Improving the Efficiency of Slow Sand Filtration with Non-woven Synthetic Fabrics

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Both the extent of application and satisfactory operation of slow sand filters in the UK and developing countries have been limited in part by the difficulty and cost of filter cleaning. A recent innovation for improving both the performance of the slow sand filter and the cleaning operation involves the placing of a non-woven synthetic fabric layer on the top surface of the sand bed to concentrate the purification process. Preliminary pilot-plant studies within the last five years are reviewed in this paper together with the development of a theoretical interpretation of the physical properties required by the fabric for optimal treatment performance.

In the UK, slow sand filtration is an important potable water treatment process. A nationwide survey published in 1980(1) indicated that some 27.6% of the total output from water treatment plants is treated by slow sand filtration, either as the sole filtration process or in combination with rapid filters. In the Thames Water Authority region in particular, more than 70% (approximately 2,000$\mathrm{Mld^{-1}}$) of water treatment capacity involves slow sand filtration as a secondary treatment process(2). Traditionally, slow sand filters operate at low filtration rates, 0.1 to 0.2$\mathrm{mh^{-1}}$, which have been shown to ensure a very high degree of physical and biological quality improvement. However, there is currently considerable interest being shown in ways of increasing the filtration rate of slow sand filters and in improving their operational performance generally(2). In particular, the Thames Water Authority(2) estimates that over 70% of the direct operation costs for slow sand filters are associated with filter cleaning and resanding, and it has concluded that reducing the average frequency of filter cleaning and resanding could reduce operating costs significantly.

The potential benefits of employing synthetic fabrics with slow sand filtration were first considered seriously in 1982 in parallel collaborative research projects by Imperial College, London and Surrey University(3, 4); these will be discussed later. Broadly, these and subsequent studies since 1982(5-7) have provided experimental evidence to show that the application of a layer of non-woven fabric on top of the sand media in a slow sand filter can extend substantially the filter run time. Laboratory and pilot-plant studies are continuing at Imperial College in order to define the optimal specification for the fabric and to quantify the extent of the consequential benefits to the filtration process.

Properties of synthetic fabrics

The term 'synthetic fabrics' refers to man-made textiles in the sense that components which form the textile (ie, fibres, webs or yarns) are produced artificially in contrast to, say, cotton textiles whose fibres are produced by natural processes. In general, synthetic fabrics can be subdivided into wovens, non-wovens and composites; the latter refers to a fabric made up of a combination of both woven and non-woven elements. The term 'non-wovens' has been the subject of much descriptive controversy in the context of limits of its applicability in classification, as pointed out by Shoemaker(8), Sandstedt(9) and Purdy(10). The term 'woven' includes all synthetic fabrics made from yarns or tapes which are in turn made up of several fibres. All synthetic fabrics produced by weaving or knitting fall into this category and, occasionally, some fabrics made by a combination of the two processes are also regarded as wovens. Since the majority of woven fabrics made from tapes or mono-filament yarns are very thin (usually less than 1.0mm) they are not considered appropriate for application with slow sand filters.

Non-wovens can be divided into three product categories according to the production techniques.

Wet laid. The first category is the 'wet-laid' type whose production involves water extraction, drying and rolling of a dispersion of synthetic fibre staples in water. Binders are or can be added at convenient stages of the production.

Dry laid. The second category is the 'dry-laid' type which includes the largest and most diversified products. Its production involves the formation of webs by carding or air laying and subsequent subjection to either needle-felting, jets of high pressure water on an anvil screen (spunlaced), saturation or spraying with an aqueous resin.

Spun bonded. The third category, the spunbonded type, involves quite novel production methods in which a bulk thermoplastic polymer is converted to fibre form by melt-spinning using synthetic fibre technology. Bonding can be invariably accomplished by heat, pressure and/or chemical activation. It should be noted that commercial non-woven fabrics exist which are thermally bonded and needle-felted or spunbonded and needle-felted.

The fibres of synthetic fabrics consist of polymers of organic compounds made up of long, chain-like molecules with repeating molecular units linked by covalent bonds. The process of polymerisation, in which small molecules of the monomer undergo chemical reactions to form long chains, may proceed in a variety of ways, but addition and condensation polymerisation are the principal categories. Although many polymerisation reactions exist at laboratory scale, only a few of them are employed in the commercial production of synthetic fibres(11). The principal synthetic fabrics produced at present are made of polyester, polyethylene, polypropylene, polyamide or vinyl polymers.

