CHAPTER 1

An Introduction to Filter Media

The process of filtration is widely used throughout industry, commerce and domestic life. It covers the production of potable water by reverse osmosis, through the protection of delicate components from the impact of large solid particles, and the clarification of beer, to the separation of waste sewage sludges. Filtration involves the physical separation of one or more components from a suspension or solution in a fluid, by passage of that fluid through or across a barrier that is permeable only to some of these components.

The key element in this description is the barrier, permeable only to part of the feed suspension or solution. This barrier is the filter medium, and a filter is then any mechanical structure that holds the medium in the most efficient way.

1.1 Definition of Filter Medium

It has rightly been said that the heart of any filter is the filter medium. Unless it is fitted with an adequate medium, even the most ingenious filter is useless. So what exactly is a filter medium?

The, now ageing, *Filtration Dictionary and Glossary*(1) defined a filter medium as 'any permeable material used in filtration and upon which, or within which, the solids are deposited'. This definition was not broad enough for the first edition of this Handbook, because it surprisingly assumed that only solid particles are relevant, and therefore excluded the many instances where particles comprise droplets of liquid. The following improved definition was then suggested as sufficiently all embracing: 'A filter medium is any permeable material upon which, or within which, particles are deposited by the process of filtration'.

However, even that breadth of coverage is no longer enough, because a large proportion of filtration operations now concern molecular and ionic species in solution. Accordingly, a revised definition is suggested in this new edition of the Handbook, to take note of this additional need:

A filter medium is any material that, under the operating conditions of the filter, is permeable to one or more components of a mixture, solution or suspension, and is impermeable to the remaining components.

The retained components may be particles of solid, droplets of liquid, colloidal material, or molecular or ionic species in solution, while the permeate (or filtrate) will normally be the suspending fluid or solvent, possibly together with some of the other components.

The purpose of this Handbook is to describe the materials used to make filter media, to highlight their main characteristics, and to advise upon their selection and use.

1.2 Filters and Their Media

In the definition of filter medium given above, the nature of the filter itself is not defined. A filter is any device in which a separation is achieved among other components of a suspension or solution, in a fluid – which may be a liquid or a gas – where the separation is caused by mechanical means, without the involvement of a change in phase (such as the melting of a solid, or the evaporation of a liquid). Filtration is almost entirely a characteristic of the size of the particle, droplet or molecule being separated, whereas relative particle density is a more important feature in sedimentation.

As is often the case in attempting a perfect definition or classification, the boundaries involved in defining filtration in this way are less than absolutely precise. Thus, some membrane separations do involve a change in phase; some filtration processes involve electrical as well as mechanical forces; and some processes involve chemical forces as well as physical ones. Most significantly, the process of dry screening (sieving or sifting) involves the passage of part of a mixture of granular solids through a screen – the filter medium – with little or no passage of a fluid at all, yet this is clearly a filtration process.

That said, the bulk of filtration processes involve the removal of particles, droplets or molecules from a fluid, by means of a physical barrier, the filter medium, through which they will not pass by virtue of their size. A particular form of filter may be able to use a wide variety of filter media, to achieve the same, or different, separations.

1.2.1 Purposes of filtration

There are two main purposes in filtration:

- to remove impurities from a fluid, and
- to recover valuable materials from suspension in a fluid (usually a liquid).

The first of these ('clarification') normally employs finely porous filter media, and aims to remove as much of the impurity as possible, and preferably all of it. The second ('harvesting') also aims for as complete a recovery as possible of the wanted material, but uses coarser media, mainly because the cake of recovered solid does most of the filtering, and also is less concerned with the clarity of the filtrate.

Here again the division is not exhaustively precise: some harvesting processes remove waste solids for subsequent treatment, while some clarification removes only some of the suspended solids (ahead, for example, of a finer filtration process). Filtration may also be used to classify a suspended solid into two separate size fractions.

The choice of filtration equipment involves selection both of the right medium, and of the best type of filter in which to mount it. The harvesting processes are more limited in equipment choice, because of the need to remove accumulated solids in relatively large quantity, often leading to the need for complex types of filter. Clarification duties are much less concerned about solid removal, and so can be satisfied by simpler (and, therefore, cheaper) filters, with correspondingly simpler media formats.

1.2.2 Filtration mechanisms

In terms of the way in which a particle, say, is trapped by a filter medium, and so removed from the fluid, four basic mechanisms can be distinguished. Their distinctive characteristics are briefly outlined as follows.

(a) Surface straining. Here the particle that is larger in size than the pores of the medium deposits on the surface, and stays there until it is removed. Particles that are smaller in size than the pores pass through the medium. As shown schematically in Figure 1.1, this is the main operating mechanism for bar screens, and plain woven monofilament mesh. It also plays a major role in filtration with membranes.

(b) Depth straining. For media that are relatively thick by comparison with their pore diameters, particles will travel along the pore until they reach a point where the pore narrows down to a size too small for the particle to go any further, so that it becomes trapped. Felts and other non-woven fabrics utilize this mechanism, which is illustrated in Figure 1.2.

(c) Depth filtration. Now a particle can also be trapped in the depth of the medium, even though it is smaller in diameter than the pore at that point. Such

Figure 1.1. Filtration by surface straining(2).

behaviour involves a complex mixture of physical mechanisms. Particles are first brought into contact with the pore wall (or very close to it), by inertial or hydraulic forces, or by Brownian (molecular) motion. They then become attached to the pore wall, or to another particle already held, by means of van der Waals and other surface forces. The magnitude and efficacy of these forces may be affected by changes in factors such as the concentration and species of ions in an aqueous solution, or the humidity of a gas. This mechanism is illustrated in Figure 1.3, and is important for most media, but especially for high-efficiency air filters and in deep bed (sand) filters.

(d) Cake filtration. Here a thick layer or cake of particles accumulates on the surface of the medium, and then acts as the filter medium for subsequent filtration. If the particles (or some of them) are larger than the pores, then cake filtration may follow an initial period of surface straining. But cake filtration can occur even when the particles are all smaller than the pores (down even to about one-eighth of the pore diameter), especially if the solid concentration is relatively high (say, greater than 2% by weight in a liquid). This happens by the bridging of the particles across the entrance to a pore, as shown in Figure 1.4, to form a base upon which the cake will then grow.

Quite clearly, any real filtration process will probably involve a combination of two or more of the above mechanisms. The two straining processes will quickly

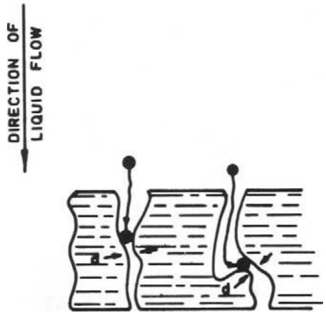

Figure 1.2. Filtration by depth straining(3).

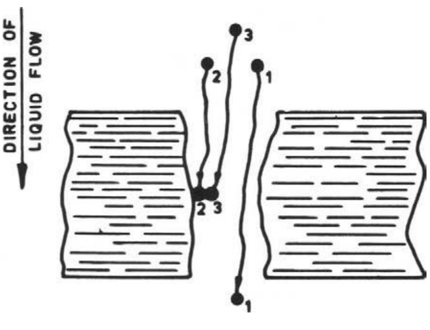

Figure 1.3. Depth filtration mechanism(3).

blind the medium, as the pores progressively block, requiring some kind of cleaning process to be implemented.

On the other hand, this simplified summary of a complex subject serves to emphasise that the mechanisms of filtration may result in the trapping of far smaller particles than might be expected from the size of the pores in the medium. The actual mechanism or combination of mechanisms pertaining in any specific instance is dependent on the characteristics both of the medium and of the suspension being filtered. The relationships between the four basic mechanisms and the two broad categories of practical filtration (clarification and harvesting) are summarized in Table 1.1.

It is important to realize that the fluid being handled can have a significant influence. For example, whereas a fine sintered metal medium will remove particles as small as 0.4 μm from a gas, the same sintered metal, when used to filter liquids, will not be effective below about 2 μm. Differences in performance also occur between aqueous and organic liquids, presumably because of their different electrical properties, which influence the build-up of static charges.

Special mention should be made of the mechanisms that commonly occur with woven fabrics. It is quite normal that a new, or freshly cleaned, fabric will initially allow some particles to pass through, whether used to filter a gas or a liquid. The clarity or quality of the filtrate will then improve progressively, as the characteristics of the fabric are altered by some of the solid particles, as they become embedded both between and within the individual yarns. Once this depth filtration has been completed, then surface or cake filtration proceeds.

