CHAPTER 10

Packed Beds

Apart from the specific use of granular activated carbon in some combination filters, all the media discussed in this Handbook so far have been continuous, even if made from discrete particles or fibres. Now it is the turn of those discrete particles or fibres, used in bulk, to be described, as they are themselves used as filter media.

10.1 Introduction

The structure of this chapter is based on the recognition that there are two distinct modes for utilizing loose powders, fibres and granules as filter media. These are:

- precoat filtration (including filter aids), and
- deep-bed filtration.

Precoat filtration is so named since, prior to each filtration cycle, there is a preliminary phase during which the surface of the filter is coated with a fresh layer of precoat powder, which is deposited by filtration of a specially prepared suspension. The main filtration then takes place through this layer, which acts as the filter medium, so that the collected process solids accumulate as a cake on top of the precoat, as illustrated in Figure 10.1; both layers of solid (precoat plus process solids) are discharged together when the filter is cleaned (e.g. by backwashing). It is implicit that the precoat layer is formed on the surface of a secondary filter medium (usually a very open cloth or wire mesh), which the precoat protects from plugging.

Precoat filtration is most commonly associated with the clarification of liquids, using equipment such as pressure leaf filters, candle filters or rotary vacuum filters. Less common is its role in the filtration of difficult dusts using filter bags in fabric filters[1].

Deep-bed filtration, as its name implies, involves filtration vertically through a packed bed of granular or fibrous material, whose height is considerably greater than even the thickest of continuous filter media. It is typified by the conventional sand filter, which clarifies water by depth filtration mechanisms as it flows through a bed of graded sand that may be up to 1 m in depth.

Deep-bed filters are of very simple construction: a vessel (usually cylindrical), a supporting grid at the base of the vessel, and the bed of granules – plus the necessary inlet and outlet piping. Effectively, the medium is the filter.

Materials such as activated carbon, fuller's earth and ion exchange resins, which are used in deep packed beds of granules, but which function by other mechanisms (primarily adsorption), are excluded from coverage by this chapter since they are not strictly filter media, even though occasionally they overlap in their applications.

It should be noted that, in addition to being used as a precoat, the various types of granular and fibrous materials discussed below are also frequently used as *filter aids* (or body aids) in the filtration of liquids. In this role their function is to accelerate the filtration of a difficult suspension, typically where the solids are very fine, gelatinous or in low concentration. To offset these factors, a controlled quantity of filter aid powder is dispersed into the feed suspension so that the suspended solids and the powder are intimately mixed and therefore are removed together as a mixed cake during filtration. In this way it is possible to produce a more porous cake so that the filtration process proceeds faster and more easily.

Optimizing this use of filter powders involves decisions in respect of the dosage, type and grade of the filter aid, which may differ from that used as the precoat. Logically it is often appropriate to consider alternative separation techniques, including the use of pre-treatment reagents that act as 'filter aids' by means of

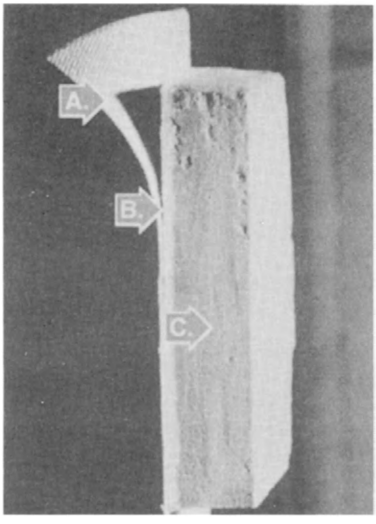


Figure 10.1. The three layers in precoat filtration: (A) a filter cloth or mesh, (B) the precoat layer protecting the cloth from plugging, (C) the filter cake.

chemical reactions. These topics are outside the scope of the present text but are dealt with at length elsewhere[2].

10.2 Precoat Media

A useful overview of the available types of precoat filter media is provided by Table 10.1, which is based on the product range of one leading supplier.

Recommended thicknesses for the precoat layer are typically in the range 1.5–3 mm, corresponding to 500–1000 g/m^2, applied by filtering a dilute suspension at a flow rate of 40–80 $l/m^2/min$. One leading supplier (Celite) recommends the apertures in the supporting septum or mesh to be no less than 0.13 mm; another (Grefco) relates the suitability of a range of screens to the different grades of its products as summarized in Table 10.2. Finer grades may be supported on one or two layers of increasingly coarse grades.

The materials used as precoats are both inorganic and organic, characterized by being relatively light and voluminous, so as to be able to set up the basic filter cake layer on the support quickly and efficiently. The materials include:

- natural silica – diatomite and perlite;
- cellulose and wood flour; and
- inactive carbon, polymers and miscellaneous powders.

Table 10.1 Summary of major types of filter aids[a]

Product	'Dicalite' diatomite	'Dicalite' perlite	'Solka-Floc'
Composition	Silica	Glassy silica	Cellulose
Number of grades	15	8	8
Range of relative flow rates[b]	1–23	1.7–9.3	5–23
Specific gravity	2.25–2.33	2.34	1.5
Wet cake densities	0.32–0.38	0.24–0.34	0.17–0.34
Retention on coarse screens	Good	Good	Excellent
Solubility (at room temperature)			
In alkalis	Slight in dilute	Slight in dilute	None in dilute
In acids	Slight in dilute	Slight in dilute	None in dilute
Prime advantages and applications	General use for maximum clarity. Reduced dosage on pressure and vacuum filters.	Outstanding on rotary filters.	Excellent for precoating coarse screens. Highest purity for adsorption of oil from condensate and removal of iron from caustic.

[a] Illustrated by 'Dicalite' and 'SolkaFloc' products of Grefco, Inc.

[b] Water permeability ratio relative to Dicalite 215 assumed as 100.

Table 10.2 Suitability of various screens as supports for precoat

Mesh per cm:	8×8	20×20	24×24	32×32	10×44
Apertures (cm):	0.89	0.32	0.25	0.24	0.008
Diatomite grades					
215	No	No	No	No	No
Superaid	No	No	No	No	No
UF	No	No	No	No	No
Speedflow	No	No	Yes	Yes	Yes
Special					
Speedflow	No	No	Yes	Yes	Yes
Speedplus	No	No	Yes	Yes	Yes
Speedex	No	No	Yes	Yes	Yes
4200	No	No	Yes	Yes	Yes
4500	No	Yes	Yes	Yes	Yes
5000	No	Yes	Yes	Yes	Yes
6000	No	Yes	Yes	Yes	Yes
Perlite grades					
416	No	No	No	No	No
426	No	No	No	No	No
436	No	No	No	Yes	Yes
476	No	Yes	Yes	Yes	Yes
CP 150	No	Yes	Yes	Yes	Yes
4106	No	Yes	Yes	Yes	Yes
CP-175	No	Yes	Yes	Yes	Yes
4156	No	Yes	Yes	Yes	Yes

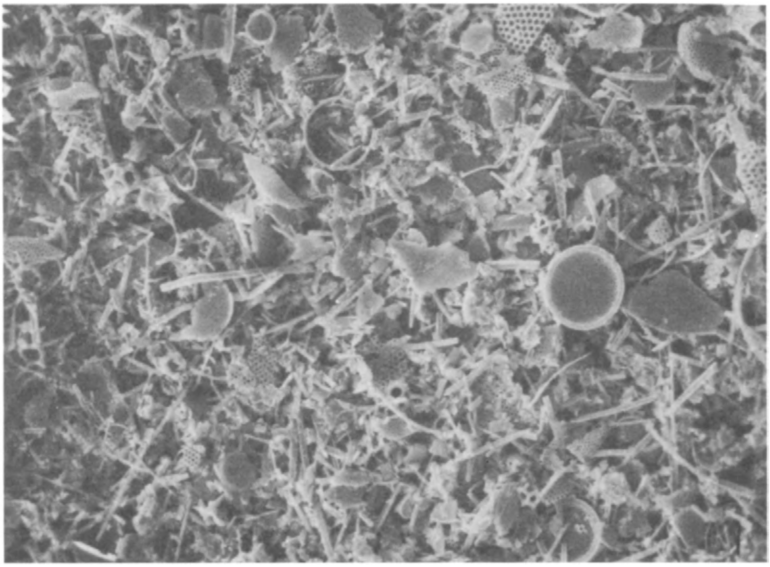


Figure 10.2. Diatomite filter aid at low magnification.

10.2.1 Diatomite

Known also as diatomaceous earth and kieselguhr, diatomite is the classic material for use either as a precoat or as a filter aid. Diatomaceous earth is the fossilized remains of microscopic algae, several million years old, of which over 10 000 varieties have been recorded. Figure 10.2 shows the characteristic appearance of a typical diatomite material under low magnification.

The name 'diatom' is derived from the Greek word meaning 'to cut through', referring to the way in which the individual cells are joined together into zigzag chains that are easily separated. But it also aptly describes the way in which single cells of algae reproduce or replicate by dividing into two almost equal parts. This division happens very simply, since all the different species have an outer shell basically very similar to a pillbox, with one half fitting neatly into the other; it is the difference in shape of the plan view of the pillbox, as shown in Figure 10.3, that gives each diatom its own characteristic appearance. As the diatom grows, the plan view remains unaltered, but the two parts of the shell are forced progressively apart, until cleavage results in two diatoms, where previously there was only one.

The shell of the diatom is virtually pure silica, which is extracted from the water in which diatoms live. After the death of the diatom, the silica shell survives, because of the chemical stability of silica. It is a vast multitude of these minute skeletons that goes to make up a bag full of diatomite for use in industry.

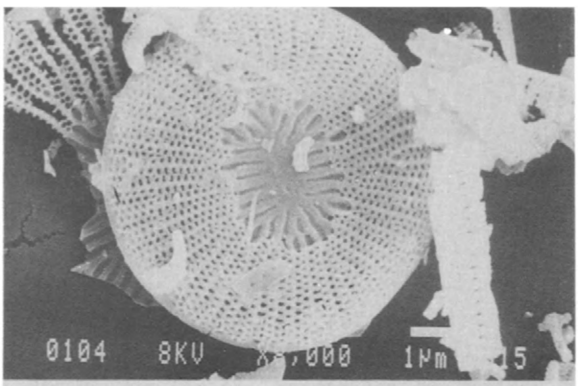
Diatoms occur in both salt and fresh water, and fossilized deposits occur around the world, where former seas and lakes have long since dried up. The commercial value of these deposits varies greatly, due both to soluble impurities and to insoluble contaminants such as clay. Commercially important deposits include those in Algeria, France, Iceland, Japan, Spain and California in the USA.

The deposits are worked by open-cast methods, the amorphous rock being then subjected to a sequence of crushing, grinding, screening, washing, drying and calcining operations. Three basic types of refined product are produced, one without calcining and two with; of the latter, one involves the addition of a fluxing agent such as soda ash. The effect of this refining is that the initial light rock, with a density of 300–500 kg/m^3 and containing 20–40% of water by weight, is converted into a series of ever lighter materials, with bulk densities between 100 and 150 kg/m^3. Moreover, calcining affects the surface of the diatoms, increasing the particle size and reducing the surface area, but markedly increasing the relative filtration rates, as can be seen in Table 10.3.

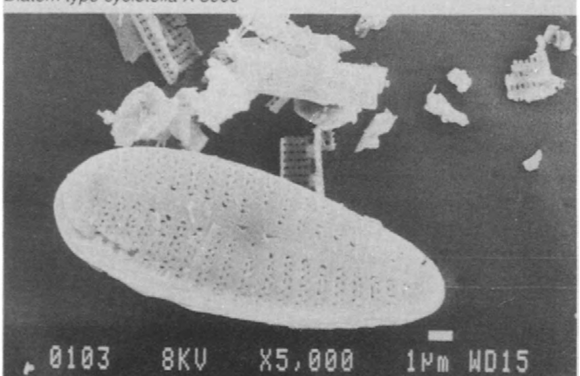
There is inevitably some variation in the chemical composition of the various competitive grades of commercially available diatomite, but the differences are generally relatively small as compared with the composition of alternative materials such as perlite; Table 10.4 shows typical figures for one manufacturer for the composition of refined diatomites.