The lack of consistency in testing methods makes it difficult to compare the properties of any type of textile fabrics with others solely on the basis of the specifications of individual manufacturers. According to Ruddock(12), although properties within one polymer group can vary widely, in general polyamides tend to show significantly greater mechanical strength than other materials. Billmeyer(13) suggests that the water absorption capacity of most synthetic fabrics is generally small, with the exception of polyamide (Nylon – 6.6). Canon(14) has indicated that in general polyesters are highly susceptible to attack by alkalis and polyamides to acids, while in contrast Billmeyer(13) ranks polyvinyl chlorides and polyethylene as two of the most resistant fabrics to either acids or alkalis. Polypropylene is also highly resistant to most acids, alkalis and oxidising agents used in potable water treatment practice(15, 16) and since the melt-spun polypropylene fibre is free from polar groups it has a good fibre stain resistance(16). Polypropylene also has a high resistance to dry heat(15) and to UV light degradation when stabilised (14, 15). Acrylic binders used in some manufacturing processes are suspected of being subject to irreversible biochemical attacks(15) and therefore fabrics bonded with such resins should be used with care.

A recent survey by the authors of a selection of commercial non-woven synthetic fabrics has demonstrated a wide range of physical properties as shown in Table 1.

Mode of action

It is well-known that the process of purifying contaminated influent waters by slow sand filters is principally localised in the top 2 to 3cm of the sand bed(17) although there is evidence that turbidity and bacteria are removed throughout the whole depth of the filter(4, 18). The high particle capture efficiency of the filter media arises from the relatively low filtration rates (0.1-0.2m/h) and small sand grain size (effective size, 0.30mm) in accordance with classical filtration theory(19). The accumulation of captured inert solids and micro-organisms, together with the growth of biological populations, gives rise to increasing hydraulic resistance to flow manifested as an increasing process pressure head loss. Once the process head loss limit is reached, the filter will no longer be able to maintain the specified flow rate and removal of the top sand layer for cleaning is required.

The rationale of applying a non-woven fabric layer on the top surface of the sand filter is to concentrate the major part of the purification process within the fabric layer instead of within the top layers of the sand. The speculated benefits arising from this are two-fold:

☐ The simplification of the filter cleaning by the removal and washing of the fabric alone;

☐ The extension of filter run times by a lower rate of pressure head loss development within the fabric.

For small-scale filter units, the relative simplicity of the filter cleaning operation with a fabric layer is clear and recent evidence from experimental filter plants of unit areas up to 28$\mathrm{m^2}$(3, 4) have demonstated this. This aspect is of particular significance with the use of small-scale slow sand filters in rural water supplies in developing countries and the need to reduce maintenance requirements. For medium-to-large scale filter units the aspects of fabric removal and cleaning has not yet been seriously studied.

The structural properties of non-woven as indicated in Table 1, suggest that a considerably more efficient filtration medium than sand may be available and employed. As will be seen subsequently, the porosity, fibre diameter and specific fibre surface area, in particular, determine the filtration performance and permeability of the fabric medium. By careful selection of these properties, a fabric which gives an optimal filtration performance may be chosen.

Theoretical aspects

The following theoretical descriptions are limited to the performance of filter media in the absence of biological effects.

For a given fabric layer with an assumed single uniform fibre of circular cross-section, it can be shown that the fabric porosity is related to the specific surface of the fibres by the fibre diameter:

$$\varepsilon_o = 1 - (d_f s_o/4) \qquad (1)$$

Fig 1 shows this relationship for typical fibre diameters and the corresponding values for the commercial fabrics mentioned in Table 1. For comparison, Fig 1 also shows the region of typical values of porosity and specific surface for sand media in slow sand filters. The specific surface for sand media is determined from the theoretical expression:

$$s_o = 6\,(1 - \varepsilon_o)/\psi\, d_s \qquad (2)$$

In general, the two important properties of any filter medium are its 'permeability' and 'filterability'. The permeability, as defined in Darcy's Law, is a measure of the medium's resistance to pore water