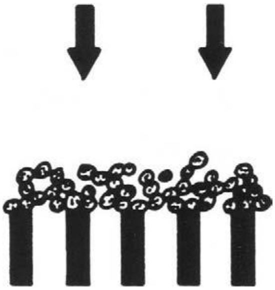

Figure 1.4. Cake filtration mechanism[2].

Table 1.1 The role of filtration mechanisms in practical filtration (× indicates a major role; + indicates a minor role)

Mechanism	Harvesting	Clarification
Surface straining	+	×
Depth straining		×
Depth filtration		×
Cake filtration	×	+

Similar in principle to this last process, the characteristics of the medium may be altered by an initial deposit of solids, or *precoat*, on the surface of the medium, in order to produce a less open medium. This precoating process is used either to prevent loss of valuable material in the initial stage of the filtration, or to prevent passage though the filter of material not wanted downstream of the filter. (Precoat material is often called a *filter aid*, which it clearly is, although the latter term is more correctly used for material added continuously to the feed stream of a filter to improve the filtration performance of the resulting cake.)

The mechanisms illustrated in Figures 1.1–1.4 are all variants of one major group of filtration processes, in which all of the fluid flows through the medium, leaving any separated material within or upstream of the medium. This is known as *through-flow* filtration (also as *dead-end* filtration). This is the traditional way in which filtration processes were operated. An alternative process now exists, as a significant part of the filtration business, in which the main fluid flow is directed across the surface of the medium, with only a portion of the fluid passing, at right angles to the main flow, through the medium. Material deposited on the upstream surface of the medium is then largely swept away by the fluid flow, which often runs in a recycle loop. This technique is known as *cross-flow* filtration (also as *tangential* or *parallel* filtration).

1.2.3 Types of filter

Although this Handbook make no pretence whatever to being a handbook of filtration technology, it is difficult to understand the spectrum of filter media without some reference to the range of types of filter within which they are used. Accordingly, Table 1.2 sets out a reasonably full list of the various types of filter, arranged schematically by nature. The wide range of types illustrated is mainly for liquid filtration, with a much smaller range used for gas filtration, as is indicated in Table 1.2.

Filter media of one kind or another are employed in all of these types of filter, and the various chapters of this Handbook will highlight which media are best suited to which type of filter. All filters exist for the 'simple' purpose of holding a piece of filter medium firmly across or parallel to a flow of fluid, but the way in which they perform this task can be very different from one type to another. Accordingly, filters differ very widely in complexity, from the simple tubular housing of a cartridge filter or strainer, to the complex machine that is a tower press or a rotary vacuum drum filter.

As has already been mentioned, the first group of equipment types in Table 1.2, screens, frequently operate with no fluid flow at all through the filter medium. Screening is mostly an operation at the coarser end of the filtration size spectrum.

The remainder of the items in Table 1.2 all involve fluid flow, and are used over the whole size spectrum, with filter media chosen to give the required degree of separation. The equipment type classification is intended as a help to understanding, rather than exhibiting precise divisions among the various types of equipment mentioned, and several examples exist where the equipment could be classified in more than one place.

Table 1.2 Types of filter

Screens			
	Stationary		
		In-line strainers[a]	
		Horizontal or slightly inclined	
		Curved ('sieve-bend')	
		Vertical	
	Moving		
		Continuous (vertical, or rotating drum)	
		Oscillating (vibrating or gyratory)	
Demisters[b]			
Depth filters			
	Pads and panels[a]		
	Thick cartridge[a]		
	Deep bed ('sand')		
Surface/cake filters			
	Vacuum		
		Batch	
			Nutsche (manual or scroll discharge)
			Rotary table
			Tilting pan (single or rotating/indexing)
			Leaf or tubular element
		Continuous	
			Rotary drum (range of discharge mechanisms)
			Rotary disc
			Indexing disc
			Belt (single or multiple chambers)
	Gravity		
		Flat bed (roll)[a]	
	Fluid pressure		
		In-line	
			Basket strainers
			Sheets
			Capsules[a]
			Pads and panels (cassettes)[a]
			Bags, sleeves and pockets[a]
			Cartridges (wide range of designs)[a]
			Other membrane filters (spiral wound, tubular, etc.)
		Pressure vessel	
			Tubular element (bag or candle filter)[a]
			Filter coalescers
			Flat elements (sheet, plate, leaf)
			Thickeners
			Rotary (drum, submerged drum, Fest, etc.)

Table 1.2 (*continued*)

	Filter press	
		Simple plate and frame
		Chamber press (membrane plate, plate press)
		Tower press (continuous medium)
	Variable volume (tube press)	
Mechanical pressure		
	Band press	
		Horizontal
		Vertical
	Screw press	

This list is mainly of filters used for liquid separations, except for those items marked:

[a] versions for gas and liquid filtration;

[b] gas filtration only.

1.3 Range of Filter Media

The number and variety of materials embraced by the definition of filter medium given in Section 1.1 are truly vast, ranging from metal plates with holes measured in centimetres, to microporous membranes, and from sheets of woven cloth to beds of sand. Filter media may be made from any material that can be rendered permeable or made into a permeable form, including:

- inorganic minerals
- carbon and charcoal
- glass
- metals
- metal oxides and other fired ceramic materials
- natural organic fibres
- synthetic organic fibres
- synthetic sheet material.

The materials can then be made up into filter media in a variety of forms: rod or bar, sheet, loosely packed or bonded fibres or granules, wire or monofilament, and so on.

A more comprehensive glimpse of this diversity is provided by Table 1.3, which has progressed through several evolutionary stages(4–6), since it was first devised by one of the authors in 1965, as a framework to impose some sort of order on the confusing multitude of options. It is a modified form of the 1981 version that is reproduced here, although the numerical values have been updated. In this table, media are arbitrarily arranged approximately in the order of decreasing rigidity; it is not suggested that this arrangement has any sort of fundamental basis, although rigidity is often a significant factor in matching media to their containing filters.

Close inspection of Table 1.3 quickly reveals the difficulty of dividing media into precisely defined types, on a consistent basis, with sharp divisions between categories. For example, this is especially true of modern membranes; in 1965, when the classification was first developed, these were only just emerging from their long-established role as a fragile tool in the research laboratory, and could reasonably be grouped together with other forms of plastic sheets. Now they are

Table 1.3 Classification of filter media, based upon rigidity

Main media type	Subdivisions	Smallest particle retained (μm)
Solid fabrication	Flat, wedge-wire screen	100
	Wire-wound tubes	10
	Edge-type	10
	Stacked discs	5
Metal sheet	Perforated	20
	Sintered woven wire	1
	Unbonded mesh	5
Rigid porous media	Ceramics and stoneware	1
	Sintered metal powder or fibre	1
	Carbon	1
	Sintered plastic powder or fibre	< 1
Cartridge	Yarn wound	5
	Bonded granule or fibre	1
	Pleated sheet	< 1
Plastic sheet	Perforated	10
	Sintered woven filament	5
	Woven mono- or multifilament	10
	(Membrane)	
Membrane	Ceramic	< 0.1
	Metallic	< 0.1
	Polymeric	< 0.1
Woven media	Staple fibre yarn (polymeric filament)	5
Non-woven media	Dry-laid (felts)	10
	Wet-laid (papers)	2
	Wet-laid (sheets)	0.5
	Special polymeric (spun bonds, etc.)	0.1
Loose media	Fibres	1
	Powders	< 0.1

of major industrial importance, thanks to the availability of a continually expanding range of robust polymeric, metallic and ceramic membranes.

Clearly, not all permeable materials are necessarily usable as filter media, but certain of their inherent properties potentially enable them to be applied in this way, if they are combined with a compatible filter in an appropriate operating environment.

Neither is it necessarily true that a particular form of a material would be suitable as a filter medium in its original shape or format. For example, a loosely formed yarn of fibrous material is of no use as a filter medium, if it remains as a single yarn. However, once it is wound around a supporting core, with successive layers of yarn wound at an angle to the previous layer, then it becomes an excellent form of filter medium.

Such a construction represents one form of filter cartridge, and the medium only exists as such because of its particular format. It follows from this situation that the filter cartridge may be almost indistinguishable from the material from which the filter medium is itself made. Because of this indistinct boundary between media and filter elements (including filter bags and panels), this Handbook covers filter cartridges, and other replaceable elements, in addition to the bulk material from which any particular filter medium is made.

1.4 The Filter Media Business

The industrial context within which media are made and supplied to their end users deserves some comment at this point. The great variety of media, not surprisingly, leads to a considerable variety in the types of company involved with the supply of media. Some are devoted to its manufacture, while for others it may be only a small part of the total company activity.

