Pre-Filtration of Very Highly Turbid Waters Using Pebble Matrix Filtration

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ABSTRACT

As a solution to very high turbidity problems associated with slow sand filters, a new pretreatment method has been developed at University College, London. Initial experiments with a model using a bed of fine sand (effective diameter d. = 0.32 mm) demonstrated that maximum loadings on slow sand filters should not exceed 25 mg/l at a filtration velocity of 0.2 m/h for satisfactory run times (approximately 5 weeks). However, a literature survey revealed that many tropical rivers may carry several hundred (or even a few thousand) milligrammes per litre of suspended solids during monssoon periods. A need for pretreatment methods is therefore obvious.

A novel process, called pebble matrix filtration, can protect slow sand filters by reducing the suspended-solids concentration of monsoon river waters (containing up to 5000 mg/l) to below 25 mg/l. The paper briefly describes the principles lying behind the treatment process of pebble matrix filtration, and suitable operational parameters are given at flow rates of 0.72–1.56 m/h for tested suspended-solids concentrations of 500, 1000, 2000 and 5000 mg/l kaolin clay in London tap water, with achieved run times of up to 116 h to head losses not exceeding 1.5 m. Filter cleaning is described by a method called 'drainage and backwash'.

Key words: Very high turbidity; slow sand filtration; pretreatment; pebble matrix filtration; drainage; backwash.

INTRODUCTION

The main drawback in applying slow sand filtration to highly-turbid surface waters in tropical regions is that the suspended silt quickly blocks the filter, necessitating frequent cleaning. At times of high-intensity rainfall in regions where periodic heavy rains (monsoon season) occur, large quantities of suspended matter wash into rivers and the water becomes very turbid. For example, it has been reported[1] that in Kenya, the Sabaki River has occasionally contained a suspended-solids (SS) concentration of more than 15 000 mg/l during flood flows. A detailed study[2] revealed that the monsoon SS concentrations in tropical rivers can reach up to 30 000 mg/l, although these extremes are occasional. The duration of periods of high turbidities can vary from a few days to as much as 50% of the year. In general these solids are inorganic in origin, and a major part (about 80–90%) of the material consists of particles below 20 μm in size. Such high levels of turbidity render slow sand filters inoperative; however, they can still be used provided that most of the suspended material is removed by pretreatment methods. Hence, there is a need for pretreatment, and the need is immediate.

PRELIMINARY EXPERIMENTS

Preliminary experiments were carried out, using a laboratory-scale slow sand filter (SSF), to study its performance and then to develop design guidelines in relation to maximum input turbidity/suspended-solids concentrations.

The apparatus comprised a 110-mm internal dia., 1.50-m long Perspex tube, and contained a 0.60-m depth of fine sand (d_{10} = 0.32 mm) on top of support gravel. The model SSF was seeded with active biological material ('Schmutzdecke') from Coppermills water-treatment works (Thames Water), and was illuminated artificially to encourage the biological activity in the Schmutzdecke. The filter was then commissioned using tap water containing a small amount of glucose/glutamic acid (3–5 mg/l BOD), and the development of headloss was monitored with in-depth manometers. After several weeks' operation at 0.18 m/h, the filter was scraped to conform with normal cleaning practice; this established the baseline of operation without turbidity load. The next experimental phase commenced with a steady concentration of 25 mg/l followed by 50 mg/l of kaolin clay in the influent, to determine the effect on (a) filtrate quality, (b) headloss development, and (c) Schmutzdecke activity. A continuous concentration of 25 mg/l kaolin allowed a filter run of about 5 weeks at a terminal headloss of 1.0 m, producing a filtrate containing below 1 mg/l SS. However, if the input SS concentration is limited only by occasional peak loads of 25 mg/l, filter runs of more than 5 weeks can

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be expected. When the concentration was increased to 50 mg/l the filter clogged up in 1.5 weeks. These experiments established the limit of 25 mg/l SS to be allowed onto sand filters at a filtration velocity of 0.2 m/h, for their continuing performance, and indicated that when the raw water contained more than 25 mg/l SS it must be pretreated to below this value before applying it onto a slow sand filter.