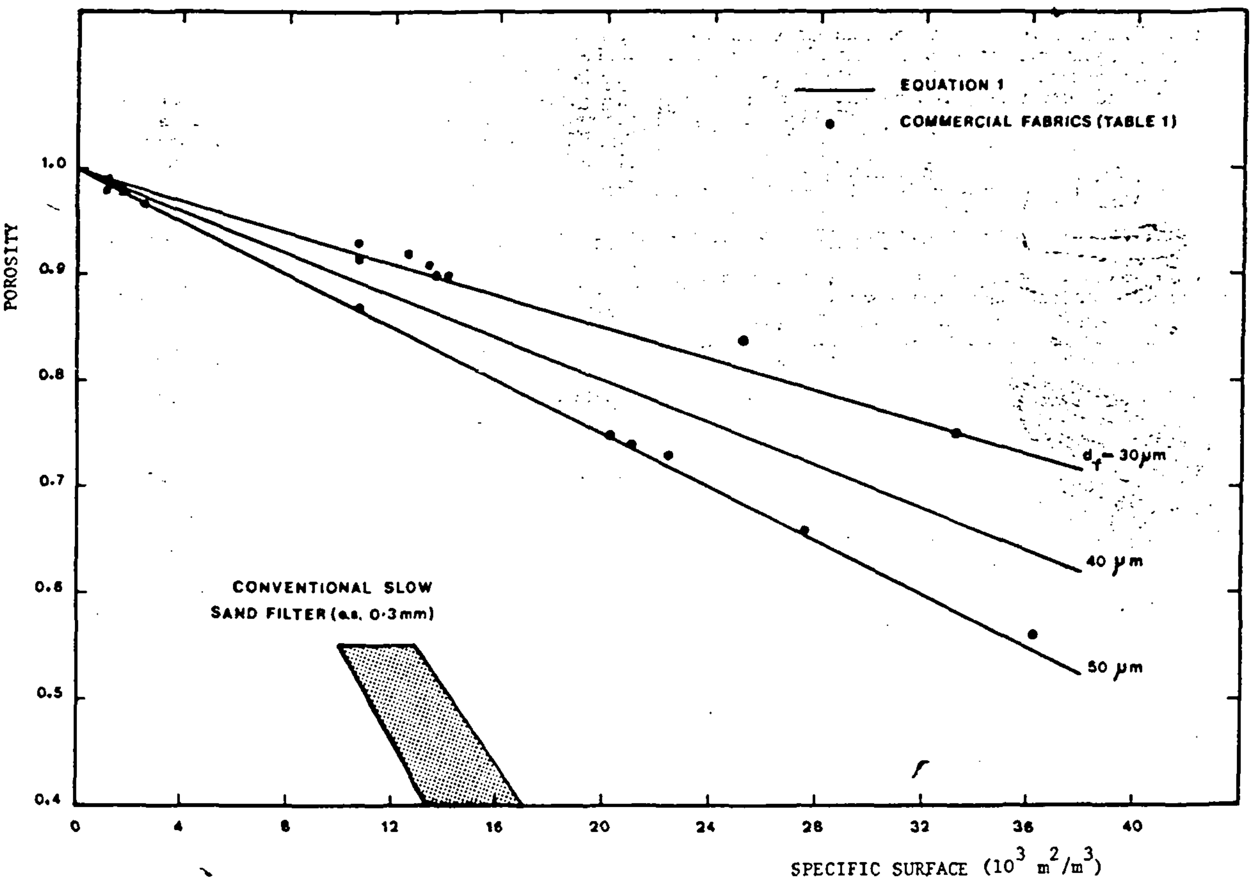


Fig 1. Relationship between porosity and specific surface for fabric media

flow, whilst the filterability is some measure of the ability of the medium to retain influent particle mass.

Fabric permeability. For deep bed granular media, the permeability can be expressed mathematically in terms of the properties of the media by combining the Kozeny-Carman equation and Darcy's equation:

$$K = (g/k^1\upsilon)\,(\varepsilon_o{}^3/s_o{}^2) \qquad (3)$$

The Kozeny-Carman filter constant, k^1, is relatively unchanging for many granular media ($k^1 = 4.5 \pm 1$ ⁽²⁰⁾) and a value of 4.5 is commonly adopted for beds of spherical grains. For media of high porosity such as fibrous media ($\varepsilon_o > 0.7$) Kozeny's equation does not apply and theoretical values of k^1 increase rapidly with porosity. This can be seen in Fig 2 where experimentally determined values of hydraulic conductivity (K) for various selected fabrics are plotted with corresponding values of the parameter ($\varepsilon_o{}^3/s_o{}^2$). Details of the selected fabrics are given in Table 2.

Theoretical values for the permeability of fibrous media may be determined by employing one of various cell models. The models of Happel(21) and Kuwabara(22) in particular are based on the assumption that fibres are randomly orientated in a transverse plane to the fluid flow and produce explicit expressions for the permeability in terms of the fibre size and media porosity. In the case of Happel's model:

$$K_h = d_f{}^2\,[-\ln\gamma - (1-\gamma^2)/(1+\gamma^2)]/32\gamma \qquad (4)$$

where K_h is the permeability factor (= K υ/g)
and γ is the fibre volume fraction (= $1-\varepsilon_o$)

This expression is shown in Fig 3 for three fibre sizes together with experimentally determined values for K_h for the fabrics detailed in Table 2.