Five main stages can be seen in the industry:

(i) the maker of the basic material from which the medium is to be made: a metal wire, a natural or synthetic fibre, a ceramic powder, an extruded plastic filament, and so on;
(ii) the conversion of some of these basic materials into a form in which they can be used to make filter media: the spinning of fibres or the twisting of filaments into a yarn, the crimping of a wire, etc.;
(iii) the formation of the bulk media: the weaving of a cloth or monofilament mesh, the moulding and sintering of a plastic or metal fibre or powder, the production of paper, the preparation and processing of a sheet of membrane (all together with any necessary finishing processes);
(iv) the conversion of the bulk medium material into pieces of the particular size and shape required for the medium to fit the filter (especially for makers of replacement media for existing filter units), which may include, for example, the pleating of flat material;
(v) the making of the filter itself, including the fitting or adapting of the medium to its position in the filter.

A sixth stage – the distributor or wholesaler – may exist at several inter-stage points in this series, or between the last and the final user. The creation of a stand-alone filter element, such as a cartridge, might be considered as part of stage (iv), or as a further stage between stages (iv) and (v) – and then bypassing stage (v), by direct sale to the end user.

Many companies in the industry exhibit combinations of two or more of these stages (vertical integration), but this may result in limitation of the markets for the products of the earlier stage.

Some media, of course, do not exhibit all these stages: sand filters go from the supplier of the graded sand straight to the deep bed filter maker. Most, however, show several, with some of the most common (woven fabrics, needle felts) exhibiting all of them. This complicated market structure obviously has its impact on a Handbook of this kind – which basically looks only at the products of stages (iii) and (iv).

1.5 Properties of Filter Media

A successful filter medium is likely to be required to combine many different properties, ranging from its filtration characteristics and its chemical resistance to its mechanical strength, the dimensions in which it is available, and its wettability. In fact, some 20 significant properties were identified by one of the authors(7) in exploring the extent to which these are, or could be, used for systematically selecting media for specific applications

These properties may be conveniently divided into three major categories:

- machine-orientated properties, which restrict the use of the medium to specific types of filter, such as its rigidity, strength, fabricability, etc.;
- application-orientated properties, which control the compatibility of the medium with the process environment, such as its chemical and thermal stability; and
- filtration-specific properties, which determine the ability of the medium to achieve a specified filtration task, such as its efficiency in retaining particles of a defined size, resistance to flow, and so on.

The three categories are listed in more detail in Tables 1.4–1.6. The significance and potential for quantifying the individual properties are discussed in turn in the following sections of this chapter, the components of Tables 1.4 and 1.5 being covered by the remainder of Section 1.5, and those of Table 1.6 by Section 1.6.

1.5.1 Machine-orientated properties

Those properties of a filter medium that are of particular concern to the mechanical implementation of the filter itself are described in this section.

1.5.1.1 Rigidity

It is virtually a subconscious reflex to use rigidity as a primary criterion of the possible compatibility of a filter medium with a specific type of filter; it was for this reason that rigidity was used as the basis of the general classification of media in Table 1.3. Nonetheless, it is relatively rare for the rigidity to be measured or for a value to be quoted.

The scientific basis of measurement is the Young's modulus of elasticity, values of which, for the basic material from which media are made, are available in appropriate reference books. In practice, these values are generally not directly applicable to filter media in their various fabricated forms.

The paper and textile industries each have their own standard procedures for measuring what is generally termed *stiffness*. The test for paper (BS 3748:1992) measures the force in grams to deflect a strip through a defined angle; the textile test (BS 3356:1961) is more empirical and records the *overhang length* of a strip necessary for it to bend through an angle of 41.5° from the horizontal, under its own weight. The textile data may be reported as *bending length*, which is half the overhang length, or as *flexural rigidity*, G, given by:

$$G = 0.00167ML^2$$

where M = cloth mass per unit area (g/m^2); L = overhang length (cm).

Table 1.4 Machine-orientated properties

1	Rigidity
2	Strength
3	Resistance to creep/stretch
4	Stability of edges
5	Resistance to abrasion
6	Stability to vibration
7	Dimensions of available supplies
8	Ability to be fabricated
9	Sealing/gasketing function

Table 1.5 Application-orientated properties

1	Chemical stability
2	Thermal stability
3	Biological stability
4	Dynamic stability
5	Absorptive characteristics
6	Adsorptive characteristics
7	Wettability
8	Health and safety aspects
9	Electrostatic characteristics
10	Disposability
11	Suitability for reuse
12	Cost

Table 1.6 Filtration-specific properties

1	Smallest particle retained
2	Retention efficiency
2.1	The structure of filter media
2.2	Particle shape
2.3	Filtration mechanisms
3	Resistance to flow
3.1	Porosity of media
3.2	Permeability
4	Dirt-holding capacity
5	Tendency to blind
6	Cake discharge characteristics

1.5.1.2 Strength

The strength of a material is generally characterized by generating stress/strain data using an extensometer. The main parameter thereby quantified is usually the tensile strength, but others frequently quoted are the rupture strength, the yield strength, the yield point, the elastic limit and the ultimate elongation.

With filter media, only limited use appears to be made of these basic mechanical properties. It is common practice for the literature of a supplier of monofilament meshes to include the *tensile strength* and *elongation* of the material from which the filaments are made. Tensile strength values are generally also supplied for sintered metals.

Whereas tensile strength would seem to be a useful parameter for porous ceramics, in practice the industry generally uses *cross breaking strength*, for which a standard test procedure is available (BS 1902 Part 1A:1966).

With other media, various strength criteria are preferred, sometimes involving misuse of a term such as tensile strength. For example, the standard test for paper (BS 4415:1969), whilst described as measuring tensile strength, omits reference to the thickness of the sample. For textiles, a similar standard test (BS 2576:1967) determines what is more aptly termed the *breaking load*.

Both the textile and the paper industries also have standard procedures for measuring the *resistance to tearing* and the *bursting strength*. The latter, which may be on either a wet or a dry sample, is an empirical value that depends on the diameter of the disc tested. It is readily measured using commercially available apparatus conforming to the appropriate standards (BS 3137:1972 for paper, BS 4768:1972 for textiles).

1.5.1.3 Resistance to creep/stretch

This property is of particular importance in respect of the use of textiles on certain types of filter, notably fabric dust filters and belt type filters for liquids. With this in mind, media manufacturers routinely use tensile tests primarily to predict cloth extension at loads that will be somewhat higher than those applied by the filter equipment. In the case of fabrics for dust collection applications, some equipment manufacturers actually indicate the stress–strain characteristic in their specifications, e.g. max. 2–2.5% extension at 5 kgf/5 cm. However, since this information is not always available, and since it is known that the force applied by equipment is in general quite low relative to the overall strength of the fabric, tests are usually carried out to indicate the material's extensibility at low loads, e.g. 2, 5 and 10 kgf/5 cm. Furthermore, since the stress–strain properties of textile fibres and filaments are affected by temperature, one media manufacturer (Madison Filter) has engaged a facility that will actually enable the tensile work to be carried out at elevated temperatures. Resistance to stretch is equally important in fabrics that are engaged in filter belt (liquid filtration) operations, where even relatively low loads could result in a belt extension up to and sometimes beyond the stroke of the filter's tensioning system.

1.5.1.4 Stability of edges

Whilst edge stability is clearly of importance with certain types of woven and non-woven media, there is no recognized method of assessment other than visual subjective judgment.

1.5.1.5 Resistance to abrasion

The ability of a filter medium to resist abrasion depends primarily on the hardness of the material from which the medium is formed (e.g. the hardness of nylon in a woven or non-woven fabric). Hardness may be measured in terms of various empirical scales, such as that which the mineralogist F Mohs devised in 1812, based on which material will scratch another, or one of those (Brinell, Rockwell, Shore, Barcol) involving measurement of the indentation caused by a loaded ball or pointer.

Direct empirical measurement of abrasion resistance is a common requirement in the textile industry. Examples of the techniques used are the Martindale wear tester, which counts the number of rotations of a rubbing abrasive surface until a hole is formed; and the Stolle tester which checks the number of flexings of a strip in close contact with a rod.

1.5.1.6 Stability to vibration

Whilst the stability of filter media to vibration can occasionally be of importance, no basis of guidance is available other than general structural considerations.