Far more variation between competitive products is likely to occur in respect of particle size analysis, because of differences both in the quarried rock and in the equipment and techniques used to process it; moreover, it is essentially a subjective matter to decide the best balance of fractions to produce from an initial mixture of particles ranging from about 1 to 100 µm. The data given in Table 10.5 for one manufacturer's range of products are therefore likely to differ considerably from those of a competitor.

In practice, these filter aids are generally characterized by their performance when submitted to a filtration test; unfortunately, each manufacturer tends to have its own test procedure, and then to express performance as a ratio to the slowest filtering material in its own range. Typically, the procedure is to form a precoat layer and then to filter through it under pressure a batch of either water or a slurry to which some filter aid has been added, recording the cumulative volume of filtrate with time. The nature of the aqueous slurry varies, sugar liquids being used by some manufacturers, while others use water containing bentonite clay; the reason for using a slurry is that, besides giving a measure of flow rate, the test then makes it possible to evaluate both the achievable degree of clarity and the ability of the filter aid to maintain the porosity of the cake as it is deposited.



Diatom type cyclotella X 3000



Diatom tyoe Navicula X 5000

Figure 10.3. Diatoms at high magnification.

A summary of the typical properties of one range of diatomite media is provided in Table 10.6. The permeability figures are expressed both as a relative flow rate compared with a nominal value of 100 for the slowest grade, and in darcies. The results of the empirical tests to determine that size of particles which can be retained by certain grades are given in Figure 10.4.

Table 10.7 gives some guidance on the correspondence of certain grades of competitive diatomite media. It reproduces a modified version of an original publication by Eagle-Picher.

10.2.2 Expanded perlite

Since it was first introduced in the 1950s, expanded perlite has established itself as a serious competitor to the diatomite that had dominated the precoat market for the previous half century. Both types of material derive from vast geological deposits, the processing of which have many similarities; but their origins, and hence their chemistry and physical characteristics, are very different.

Table 10.3 Effect of calcining on the properties of 'Dicalite' diatomaceous earths

	Natural	Calcined	Flux calcined
Relative filtration rate	1	1–3	3–20
Wet cake density (g/cm^3)	0.24–0.35	0.24–0.37	0.26–0.34
Sedimentation particle size distribution (%)			
+40 μm	2–4	5–12	5–24
20–40 μm	8–12	5–12	7–34
10–20 μm	12–16	10–15	20–30
6–10 μm	12–18	15–20	8–33
2–6 μm	35–40	15–45	4–30
−2 μm	10–20	8–12	1–3
% retained on 325 mesh screen	0–12	0–12	12–35
Specific gravity	2.00	2.25	2.33
Surface area (m^2/g)	12–40	2–5	1–3
pH	6.0–8.0	6.0–8.0	8.0–10.0

Table 10.4 Typical chemical analysis of refined diatomites[a]

	Natural	Calcined	Flux-calcined
SiO_2	85.8	91.1	89.6
Al_2O_3	3.8	4.0	4
Fe_2O_3	1.2	1.3	1.5
CaO	0.5	0.5	0.5
MgO	0.6	0.6	0.6
P_2O_5	0.2	0.2	0.2
TiO_2	0.2	0.2	0.2
Na_2O+K_2O	1.1	1.1	3.3
Ignition loss	3.6	0.5	0.2
Water	3.0	0.5	0.1

[a] Data for three typical grades of the range of Johns Manville Co. Ltd.

Table 10.5 Typical particle size[a] analyses of Celite diatomites[b]

Weight % finer than micron size (laser size)																	Median particle size in microns
Micron size	1.0	1.5	2.0	3.0	4.0	6.0	8.0	12.0	16.0	24.0	32.0	48.0	64.0	96.0	128.0	196.0	
Celite 5000	2	2	4	6	10	19	27	41	54	69	78	90	93	97	100	100	14.7
Filter Cel	2	3	4	8	12	22	31	45	58	72	80	92	94	98	100	100	14.0
Celite 577	2	3	4	7	12	21	30	41	52	66	75	83	87	95	99	100	14.6
Std. Super-Cel	2	3	4	6	9	17	25	39	52	69	77	90	93	99	100	100	15.4
Celite 512	2	2	4	5	8	15	22	36	49	65	75	87	92	97	99	100	16.4
Hyflo Super-Cel	2	2	3	5	7	11	16	25	36	53	67	86	91	97	99	100	22.3
Hyflo RV	1.4	1.7	2.7	3.4	4.5	6.2	8.3	13.5	25.6	37.9	50.2	67.6	75.7	88.3	94.8	100	30
Celite 501	2	2	3	4	6	9	13	20	32	50	64	82	88	95	99	100	24.3
Celite 503	2	2	3	4	5	7	10	16	25	42	56	76	84	92	98	100	28.6
Celite 503 RV	1	1.4	2.2	2.7	3.9	4.8	6.1	9	14.4	26	37.1	56.2	63.7	76.1	81.1	100	40.0
Celite 535	1	2	3	4	5	7	10	16	23	36	49	70	79	91	98	100	34.3
Celite 545	1	2	2	3	4	5	6	9	14	26	40	55	78	92	99	100	36.2
Cellite 560	1.3	1.6	2.3	3.2	4.5	6.9	9.5	13.9	19.2	26.2	34	47.8	55.8	70.1	92.5	100	55

[a] The coarsest particles of the coarser grades of filter aid exceed the dynamic range of a laser sizer, so data shown for those grades indicate a somewhat finer particle size distribution than actual.

[b] Celite Corporation.

Perlite is a rock of much the same composition as granite, and, like granite, is of volcanic origin; its formation and properties result from molten lava discharging from an erupting volcano into water, where it was quenched and rapidly cooled. Perlite is consequently a super-cooled liquid or natural glass, differing from true rocks such as granite in being amorphous, with no crystalline

Table 10.6 Typical properties of 'Dicalite' diatomite filter aids[a]

Dicalite grade	Colour	Specific gravity (kg/m³)	Relative flowrate[b]	Permeability (darcies)	Dry bulk density (kg/m³)	Wet cake density (kg/m³)	Particle[c] median size (μm)	pH of 10% slurry	Moisture content (%)
Calcined									
215	Pink	2.25	100	0.02	128	384	10	6–8	<0.5
Superaid	Pink	2.25	140	0.04	128	384	10.5	6–8	<0.5
UF	Pink	2.25	200	0.08	128	384	11	6–8	<0.5
Speedflow	Pink	2.25	320	0.22	160	368	16	6–8	<0.5
231	Pink	2.25	430	0.36	144	368	19	6–8	<0.5
Flux-calcined									
341	White	2.33	510	0.65		368	22	9–10	<0.2
Speedplus	White	2.33	700	1.00	160	352	32	9–10	<0.2
375	White	2.33	820	1.40		352	35	9–10	<0.2
Speedflex	White	2.33	930	1.80	224	352	40	9–10	<0.2
2500	White	2.33	1080	2.40		336	48	9–10	<0.2
4200	White	2.33	1300	3.30	256	336	59	9–10	<0.2
4500	White	2.33	1450	4.00	256	336	64	9–10	<0.2
5000	White	2.33	1600	5.00	304	384	71	9–10	<0.2
6000	White	2.33	2000	8.00	320	384	77	9–10	<0.2

[a] Grefco, Inc.
[b] Compared with Dicalite 215 rated as 100.
[c] Median particle diameter by Malvern analyzer.

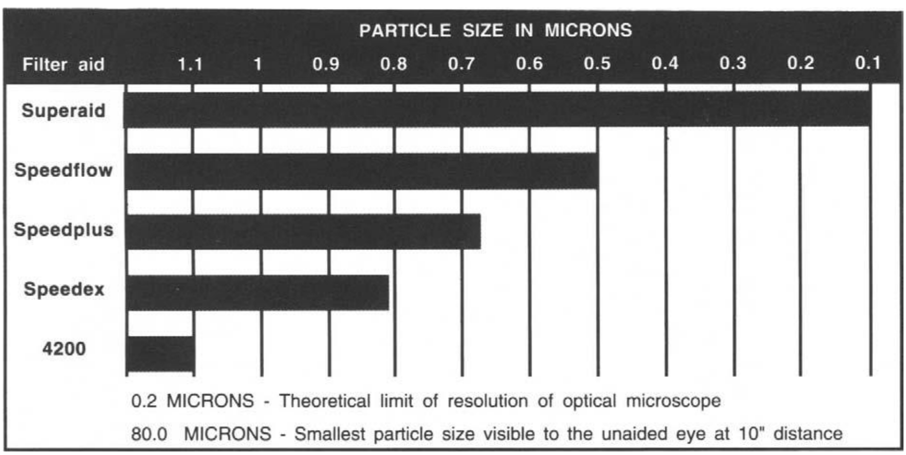


Figure 10.4. Chart showing the sizes of particles removed by five grades of 'Dicalite' filter aids.

structure. Instead, it comprises a mass of small pearl-like 'pebbles', which give the mineral the names pearlstone or perlite. The pebbles may be up to 25 mm across, but are generally the size of lead shot or smaller. Occluded within them, as a result of the quenching of the lava, is a small amount of water; this, together with other water absorbed into the mineral at a later stage, gives a total water content of 3–4%.

Table 10.7 Equivalent grades of diatomite filter aids from four major suppliers

Standard ratios[a]		Eagle-Picher	Celite	Dicalite	Ceca
Flow rate	Clarity				
100	1000		Filter Cel, Celite 505 and 577	Dicalite 215, UF Grade Superaid	CBL3 CBL
200	995	Celatom FP-4	Standard Super Cel	Speedflow	CBR
300	986	Celatom FW-6	Celite 512	Dicalite 231 Special Speedflow	DCB-R
700	970	Celatom FW-12	Hyflo Super Cel	Speedplus CP-100, 689	DIC-B
800	965	Celatom FW-14	–	375	DIC
950	963	Celatom FW-18	Celite 501	CP-5	DIC-S
1000	960	Celatom FW-20	Celite 503	Speedex, 757	DIC 3
2500	940	Celatom FW-50	Celite 535	4200, CP-8	DIT-R
3000	936	Celatom FW-60	Celite 545	4200, 4500	DIT-2R
5500	927	Celatom FW-80	Celite 560	5000	DIT-3R

[a] Based on bomb filter tests with 60° Brix raw sugar solution, 80°C.

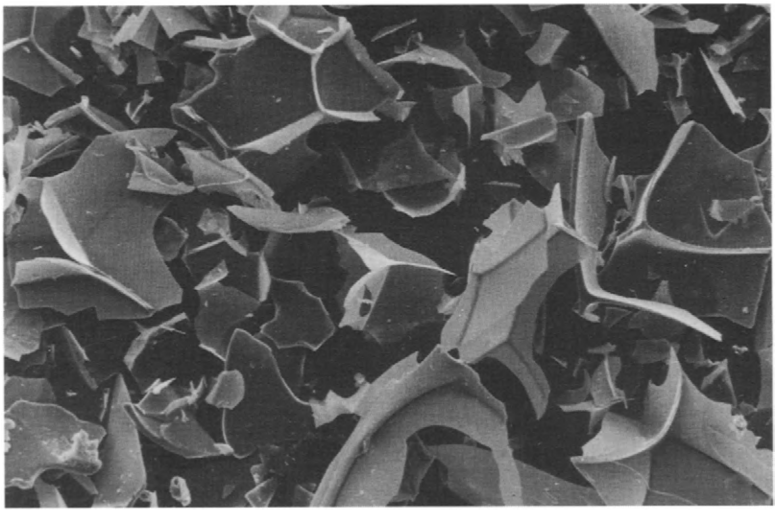


Figure 10.5. 'Harborlite 900S' expanded perlite at high magnification.