Head loss development. *As the filtration process proceeds, the*

Table 1. Physical properties of 20 selected commerical *non-woven synthetic fabrics**

Property	Maximum	Minimum
Thickness (mm)	20	0.36
Porosity (calculated)	0 99	0.56
Fibre diameter (µm)	48	27
Bulk density (g/cm³)	0 40	0.02
Specific surface area† (m²/m³)	36.3 × 10³	1 1 × 10³

* Data provided and/or calculated from suppliers' information
†Total fibre surface area per unit fabric volume

Table 2. Commercial fabrics selected for experimental study

Fabric	Material	Fibre size (µm)	Porosity
1	PP.	39 2 55.5	0.56
2	PP	27.9-30 5/41.4	0.75
3	PP/PET	40	0.75
4	PP	48	0.87
5	PE	30	0 90
6	PP	27.9 30 5/41.4	0 90
7	PE	27 3	0 92
8	PP	29	0 92
9	PE	27.3	0 93
10	PE/PVA	39 6	0 97
11	PE/PVC/PA	50/40/40	0.98

PP	– Polypropylene	PA	– Polyamide
PET	– Polyethylene	PVA	– Polyvinyl acetate
PE	– Polyester	PVC	– Polyvinyl chloride

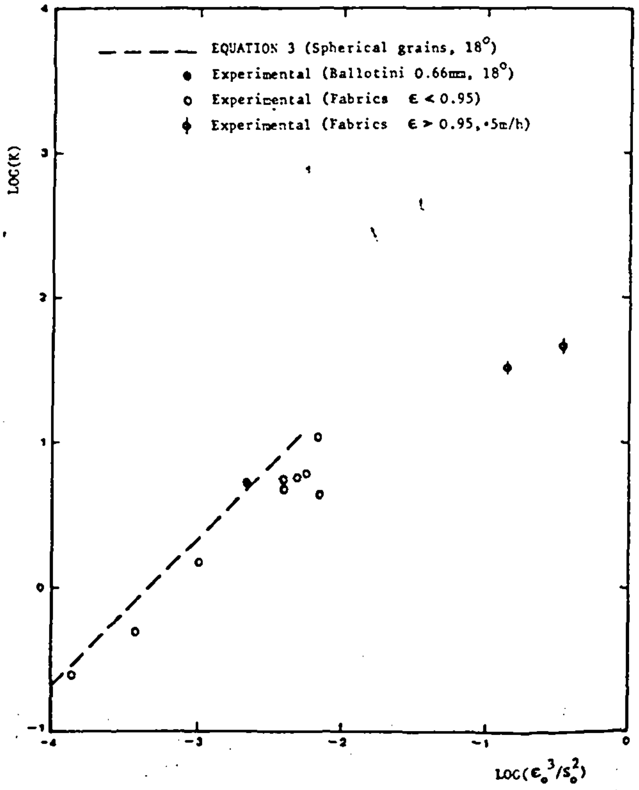


Fig 2. Relationship between hydraulic conductivity (K, mm/s) and the media parameter $\varepsilon_o{}^3/s_o{}^2$ (mm²) for granular and fabric media

accumulation of deposited material gives rise to an increasing resistance to flow. The head loss gradient for granular media has been shown already (equation 3) to be a function of the specific media surface area and the media porosity, both of which alter during filtration. Ives(19) has indicated a theoretical expression for the head loss gradient during filtration in terms of the specific deposit, σ, as follows:

$$\left(\frac{\partial H}{\partial L}\right)_t = \left(\frac{\partial H}{\partial L}\right)_o \left(1 + \frac{b\sigma}{\varepsilon_o}\right)^z \left(1 - \frac{\sigma}{\varepsilon_o}\right)^y \qquad (5)$$

where b is the media packing constant $(= \varepsilon_o/(1-\varepsilon_o))$.

For the special case where $z = 2$, $y = -1$, Ives was able to show that to a first approximation (particularly when $\sigma \ll \varepsilon_o$):

$$\left(\frac{\partial H}{\partial L}\right)_t = \left(\frac{\partial H}{\partial L}\right)_o \left[1 + \left(2b+1\right) \frac{\sigma}{\varepsilon_o}\right] \qquad (6)$$

This relation has also been proposed from empirical observations(23).

The rate of head loss developed can in turn be approximated from equation (6):

$$\frac{d}{dt}\left(\frac{\partial H}{\partial L}\right)_t = \left(\frac{\partial H}{\partial L}\right)_o \left(\frac{2b+1}{\varepsilon_o}\right) \frac{d\sigma}{dt} \qquad (7)$$

Writing the media packing constant in terms of porosity gives:

$$\frac{d}{dt}\left(\frac{H}{\partial L}\right)_t = \left(\frac{\partial H}{\partial L}\right)_o \frac{(1+\varepsilon_o)}{\varepsilon_o(1-\varepsilon_o)} \frac{d\sigma}{dt} \qquad (8)$$

Thus, in qualitative terms it can be seen that for two filter media with similar particle capture efficiencies their comparative rate of head loss development is inversely related to the magnitude of their clean bed porosities (and directly related to their initial head loss gradients).

