraulic conditions. For the finer weave geotechnical fabrics permeance will be the correct measure in many constructional cases, such as fabrics protecting soil which supports structures, e.g. sealed road subbases, building pads, etc. This paper concentrates on such applications.

It is well known that soil is strongest in its dry condition. If a dry condition can be maintained, much greater bearing capacity can be utilized in structural design. It might be thought therefore that the best geotechnical fabric for roads, building pads, etc. is one which not only utilizes the reinforcing strength of the fabric, or its separation properties, but most particularly is impermeable (so as to preserve the dry soil strength). Wholly impermeable fabrics with the requisite tear strength are at present expensive and much stiffer (because thicker) than the permeable fabrics, causing problems of handling on a construction site. The fabric manufacturer should therefore consider whether he can produce a geotechnical fabric with a range of specified permeabilities (ranging from near impermeable to freely permeable) without sacrifice either of strength or of lightness and flexibility. (Lightweight is an obvious advantage, inasmuch as transport costs are heavy and increasing).

From the point of material economy alone, it is obvious that if a specific permeability is suitable to a specific construction task, it is wasteful and costly to use either a lesser or a greater permeability.

The Modification and Control of Fabric Permeability.

Fabric permeability can be modified commercially without incurring undue expense, and with good control of the product permeability, in two ways.

Both methods are concerned with control of the wetting angle , and hence the wetting pressure. The contact angle of water on the surface of the fabric threads substantially influences bulk water transport and surface ion migration. But many of the fibres in present use already have reasonably high water contact angles. Nevertheless, this situation can be further improved, namely by preferred weave orientation, and by fabric filament coating.

The practical nature of preferred weave orientation was elucidaded and demonstrated more than 30 years ago by Cassie and Baxter (1944) in a relatively unnoticed but highly significant paper. They showed both theoretically and experimentally that a material woven from paralled fibres, whose individual advancing contact angle was quite low (even as low as 55°), could be made to show a macro water-advancing contact angle greatly in excess of 90° - i.e. the fabric became water-repellent purely because of the fibre dimension and the inter-fibre spacing.

The Cassie & Baxter equation is

$$\cos\theta = f_1 \cos\theta_A - f_2$$

where $f_1 = \{\pi r/(r+d)\}\ (1-\theta_A/180^{\circ})$

and $f_2 = 1 - r\sin\theta_A/(r+d)$

for fibres of radius r and surface to surface separation 2d, θ_A being the advancing contact angle on the woven fabric. For example, a material with $\theta_A = 105^{\circ}$, and fibre radius 0.07 mms, when woven into a fabric with filament spacing 0.18 mms imparts a wetting angle of 145° to that fabric.

This type of approach does not appear to have been commercially exploited as yet.

The second method of permeability control, by fabric filament coating, has been investigated in this University.

Water transmission in all modes is curtailed either by increased water repellency of the fibre, or by reduced area of the inter-fibre voids, or by both. Neither from material economy or stiffness considerations is it desirable to use thick coatings, and the ideal situation is shown in figure 1, where the fabric mechanically protects the weaker waterproofing agent, whose only requirement apart from water-repellency will be durability to chemical or thermal changes.

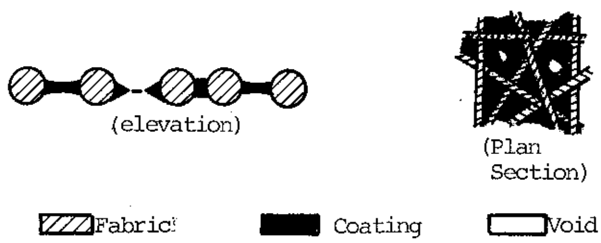


Fig. 1: Irregular spaced fibres, thinly coated.

This type of permeability control can be exercised most conveniently by saturation, a commercial technique similar to the dyeing of cloth - i.e. the fabric is passed through a bath of the appropriate impregnation reagent, excess reagent is drained or pressed off, and the treated fabric allowed to dry. Ingles and Lawson (1977) report a number of such treatments for permeability control of a multibonded heterofilament textile which, by virtue of the close spacing of the felted filaments, is particularly suitable for such modification of properties. Table 1 illustrates the degree of permeability control which can be achieved by suitable impregnation. It is noteworthy that coal tar is extremely effective. No doubt a search for other abundant, cheap reagents would be rewarding.