The expanded perlite, for use as a precoat, is prepared from the mineral by a sequence of operations that include crushing, grinding, screening and calcining. The key operation, however, is the rapid heating of the crushed perlite to its softening point, when the occluded water vaporizes, causing the individual pebbles to expand to some 20 times their initial volume. The small hollow balls thus formed are subsequently broken up by grinding, to give a mixture of thin irregularly shaped particles, which, as can be seen in Figure 10.5, are rather like pieces of eggshell. Some of the fragments are so shaped that they contain cavities in which small air bubbles can be trapped, thereby causing them to float to the surface when dispersed in a liquid; these floaters can cause operational difficulties if present in sufficient amounts.

By careful control of the manufacturing process, the density of expanded perlite can be varied over a considerable range, to suit the intended application. Typically, expanded ores direct from the furnace are reported by Blunt(3) to have bulk densities in the range 30–60 kg/m^3. Following subsequent grinding and classification, products intended for use as precoat or filter aids may have bulk densities from about 60 up to more than 150 kg/m^3. It is their very low density that enables expanded perlites to compete so strongly with the much denser diatomites, since the weight of perlite needed to form a precoat is thereby proportionally less.

Table 10.8 gives the chemical analysis of a typical expanded perlite, and it can be seen to differ significantly from the composition of diatomites in Table 10.4, notably in respect of sodium and potassium. Particle size analysis data, including the content of floaters, are provided in Table 10.9, while Table 10.10 summarizes the typical properties of one commercial range of perlites.

Based on permeability data in expressed in darcies, the relative flow rates of perlites can be compared with those of diatomites. Figure 10.6 thus summarizes the three different product ranges of Grefco (including its Solka-Floc cellulose fibre materials). It is important to note, however, that equivalence in flow rate does not correspond to identical performance in terms of the clarification achieved; where maximum clarity is required, diatomite is likely to be superior, since it is more effective in removing submicrometre particles, as indicated in

Table 10.8 Chemical analysis of a typical expanded perlite[a]

	% weight
SiO_2	74.7
Al_2O_3	13.2
Fe_2O_3	0.67
CaO	0.83
MgO	0.03
P_2O_5	Trace
TiO_2	0.01
Na_2O	4.40
K_2O	5.08
Ignition loss	1.0

[a] Johns Manville Co. Ltd.

Table 10.11, which compares these media in respect of several other criteria as well.

An interesting refinement in processing perlite is recommended by Mayer, based on cooperation between DuPont as a user and Nord Perlite as a manufacturer(4). Laboratory- and plant-scale investigations and trials revealed the impact of the content of particles smaller than 1 μm on performance when pressure filtering waste waters. As shown by the data in Table 10.12 comparing the performance of specially prepared Perflo 30SP with standard quality competitive materials, the shortest filtration was achieved with the Perflo material. Moreover, whereas there is no evidence of a correlation between filtration time and any of the other size analysis parameters in the table, there is a strong relationship to the Sedigraph weight percent of fines of less than 1 μm.

10.2.3 Cellulose fibres

In comparison with diatomite or expanded perlite, natural cellulose fibres have certain advantages for precoat filtration, as a consequence both of their distinctive structure as seen in Figure 10.7, and of their different chemistry. With their lengths varying from as low as 20 μm up to 600 μm or more, it is not surprising that these fibres rapidly form precoats, with little if any penetration through the supporting screen; moreover, the precoat is more stable to pressure fluctuations during the subsequent filtration cycle, and in addition it releases cleanly from the screen when the filter is cleaned. Because of these characteristics, cellulose fibres are frequently used in combination with other types of precoat, either as a preliminary layer or in the form of a mixture.

The cellulose fibres are derived from wood chips, which are subjected to an extensive sequence of processing stages to dissolve out the lignin and other soluble impurities such as wood resins and miscellaneous polymerized sugars. The resultant highly purified pulp is formed into sheets that are dried and then mechanically processed to separate and break up the individual fibres into short

Table 10.9 Typical particle size analyses of expanded perlites[a]

Grade	Permeability (darcies)	Floaters (%)	Micron diameter[b] at which wt.% is <					Wt.% on 106 μm mesh
			10%	25%	50%	75%	90%	
J300S	4.5	5.6	16	–	41.6	–	88	20
J250S	3.9	5.0	15	31	48	–	89	18
J150S	3.2	5.0	14	24	36	56	85	16
J100	2.2	3.7	–	21	33	52	–	18
J2	1.6	2.1	–	19	30	47	–	7
J1	1.2	1.2	–	17	29	46	–	2.5
J4	1.2	2.3	–	17	28	45	–	5.5
J208	0.4	0.5	–	11	20	31	–	2.0
J206	0.15	0.5	–	–	18	–	–	0.9 on 45 μm mesh

[a] Harborlite (U.K.) Ltd.

[b] By Coulter analyzer.

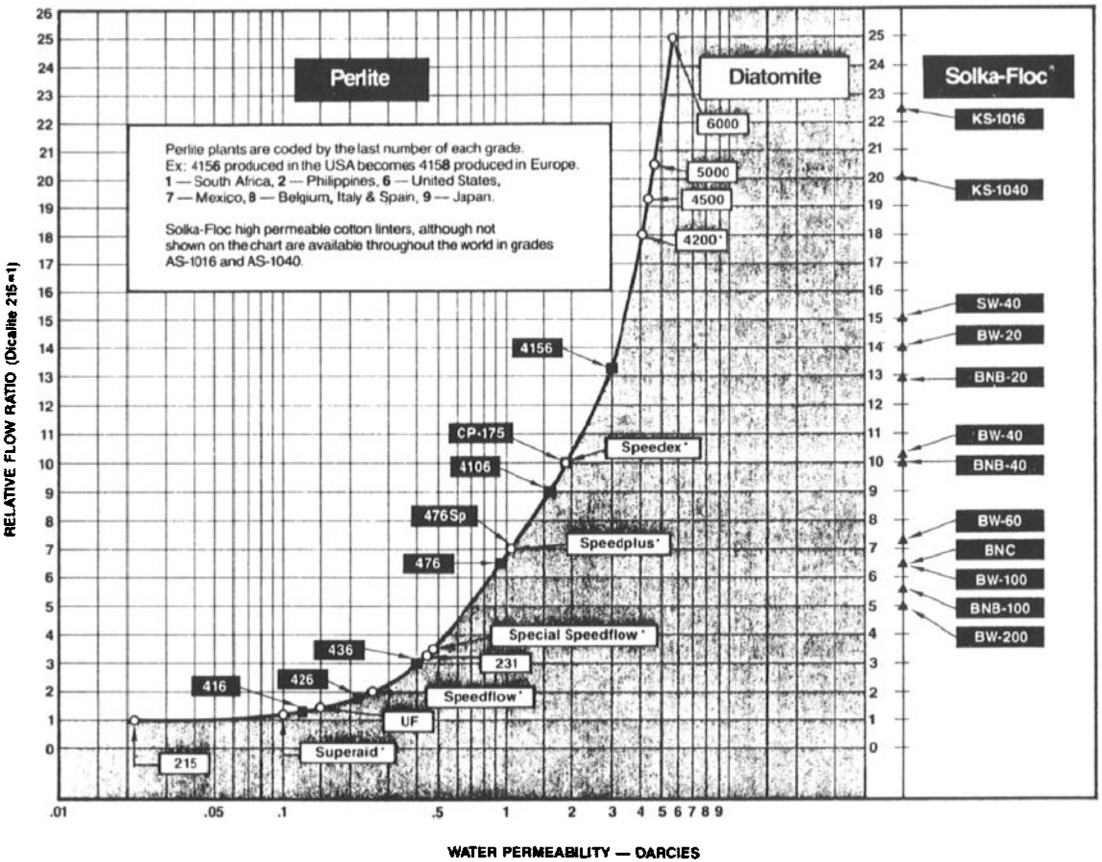


Figure 10.6. Relative flow rate chart for 'Dicalite' filter aids.

Table 10.10 Typical properties of 'Dicalite' expanded perlite filter aids[a]

Dicalite grade	Colour	Specific gravity (kg/m³)	Relative flowrate[b]	Permeability (darcies)	Dry bulk density (kg/m³)	Wet cake density (kg/m³)	Particle[c] median size (μm)	pH of 10% slurry	Moisture content (%)
416	White	2.34	170	0.06	88	336	11	5–8	<1.5
426	White	2.34	300	0.18	80	272	14	5–8	<1.5
436	White	2.34	400	0.34	96	272	24	6–9	<1.5
456	White	2.34	520	0.56	n/a	256	31	6–9	<1.5
476	White	2.34	640	0.84	112	240	37	7–9	<1.5
476SP	White	2.34	700	1.00	144	256	42	7–9	<1.2
4106	White	2.34	800	1.30	144	256	50	7–9	<1.0
4156	White	2.34	930	1.80	176	272	57	7–9	<1.0

[a] Grefco, Inc.
[b] Compared with Dicalite 215 rated as 100.
[c] Median particle diameter by Malvern analyzer.

lengths prior to final classification into a series of low-density, free-flowing powders. These comprise pure cellulose, which is chemically inert, containing only trace amounts of inorganic elements, as indicated by Table 10.13; it is consequently ashless, which facilitates disposal by incineration, as well as recovery of catalysts or rare metals.

Examples of these fibres are the Solka-Floc products, whose flow properties are included in the summary chart of Dicalite filter aids reproduced in Figure 10.6. Their other main properties are listed in Table 10.14, while Table 10.15 summarizes the typical applications of the various grades; note that, for economy applications where high purity is not essential, some less refined grades (BNB and BNC) are available.

Table 10.11 Summary guide comparing diatomite and perlite[a]

	Diatomite	Perlite
Typical wet density (g/l)	360	180
Particle size removal	Submicron and above	Less efficient for submicron particles
Particle quantity removal	Typically <0.5% w:w	Typically <2% w:w
Max. operating pressure	6 bar	4 bar
Penetrability in rotary vacuum filter cakes	Good resistance	Usually poor resistance
Ease of filter cloth cleaning	Very easy	'Sticky' cake
Precoating candle filters	Admixture with perlite or cellulose recommended	Very good

[a] Celite France.

Table 10.12 Influence of content of submicron particles on performance of expanded perlite

Parameter	Perflo 30SP[a]	Standard filter aids		
		A	B	C
Weight % <625 mesh	27.0	68.8	39.3	35.4
Coulter Counter analysis				
weight % <2 μm	61.8	70.0	65.4	54.7
D_{50} size (μm)	1.5	1.4	1.5	1.8
Sedigraph analysis				
weight % <1 μm	1.0	9.0	6.0	3.5
D_{50} size (μm)	4.8	3.7	4.6	5.2
Relative filtration time	1.0	2.0	1.8	1.5

[a] Special grade of Nord Perlite filter aid.

An extensive range of precoat and filter aid products is made from wood and other vegetable cellulose by the German company Rettenmaier. The main range of products is described in Table 10.16, with more details of filtration characteristics given in Table 10.17. Figures 10.8 and 10.9 show the relationship between permeability and clarifying action for two of the product ranges.