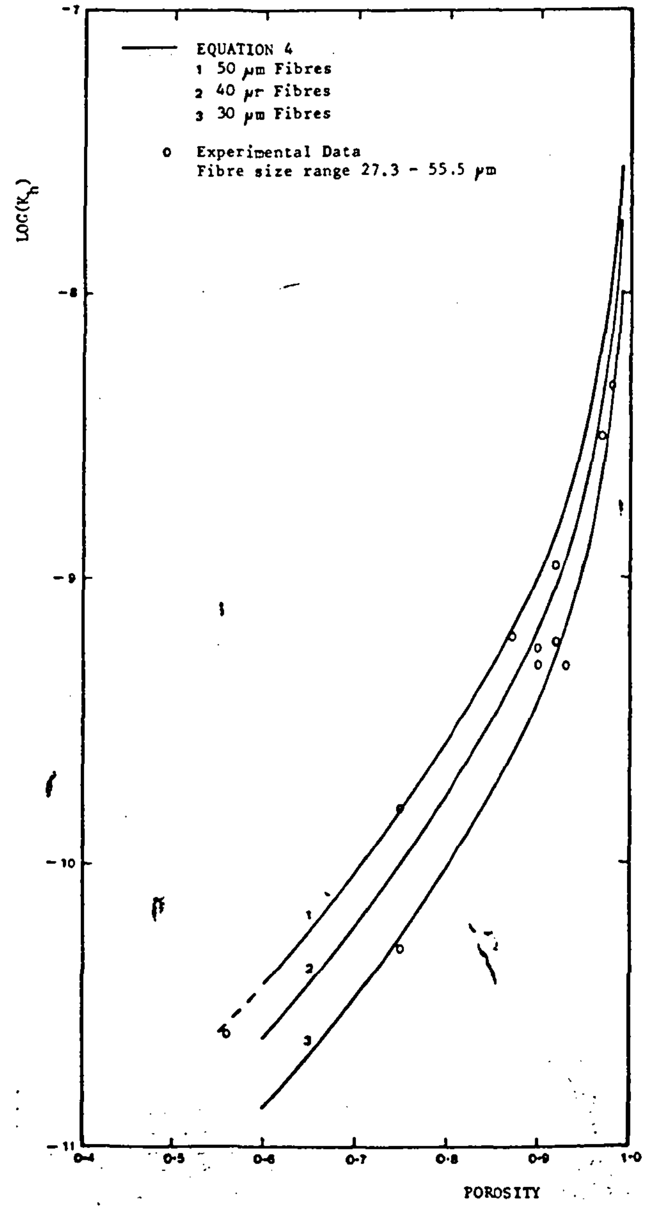


Fig 3. Theoretical and experimental relationship between permeability factor (K_h, m²) and porosity for fabric media

Fabric filterability. The filterability of a filter medium refers to the ability of the medium to remove particles from a flowing suspension. For granular media, and particularly under 'clean' conditions at the commencement of filtration, simple theoretical models for the filtration process are well established. The fundamental theoretical hypothesis is that the removal of suspension (n) with respect to depth in the filter is first order:

$$-dn/dL = \lambda n \qquad (9)$$

The equation assumes that initially every layer of the filter is equally efficient at removing particles from suspensions, and that in every layer *the suspension entering it and leaving it is uniformly* dispersed and unchanging in nature. For a filter of uniform fibres a simple theoretical approach considers the collection efficiency of a single fibre. Thus, the overall filter performance is related to the single fibre collection performance by equating the difference in particle concentration entering and leaving to the net collection by all the fibres in a differential depth dL of the filter, thus:

$$-v\,dn/dL = I\,(4\gamma/\pi d_f^2) \qquad (10)$$

where I is the average rate of collection of entrained particles per unit length of fibre.

If isolated particle-fibre encounters are predominantly responsible for particle removal, I is directly proportional to n and it is convenient to introduce the dimensionless single fibre efficiency η_f defined as:

$$\eta_f = I\,(d_f vn)^{-1} \qquad (11)$$

Then η_f is independent of particle concentration and substitution of equation (11) into equation (10) to eliminate I gives:

$$-dn/dL = (4\gamma\,\eta_f/\pi\,d_f)n \qquad (12)$$

The single fibre collector efficiency can be considered as the product of the overall single fibre collector transport efficiency, η, and the particle-fibre attachment efficiency, α.

Hence:

$$-dn/dL = (4\gamma\,\eta\,\alpha/\pi\,d_f)n \qquad (13)$$

Thus, from equations (9) and (13) the filter coefficient λ can be expressed as:

$$\lambda = 4\gamma\,\eta\,\alpha/\pi\,d_f \qquad (14)$$

Equation (14) can be simplified by expressing the filter coefficient *in terms of the specific surface of the fibres via equation (1):*

$$\lambda = s(\eta\alpha/\pi) \qquad (15)$$

From this equation, it would appear that the filtration coefficient is simply dependent on the specific surface of the fibres. However, experimental evidence and more detailed theoretical considerations *of particle trajectories has shown that λ is also dependent on the flow* velocity, fibre diameter, and particle size and density; this may be explained as follows.