1.5.1.7 Dimensions of available supplies

The dimensions in which pieces of media are available are controlled by the techniques and machinery of the manufacturer. For example, woven fabric (including wire cloth) cannot be wider than the width of the loom; in practice, where the uniformity is critical, the usable width may be significantly less.

1.5.1.8 Ability to be fabricated

Combining a filter medium with a filter often demands the use of one or more fabrication techniques, such as cutting, bending, welding, adhesive bonding or stitching. Which of these is possible depends on the individual medium. Care must always be exercised in employing such techniques to ensure that their use does not create wider pores or other imperfections in the medium at a point where its filtration ability might be critical.

1.5.1.9 Sealing and gasketing function

The seal around the edge of a sheet of filter cloth is of critical importance, and often is partly dependent on the cloth itself acting here as a gasket, as in a conventional filter press. Effectively, the cloth is being required to be permeable in one area and impermeable in another. Natural fibres are soft, readily absorb liquids and deform easily; thus they tend to give a fairly good seal. Synthetic fibres, however, especially monofilaments, are relatively hard and have a low absorptive capacity, so that compression alone is less likely to make a good seal; a convenient answer to the sealing problem is to impregnate the appropriate area with a suitable impervious elastomer such as neoprene or nitrile rubber.

1.5.2 Application-orientated properties

The following notes describe those characteristics of a filter medium that are of particular importance in the system that involves the filtration process.

1.5.2.1 Chemical stability

The ability of a filter medium to withstand a specified chemical environment can generally be checked easily from published technical data, provided that the chemical nature of the medium itself is known. With synthetic fibres, this can in practice be a source of some difficulty, since the nature of the fibre may be hidden behind a trade name; the full measure of this problem is demonstrated by the list of some 5000 entries in a major glossary of fibre names, *The World Fibres Handbook*(8). Some of the more common names are listed in Table 2.1 of Chapter 2.

1.5.2.2 Thermal stability

Although subject to the same potential difficulty of identifying the chemical nature of the fibre from which a filter medium is made, its compatibility with a specific operating temperature can be determined from published data. This may also depend upon the chemical environment.

1.5.2.3 Biological stability

This is generally of importance only with natural fibres (e.g. cotton), rather than synthetic materials, which are not usually susceptible to biological degradation.

1.5.2.4 Dynamic stability

The shedding of fibres, or the migration of fragments of filter media into the filtrate, is a matter of serious concern with certain types of critical applications, such as controlling the environment in a clean room, or producing ultraclean water for use in the electronics industry.

The more the medium contains small pieces of original material (fine fibres or powder), the greater the potential for shedding.

1.5.2.5 Absorptive characteristics

Absorption is typified by the ability of blotting paper to soak up substantial amounts of ink or other liquid into the depth of the paper. More precisely, it is defined as a physicochemical process in which a substance associates with another, to form a homogeneous mixture(1); thus, a soluble gas is absorbed into a liquid to form a solution.

In the context of filter media, absorption of water causes the fibres of cellulose paper or cotton cloth to swell and the space between adjacent fibres to reduce, so that the filtration characteristics of the medium may change significantly.

1.5.2.6 Adsorptive characteristics

In contrast to absorption, adsorption occurs only at the surface of the solid or liquid adsorbent, producing there a high concentration of a particular component. The in-depth adsorption that occurs with activated carbon results from its microporous capillary structure, and its correspondingly very high internal surface area. The adsorption mechanism depends on intermolecular attractive forces (e.g. van der Waals forces).

With filter media, the adsorption of specific types of molecule or ion onto the surfaces of fibres may radically affect performance, especially of a medium that functions by depth filtration mechanisms. The tendency of a fabric to blind may also be affected.

1.5.2.7 Wettability

The practical significance of wettability is demonstrated by the relatively high pressure required to initiate the flow of water through a PTFE medium, because it is hydrophobic; by contrast, a liquid such as alcohol, which wets PTFE readily, will commence to flow at a far lower pressure.

Theoretically, whether or not a given liquid will wet a specific filter medium can be predicted from knowledge of the surface tension of the liquid against the solid, on the one hand, and against air (or the other gas in the system) on the other hand; wetting will occur if the surface tension against the solid is the greater. In practice, it is often difficult to use this simple relationship because of the absence of the necessary surface tension data; moreover, surface tension values may be altered dramatically by the presence of very small amounts of some impurity, either in the liquid or on the solid surface.

1.5.2.8 Health and safety aspects

One potential source of hazard is the risk of an electrostatic discharge, which is a recognized problem with dust filtration and can also occur under very different circumstances when filtering organic liquids; this is discussed in more detail in the next subsection. Other hazards may be of a more chemical or physical nature, notably in handling powdered filter aids, the inhalation of which can be harmful. Handling problems may also occur in disposing of used media, especially if contaminated with hazardous materials; disposability is also discussed separately below.

1.5.2.9. Electrostatic characteristics

Hazardous electric discharges can occur as a consequence of static generated by filtration through some types of filter media. This risk is best known in the application of fabric bag filters for dust collection from exhaust gases and air. The phenomenon is less common with liquid filtration, because of the high conductivity of water and aqueous solutions. But it can be significant with organic solvents and hydrocarbons, especially those with a very low conductivity(9,10); if this is combined with a low flash point, there may well be risk of an incendive discharge (i.e. a static discharge capable of causing ignition).

There is an important difference between gas/air filtration and liquid filtration that merits emphasis: this concerns the location of a static charge. A clean gas flowing through a filter medium cannot become charged, but a clean liquid can. With a gas, it is only any particles it contains that may become charged, not the gas itself; dust (or liquid droplets) collecting on a fabric bag may be charged, but there will be no charge in the filtrate unless it contains some particles.

By contrast, the liquid itself may become charged by filtration, and so will produce charged filtrate. Under normal circumstances, this charge will decay safely at a rate that depends on the electrical conductivity of the liquid, typically requiring a period of perhaps 30 seconds. Initially, however, a high voltage discharge may occur from the surface of the charged liquid, as it collects in a receiving vessel; this risk can be avoided by providing adequate dwell time in the piping system between the filter and the tank inlet. An alternative technique, which is standard practice for refuelling aircraft, is to dose the fuel with an antistatic additive at a concentration of about 1 ppm.

Antistatic fabrics, of relatively high electrical conductivity, are available to control the build-up of static in dust filters; some of these have metal fibres woven into the fabric, while others depend on a conductive coating of the polymeric fibres. This approach is of little benefit for liquids, which can be charged even by sintered metal and woven wire.

A totally different aspect of electrostatic behaviour is that in which fibres are intentionally charged, so as to improve the collection efficiency of particles by the medium. This is an important topic in filtration both of liquids and gases, and merits a key section later in this Handbook.

1.5.2.10 Disposability

Used and discarded filter media form part of the effluent from a plant, and must therefore receive appropriate attention to avoid causing pollution. For example, it is generally no longer possible simply to discharge precoat residues into the nearest sewer; a secondary filter may be required to collect and dewater these materials. Special arrangements may be necessary to dispose of contaminated filter cloths or cartridges.

An important feature these days is the need to recycle as much waste material as possible, and it is therefore becoming important that filter media and their appropriate housings, where these form a disposable cartridge, for example, should be made of the same material to enable simple recycling at the appropriate place after disposal.

1.5.2.11 Suitability for reuse

Some filter media can only be used once, and then must be discarded and replaced, while others have an indefinite life. Yet others fall somewhere in between, their useful life often depending on how they are used and cleaned. This factor can obviously have a profound cost implication.

1.5.2.12 Cost

Understandably, the cost per unit area of the myriad of different commercially available types and grades of filter medium varies 10,000-fold or more. This can be seen from the list of very approximate prices (£/m^2) assembled in Table 1.7; of course, these very rough figures by no means tell the whole story, since they take no account of the commercial realities of competitive tendering and bulk buying, nor of the substantial wastage from off-cuts imposed, for example, by the geometry of some filters. Even more pertinent is the impact if the medium can be repeatedly reused.

In practice, the cost of the filter medium may account for a substantial part, either of the capital cost or of the running cost of a filter, or even of both.

1.6 Filtration-specific Properties

Those properties of a filter medium that control its ability to undertake a filtration process are clearly the most important of its characteristics. These are now described in the following notes.

1.6.1 Smallest particle retained

The most obvious question to ask about a filter medium is: what is the smallest particle it will retain? Ideally, Table 1.3 should include a precise answer to this question for each of the types of media listed. Any attempt to do this immediately raises a host of difficulties about defining and measuring the 'smallest particle', in view of the diversity of the shapes of real particles, simple spheres being rare.