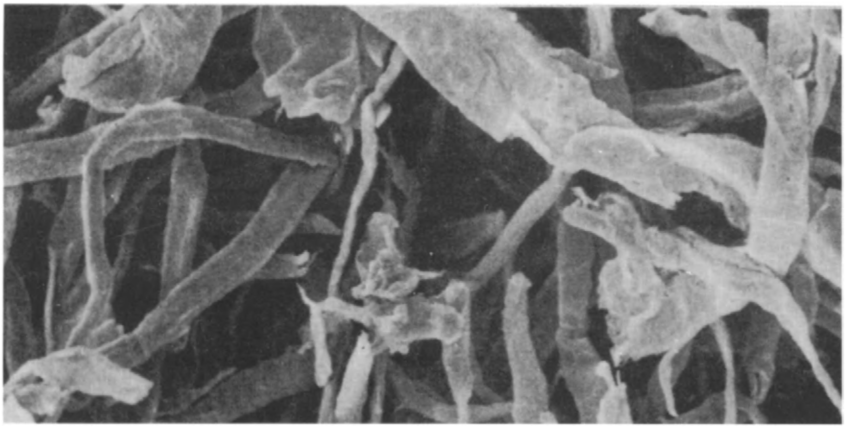


Figure 10.7. Celite 'Fibra-Cel SW-10' cellulose fibres at ×200 magnification.

Table 10.13 Typical element content of 'Solka-Floc' cellulose fibres[a]

	ppm element
Sodium	380.0
Calcium	260.0
Iron	120.0
Aluminium	3.8
Magnesium	31.0
Potassium	37.0
Silicon	15.0
Barium	4.1
Boron	0.34
Lead	2.0
Manganese	1.5
Chromium	0.12
Nickel	0.23
Molybdenum	0.23
Tin	0.41
Lithium	0.40
Copper	1.3
Silver	Trace
Titanium	0.17
Strontium	1.2
Other elements	Nil

[a] Grefco, Inc.

A major development by Rettenmaier[5] has been its "Extract-Free Cellulose" (EFC), for which natural cellulose has been treated by solvent extraction to remove extractable components that might otherwise have led to odour, taste or colour in the filtrate. EFC is marketed under the product name of Filtracel, and is an economical way to achieve a precoat with US FDA approval for use with foodstuffs. Details of the Filtracel products, which now outsell all of the other Rettenmaier lines put together, are given in Table 10.18.

Cellulose fibres are frequently blended with other media, especially diatomites, to facilitate precoat formation and minimize initial penetration through the supporting screen, as well as strengthening the precoat bed, so that it is more resistant to fluctuations in flow rate and pressure. An example of a range of blended cellulose/diatomite powders, with variations in both the proportions and the grades, is summarized in Table 10.19.

Eagle-Picher has a corresponding range of mixed diatomite and cellulose, marketed under the brand name Dialose, based on six grades of the Celatom diatomite (FP-4, FW-6, -12, -14, -20 and -60), mixed with one grade of Pre-co-Floc cellulose fibre (PB-40M), in five different proportions (5, 7.5, 10, 15 and 20% of cellulose fibre).

10.2.4 Wood flour

Wood flour is produced by a process of grinding and double sifting, and is utilized in a wide diversity of industrial applications. Typical standard grades are characterized by screen sizes: 25 mesh (600 μm), 60 mesh (250 μm), 90 mesh (180 μm), 120 mesh (125 μm), 180 mesh (90 μm), and 300 mesh (53 μm).

Table 10.14 Typical properties of 'Solka-Floc' cellulose filter aids[a]

Grade	Colour	Density (kg/m^3)		Specific gravity	% Retention (US Std. Screens)[b]			Fibre length (μm)	pH	Ignition loss
		Loose weight	Filter cake		40M	100M	325M			
KS-1040	White	55	175	1.5	16.0	53.0	87.0	–	7.0	99.8
KS-1016	White	50	170	1.5	16.0	52.0	87.0	290	7.0	99.8
SW-40	White	65	165	1.5	0.5	37.0	81.0	100–140	6.5	99.8
BW-20	White	105	215	1.5	9.0	33.0	68.0	80–120	6.0	99.8
BW-40	White	130	225	1.5	1.0	14.0	56.0	50–60	6.0	99.8
BW-100	White	175	270	1.5	TR	8.0	38.0	45–55	6.0	99.8
Special BW-100	White	200	305	1.5	TR	6.0	31.0	35–45	6.0	99.8
BW-200	White	230	305	1.5	0	2.4	25.0	30–35	6.0	99.8
BNB-20	Brown	95	190	1.5	10.0	31.0	63.0	80–120	7.0	98.7
BNB-40	Brown	105	200	1.5	3.0	23.0	59.0	60–100	7.0	98.9
BNB-100	Brown	135	230	1.5	1.0	3.0	25.0	35–45	7.0	98.9
BNC	Grey	130	250	1.5	5.0	17.0	52.0	–	7.0	98.6

[a] Grefco, Inc.

[b] Apertures of US screens: 40M=425 μm; 100M=150 μm; 325M=45 μm.

A detailed investigation of the potential of some of these flours for use as precoats was undertaken by Wakeman[6], who reached cautiously favourable conclusions, despite the compressibilities being relatively high as compared with

Table 10.15 Typical applications of 'Solka-Floc' cellulose filter aids[a]

Applications		Grades
1.	Alkaline chemicals – e.g. 50% sodium hydroxide, sodium silicate, preparation of alumina and plating solution, where the soluble silica in diatomite and perlite makes them unsuitable	KS-1040 KS-1016 SW-40 BW-20 BW-40
2.	Brine filtration – electrolytic cells of chlorine/caustic plants	BW-100 BW-40
3.	Condensate – removes solid particles and traces of oil	BW-40 BW-100 BW-40 BW-100 special
4.	Emulsions – breaks oil-in-water and water-in-oil	BW-20 BW-40
5.	Catalysts and rare earth metals – ashless 'Solka-Floc' aids recovery by incineration	BW-40 BW-100
6.	Beer and beverages – avoids bleed-through of diatomite or perlite	KS-1040 KS-1016 SW-40 BW-40
7.	Miscellaneous chemicals – where highest purity is not the prime consideration, lower cost unrefined fibres are economic	BNB-20 BNB-40 BNB-100 BNC

[a] Grefco, Inc.

Table 10.16 Rettenmaier's range of cellulose fibre products*

Product	Source	Composition
Lignocell	Natural untreated wood cellulose fibres	60–75% cellulose; 20–35% lignin; 3–5% extractables
Rehofix	Natural vegetable fibres from annual plants	70% cellulose; 20% lignin; 10% carbohydrates
Vitacel	Highly purified α-cellulose powder from wood	99.5% cellulose
Arbocel	Highly purified α-cellulose fibre from wood	99.5% cellulose
Vivapur	Micro-crystalline cellulose from wood	99.7% cellulose

* J Rettenmaier & Söhne GmbH & Co.

conventional precoats. Data illustrating the effect of compression on porosity, permeability and specific cake resistance are reproduced in Tables 10.20–10.22. An indication of their solubility in various solvents is provided by Table 10.23. As a low-cost material, wood flour has proved to be successful for certain precoat filtration duties, such as for removing protein from glucose solutions.

10.2.5 Inactive carbon

Filter aids of inactive carbon have occasionally been produced, using coal as the ultimate raw material; it is uncertain if any are currently available commercially. As part of a development programme for the direct liquefaction of

Table 10.17 Filtration properties for Rettenmaier cellulose products[a]

Property	Lignocel	Rehofix	Vitacel	Arbocel	Vivapur[b]
Number of grades	7	2	4	19	
Fibre length (μm)	20–350	80–400	20–350	20–2000	10–200
Dry bulk density (g/l)	100–150	300–500	60–270	10–270	150–360
Wet cake density (g/l)	120–230		90–280	40–350	150–400
Permeability (darcies)	1–32	>5	0.8–10	0.8–15	0.2–15
Permeability[c] (per min)	210–4000	>1000	100–3500	100–2500	40–2000
Chemical stability	Low	Low	Very high	Very high	Very high
pH range	2–11	2–11	1–14	1–14	1–14
Max temperature (°C)	180	180	200	200	200

[a] J Rettenmaier & Söhne GmbH & Co.
[b] Vivapur is a very minor product by comparison with the others.
[c] Permeability as measured by Schenk 'Wasserwert-Methode'.

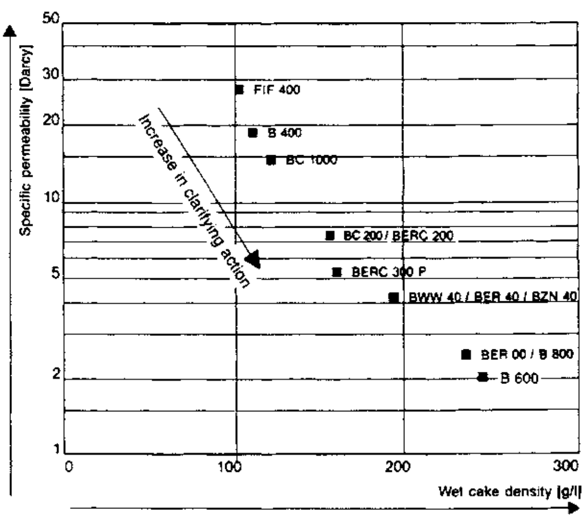


Figure 10.8. Permeability and clarifying action of 'Arbocel' cellulose filter aids.

coal, Kimber and Davies[7] report that (the then) British Coal evaluated the precoat performance of six carbonaceous products derived from coal and petroleum as possible alternatives to Celite 560; the materials tested were petroleum cyclone fines (a by-product of calcined coke), calcined petroleum coke crushed to nominally 100 μm, regular petroleum cokes crushed to nominally 50 and 100 μm, coal extract cokes crushed to nominally 100 μm, and pitch cokes (from coal liquefaction). Best results were achieved with petroleum cyclone fines, the other materials all deteriorating more rapidly. The specific filtration resistances of all coke cakes were less than 3×10^{10} m/kg, within the range of commercial filter aids.

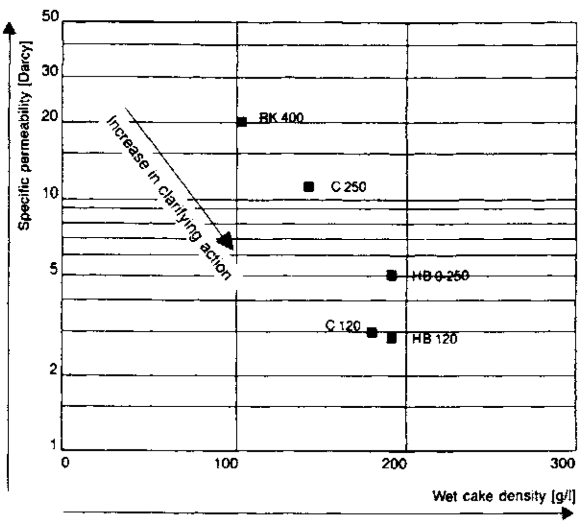


Figure 10.9. Permeability and clarifying action of 'Lignocel' cellulose filter aids.

Table 10.18 Properties of Filtracel EFC cellulose precoat fibres[a]

Property	EFC 100	EFC 450	EFC 800	EFC 1000	EFC 1400	EFC 2000	EFC 3500
Fibre length (μm)	30–50	30–100	50–150	70–150	80–180	150–250	800–3000
Dry bulk density (g/l)	125–180	110–160	110–145	105–130	105–145	120–180	130–170
Wet cake density (g/l)	155–190	155–180	150–165	150–160	150–162	150–190	145–170
Permeability (darcies)	0.3–1.0	2.1–3.8	4.7–6.5	6–8	9–11	12–17	20–28
Permeability[b] (per min)	50–150	350–550	700–900	850–1150	1300–1500	1800–2200	3000–4000

[a] J Rettenmaier & Söhne GmbH & Co.