For suspension particles of diameter > 1μm passing vertically downwards through a fabric layer, the classical theoretical transport mechanisms of most significance are interception and sedimentation. *Based on a single cylinder model the respective transport efficiencies* are (as summarised by Spielman(24)):

Interception –

$$\eta_I = 2\,A_F\,(d_p/d_f)^2 \qquad (16)$$

provided $d_p/d_f < 0.1$.

Sedimentation (codirectional) –

$$\eta_s = (1 + d_p/d_f)\,v_s/v \qquad (17)$$

where v_s is the Stokes settling velocity of the particle.

The combined effect of these two mechanisms is usually approximated by assuming addivity, hence:

$$\eta = \eta_I + \eta_s \qquad (18)$$

Thus, in qualitative terms the transport efficiency increases with particle size (and density) and decreases with flow velocity and fibre size.

The attachment efficiency, α, is currently considered to be determined by the net effect of van der Waals attraction force between particles and fibres, and resistive forces. The resistive forces arise from the electrical double layer interaction of the charged surfaces of the particles and fibres (the same sign), and viscous fluid forces when the separation between a particle and a fibre is of the order of one particle diameter.

Previous research studies

Experimental studies of the performance of slow sand filter units with non-woven fabric layers have been carried out within the last five years and mainly by research groups at Imperial College, London and the University of Surrey (Table 3). Until the work of Bridges(6) began to compare directly the performance of different types of fabrics, the choice of fabric for study had been largely empirical. Moreover, two types of fabric have now become integral components in two operational package slow sand filter systems without a full comparative assessment of alternative materials and multi-layer configurations being carried out; this is the subject of current research at Imperial College.

Filter run times. Three separate studies have carried out experimental trials of a slow sand filter with a fabric layer in parallel with a reference filter (no fabric). Wheeler *et al.*(4) considered the performance of two layers (28mm total thickness) of a high porosity material (≃ 98%) and found that the average filter run time was 16.7 days as compared to 5.2 days for the reference filter (improvement factor of 3.2). The Water Research Centre(7) also considered a high porosity fabric (≃ 97%) and found that a single layer (15mm thickness) increased the average filter run time by a factor of two when compared to the reference filter. Most recently, Bridges(6) has made a preliminary, parallel study of five different fabrics (single layer) and his results are shown in Table 4. Again, the results indicate that for the three fabrics with significant thickness (> 4mm) an increased filter run length can be achieved by the presence of a fabric layer. In all three studies, the filtration rate was in the range 0.24 to 0.34m/h.

Particle (silt) retention. It has been stated earlier that a principal objective in using a fabric layer is to move the location of the purification process from the top layer of sand into the fabric. Consequently, the fabric filtration properties must be such that particle penetration through the fabric and into the sand must be minimised. In each of the experimental studies detailed in Table 3, particle penetration through the filter and into the sand was reported and generally it was the pressure head loss resulting from particle deposition in the sand that terminated each filter run. The Water Research Centre(7) reported that at the end of each filter run (ie at limiting head loss) the same extent of material penetration into the sand had occurred (≃ 50mm) for the filter with fabric and the reference filter. The penetration of particles is not surprising since, with the exception of the study by Bridges(6), all the previous studies have employed high porosity, low specific surface fabrics that would be expected to have a low particle capture efficiency. Wheeler *et al.*(4) measured the amounts of solids deposited (silt) in the two layers of fabric and in the top 2cm of sand of an experimental slow sand filter and found that approximately 44% (by volume) of the total solids retained had penetrated and deposited in the sand. In later work, with six equal layers (90mm thickness) of a high porosity fabric, Wheeler *et al.*(5) showed that over 80% of solids retained by the multilayer fabric were retained in the top layer alone and 99% in the top two layers. In the same experiment Wheeler *et al.* also reported a similar degree of solids penetration into the sand (47% of total silt extracted from fabric and top 5cm of sand), Notwithstanding the appreciable amounts of accumulated solids within the fabrics during filtration, both Wheeler *et al.*(4) and Bridges(6) reported negligible flow resistance (head loss) across the fabrics at the end of each filter run.

Overall purification performance. The Water Research Centre(7) in its study reported that over a three month period of filter testing there was no significant difference in overall treatment performance between the filter with fabric and the reference filter in terms of mean turbidity and mean UV absorbance. Bridges(6) also reported identical reductions in turbidity for his reference filter and the five parallel filters with fabrics. Overall bacterial removals (Presumptive *Escherichia coli* and 37°/48h Plate Count) during the two filter runs were similarly equivalent in Bridges' study although it should be noted that influent concentrations were low and the reference filter consistently achieved > 99% *E. coli* removals after maturation. However, recent work by Wheeler(18) has demonstrated significant micro-biological