Therefore, whilst some 'smallest particle' figures are included in Table 1.3, it must be emphasised that they are intended only to provide a broad indication; they should be read in conjunction with the discussion that follows. What is much more meaningful is to characterize a filter medium in terms of its retention efficiency against particles of a standard test powder or aerosol.

1.6.2 Retention efficiency versus particle size

Figure 1.5 shows two typical grade efficiency curves relating to the filtration of a hydraulic fluid containing iron oxide; they demonstrate how the retention efficiency of a filter medium decreases as the size of the particles reduces. As illustrated, the actual shape of such curves may very widely; here, the felt and wire gauze both have a cut-off (i.e. 100% efficiency) at 35 μm, but the effectiveness of the wire gauze falls away rapidly, whereas the felt performs reasonably well down to a much smaller size.

The particle size corresponding to 100% retention (i.e. 35 μm for both curves in Figure 1.5) is generally known as the 'cut-off point', while the filter medium may be described as '35 μm absolute'. More usual practice is to rate a medium in terms of the particle size at which it has a somewhat lower efficiency, such as 98%; this immediately differentiates between the two examples in Figure 1.5.

Table 1.7 Typical costs of various types of filter media

Class	Type	Cost (£/m^2)
Cellulose paper	Resin impregnated	0.25–0.5
	Unimpregnated	0.15–0.25
Glass paper		0.4–0.8
Filter sheet	Asbestos free	4–6
Membrane	Acrylic copolymers	60–100
	Cellulose	45–75
	Cellulose esters	90–150
	'Nuclepore' polycarbonate	125–220
	Nylon	70–130
	Polyethersulphone	75–140
	PTFE on polypropylene substrate	400–500
	UF membranes	75–135
Mesh (monofilament)	Polyamide (5–200 µm)	20–95
	Polyester (5–200 µm)	20–100
	Stainless steel (5–100 µm)	35–175
Needle felt	Staple fibre	3–7
	Polyamide	5–7.5
	Polypropylene	4–5
Non-woven: spunbonded	Polyester	0.1–2.5
	Polyethylene	0.1–3
	Polypropylene	0.05–2
Non-woven: melt blown	Polyester	0.2–3
	Polypropylene	0.1–2.5
Porous ceramic	25 mm thick	200–300
Precoat powder	Coating 0.6 kg/m^2	0.25–0.4
Sintered stainless steel	Powder (1.6 mm thick)	260–380
	Metal fibre (0.8 mm thick)	250–360
	Mesh (5 layer)	700–1200
Woven fabric	Cotton	5–7.5
	Polyamide – multifilament	5–7.5
	Polyamide – staple	6–8.5
	Polyester – multifilament	4–6
	Polyester – staple	5–8.5
	Polypropylene – multifilament	4–6
	Polypropylene – staple	5–7.5
	Aramid (filament warp/staple weft)	12.5–15
	Glass (filament warp/staple weft)	5–8
	PTFE	35–40

It is important to note that any grade efficiency curve is strictly only valid for the test conditions under which it was generated. This restriction applies not only to factors such as the nature and concentration of the solid particles, but also to the properties of the liquid (e.g. its viscosity, pH, polarity, etc.), and to the filtration velocity (i.e. the flow rate per unit area).

Another form of expression used to quantify the relationship between particle size and retention efficiency is the beta ratio, which compares the size analysis of samples taken simultaneously upstream and downstream of the filter and is defined as:

$$\beta_n = N_u / N_d$$

where N_u = number of particles > n µm per unit volume of liquid upstream;
N_d = number of particles > n µm per unit volume of liquid downstream.

The major parameters that affect the retention efficiency, and hence, to a large extent, the filtration performance are: the structure of the medium; the shape of the particles; and the filtration mechanism.

1.6.2.1 Structure of filter media

This chapter commenced with one definition of a filter medium as: 'any permeable material upon which or within which particles are deposited by the process of filtration'. Implicit in this definition is the assumption that the medium comprises a mass of holes separated from each other by some kind of solid wall; it is also implicit that the medium has a finite thickness.

From these factors spring several possible variations, which alone or in combination can greatly affect the filtering characteristics. These are the size and cross-sectional shape of their holes; their morphology within the thickness of the

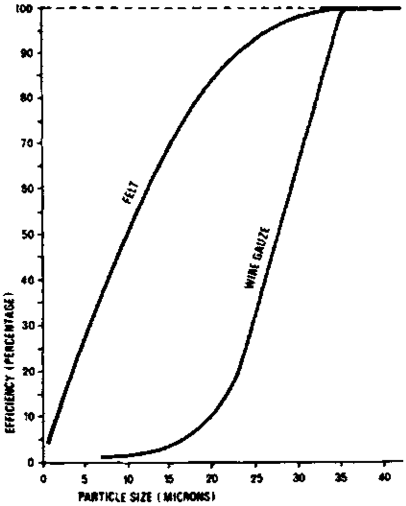

Figure 1.5. Grade efficiency curves for two media (felt and woven wire) with the same cut-off point at 35 µm but very different efficiencies against smaller particles.

medium (i.e. whether they are straight or tortuous, and whether they vary in size and shape within the medium); the number of holes per unit area; and the uniformity of each of these factors. The characteristics of a filter medium depend, in practice, partly on the intrinsic properties of the material from which it is made, and partly on the fabrication techniques employed in its manufacture. Thus, in the simplest case, a perforated metal sheet is made by drilling or cutting circular, rectangular or otherwise shaped holes in a solid sheet, so that the size, shape and spacing of the holes will be uniform within the limits of the engineering techniques used; similarly, the plate will be of uniform thickness, and each hole will usually pass directly through the plate by the shortest possible path. A plane weave wire cloth of light gauge will be broadly similar with approximately rectangular holes, although probably there will be more holes to permit flow and less metal to obstruct it than in a perforated sheet with holes of similar size.

This simple picture changes as the gauge of the wire becomes heavier, and as the weave is elaborated to give the more durable wire cloths generally used in filtration. As can be seen from Figure 1.6, the form of the holes becomes far more complex so that they can no longer be realistically described by the simple measurement of their plan view. Instead their *effective pore size* is determined by a performance test against particles of known size, or the *equivalent pore diameter* is determined by a *bubblepoint* test (using pressure to force air bubbles through the medium once it is immersed in a liquid).

Woven fabrics introduce further complications, since the more flexible nature of yarns makes it impossible to weave them with the same precision as wire; moreover, the yarns are often neither as uniform in diameter nor as smooth in surface as a wire, especially if they are of staple wool-like structure, spun from short fine fibres (Figure 1.7). An added complication then is the difference in flow path through the microstructure of such yarns as compared with that between adjacent yarns.

Even less definable structures occur with other media, such as needle felts (Figure 1.8), paper (Figure 1.9), porous ceramic (Figure 1.10), sintered metal (Figure 1.11) and polymeric membranes (Figure 1.12). With rare exceptions, it is almost meaningless to try to measure the size of the pores of these under a microscope, the practical choice being between a performance test and a bubble point test; membranes made by irradiation, such as Nuclepore, are an obvious exception, as Figure 1.13 illustrates.

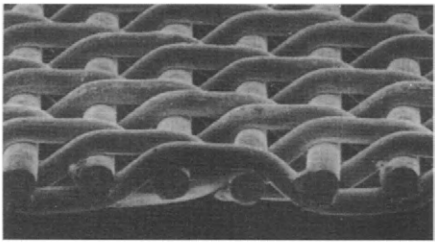

Figure 1.6. An example of woven wire mesh.

1.6.2.2 Particle shape

Despite the fact that it is common practice to refer to the size of particles by a single linear dimension (e.g. 10 μm), with rare exceptions this is an approximation that can be slightly or greatly misleading. It implies that the particles are spherical, which may be true of some bacteria and other organisms, of metal shot and of fly ash (although the latter often comprises a mixture of hollow spheres and fragments of shattered spheres). But in general, particles are more likely to be almost any shape other than spherical, ranging from plates and deformed blocks to needles.