PEBBLE MATRIX FILTER

The pebble matrix filter (PMF) is derived from an initial development in the USSR where the description 'Karkasno-Zasypny filt'r' (skeleton-fill filter) was used. It was originally conceived as a tertiary filter for sewage treatment, but the literature[3,4] is not very informative, and there is no evidence that it has been used in practice. In principle the filter consists of a *matrix of large pebbles about 50 mm in* size (the 'skeleton'), which is infilled for part of its depth with sand (Fig. 1). The suspension approaching the filter first passes through a layer of large pebbles (L_1), and then through a layer of mixed pebbles and sand (L_2). *Hence the title* 'pebble matrix filtration' seemed more appropriate than the original Russian translation. The arrangement creates a crude two-layer filter where the pebbles alone have some pre-filtering effect (Fig. 2). As the suspension moves downwards, particles settle on top of the pebbles as dome-like deposits, thus indicating that gravity is almost certainly the dominant removal mechanism in the pebble bed.

In the lower part, the pebble matrix with sand removes a major proportion of the suspension with a remarkably low decrease in pressure. The continuing high permeability is thought to be due to the presence of lens-like cavities found beneath the pebbles (Fig. 3), together with a significant boundary flow (wall effect) over the pebble surfaces adjacent to the sand grains. Also, observations inside the pebbles/sand bed using fibre-optic endoscopes (borescopes) revealed that filtration is responsible for the clarification of suspensions in this part of the PMF. Therefore it is considered that the removal in the pebble/sand bed is governed by the generally-accepted deep-bed filtration mechanisms.

Initial Headloss

As mentioned earlier, due to the presence of pebbles the initial headloss in the PMF is considerably lower than in conventional sand filters, therefore the Kozeny-Carman equation cannot be directly used to evaluate initial headlosses in this filter.

The Kozeny-Carman equation can be written in the form:

$$(H/L) = k_0 . (\mu/\rho . g) . (Q/A) . s^2/f_0^3 \qquad \dots (1)$$

where:
A = plan area of the filter
H = initial headloss
L = bed depth
Q = volumetric flow
g = gravitational acceleration
s = $[(1-f_0) . 6/d_e]$ the specific surface of the sand grains
d_e = effective diameter (d_{10})
f_0 = initial porosity of the bed
k_0 = headloss constant (= 5.0)
μ = absolute viscosity
ρ = density of water