[b] Permeability as measured by Schenk 'Wasserwert-Methode'.

The various grades of the different carbonaceous materials that have been produced appear all to have broadly corresponded to the coarser end of the range of diatomites and perlites. Their special value would be in their chemical inertness as compared with silica.

10.2.6 Other materials

In principle, any inert bulky granular material could be used as a precoat. Because of their chemical inertness and insolubility, powders of synthetic polymers are potentially applicable as precoat materials and are occasionally reported in use.

Almost any commercial by-product or waste powdered material might be a suitable substitute for a commercial precoat or filter aid. In practice, even if it proves possible to achieve consistently satisfactory standards of qualitative

Table 10.19 'Fibra-Cel' blends of diatomite and cellulose filter aids[a]

Grade[b]	DE component	Cellulose (%)							
		2.5	5	7.5	10	12.5	15	17.5	20
Fibra-Cel 1	Filter-Cel®	A	B	C	D	E	F	G	H
Fibra Cel 2	577	A	B	C	D	E	F	G	H
Fibra Cel 5	Standard Super-Cel®	A	B	C	D	E	F	G	H
Fibra Cel 6	512	A	B	C	D	E	F	G	H
Fibra Cel 7	Hyflo Super Cel®	A	B	C	D	E	F	G	H
Fibra Cel 9	503	A	B	C	D	E	F	G	H
Fibra Cel 10	535	A	B	C	D	E	F	G	H
Fibra Cel 11	545	A	B	C	D	E	F	G	H

[a] Celite Corporation.
[b] Example of grade: Fibra-Cell 6F comprises Celite 512 + 15% cellulose.

Table 10.20 Effect of compressive load on porosity of wood flour

Compressive load[b]	Porosity[a]		
	Wood flour grade		
	120	180	300
0	0.8452	–	–
11.1	0.8420	0.8225	0.8230
16.0	0.8300	0.8100	0.8075
20.8	0.8225	0.8045	0.7990
25.7	0.8125	0.7955	0.7930
35.5	0.8015	0.7890	0.7750
46.0	0.7955	0.7785	0.7660
55.0	0.7920	0.7705	0.7590
64.9	0.7820	0.7660	0.7500

[a] Dimensionless.
[b] Units: kg/m^2.

performance with a low- or zero-value material, a careful analysis of all the relevant cost factors is more likely ultimately to reveal a deficit than a profit.

An interesting example is the RHA filter aid material pioneered by enviroGuard Inc. RHA is an abbreviation for rice hull ash, of which some four million tons are generated in the USA annually, as waste material from milling

Table 10.21 Effect of compressive load on permeability of wood flour

Compressive load[b]	Permeability[a]		
	Wood flour grade		
	120	180	300
0	4.61×10^{-12}	–	–
11.1	1.72×10^{-12}	8.60×10^{-13}	1.20×10^{-12}
16.0	1.61×10^{-12}	7.70×10^{-13}	7.26×10^{-13}
20.8	1.18×10^{-12}	6.49×10^{-13}	6.32×10^{-13}
25.7	1.06×10^{-12}	5.20×10^{-13}	6.00×10^{-13}
35.5	8.50×10^{-13}	4.69×10^{-13}	8.06×10^{-13}
46.0	9.44×10^{-13}	3.68×10^{-13}	4.21×10^{-13}
55.0	8.30×10^{-13}	3.65×10^{-13}	3.89×10^{-13}
64.9	6.30×10^{-13}	3.54×10^{-13}	3.21×10^{-13}

[a] Units: m^2.
[b] Units: kg/m^2.

Table 10.22 Effect of compressive load on specific filtration resistance of wood flour

Compressive load[b]	Specific filtration resistance[a]		
	Wood flour grade		
	120	180	300
10	2.64×10^{9}	4.62×10^{9}	4.64×10^{9}
20	3.45×10^{9}	6.11×10^{9}	5.96×10^{9}
30	4.06×10^{9}	7.59×10^{9}	7.29×10^{9}
40	4.40×10^{9}	8.54×10^{9}	8.10×10^{9}
50	4.87×10^{9}	9.01×10^{9}	8.54×10^{9}
60	5.20×10^{9}	9.26×10^{9}	8.70×10^{9}

[a] Units: m/kg.
[b] Units: kg/m^2.

Table 10.23 Solubility of wood flour

Liquid	pH	Colour change of solution?[a]
Dilute sulphuric acid	1	Yes
Dilute hydrochloric acid	1	No
Benzene	4	Yes
20% sodium hydroxide	11	Yes
Water	7	No

[a] Attributed to chemical reaction.

and processing rice. It is 95% amorphous silica with 5% carbon, and minimal amounts of trace elements, so it is an obvious potential substitute for conventional filter powders. Encouraging results were reported by Rieber[8] from both laboratory and plant trials.

10.3 Deep-bed Granular Media

Many different granular and crushed materials have been used to form the deep beds employed in the large gravity and pressure filters common to the water purification and sewage treatment industries. In addition to sand, which is the classic and most common material, others used include garnet, ilmenite, alumina, magnetite, anthracite and quartz; coke and pumice have also been used but, because of their porosity, they are troublesome to clean and consequently give rise to the danger of uncontrolled breeding of bacteria.

The suitability of a granular material for use in a deep bed filter depends both on the application and on the type of filter. Conventionally, there are two main types that operate with gravity flow downwards through a 0.6–1.0 m deep bed; these are identified respectively as 'slow' and 'rapid' sand filters.

Slow sand filters operate with a velocity of 0.1–0.2 m/h down through the bed. They function by a form of straining through the so-called 'schmutzdecke' or biological layer that forms on the surface of the bed. They are cleaned occasionally by the reasonably complete removal of this layer, without disturbing the rest of the bed.

Rapid sand filters utilize a velocity of 5–15 m/h and function by depth filtration within the bed. They are cleaned frequently by cessation of process flow, followed by a reverse upward flow of wash water at such a rate that the bed expands and releases the trapped dirt particles; this cleaning flow may be augmented by some form of agitation, such as injecting compressed air below the bed or hydraulic jets impinging on the surface. This cleaning process has an important secondary effect, which is to reclassify the granules of the bed based on the combined influence of their size and their density, so that the washed bed is graded from finest at the top to coarsest at the bottom.

A variety of other types of filter have been subsequently developed from the rapid sand filter, starting with pressurized versions such as that illustrated in Figure 10.10. A more radical variation is the use of upward flow so that the incoming raw water encounters the coarsest granules first and the finest last (as in the Immedium filter). These beds are also washed by an expanding upward flow, with the dirty effluent withdrawn separately.

Multi-layer filters with conventional downward filtration achieve the same results by means of beds comprising two or more materials of different densities so that the hydraulic classification of cleaning places the finer, denser particles on top of the coarser, less dense particles.

The most modern version of the rapid sand filter is that which uses a moving bed of sand, whereby both filtration and cleaning proceed continuously and simultaneously. Recent evidence (from the US EPA) suggests that such filters can be as effective as membrane filtration plants in the removal of such pathogens as *Cryptosporidia* and *Giardia* from water intended for drinking.

10.3.1 Characterization of granular media

A practical approach to assessing the suitability of granular materials for use as deep-bed filter media has been provided by Ives[9]; the physical properties identified as being of interest were particle size, particle shape, density, durability, solubility, cleanliness and settling velocity. An indication of the variation of some of these properties is provided by Table 10.24, reproduced from Mohanka[10].

Many of Ives' procedures have been included or adapted in the 'Granular Filtering Materials Standard' first published in 1993 by the then British Effluent and Water Association (BEWA), and in a final version in 1996[11] by British Water (into which BEWA had merged). This document specifies a total of 15 items of information, as listed in Table 10.25, which are recommended for inclusion in a supplier's data sheet for a product offered as a filter medium for water, and discusses each in some detail.

The discussion below is based mainly on Ives but also includes some references to the British Water document. Both omit any measurement of filtration efficiency; the reason for this is the complex nature of deep-bed filtration, which involves interaction between a suspension and filter medium. As Ives

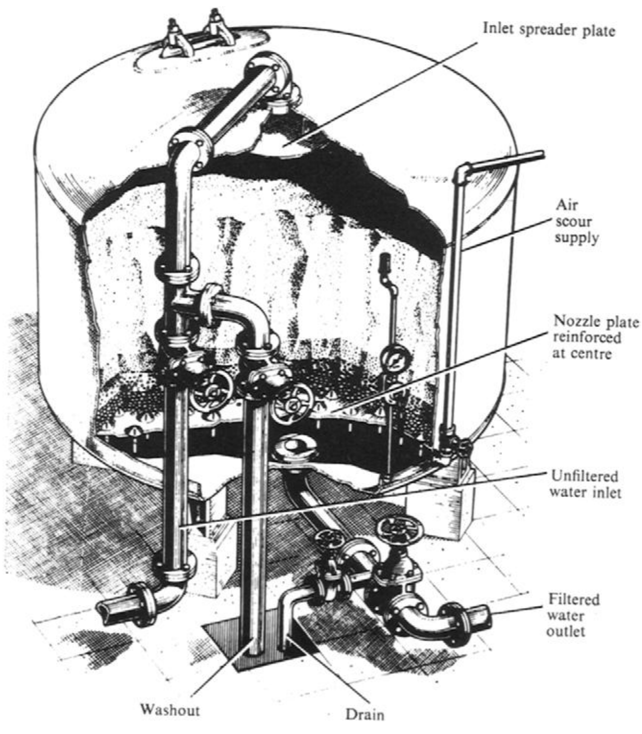


Figure 10.10. A vertical pressure sand filter.

Table 10.24 Physical characteristics of various granular filter media

Physical parameters	Multilayer filter				
	Polystyrene	Anthracite	Crushed flint sand	Garnet	Magnetite
Sieve size (mm)	3.175–2.057	1.676–1.405	0.853–0.699	0.599–0.500	0.500–0.422
Fall velocity (cm/s)	3.30	6.35	8.10	9.40	10.95
Hydraulic diameter (mm)	2.50	1.14	0.60	0.467	0.415
Sphericity	1.00	0.745	0.78	0.865	0.90
Density (g/cm^3)	1.04	1.40	2.65	3.83	4.90
Porosity	0.35	0.425	0.464	0.47	0.42
Physical parameters	Sand filter				
	Crushed flint sand	Crushed flint sand	Crushed flint sand	Quarry sand	Quarry sand
Sieve size (mm)	0.500–0.422	0.599–0.500	0.853–0.699	1.676–1.405	2.411–2.057
Fall velocity (cm/s)	5.00	6.54	8.10	16.85	20.90
Hydraulic diameter (mm)	0.38	0.435	0.60	1.165	1.36
Sphericity	0.83	0.80	0.78	0.765	0.62
Density (g/cm^3)	2.65	2.65	2.65	2.65	2.65
Porosity	0.464	0.464	0.464	0.39	0.39

Table 10.25 Information recommended by British Water for inclusion by granular media suppliers in their product data sheets

1.	Type of material, e.g. sand, anthracite	
2.	Information relating to the size grading available, e.g. standard available grades	
3.	General description, e.g. appearance and shape of material	
4.	Source and production procedure. Geological classification, if relevant	
5.	Dirt (dust) content limits	
6.	Grain effective specific density	
7.	Bulk density (in backwashed condition)	
8.	Abrasion resistance (state if water only or air and water)	
9.	Friability data	
10.	Poured and packed voidage	
11.	Acid solubility	
12.	Impact resistance (support material only)	
13.	Impurity leach data	
14	Backwash	(a) head loss data for standard gradings (b) expansion versus upflow @ 5, 10, 15 and 20°C, for standard grades
15	Filtering head loss data at rates of 5–15 m/h	

commented[12], there is no such thing as a 'good filter' unless the suspension to be filtered is simultaneously specified: in some cases, coarse grains are required, in others finer grains or multiple layers of different materials.