A measure of the extent to which particles depart from the ideal sphere is given by the magnitude of their shape coefficients, K_a and K_v. Using these coefficients, the surface area and volume of a particle are related to its 'average' diameter, D_{av}, as follows:

surface area = $K_a d_{av}^2$
volume = $K_v d_{av}^3$

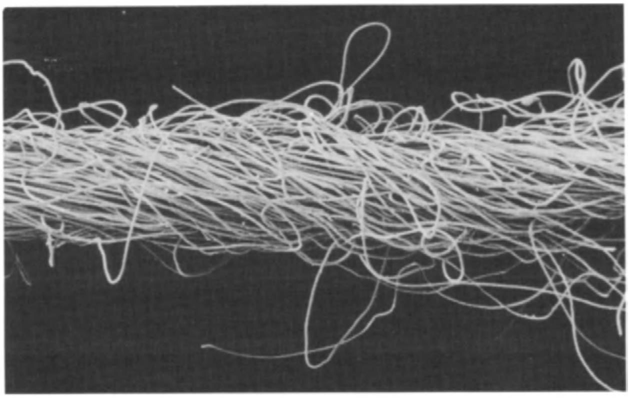

Figure 1.7. A spun staple yarn magnified.

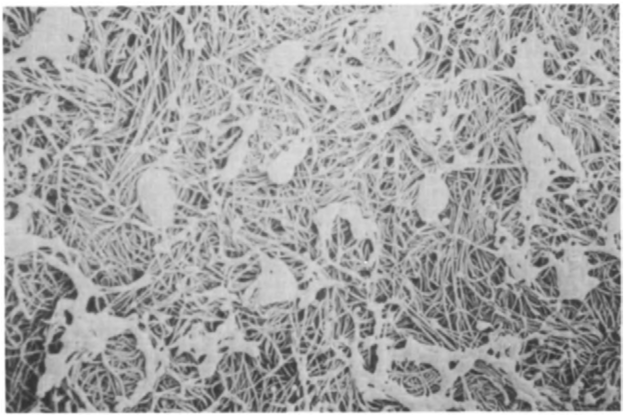

Figure 1.8. Magnified view of the surface of a needlefelt. The solid areas result from singeing.

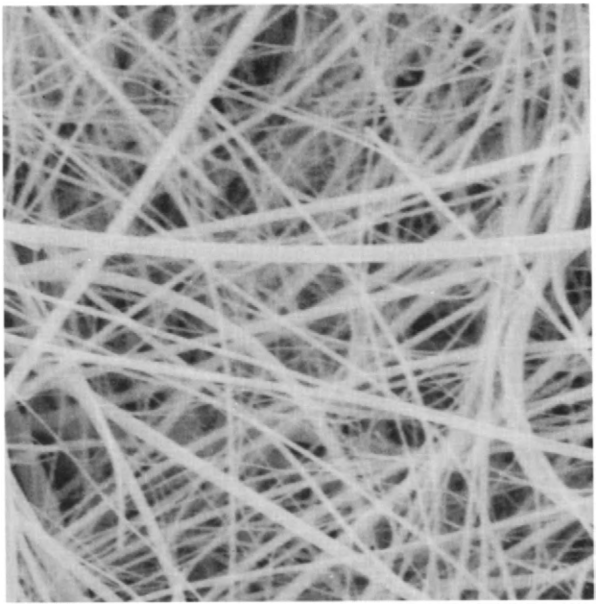

Figure 1.9. Paper of glass microfibres.

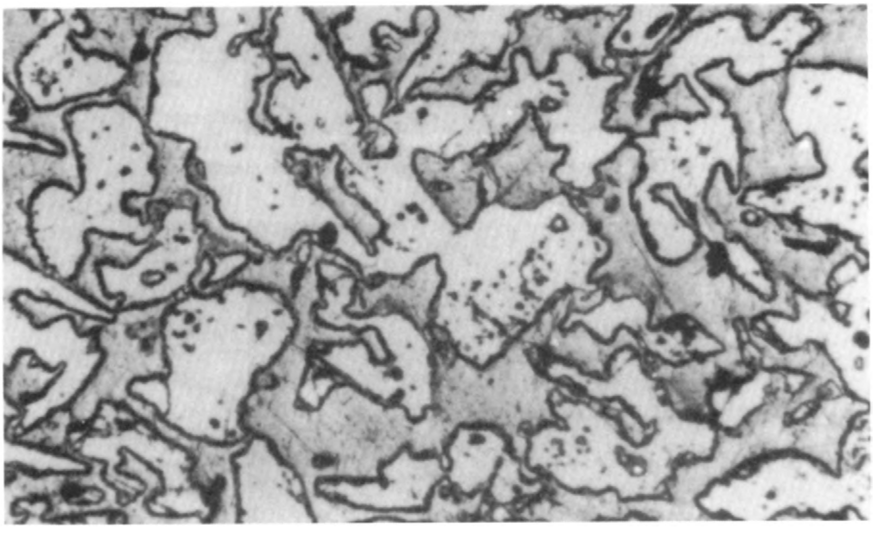

Figure 1.10. Photomicrograph of polished porous ceramic. Dark areas are pores.

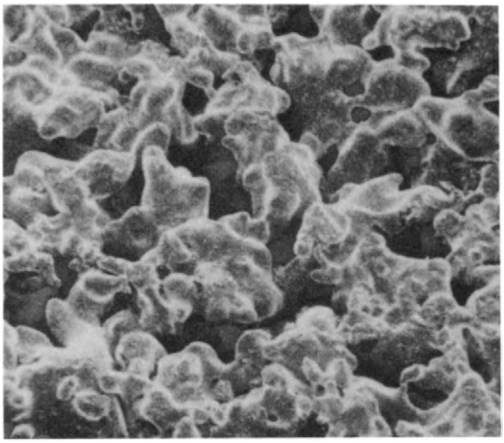

Figure 1.11. Photomicrograph of sintered metal powder.

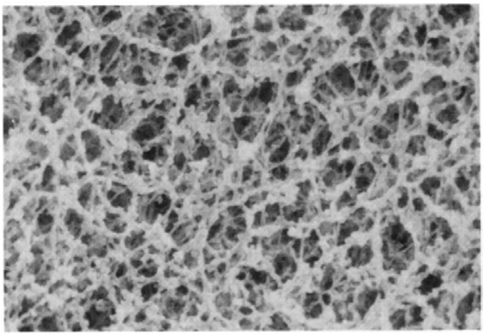

Figure 1.12. Photomicrograph of a typical polymeric membrane.

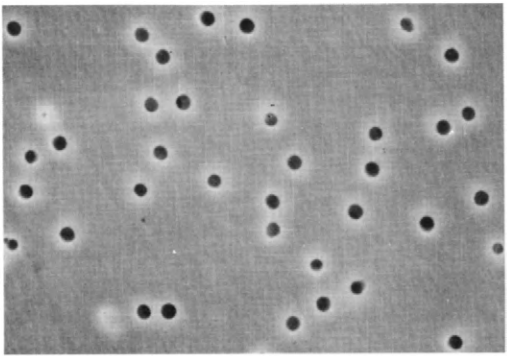

Figure 1.13. Photomicrograph of 'Nuclepore' track-etched membrane.

For spherical particles, $K_a = \pi$ (= 3.412) and $K_v = \pi/6$ (= 0.502). The few examples in Table 1.8 demonstrate the large variation that can occur with industrial particles(11).

1.6.2.3 Filtration mechanisms

The detailed examination of filtration mechanisms, both the way in which particles interact with the medium and the way in which the fluid flows through the medium, have been discussed in a previous section (Section 1.2.2). It is clearly of considerable importance to the filtering process as to which of the mechanisms of filtration is employed.

The practical effects of the differences in the structure of filter media, combined with the mechanisms of filtration, are well illustrated in Figure 1.5 above, which shows the filtering efficiencies of felt and wire mesh against particles with sizes ranging to above 40 μm. Both media have a cut-off point of 35 μm, above which they stop 100% of the particles. However, the effectiveness of the wire mesh falls away rapidly as the particles become smaller, because it functions only by surface straining. By contrast, felt continues to perform reasonably well down to a much smaller particle size, thanks to depth straining and/or depth filtration.

1.6.3 Resistance to flow (clean media)

The resistance to flow of a filter medium depends both upon the size of the individual pores and on the number of pores per unit area. The ideal medium would comprise a mass of holes divided by the thinnest possible walls, thus presenting the maximum open area through which fluid can flow. In practice the holes account for only a relatively small part of the surface, the exact proportion depending on the properties of the material from which the medium is made and the manufacturing process used. Very large differences in resistance to flow exist among the diverse ranges of available media.

This resistance can be of major importance in industrial applications, since it may affect both capital and running costs, so that considerable care may be required in selecting a medium for a specific duty. This can be made more

Table 1.8 Shape coefficients of typical particles

Particle	Area coefficient	Volume coefficient
Sphere	3.142	0.502
Copper shot	3.14	0.524
Sand	2.1–2.9	–
Worn sand	2.7–3.4	0.32–0.41
Pulverised coal, limestone	2.5–3.2	0.20–0.28
Coal	2.59	0.227
Mica	1.67	0.03
Aluminium flakes	1.60	0.02

complex by differences in definitions used to characterize the flow resistance of media, impeding a direct comparison of published data from different sources and for different media.