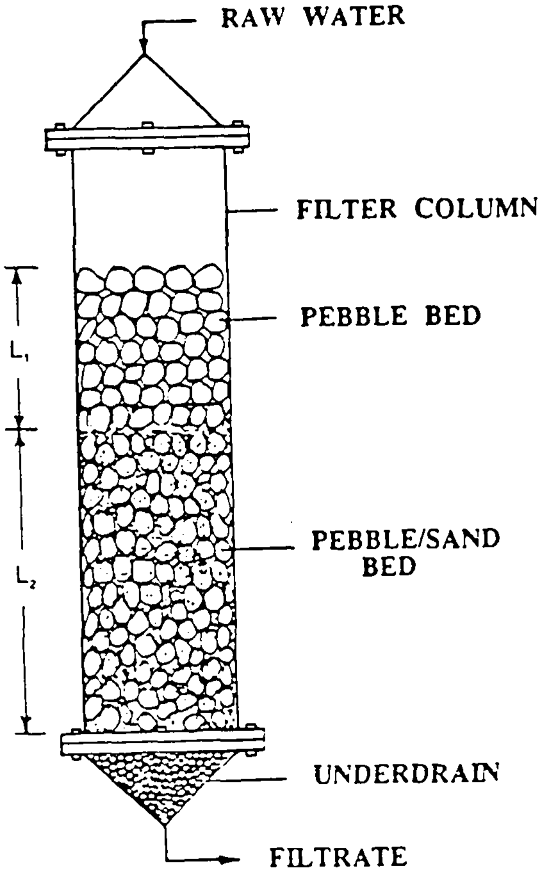


Fig. 1. Diagrammatic representation of pebble matrix filter

However, it may also be possible to use this expression for pebble matrix filtration if A, f_0 and d_e are modified appropriately before using them in the equation. If the pebble porosity is taken as f_2, the plan area of the filter (A) can be modified by replacing it with the effective filter area A_e (= A × f_2). The porosity term f_0, which is valid for uniform

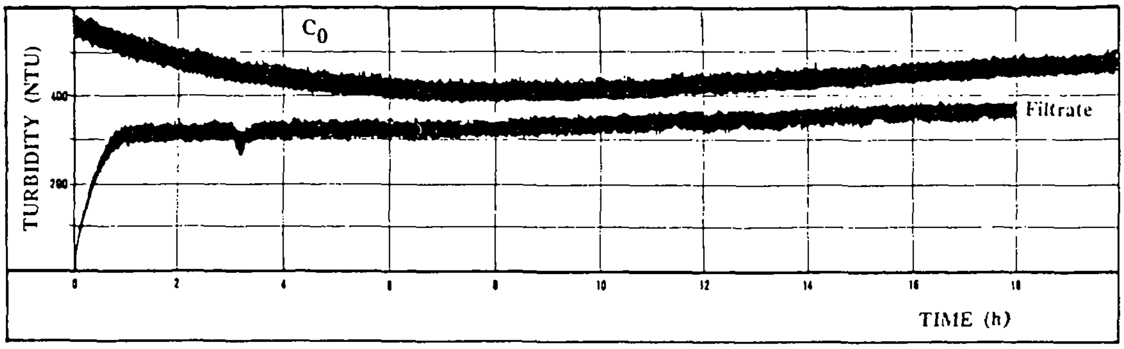


Fig. 2. Quality of filtrate v. time for pebble bed

media, has to be replaced with the porosity of the pebble/sand mixed bed or the micro-porosity, f_m, which can be calculated experimentally as follows:

For the pebble and sand part (lower part) of the filter only:

(i) Apparent volume of sand, V_1 = apparent volume of pebbles × pebble porosity, f_2.
(ii) Actual volume of sand, V_2 = mass of sand/density of sand

Therefore

$$\text{micro-porosity } (f_m) = (V_1 - V_2)/V_1 \qquad \ldots \quad (2)$$

In equation (1) the diameter d_e is usually taken as d_{10}, and this would only represent the sand media without pebbles; therefore this term has to be modified in such a way that both the sand and pebbles are represented by a new diameter, term (d_{pmf}), for the PMF. Consequently, by considering a cross-section through the filter, and assuming that pebbles and sand have the same shape, the following relationship was used to express the new diameter, term d_{pmf}, for the PMF:

$$\frac{[(A - A_p(1 - f_1) + A_p]}{A(1 - f_1)} = \left(\frac{d_{pmf}}{d_{10}}\right)^2 \qquad \ldots \quad (3)$$