10.3.1.1 Particle size

Granular media are generally characterized by sieving tests that report the mass retained on a series of successively finer screens. The data are conventionally expressed graphically as the cumulative percentage finer than the size of openings in each screen, as in Figure 10.11.

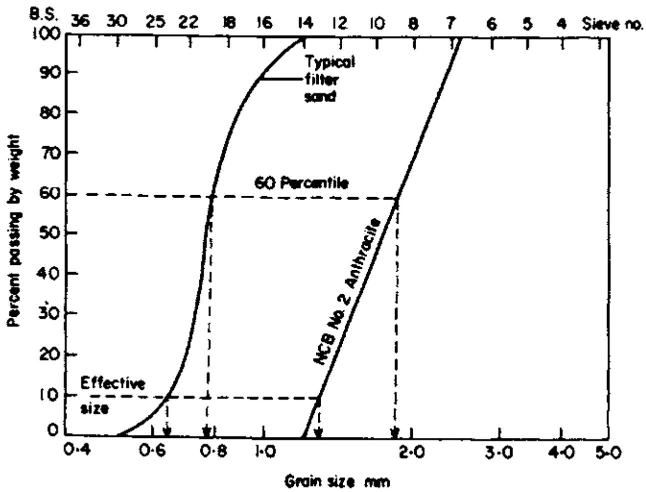


Figure 10.11. Grain size distribution of typical waterworks filter sand and anthracite. Note: The 10-percentile is the Hazen effective size: inverse ratio of this to 60-percentile is the Hazen uniformity coefficient.

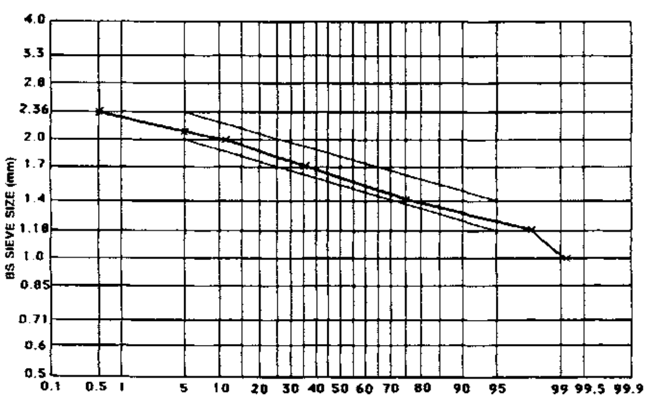


Figure 10.12. Example of a plot of sieve test data on a log/probability basis, with tramline limits (based on an example in British Water Standard[11]).

The British Water standard recommends the use of the log/probability form of plot illustrated in Figure 10.12. An advantage of this format is that the acceptable tolerance limits can be defined as a pair of parallel 'tramlines', as shown.

There are several different numerical forms of expression of particle size and size range, which are summarized in the following notes.

(a) Percentile limits of 5% and 95%. The size range is defined in terms of the lower and upper sieve sizes, the lower being that which retains 95% or more by weight (i.e. passes 5% or less), and the upper that which retains 5% or less (i.e. passes 95% or more). The sieve sizes should preferably be specified by the dimensions of their openings in millimetres (rather than as sieve numbers or meshes per centimetre or inch). This corresponds to the British Water definition. Thus, a 0.5–1.0 mm material specifies not more than 5% by weight is below 0.5 mm or above 1.0 mm.

(b) Hazen effective size and uniformity coefficient. These two parameters were invented by the American engineer Hazen for slow sand filters, wherein the sand sizes remain fixed. It is common practice but inappropriate to apply them also to the stratified beds of rapid sand filters; British Water recommends that this use should be discontinued.

The *effective size* is the sieve size d_{10} that 10% by weight would pass, as indicated in Figure 10.11. The *uniformity coefficient* is the ratio d_{60}/d_{10}, where d_{60} is similarly the sieve size that 60% would pass. The larger the value of this coefficient, the greater the range of grain sizes.

Hazen discovered empirically that, if all the sand of a bed is replaced with grains of one size only, then that size must be d_{10} for the head loss (or hydraulic resistance) for the two beds to be identical; this contrasts with the expectation that the average or modal size d_{50} would produce this effect. The explanation that subsequently emerged is that the modal size *by number* is approximately equal to d_{10} *by weight*; and head loss is determined by surface area, which depends on the size and number of grains, not on their weight.

Later research demonstrated that, even when restricted to slow sand filters, the uniformity coefficient is of little relevance to the performance of the filter[13].

(c) Hydraulic diameter (d_h). This is a concept introduced by Ives enabling the shape of a particle to be expressed quantitatively in terms of its sphericity. It is the diameter of a spherical particle that has the same settling velocity in water as the actual particle.

The hydraulic diameter can be calculated from the observed settling velocity of a particle by calculation of the drag coefficient for the particle, C_D, in the form of the dimensionless group relation between drag coefficient and Reynolds number, Re:

$$\frac{C_D}{Re} = \frac{4g(\rho_s - \rho)\mu}{3\rho^2 v_s^3}$$

where ρ_s = particle density, ρ = liquid density, μ = liquid viscosity, v_s = particle settling velocity. The Reynolds number for the particle is given by:

$$Re = \rho d_h v_s/\mu$$

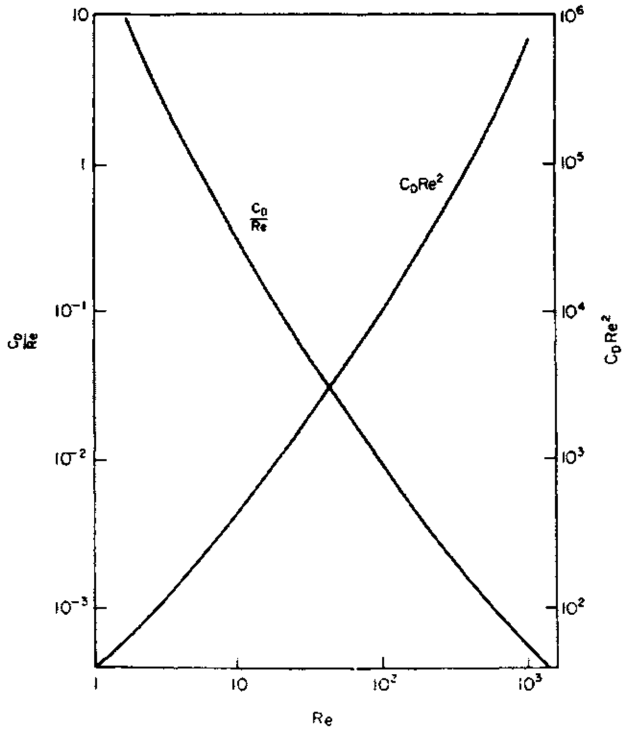


Figure 10.13. Curves of dimensionless groups C_D/Re and C_D/Re^2 versus Reynolds number Re.

and can be determined from the curve in Figure 10.13, and the hydraulic diameter calculated by rearranging the definition of Reynolds number:

$$d_h = \mu Re/\rho v_s$$

(d) Hydraulic size. This is a term preferred by the British Water standard over Ives' hydraulic diameter. Hydraulic size, D_H, is defined as 'the uniform grain size that would produce the same resistance to flow as the material under consideration (at the same voidage)'. The concept of hydraulic size is based on a theoretical model of the filter bed as a series of discrete layers corresponding to the sizing fractions retained on a set of test sieves. Each layer is characterized by the respective sieve aperture (i.e. the grain size) and by the retained percentile (i.e. the relative thickness of the layer).

The theoretical background to this was summarized by Stevenson(14), utilizing the relationships developed by Kozeny and Carman to evaluate the particle size that gives the same surface area as the actual mixture and therefore has the same hydraulic behaviour.

The British Water standard and Stevenson's paper both provide a very simple calculation procedure for evaluating D_H, comprising the following four steps:

1. divide the percentage retained on each successive sieve by the size of the sieve aperture;

2. add up all the figures thus obtained and divide by 100;
3. obtain the reciprocal of the above sum; and
4. add 10% to the reciprocal, to correct the 'retained' size to the centre size between adjacent sieves (sieves are spaced at 20% increments).

A specimen calculation in this manner is shown in Table 10.26.

10.3.1.2 Particle shape

The shape of a particle is important because it affects the way in which the particle settles into the packed bed, and the consequent bed voidage. An indication of the extent to which the shape of particles departs from the spherical is provided by the list of shape coefficients for a range of materials in Table 10.27. This utilizes two different shape coefficients, K_a and K_v, by which the surface areas and volumes of particles are related to the 'average' diameter, d_{av} – an average depending on the sizing technique used:

Surface area = $K_a d_{av}^2$

Volume = $K_v d_{av}^3$

Table 10.26 Specimen calculation of hydraulic size

Sieve aperture (mm)	% retained	Calculation
2.8	0.1	0.04
2.36	0.5	0.21
2.0	10.2	5.1
1.7	22.1	13.0
1.4	42.3	30.25
1.18	22.5	19.1
1.0	1.4	1.4
0.85	0.3	0.35
0.71	0.5	0.7
	100.0	70.1

Divide 70.1 by 100= 0.701
Reciprocal = 1/0.701= 1.43
Add 10%= 0.14
Hydraulic size= 1.57 mm

Table 10.27 Shape coefficients for typical granular materials

Particle	Area coefficient K_a	Volume coefficient K_v
Sphere	π=3.142	$\pi/6$=0.502
Copper shot	3.14	0.524
Sand	2.1–2.9	–
Worn sand	2.7–3.4	0.32–0.41
Pulverized minerals (coal, limestone)	2.5–3.2	0.2–0.28
Coal	2.59	0.227
Mica	1.67	0.03
Aluminium flakes	1.60	0.02

By contrast, Ives preferred a hydrodynamic definition of *sphericity* that relates the sieve size of a particle, d_s, to the hydraulic diameter, d_h (the size of a sphere having the same settling velocity in water as an actual particle). Thus the sphericity is given by:

$$\psi = d_h / d_s$$

Some typical values for sphericity are given in Table 10.28; values below 0.6 suggest an undesirable flaky shape.

In discussing what shape is desirable for filter media particles, Ives[12] commented that there is agreement that flakes are undesirable, but differing opinions on the benefits or disadvantages of being near to spherical roundness. He reported comparative tests to assess the relative quality of filtrate achieved by filtering a suspension through identical beds (in terms of depth and particle size fraction) of glass beads ($\psi = 0.98$), sand ($\psi = 0.85$) and anthracite ($\psi = 0.70$); it was found that anthracite was best, sand next and round glass beads worst. The differences were shown not to be due to surface electrochemical effects, since all had similar zeta potentials (about −20 mV). It is interesting also to note published opinions criticizing highly rounded filter media[15,16].

Elsewhere, Ives reports that a study of the mechanisms of deep-bed filtration shows that changes in local flow direction caused by angularity of the filter medium lead to improved capture of particles[17]. Confirmation of this is provided in the USA where Hambley[18] stated that 'side by side column tests of highly angular sand will markedly out-perform round sand in improved effluent turbidity, in run time to break through, and/or in run time to limiting head loss'; moreover, this has been verified in actual practice with filters of all types, including dual media and multimedia high-rate filters. Hambley concluded that sphericity should be less than 0.6 – the exact opposite of the conclusion of two paragraphs above, which probably set too high a limit on sphericity.

The British Water standard does not focus specifically on shape excepting once in a mention under general description, and then in its list of definitions, which includes *aspect ratio* ('the ratio of the largest to the smallest dimension of a given grain') and sphericity ('the ratio between the surface area of the sphere with the same volume as the grain and the actual surface area of the grain').