The actual resistance to flow of a fluid through a clean medium is a combination of the porosity of the medium material (i.e. the physical structure of the pores and surrounding material) and the permeability of the medium to the appropriate fluid (i.e. the ease or otherwise with which that fluid flows through the medium).

1.6.3.1 Porosity of media

With some types of media, direct measurement is possible of the relative areas of free and obstructed surface. While this does not give the actual resistance to flow, it is a simple and convenient mode of comparison, which quickly brings out the extent of variation that may occur. For example, the slot-shaped holes of a wedge-wire screen give a totally free area of only 5–10%, whereas the corresponding figure for perforated metal sheet with fine holes is typically about 30%. With square weave wire mesh, the free area decreases to 30–35% for the finest meshes; these are generally too weak mechanically for use in filtration, where instead use is made of dutch weave for which the free area is limited to 15–25%. Similar figures, but expressed as the percentage porosity, provide an interesting comparison among a wide diversity of media, and are summarized in Table 1.9.

The porosity of sintered metals, ceramics and stoneware is greatly affected by variations in the shape, size and size distribution of the particles used in the manufacturing process. Morgan has given a useful summary of the theoretical considerations, showing that the variations in porosity possible with spherical particles of both uniform and mixed sizes ranges downwards from a maximum of 47.6%(12). In practice, the influence of factors such as particle shape and bridging between particles makes it possible to produce certain grades of

Table 1.9 Typical porosities of filter media

	% free area
Wedge wire screen	5–40
Woven wire:	
twill weave	15–20
square	25–50
Perforated metal sheet	30–40
Porous plastics (moulded powder)	45
Sintered metal powders	25–55
Crude kieselguhr	50–60
Membranes	80
Paper	60–95
Sintered metal fibres	70–85
Refined filter aids (diatomite, perlite)	80–90
Plastic, ceramic foam	93

ceramics with porosities as high as 70%. Generally, both high porosity and fine pore size result from the use of finer particles, but at the expense of a decrease in mechanical strength.

Porous plastics made by sintering powders have porosities similar to those of sintered metal powders and ceramics. Polymeric membranes, which are made by very different processes, have very high porosities of about 80%, while figures up to 97% are reported for reticulated plastic foams.

In the case of precoats of irregular-shaped particles of materials such as diatomite, the porosity is generally 80–90% (although crude kieselguhr may be as low as 50%), whereas fibrous materials, such as cellulose paper and filter sheets, range up to about 90%.

1.6.3.2 Permeability

The permeability of a filter medium, a vital measure of the medium's capability for filtration, is determined experimentally, generally by observing the rate of flow of a fluid under a defined pressure differential. The immense variety of expressions formerly used for the permeability of filter media is illustrated by Table 1.10; this was originally assembled(5) in 1966, since when there has fortunately been considerable progress in standardization, so that permeabilities now are generally expressed in two main forms, even if in a considerable variety of units. The more common form, appropriate for sheets of media but effectively treating thickness as a constant, characterizes them in terms of the rate of flow of a specified fluid per unit area. A far less widely used form, which is more rigorous fundamentally and takes cognisance of the thickness, characterises a medium by its permeability coefficient.

Air and water (but especially air) are the two fluids most widely used in the assessment of permeability, although in certain fields other liquids such as oils are used. The techniques employed, and hence the data generated, vary from the one extreme of using a fixed rate of flow and observing the corresponding differential pressure, to the other of using a fixed pressure and observing the time required for the flow of the specified volume of fluid.

The most common form for expressing permeability disregards the thickness of the medium, so that the permeability is empirically quantified by the flow rate of air per unit area, under a defined differential pressure. An appropriate example of this method is the Frazier scale widely used internationally in the paper and textile industries; this is based on the flow of air and was formally specified as cubic feet per minute per square foot of material at a differential pressure of 0.5 inches water gauge. Metric versions require care since they may use various combinations of definitions of air volume (litres or cubic metres), time (minutes or seconds), area (square centimetres, decimetres or metres) and differential pressure (12.5, 20 or 25 mm water gauge or corresponding values in pascals).

A more fundamental expression is the permeability coefficient of the medium, K_p, which is defined by the Darcy equation describing flow through a porous layer:

$$P/L = Q\mu/AK_p$$

Table 1.10 Examples of the variety of permeability scales formerly used

Nature of medium	Type of permeability scale	Typical data
Sintered metals	gpm of water or cfm of air/sq ft at pressures in psi, through defined thickness (usually $^1/_8$ in) generally as graphs	5 μm pore, Δp1 psi – 25 cfm of air/ft^2 1.2 gpm of water/ft^2 20 μm pore, Δp1 psi – 48 cfm of air/ft^2 6.5 gpm of water/ft^2
Ceramics	(a) gpm of water or cfm of air at pressure in psi (b) mm Hg, either/ft^2 or per element; usually through defined thickness of about $^1/_2$ in	15–20 μm pore. (a) 100 scfm/ft^2 of air at 10 psig Δp=275 mm Hg (b) 5 gpm/ft^2 water, Δp=75 mm Hg
Woven metal	gpm of water/sq in at 1 psi	100 mesh square weave, 0.0045 in wire, 30% open area – 12.1 gpm/sq in. 47 μm dutch twill, 50 × 700–3.0 gpm/sq in
Woven fabrics	cfm of air/sq ft at 0.5 in WG	cotton twill – 3–15 cfm/ft^2 monofilament nylon – 300–900 cfm/ft^2 multifilament nylon – 5–500 cfm/ft^2 glass – 2–20 cfm/ft^2
Non-woven fabrics	(a) cfm of air/sq ft at 0.5 in WG (b) gpm of water/sq ft at 1 psi	(a) 0.5–230 cfm of air/ft^2 (b) 3–500 gpm of water/ft^2
Paper	(a) time for flow of e.g. 1000 cc water at pressure of e.g. 245 mm Hg (b) time for flow of fixed volume of air at defined pressure (c) litre of air per min/10 cm^2 at pressure of 10 cm WG (d) pressure needed to produce flow of e.g. 1 cfm/10 cm^2 (e) rate of air flow/unit area divided by pressure drop, e.g. cm/s/100 cm^2 divided by cm WG	(a) 4–100 s (b) 1$^1/_2$–50 s (c) 40–400 l (d) 1–73 cm WG (e) 7.5–150
Sheets	gph of water either/ft^2 or/sheet at e.g. 10 psi	12–800 gph/ft^2
Filter aids	(a) graph showing cumulative flow/ft^2 versus time: using sugar and other solutions containing suspended solids on a batch test basis (b) expressed as ratio, relative to slowest in some range of products (c) darcies, based on water flow	(c) 0.05–5 darcies
Sand	Head loss, ft of water	

where A = area (m^2); Q = volumetric rate of flow (m^3/s); P = differential pressure (Pa); L = depth or thickness of the medium (m); μ = kinematic viscosity (Ns/m^2). When all of these parameters are expressed in SI units as shown, the permeability K_p is expressed in m^2.

However, K_p is frequently reported in inconsistent units, notably darcies, where viscosity is defined in centipoises, the differential pressure in atmospheres and the other parameters in centimetres and seconds, so that:

$$1 \text{ darcy} = 1(\text{cm}^3/\text{cm}^2/\text{s}).\ 1(\text{centipoise})/1(\text{atmosphere/cm})$$

These relationships are considered more fully in Section 11.2 of Chapter 11, which describes examples of equipment for measuring permeability and outlines the principles of standard testing procedures.

1.6.4 Dirt-holding capacity

An important performance parameter of filters, used either for the clarification of liquids or for gas and air cleaning, is the quantity of solids (i.e. 'dirt'), which can be collected without exceeding a defined pressure drop across the filter. A high dirt-holding capacity indicates a proportionally long on-stream time between either cleaning or replacing the filter element or medium.

Great differences in dirt-holding capacity occur between one type of medium and another, as illustrated in Figure 1.14; this is due both to the structure of the medium, and to the various filtration mechanisms by which they may function. Measurement of this capacity is frequently made as part of the challenge tests used to determine filtration efficiency; however, it is important to note that the measured capacity is strictly only valid for the test conditions used, since it depends not only on factors such as the nature and concentration of the solid particles, but also on the properties of the liquid (e.g. its viscosity, pH, polarity, etc.), and to the filtration velocity (i.e. the flow rate per unit area).