TABLE 1. WATER DIFFUSION PROPERTIES FOR VARIOUS COATED MEMBRANES.

Membrane Treatment	Permeance (metric perms or gm water/m^2 .24 hrs. mmHg at 23°C)	Membrane Thickness (cm)
Untreated	720	0.065
Colacid Cationic Emulsion - R.S.	38	0.070
Colas Anionic Emulsion - R.S.	110	0.070
SMK Cationic Cutter - M.S.	3.3	0.090
Sprayed In-Situ with Fluxed R90	80	0.50
KT 0.7 Coal Tar	8.9	0.090

The impregnation (saturation) technique can be adapted very easily to produce a fabric of any specified permeability, by modification either of the saturation reagent, or saturation time or temperature, etc.

A variant of the saturation technique would be to use a cheap synthetic filler which could bond with the fabric fibres. Though this is likely to give a less durable, and a stiffer product, without the degree of permeability control obtainable from bituminous materials, it should also be investigated.

The correct Choice of Fabric Permeability for Geotechnical Applications.

The following discussion deals principally with those cases where one face of the fabric is in contact with unsaturated soil, and for which the correct measure of permeability is the permeance. Typical examples are road subbases, levee banks, and building pads. Ingles and Lawson (1977) have discussed this situation theoretically and have demostrated its practical validity in respect of a fully encapsulated road subbase.

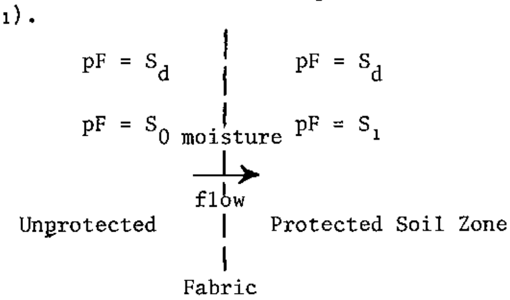
The design problem may be illustrated as in figure 2. Here the role of the fabric is to restrict water transfer from a zone whose soil suction (pF) fluctuates with time between some value S_d (the "dry" condition suction value, taken to be t = 0) at t = t_1, into another zone where the suction varies simultaneously between S_d (at t = 0) and S_1 (>0) at t=t_1. That is, the rôle of the fabric is *to reduce suction variation in a specified soil zone*. Since strength design is normally based on the lowest suction (pF) condition of the soil, reduction of the variation represents a considerable increase in the design strength that can be used (the steep relationship between suction and CBR, for instance, is shown by Richards, 1966).

It is now proposed therefore, that the design process for structures of the type referred to above, using a geotechnical fabric, should consist of the following steps:

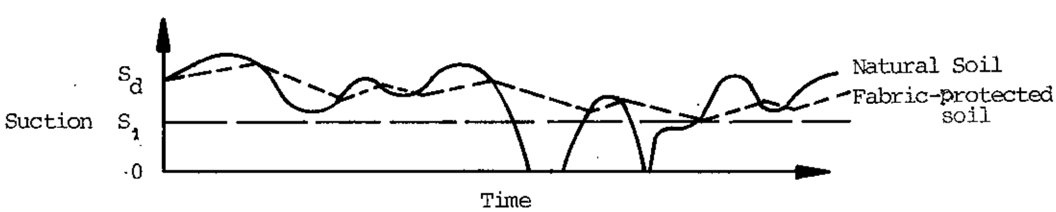
(i) determine a value for the equilibrium soil suction at the site at the time of construction (pF = S_d).

(ii) determine the 100 year return duration of inundation (or other period as appropriate to the expected life of the structure ......thus for roads a 20 year return period may be more appropriate). (t_{100} at pF = 0).

(iii) choose a suction value appropriate to the design and construction conditions. This value might be, for instance, the 1-year return period minimum suction, or less depending on the duration of the construction period and the risks involved from water advent during construction (pF = S_1).



(b)



(a)

FIGURE 2: Fabric-controlled Moisture Flow

(iv) neglecting end conditions* as small compared to the inundation period t_{100} (generally) true for arid and semi-arid environments), then $(S_d - S_1)/t_{100}$ is the suction gradient required of a separation fabric, if the protected soil is not to fall below the design strength. The suction differential must be measured in appropriate units, preferably using the scale of the (established) suction-moisture content curve for the particular soil.