Table 10.28 Sphericity and density of common granular filter media

Material	Origin	Density $(kg/m)^3$	Sphericity (shape)
Quartz sand	UK	2650	0.85
Anthracite	UK	1400	0.70
Hydroanthracite	FRG	1740	0.65
Pumice	Sicily	1180	0.75
Expanded slate	FRG	1500	0.75
Garnet	USA	3950	0.65

10.3.1.3 Density

The British Water standard distinguishes between *grain specific gravity* of non-porous and porous materials. For porous materials, the *effective specific gravity* is for a grain saturated with water.

In multi-layer beds, the buoyancy imposed by water has a significant effect on the relative density of the materials. This can be seen, for example, with the UK and German anthracites in Table 10.28, for which the densities as listed are 1400 and 1740, showing the German material to be the more dense by 24%. Underwater, however, both densities are reduced by 1000 (the density of water) to effective levels of 400 and 740, the German anthracite then being 85% more dense than the other.

10.3.1.4 Durability

It is important for filter media grains to resist attrition and degradation during the repeated backwashing operation that is an essential part of the operating cycle of rapid sand filters. Accordingly, specifications sometimes include a definition of the required degree of Moh hardness, such as 3.0–3.75 for anthracite. In practice, this is insufficient to define durability, which is not necessarily dependent just on hardness since fracture and attrition may result from brittleness.

An accelerated backwashing test was therefore devised by Ives[9]. Running continuously for 100 hours in a week, this corresponds to 1000 washings of 6 minutes each, equivalent to about 3 years of washing operations at a typical rate of one per day. The key measurement is the depth of filter medium lost from a 30 cm deep bed contained in a 1 m glass or plastic tube, at least 3 cm in diameter. A similar test is incorporated in the British Water standard.

Where Ives uses 'durability' to embrace the various types of mechanical degradation, the British Water standard distinguishes among abrasion, friability and impact resistance each of which is separately listed as in Table 10.25, and covered by the latest version of the standard.

10.3.1.5 Solubility

It is accepted practice to test media for solubility by utilizing more stringent conditions than are ever likely to occur in practice, the usual problem being some form of calcium carbonate (e.g. fragments of sea shells in beach sand) dissolving in acid. The limit set by the American Water Works Association[19] is a 5% loss by weight into 50% hydrochloric acid; 20% acid was considered adequate by Ives[9], both to establish that grains are not aggregates cemented together and to show up colours indicating the presence of soluble iron salts. This embraces the two parameters the British Water standard identifies as acid solubility and impurity leaching.

10.3.1.6 Cleanliness

Media should be free from dirt, dust, organic matter, clay, etc. This can be checked by swirling a small sample in clean water followed by a visual examination, including use of a low-power (×20) microscope.

10.3.1.7 Settling velocity

The settling velocities of individual particles can be determined by timing their movement between two fixed points in a vertical tube of water. Their value is in calculating the corresponding hydraulic diameter and the sphericity. In addition, in the form of a graphical plot such as Figure 10.14, they also provide a convenient indication of the expected stratification behaviour of mixed-media beds if water alone is used for the final phase of the backwashing. These relationships are utilized by Ives[12], but not in the British Water standard.

10.3.1.8 Head losses and bed expansion

With apparatus similar to that used for the accelerated abrasion test, the British Water standard proposes measurements of flow resistance (head loss) both during filtration and whilst backwashing. Filtration tests should cover the losses of 5–15 m/h. Backwashing involves a range of velocities to achieve levels of bed expansion up to at least 50%, using wash water at temperatures of 5, 10, 15 and 20°C.

10.3.1.9 Porosity/voidage

The British Water standard calls for measurement of the porosity or voidage under both poured and packed conditions, for non-porous materials with variation no more than ±0.5% (e.g. 39.5–40.5%).

10.3.2 Available media

Inert media of various densities are utilized in single- and mixed-media filters, so as to control the classification and pore grading of the bed structure, with coarse filtration in the lower layers and progressively finer filtration towards the top.

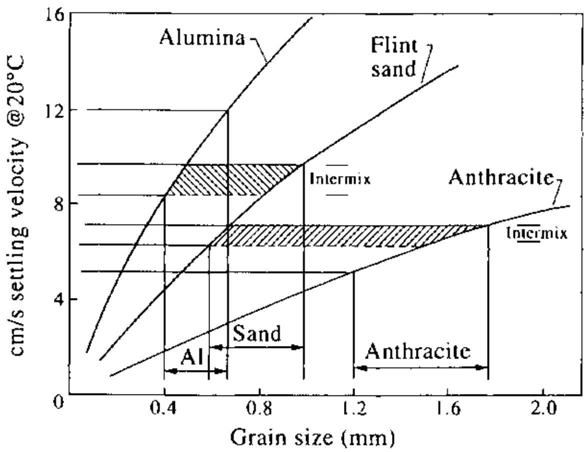


Figure 10.14. Settling velocity versus grain-size curves indicate the intermixing and layering of a three-component deep bed.

A variety of other 'active' materials used as filter media function by chemical reactions that are beneficial in the overall process of water treatment and purification by removing contaminants such as metals (aluminium, iron, manganese, lead, cadmium, etc.), cyanide ions, or hydrocarbons and other organics. These media may be used separately, be mixed with the main bed of

Table 10.29 Technical data sheet specifications of silica sands for water filtration[a]

Mechanical analysis		Aperture (mm)	BSS mesh no.	Percentage by weight retained			Nominal effective size range	Mean uniformity coefficient
Grade (mm)	No.			Typical grading		Cumulative range		
				Fractional	Cumulative			
2.8–1.18	6–14	3.35	5	Trace	Trace	0–0.5	1.25–1.70	<1.7
		2.80	6	2.0	2.0	0–5.0		
		2.36	7	9.0	11.0	5–35		
		2.00	8	16.5	27.5	10–65		
		1.70	10	27.5	55.0	25–90		
		1.40	12	28.0	83.0	70–100		
		1.18	14	14.5	97.5	95–100		
		1.00	16	2.0	99.5	99–100		
2.00–1.00	8–16	2.36	7	Trace	Trace	0–0.5	1.05–1.27	<1.4
		2.00	8	1.5	1.5	0–5.0		
		1.70	10	18.0	19.5	5–35		
		1.40	12	35.5	55.0	25–80		
		1.18	14	29.5	84.5	70–95		
		1.00	16	13.5	98.0	95–100		
		−1.00	−16	2.0	100.0	99–100		
1.70–0.85	10–18	2.00	8	Trace	0.10	0–0.5		
		1.70	10	2.0	2.0	0–5.0	0.9–1.18	<1.4
		1.40	12	23.5	25.5	10–50		
		1.18	14	39.5	65.0	40–90		
		1.00	16	22.0	87.0	70–100		
		0.85	18	12.0	99.0	95–100		
		0.71	22	0.5	99.5	99–100		
1.18–0.60	14–25	1.40	12	Trace	Trace	0–0.5	0.63–0.85	<1.4
		1.18	14	2.0	2.0	0–5.0		
		1.00	16	14.5	16.5	0–35		
		0.85	18	40.0	56.5	25–90		
		0.71	22	31.5	88.0	70–100		
		0.60	25	11.0	99.0	95–100		
		0.50	30	1.0	100.0	99–100		
1.00–0.50	16–30	1.18	14	Trace	Trace	0–0.05	0.54–0.71	<1.4
		1.00	16	1.0	1.0	0–5.0		
		0.85	18	21.5	22.5	10–40		
		0.71	22	30.5	53.0	25–90		
		0.60	25	35.0	88.0	75–100		
		0.50	30	10.0	98.0	95–100		
		0.425	36	1.5	99.5	99–100		

Table 10.29 (*continued*)

Mechanical analysis		Aperture (mm)	BSS mesh no.	Percentage by weight retained			Nominal effective size range	Mean uniformity coefficient
				Typical grading		Cumulative range		
Grade (mm)	No.			Fractional	Cumulative			
For slow sand filters								
0.71–0.25	No. 21	1.00	16	Trace	Trace	0–0.5	0.25–0.38	<1.7
		0.71	22	0.5	0.5	0–0.5		
		0.50	30	38.0	38.5	10–60		
		0.355	44	48.0	86.5	70–95		
		0.25	60	10.5	97.0	90–100		
		0.18	85	2.5	99.5	95–100		

[a] Garside Industrial Sands, CAMAS Aggregates.
Typical Properties
Source: Leighton Buzzard, Bedfordshire, UK

Geological Classification:	Lower greensand	
Chemical Properties:	SiO_2	Approximately 97%
	Loss on ignition @ 1025 °C	Not more than 1.0%
	Weight loss in acid (24h, 20% HCl, 20°C)	<1.0%
Physical Properties:	Specific gravity	2.65
	Uncompacted bulk density	1560 kg/m³
	Saturated porosity	0.41
	Particle shape – sphericity –	0.85 (sphere = 1)
	Rittenhouse Scale	0.83–0.87
	Durability (100 h accelerated wash test)	Weight loss <0.1%

sand, or constitute separate layers in multi-media filters. Typical reactive materials are calcium carbonate, manganese dioxide and aluminosilicates.

10.3.2.1 Silica sand

The specifications of six grades of filter sand available from one supplier are summarized in Table 10.29, comprising five for rapid filters and one for slow filters. Table 10.30 lists 17 rapid grades of another supplier, whose specifications for two grades for slow filters are provided in Table 10.31.

10.3.2.2 Anthracite- and coal-based media

Data for examples of anthracite- and coal-based media are provided in Table 10.32, while Table 10.33 gives the head loss (mm water) through a 1 m deep bed at filtration rates from 10 to 50 m/h.

10.3.2.3 Volcanic rock, garnet and ilmenite

Typical data for these three materials, which have densities ranging from 2440 kg/m^3 up to 4800 kg/m^3 are provided in Table 10.34. Ilmenite is available as both sand and gravel, the size analyses of which are indicated in Table 10.35.

Table 10.30 Technical data for silica sands for rapid filters[a]

Size range (mm)	Minimum within range (%)
0.20–0.50	90
0.20–0.70	90
0.40–0.63	90
0.425–0.85	90
0.50–1.00	90
0.60–1.20	90
0.80–1.25	90
0.85–1.70	90
1.00–1.60	90
1.00–2.00	90
1.40–2.00	80
1.20–2.40	80
1.20–2.80	80
1.50–2.50	80
1.70–2.50	80
2.00–3.15	80
2.00–4.00	80

[a] Universal Mineral Supplies Ltd.

Physical properties:		
	Specific gravity	2.65
	Bulk density	approx. 1600 Kg/m^3
	Hardness	6–7 Mol h
	Acid solubility	<2.0%
	Abrasion resistance. loss after 100 h back wash	maximum 2.0%
	Uncompacted prorsity	0.38–0.45
Chemical properties:	Silica as SiO_2	>96%

Table 10.31 Technical data for silica sands for slow filters[a]

Grade no.	20	25
Effective size range (mm)	0.25–0.35	0.20–0.40
Mean uniformity coefficient	<2.2	<3.0
Appearance	Dark brown/grey/angular/sub-rounded grains	
Specific gravity	2.65	
Dry bulk density	1560 kg/m^3	
Hardness	6–7 Moh	
Silica as SiO_2	90% minimum	

[a] Universal mineral Supplies Ltd.

The relationship between pressure loss and filtration rate through a 1 m thick layer of volcanic rock of various sizes is shown in Table 10.36.

10.4 Deep-bed Fibrous Media

An unusual deep bed, used in the novel Howden-Wakeman (HW) filter, is composed of loose fibres instead of conventional granules. As shown schematically in Figure 10.15, the bed of fibrous material is compressed by a perforated piston during filtration and expanded by retracting the piston for backwashing; a brief period of reciprocating action aids washing by agitation of the bed.