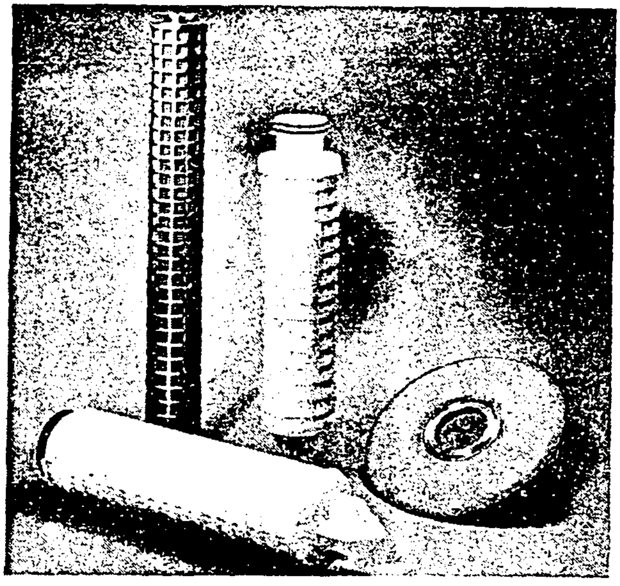
Table 3. Previous experimental studies with non-woven fabrics

Reference	Date	Details of Fabric	Size of filter unit (m^2)
Liversidge(3)	1982	one layer t = 14 s = 1671 ε = 0 98 PE PVC/PA-RSPB	28 3
Wheeler *et al* (4, 5)	1982/3	(i) Two layers t = 28 s = 1671 ε = 0 98 PE PVC/PA-RSPB	0 8/1.5
		(ii) Six layers t = 90 s = 2545 ε = 0 97 PE PVA-RSPB	1.5
Water Research Centre(7)	1984	One layer t = 15 s = 2546 ε = 0.97 PE PVA-RSPB	2 0
Wheeler(18)	1984/5	Three layers t = 45 s = 2545 ε = 0 97 PE/PVA-RSPB	1 5
Graham(25)	1985	One layer t = 14 s = 1671 ε = 0.98 PE/PVC/PA-RSPB	28.3
Bridges(6)	1985	(i) One layer t = 14 s = 1671 ε = 0.98 PE/PVC/PA-RSPB	1.5
		(ii) One layer t = 0 5 s = 17600 ε = 0 78 PP/PET-TB	1.5
		(iii) One layer t = 0 95 s = 25179 ε = 0 84 PP-NF/TB	1.5
		(iv) One layer t = 4.5 s = 10609 ε = 0.87 PP-NF/CT	1.5
		(v) One layer t = 8 s = 10615 ε = 0 82 PP-NF/CT	1 5

t – overall thickness of fabric layer (mm)
s – specific surface (m^2/m^3)
ε – porosity
PE – polyester
PVC – polyvinyl chloride
PA – polyamide
PVA – polyvinyl acetate
PP – polypropylene
PET – polyethylene
RSPB – resin spray bonded
TB – thermic bonded
NF – needle felted
CT – needle felted on carrier thread

Table 4. *Filter run times from the study by Bridges*(6)

Fabric	Porosity	Thickness (mm)	Run length (days) Run 1	Run length (days) Run 2
Reference	—	—	10.2	7.0
1	0 78	0.5	8 8	6.9
2	0.84	0 95	8.6	7.0
3	0.87	4.5	11.0	8 0
4	0 82	8.0	14.2	9 6
5	0 98	14.0	11.4	10.6



purification by three layers (45mm thickness) of high porosity fabric placed on an experimental slow sand filter. Using faecal bacteria and bacteriophage as indicator organisms (Table 5) Wheeler was able to follow their removal with depth through the fabric and sand layers.

Bridges(6) in his pilot-plant study used water taken from large storage reservoirs as his influent supply. Such water contains appreciable quantities of phytoplankton (eg algae) and his work included the determination of chlorophyll 'a' concentrations in raw and filtered water samples. Once again, the reduction in concentration of this parameter through the reference filter was so high (≃ 95%) that possible additional improvements through the use of fabrics could not be adequately quantified.

Fabric biology. The existence of biological populations within a mature slow sand filter is widely understood but only a small amount of information exists on the detailed nature of these populations and their behaviour. In particular, Lloyd(26) has identified various microfaunal groups in two pilot scale slow sand filters using a special sand profile sampler, and Bellinger(27) has considered algae in slow sand filters and has identified common species in the supernatant water and associated with the sand bed.

Evidence of the existence of micro-organism populations in fabric layers is scanty at present. The Water Research Centre(7) has reported the existence of various algal species in a high porosity fabric and these species were generally the same as found in a parallel reference filter without fabric on the same days. Wheeler(18) has identified the presence of Protozoa, Rofifera and Annelida within multiple fabric layers on a pilot-plant slow sand filter. The most commonly identified protozoa were members of the Vorticellidae, Tetrahymenina and the Oxytrichidae species of ciliated protozoa and their population densities were dispersed throughout fabric layers. From this and other experimental data Wheeler has concluded that the fabric under study seemed to provide a more favourable environment for ciliated protozoa than sand alone.