(v) Calculate the permeance required by the above design constraints from the appropriate equation.

$$K = \frac{\gamma_d\ H.\ m(S_d - S_1)}{t_{100}\ (S_d - S_0)} \qquad .....(1)$$

where K is in metric perms, γ_d is the density of the soil, H the thickness of the protected zone and m a proportionality function describing the suction - moisture content relation over the appropriate range, $S_d - S_1$ (for $S_d - S_1$ small, m will be generally a constant.) In equation (1), γ_d and H are in grams m^{-3} and m respectively & $S_d - S_0$ must be expressed in mms Hg. Strictly, $(S_d - S_0)$ would be better replaced by $\left(\frac{S_d + S_1}{2} - S_o\right)$, but again for $S_d - S_1$ small, $S_d - S_0$ is a satisfactory and conservative approximation. Equation (1) also assumes a uniform distribution of the moisture in the soil mass, which can only be an approximation. A rigorous solution of the moisture flow equations can be applied, but for rapid practical purposes it will generally suffice to assume the worst conditions by selecting a thin H value, leading to a conservative design.

(vi) Using the calculated permeance, select an appropriate fabric for the structure from fabric permeance tables. If no suitable fabric is available, adjust the design suction (iii) above to yield a K value equal to the lowest K value fabric economically available.

An illustration of the above procedure is given in Appendix A.

The geotechnical fabric thus fulfils two functions - it serves to reinforce the soil, and it permits a higher self strength value to be used for the soil. This is important, because the reinforcing value of fabrics alone is very small (Harrison and Gerrard, 1972).

But more important than any of these considerations is the role of the fabric as an "insurance against random catastrophe", that is, when used in accordance with the design principles outlined above, the fabric fulfils the role of protecting the structure against rare events. (The inundation calculation could equally have been made for seismic events, etc.)

It remains only to note that the inundation calculation method has already been applied successfully to MESL road pavement constructions in inland Australia (Ingles and Lawson, 1977). and to levee bank construction (Ingles, unplished data) which is essentially a problem in slope stability.

In regard to structures subject to continuous saturation in the vicinity of the membrane, for example earth dams, canal linings, tanks and reservoirs, the design situation is quite different and generally depends on the bulk flow (hydraulic) of the fabric.

Where saturation of the soil is frequent but not continuous, careful judgment must be made as to the appropriate design measures. Drainage channels and shoulder drains provide one example - here the soil type and the need to discharge water in the manner selected will govern design methods and choice of fabric. Obviously, in dispersive clay soils, a fabric of low permeability is desirable, whereas in sandy soils a much higher permeability is acceptable as the role of the fabric is then solely to resist scour. Another example is the building pad. If the supporting soil is a soft mud, it may be sufficient to use the membrane simply as an interpenetration barrier between the mud and a layer of free-draining aggregate or rubble. If, however, the supporting soil is an expansive clay, it is important that the superimposed "raft" should restrict possible moisture changes in the subsoil, and a restricted permeability fabric becomes imperative. The design requirements can then be evaluated by procedures similar to those outlined for occasional inundations,: in this case calculating from the moisture change in the soil between wet and dry season at the appropriate depth and for the appropriate flow path (cf. Ingles and Metcalf, 1972, p. 294).

Conclusion

It has been confirmed here and in other work, both theoretically and practically, that permeability has an important, function in geotechnical constructions and that fabrics of controlled permeability can be readily manufactured.

The role of fabrics as an "insurance against rare events" is now emphasised, and a novel method of calculation for design described.

References

American Society for Testing Materials (ASTM) (1972) E 96-66 (reapproved 1972), 622-629.

Bourdillon, M. (1975) "Utilisation des Textiles Non-Tisses pour le Drainage". Dr. Ing. These, L'Universite Claude Bernard, Lyon.

Calhoun, C.O. (1972) "Development of design criteria and acceptance specifications for plastic filter cloths", U.S. Corps Engineers Waterways Expt. Stn. Tech Rpt 5-72-7.

* *'end conditions' refers to the saturation and desaturation times involved in passing from pF = S_d to pF = 0 and reverse. More accurate estimates can be made, if desired, from the meteorological records (cf. Ingles, 1976).*

Cassie, A.B. & Baxter, S. (1944) "Wettability of Porous Surfaces", Trans. Faraday Soc. 546-551.

Harrison, W.J. & Gerrard, C.G. (1972) "Elastic Theory applied to reinforced earth", J. Soil Mech. and Fdns. Div., A.S.C.E. 98 SM 12, 1325-1345.