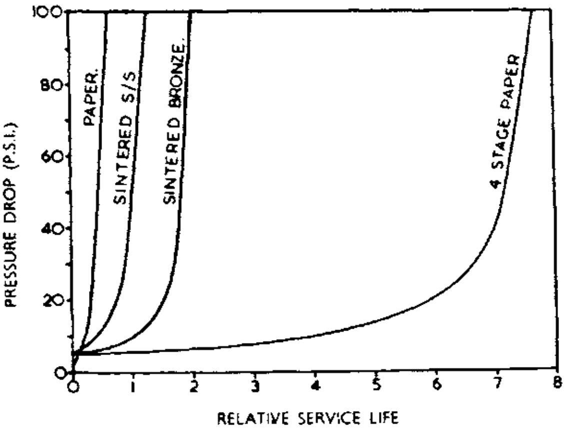

Figure 1.14. Rate of pressure rise determines the service life of media(13).

1.6.5 Tendency to blind

Unless the filter medium (or cartridge) is to be discarded at the end of a complete cycle, it is important that the accumulated solids be easily removed by a suitable cleaning procedure, whether the operation involves clarification or solids recovery by cake filtration. A medium is said to be blinded when cleaning fails to remove residual solids, which are adhering to it or embedded in it, so that its resistance to flow remains unacceptably high.

Useful empirical advice on the selection of filter cloths for liquid filtration is provided by Ehlers(14) in the form of tables: these include an indication of the order in which cloths are likely to blind, depending on the type of yarn, the structure of the yarn and the type of weave. They are reproduced in Chapter 2, as Tables 2.7–2.9. They indicate that a cloth less likely to blind is also likely to be such that it gives poorest clarity or the maximum amount of bleeding.

Rushton(15) points out that this analysis is not correct, since it ignores the division of flow, with part passing through the yarns (inter-fibre) and part around them (inter-yarn). If the proportion of the former is high, then solid particles are more likely to be carried into the depths of the yarns and to become firmly lodged, defying their removal by processes such as back-washing and increasing the likelihood of blinding. This distinction in flows was described by McGregor(16), who postulated that the split can be quantified as a factor B, which compares the actual permeability of the medium, K, with a notional permeability K_I, which would apply if the yarns were all solid filaments:

$B = K/K_I$ = actual permeability/notional permeability

For monofilament fabrics, $B = 1$, since no flow is possible through the yarns. As the value of B increases, this indicates an increasing proportion of the total flow to be passing through the yarns (inter-fibre flow), a condition that may arise due either to loosely twisted yarns or to a close weave, with various possible combinations of these giving the same B value. The 16 cloths characterized in this way by Rushton had B values ranging from 1 to 20; he concluded that a high B factor indicates a greater likelihood of blinding.

By application of the Kozeny equation, a relationship was developed whereby B can be calculated from the densities of the fibres (ρ_f), of the yarns (ρ_y), and of the medium (ρ_p), together with the number of fibres per yarn, N:

$$B = \left[1 + 1.34\left(\frac{\rho_p^2}{\rho_f^2 N} \cdot \frac{(\rho_f - \rho_y)^3}{(\rho_y - \rho_f)^3}\right)^{\frac{1}{2}}\right]^2$$

Even without the occurrence of blinding, it is frequently found that the resistance of the used medium is much greater than its original as-new value. Rushton(17) reports that, for monofilament fabrics, the combined or used cloth resistance, R_T, may be higher than that for a clean cloth, R_o, by factors as high as

6, depending on the ratio between the particle diameter and the combined dimensions of the pore and fibres in the monofilament cloths studied; smaller increases were observed with multifilament cloths, and yet smaller still with staple yarn structures.

In fact, over many years it has been realized that the overall resistance of a cake on a medium is greater than merely the sum of the resistances of the cake and the clean medium. Hatschek[18] attributed this difference to the resistance of the very first layer of particles deposited on or in the medium, and recognised that its magnitude varies with factors such as the relative sizes of the particles and pores, the shape of the particles, and the velocity of flow (which influences the orientation of the particles). The nature of this first layer has been the subject of considerable investigation in subsequent years, and the vital importance of concentration has been added to the other significant variables.

Tests with monofilament fabrics have shown that the clean cloth resistance, R_o, is only slightly increased provided that the particles are relatively large, i.e. if $D > (d_p + d_y)$, where D is the particle diameter, d_p is the pore diameter, and d_y is the filament size. Figure 1.15 depicts the usual relationship between R_T/R_o and $D/(d_p + d_y)$, and shows that, as D approaches d_p, the conditions for maximum flow resistance are obtained; this set of conditions is for 75 μm glass spheres on monofilament cloths.

The curve in Figure 1.15 may be divided into three parts (from right to left):

(a) in the first part, $D/(d_p + d_y) > 1.3$, resistance is low and cake forms on the surface of the medium;

(b) in the second part of the curve, penetration of particles into the pores occurs and resistance rises to a maximum; and

(c) in the third part of the curve, $D/(d_p + d_y) < 0.65$, bleeding occurs and resistance falls.

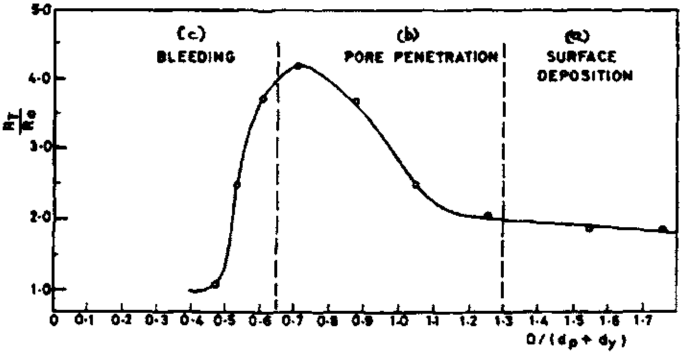

Figure 1.15. The increase in cloth resistance (as ratio used/clean) as a function of the ratio of diameters of particle and pore.

This work was extended to a few multifilament fabrics and a generalized expression developed to quantify the extent by which a clean cloth resistance R_o is increased:

$$R_T = \psi R_o$$

where

$$\psi = 1 + m(D/d_p)^{-n}$$

in which m and n are constants.

A summary of the resultant data is given in Table 1.11, which includes B values whereby the division of the flow between inter-yarn and inter-fibre modes may be seen. With admittedly scant data, it was suggested that there is a positive proportionality between B and m; in other words, a high value of B would imply a relatively large increase in the cloth resistance, R_o.

1.6.6 Cake discharge characteristics

Cake discharge characteristics are of particular importance with filter cloths used in conjunction with continuous filters such as rotary vacuum drum and disc filters, where successful continuous operation is highly dependent on the completeness with which cake is automatically removed from the working surface. The ability of a medium to discharge its cake depends very much upon the smoothness of the surface upon which the cake is residing, and hence upon the amount of fibrous material extending from the surface into the cake.

1.7 Guide to the Handbook

The bulk of this Handbook is now presented, arranged by broad class of medium material as far as possible. However, this arrangement is changed in two major sections, by the presentation of descriptions of:

- filters for air and gases, and
- cartridge filters.

Table 1.11 Influence of cloth structure on parameters in Equation 1.3

Cloth	Weave	B	m	n	Correlation coefficient between R_T and R_o
Monofilaments	Plain	1	2.25	1.65	0.98
Nylon A	Twill	2	6.30	2.07	0.98
Polyester D	Twill	2.66	9.86	2.13	0.91
Polyester B	Plain	>20	15.78	1.30	0.97

These two are categorized by the provision of filter media in particular shapes or structures, as replaceable elements, where the element itself is the important feature.

The bulk of the text covers, in order:

- fabric media, divided into woven and non-woven (dry-laid);
- wet-laid media (papers);
- filters for air and other gases;
- screens and meshes;
- coarse porous sheet and tubular media (moulded, bonded or sintered);
- membranes (cellulose, polymeric, metallic and ceramic);
- cartridges and other replaceable filter elements; and
- loose media (powders, granules and fibres).

Where appropriate, some examples are given of the way in which filter media are used in practical embodiments of filters, and some guidance is given as to the way in which filter media might be selected for efficient use. However, it should be noted that this Handbook makes no attempt to cover the technology of filtration or centrifugation, nor to be a guide to filter selection and use – for that, the reader is referred to other standard texts(6,19–21).

The Handbook continues with two further chapters, one on filter media testing and one on filter media standards, before finishing with a glossary, a list of advertisers, and the editorial index.

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