Table 10.32 Technical data for anthracite- and coal-based filter media

Product name	Anthracite	Aqua-cite	Aqua-cite 'B'	Aqua-fit
Supplier	Progenerative Filtration Ltd	Aqua Techniek bv	Aqua Techniek bv	Aqua Techniek bv
Source	Unspecified anthracite	Unspecified anthracite	Based on coal	Pennsylvania anthracite
Density (kg/m^3)	1400	710–725	Approx. 500	ca. 890
Bulk density (kg/m^3)	720	±400	Approx. 1650	ca. 1650
Chemical analysis (%)				
Carbon	90.0	>90	Approx. 90	94.7
Sulphur	0.7	0.6	Approx. 0.45	–
Volatiles	4.0–6.0	6.4	Approx. 3.5	–
Ash	2.0–4.0	2–4	Approx. 6.5	–
Water	–	1.2	Approx. 2	–
Hardness (Moh)	3–4	–	–	3.0–3.8
Solubility (%)				
In 20% HCl	<2	–	–	<5
In 10% NaOH	<2	–	–	–
Size mm (and effective size)	0.06–1.2 (0.7) 1.2–2.5 (1.3) 1.1–2.36 (1.2) 2.5–5.0 (2.6) and as requested	0.6–1.6 1.4–2.5 2.5–5.0 and as requested	0.8–1.6 1.4–2.5 and as requested	Complete range
Uniformity coefficient	<1.60	–	–	–

Table 10.33 Pressure losses (mm water) through 1 m layers of anthracite- and coal-based media

Filtration rate (m/h)	Aqua-cite media		Aqua-cite 'B' media	
	0.8–1.6 mm	1.4–2.5 mm	0.8–1.6 mm	1.4–2.5 mm
10	150	70	180	80
20	315	160	400	180
30	515	270	720	300
40	780	410	–	440
50	1000	550	–	590

Table 10.34 Other inert media for deep bed filters

Material	Volcanic rock	Garnet	Ilmenite
Produce name	Aqua-volcano	Garnet	Aqua-ilmenite
Supplier	Aqua Techniek bv	Universal Mineral	Aqua Techniek bv
Density (kg/m^3)	2440	4100	4200–4800
Bulk density	1320	2380	–
Chemical analysis (%)			
SiO_2	59.72	36.1	0.30
Al_2O_3	23.22	20.4	–
FeO	–	29.8	–
Fe_2O_3	2.66	1.7	29.90
CaO	2.36	1.55	–
MgO	0.40	6.0	–
MnO	–	1.05	–
TiO_2	–	1.8	64.70
K_2O	3.08	–	–
Na_2O	6.40	–	–
P_2O_5	–	–	0.17
V_2P_5	–	–	0.15
Ignition loss	2.06	–	–
Acid solubility	–	–	>5
Moh hardness	–	7–8	5.0–6.5
Sizes available (mm)	0.8–1.5	0.3–0.6	Sand[a]
	1.5–2.5	1.4–2.36	Gravel[a]
	2.5–3.5		

[a] See Table 10.35 for typical analyses of standard sand and gravel.

Table 10.35 Typical analyses of ilmenite sand and gravel[a]

US standard sieve no.	Sieve opening (mm)	% passing typical	% passing specification
Sand			
30	0.600	90	70–100
40	0.425	66	40–80
50	0.300	34	–
60	0.250	21	–
70	0.212	6	–
80	0.180	5	–
Gravel			
4	4.75	95	90–100
6	3.35	61	–
8	2.36	36	–
10	2.00	25	–
12	1.70	16	–
14	1.40	7	0–10
16	1.18	2	–

[a] Aqua Techniek bv.

The filter is claimed to have better filtering capabilities than conventional deep beds[20,21]. An example quoted is the 99.992% removal of 3.5 μm particles after 2 h continuous operation without backwash; effective removal of particles down to 0.2 μm is within its capability.

Various types of fibre are reported to have been used, including wool and carbon. Carbon fibres were found to be particularly attractive since they permit repeated steam sterilization without incurring undesirable side effects such as creep, which was experienced with many polymeric materials. Moreover, with diameters in the range 1–10 μm, these fibres are far smaller than the 400–3000 μm diameter of typical granules: there is a corresponding difference in porosity, 80–83% for the fibres as compared with 35–47% for granules, producing a greater dirt-holding capacity. Figure 10.16 demonstrates the dependence of the flux rate on the bulk density to which the bed is compressed.

Table 10.36 Pressure losses (mm water) through 1 m layers of volcanic rock

Filtration rate (m/h)	Media size (mm)		
	0.8–1.5	1.5–2.5	2.5–3.5
10	190	120	180
20	390	250	180
30	585	400	280
40	800	560	390
50	1030	720	510

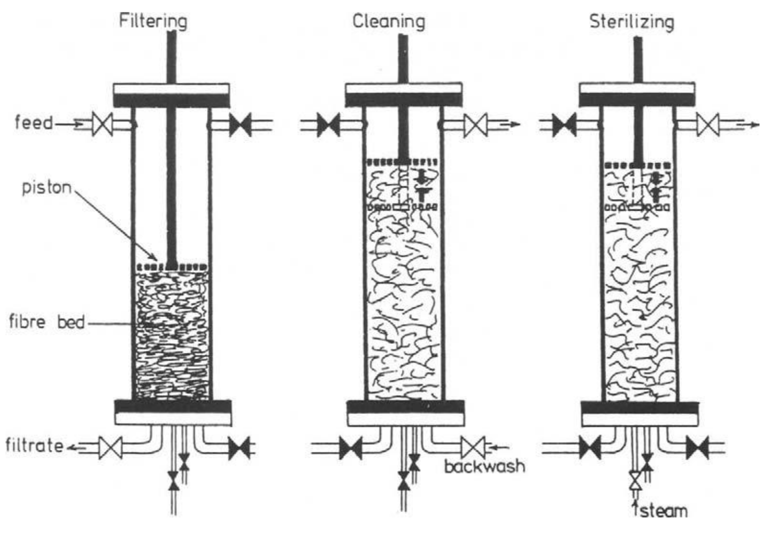


Figure 10.15. Operating modes of the Howden-Wakeman filter.

10.5 Selecting Loose Particulate Media

Both types of media discussed in this chapter are aimed at the efficient filtration of very fine solids, using relatively inexpensive means, especially in terms of the replacement of media that are full of entrapped solid particles. Precoat media enable the use of quite coarse, but strong continuous basic media in a range of filtration equipment (filter press, pressure filters with leaves or candles, and

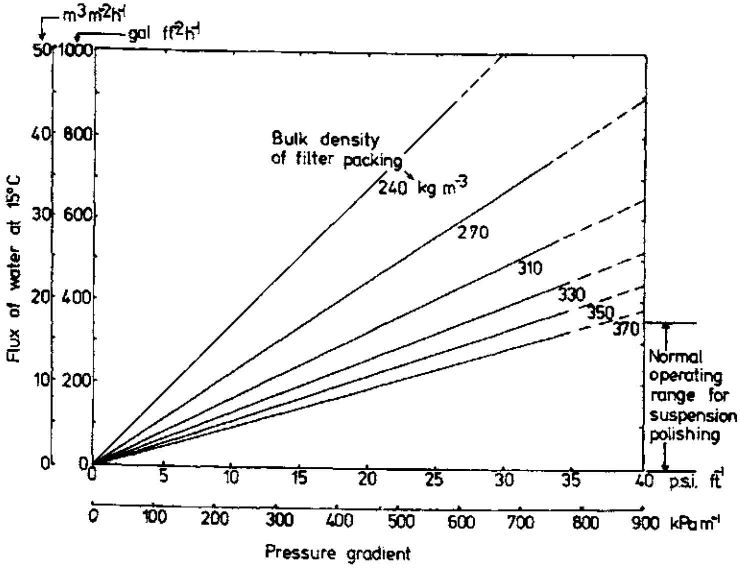


Figure 10.16. Flux versus pressure gradient of Howden-Wakeman filter.

Table 10.37 Comparative grades of diatomite materials*

Celatom DE	Celite	Dicalite	Kenite
FP-1SL	Filtercel	215	
FP-1, FP-2	505	Superaid	100
FP-1W	577	U.F.	
FP-3, FP-4	Std. Supercel	Speedflow	200
FW-6	512	Spec. Speedflow	300
FW-10			
FW-12	Hyflo	341	700
FW-14		Speedplus	900
FW-18	501	375	1000
FW-20	503	Speedex	
FW-40		2500	2000
FW-50	535	4200	2500
FW-60	545	4500	3000
FW-70	550	5000	5500
FW-80	560	5500	

* Eagle-Picher Minerals, Inc.

rotary vacuum filters), with the fine degree of filtration achieved by the precoat material, which may be a single layer or a set of layers of different sized particles (or even different materials), with the finest at the top or upstream face, to create the base for a surface filtration process, generating a cake of separated solid.

Although the granules in a deep-bed filter are graded in the same way (i.e. with finest upstream) they are intended to act by depth filtration, with the long tortuous channels through the bed being sufficient to achieve the required degree of filtration. This pattern of finest on top is a consequence of the bed expansion and resettling during every cleaning step. However, it is perfectly possible to make a deep bed from layers of different materials, such that the coarsest are in the upstream part of the bed – or to reverse the flow to upwards from the base of the bed.

Table 10.38 Comparative grades of perlite materials*

Celatom perlite	Harborlite	Dicalite	Nord	Silbrico	Femco
		416			H-2, H-1
	400	426	734	27-M	
	635	436	634	25-M	H-5S
1200	700	476-CP-100	443	23-S	H-5
1400	800	4106-CP-150		21-S	H-4
2000	900	4156-CP-175	332	19-S	H-9
4000	1800	4186		17-S	H-X
5000	1900				
6000	2000		272	15-S	H-R
	5000				

* Eagle-Picher Minerals, Inc.

Table 10.39 Comparative grades of cellulose precoat materials*

Pre-co-Floc	Arbocel	Technocel	Solka-Floc	Fibra-Cel
PB200M	BE600	50/90	BW300	
PB100M	B800		BW200	BH100
	BE00			
PB100ME	BWW40	100/150	100	BH65
PB40M			40	
PB40ME				
PB40ME-LD	BC200			BH40
PB20M				BH20
PB100	BC1000	200	20	
PB40				
PB33	B400		10	
PB33E				
PB20	FIF400		1016	

* Eagle-Picher Minerals, Inc.

10.5.1 Precoat media

An unavoidable feature of the use of precoat is that some or all of it will be discharged with the accumulated filter cake. Material must thus be chosen whose presence in the cake can be tolerated (e.g. where the cake is itself a waste product intended for immediate disposal), or which can be easily separated from the cake solids by subsequent processing. If the cake solids can withstand it, then incineration could be used to remove an ashless cellulose material.

Of the available range of precoat media, the two mineral products, diatomite and expanded perlite, and cellulose are the most common. The makers of cellulose fibre media claim that it can achieve any required degree of filtration, if properly chosen and laid down, while the mineral media suppliers usually allot cellulose to a base layer of precoat, if any.

The various grades from one or two manufacturers are described in Section 10.2, and a set of comparative grades is given in Table 10.37 for diatomite, Table 10.38 for perlite, and Table 10.39 for cellulose.

10.5.2 Deep-bed media

The largest use by far for deep-bed filters is in the processing of raw water for the production of drinking water (and, to a lesser extent, in waste water treatment). The choice of granular media for this purpose is therefore largely made on the basis of the advice in Section 10.3.1, or the British Water standard[11].

10.6 References

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