Ingles, O.G. (1976) "Surface Catchment Tanks and Dams", Symposium on Water in Rangelands, CSIRO Division of Land Resources Management.

Ingles, O.G. and Grant, K (1975) "The Effect of Compaction on Various Properties of Coarse Grained Sediments", in "Compaction of Coarse-Grained Sediments I" Elsevier, Amsterdam, 293-348.

Ingles, O.G. and Lawson, C.R. (1977) "MESL - A new appraisal", 9th Int. Conf. Soil Mech. and Foundation Engineering, Tokyo (in press).

Ingles, O.G. and Metcalf, J.B. (1972) "Soil Stabilization", Butterworths, Sydney.

McGown, A. (1976) "The properties and uses of permeable fabric membranes" in Materials and Methods for low cost road, rail and reclamation work" Sellen's, Sydney 663-709.

Richards, B.G. (1966) "Moisture Flow and Equilibria in Unsaturated Soils for shallow foundation", ASTM Symposium on Permeability and Capillarity of Soils, STP 417, 4-34.

Richards, B.G. (1974) "Behaviour of Unsaturated Soils", in "Soil Mechanics, New Horizons", Butterworths, London, 112-157.

Appendix A

An illustration of the design calculation for sporadic inundation protection is as follows.

Assume t_{100} = 90 days (ex meteorological data) and the protected thickness 15cms.

Assume the soil to have a suction curve, measured experimentally, as shown in fig. 3 (this is a normal shape for a medium heavy clay soil). In the suction range near pF 4, 1% change in moisture content is equal to 0.1 pF unit change.

Assume the S_d value at the site is found to be pF4.2, then S_1 will be pF4.1 Values can be related to vapor pressures by the equation.

$$pF = 6.502 + \log\log {}^{P}o/_{p} \quad \text{(Richards, 1974)}$$

having regard to the sign of the suction, and where p, p_o are the vapour pressures of water vapour above the soil and over free water at the same temperature, respectively.

Substituting into equation (1), remembering that $m(S_d - S_1) = .01$ and $S_d - S_0$ calculated for 30^oC and pF4.2 according to vapour pressure tables is 0.364 mms Hg, for a soil density of 2.0 gm cm^{-3}, yields:-

$$K = \frac{2 \times 15 \times 0.01}{90 \times .364 \times 10^{-4}} = 91.6 \text{ gms m}^{-2}\text{day}^{-1}\text{mmHg}^{-1}$$

Comparison with table 1 shows that four alternative treatments of the fabric would appear to meet the specification, but calculation for a 33^o temperature indicates that the sprayed in-situ treatment would fail to meet the amended valve required.

Because the calculation is thus rather sensitive to temperature, it is important to either (a) calculate for the highest in-service temperatures expected or (b) apply a safety factor suitable to the construction. It is suggested that a suitable safety factor should be about 2.0, since it is unlikely that inundation could possibly coincide with extremely high temperatures in the soil.

In the present example, the specified permeance would therefore be 46 metric perms, which is met by three alternative treatments.

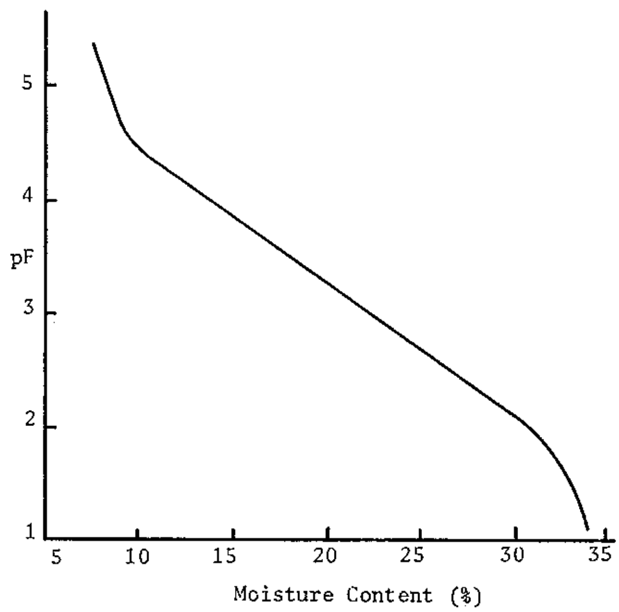


Figure 3: Suction - Moisture Content Curve (general shape, clay soil)