Fabric cleaning. Recent experience with high porosity fabrics(3, 7, 25) has found that the cleaning of fabric layers by manual hosing presents no difficulties, even when appreciable algal growth had occurred(3, 25). However, care is required when removing these fabrics in order not to disturb silt deposited within the fabric which will then enter the sand layer. For less porous fabrics, Bridges(6) has reported difficulties in fabric cleaning by high pressure hosing when a substantial zoogleal film had developed within the fabric. This aspect is also under study currently at Imperial College.

Discussion

It is postulated that the application of a non-woven fabric layer with optimal properties can considerably improve the process efficiency and operational requirements of conventional slow sand filters. The process efficiency can be considered as improved if the rate of head loss development is reduced (longer filter run times) whilst maintaining the same filter water quality and/or the filter water quality is increased for the same filter run time. It is clear from theory that both the permeability and filterability of a fabric are dependent on the structural properties of the fabric, of which the principal properties are the porosity, specific fibre surface area and the fibre size. Simple theory suggests (in the absence of biological effects) that in relative terms a fabric with a high porosity will have a high permeability and a low rate of head loss development by particle deposition. Similarly, a high specific surface area should give a high filterability. On the basis of information provided by suppliers of non-woven fabrics, particular fabrics may combine porosity and specific surface values significantly higher than typical values for conventional sand media. Such fabrics therefore offer the potential for significantly increasing process efficiency. By optimising the filterability value and depth of the fabric it may be possible substantially to limit the passage of solid material (silt) through the fabric and into the sand. If this can be achieved, then routine filter cleaning involves the removal and washing of the fabric only. In principle, this would represent a significant improvement in the operational requirements for the process but caution is necessary since in practice there may be appreciable difficulties with fabric handling and washing.

The results of pilot-plant tests reported to date have shown that an optimal fabric type and thickness has not yet been found. With the exception of the most recent study by Bridges(6), all other studies have considered the performance of very high porosity (> 97%) but low specific surface area (< 2,545m^2/m^3) fabrics which were, predictably, unable to prevent solids penetration into the sand media. Fabrics with a thickness and specific surface area greater than, or equal to, the typical 'active' sand layer (ie approximately 20-30mm, 15,000m^2/m^3) on a conventional filter are necessary to capture the bulk of the solids loading. Nevertheless, the presence of one or two layers (15-30mm) of low specific surface area fabric can retain appreciable quantities of influent solids. This can substantially improve process efficiency by increasing filter run times by factors of 1.3-3.2. The observed removal of certain indicator bacteria and viruses in such fabrics may also be the result of filtration mechanisms although the reported presence of bacterial-feeder organisms (eg ciliated protozoa) is likely to be an important contributing factor. The attempt by Bridges(6) to compare directly the performance of five, widely differing fabrics was not able to produce conclusive results since one important parameter – fabric thickness – was not made constant. However, his results did indicate that very thin fabric layers (< 1mm), even of high specific surface area, do not improve process efficiency.

Current work at Imperial College is concentrating on identifying the structural properties of a wide range of commercial non-woven fabrics and matching these to experimentally-determined permeability and filterability values. On the basis of this, subsequent pilot-plant tests will be undertaken with selected fabrics in order to identify those fabrics that optimise the slow sand filter performance and to quantify the magnitude of the process improvements.

Table 5. Removal of specific micro-organisms by triple fabric layer(18)

Microbiological Indicator	Reduction in concentration across triple fabric layer (%)†
Faecal Coliforms	51
Faecal Streptococci	41
Bacillus licheniformis bph*	54
Enterobacter cloacae bph	36
Serratia marcescens bph	46
T. coliphage	[illegible]
Erwinia carotovora	77

*bph – bacteriophage
†actual concentrations not available

Nomenclature

A_F	Cell constant
b	Media packing constant
d_f	Fibre diameter
d_s	Filter grain diameter (by sieve)
g	Gravitational acceleration
H	Pressure head loss
I	Average rate of collection of entrained particles per unit fibre length
K	Hydraulic conductivity
K_p	Permeability factor
k'	Carman-Kozeny filter constant
L	Media depth
n	Particle number concentration
s	Specific surface of media per unit bed volume
s_o	Specific surface (clean media)
v	Superficial velocity of flow
v_s	Stokes settling velocity for a particle

Greek

α	Particle-fibre attachment efficiency
γ	Fibre volume fraction
ε	Porosity of media
ε_o	Porosity of clean media
η_f	Single fibre collection efficiency
η	Single fibre collection transport efficiency
η_I	Interception transport efficiency
η_s	Sedimentation transport efficiency
λ	Filter coefficient
υ	Kinematic viscosity
σ	Specific deposit
ψ	Sphericity index

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