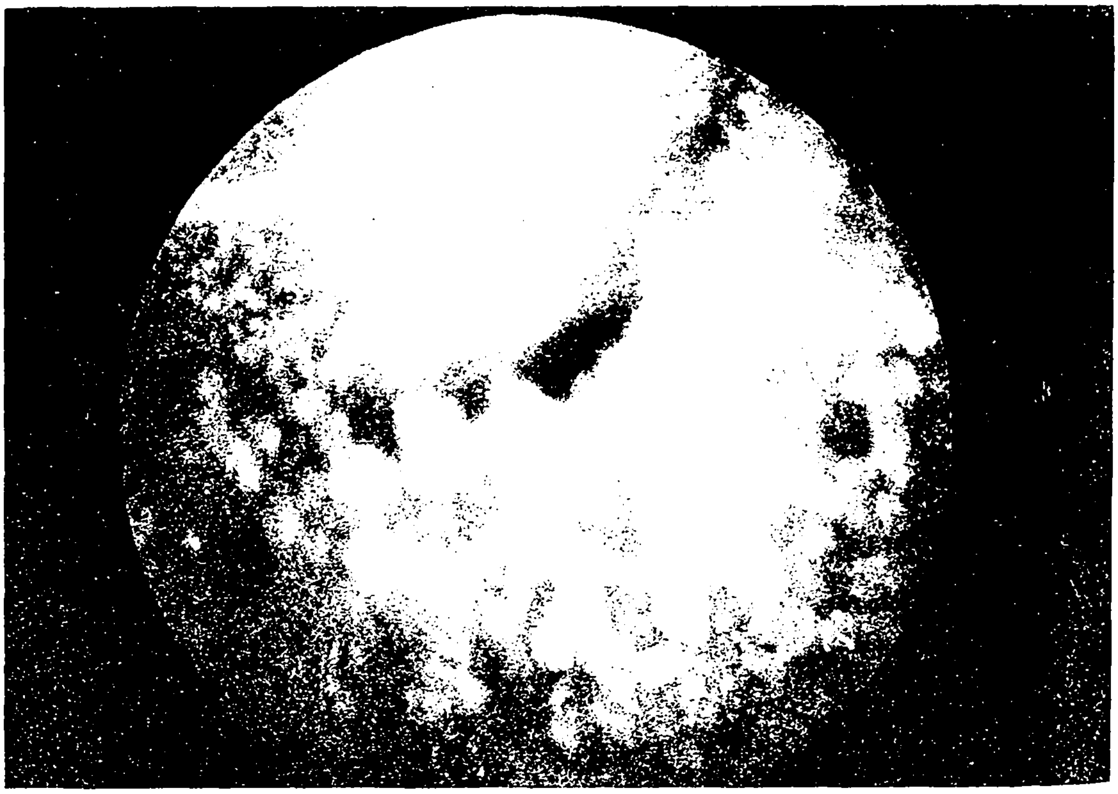
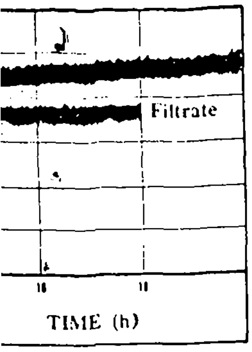


Fig. 3. Lens-like cavity underneath a pebble



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$$\left(\frac{d_{pmf}}{d_{10}}\right)^2 \quad \ldots \quad (3)$$

where: A = plan area of filter
A_p = total cross-sectional area of pebbles within area A
f_1 = porosity of sand media

and

$A(1 - f_1)$ = cross-sectional area of sand media
$[(A - A_p)(1 - f_1) + A_p]$ = total cross-sectional area of sand and pebbles

Equation (3) can be re-written as:

$$\frac{[1 - A_p/A)\,(1 - f_1) + A_p/A]}{(1 - f_1)} = \left(\frac{d_{pmf}}{d_{10}}\right)^2 \quad \ldots \quad (4)$$

Now, in terms of pebble porosity f_2, the ratio A_p/A can be written as:

$$A_p/A = (A - A\,.\,f_2)/A = (1 - f_2) \quad \ldots \quad (5)$$

Therefore, equation (4) can be simplified to obtain d_{pmf} as:

$$d_{pmf} = d_{10}\,.\,[(1 - f_1 f_2)/(1 - f_1)]^{0.5} \quad \ldots \quad (6)$$

It can therefore be concluded that, for the PMF, the initial headlosses can be evaluated by taking into consideration the modified terms with respect to filter area (A_e), porosity (f_m) and diameter (d_{pmf}) in the Kozeny-Carman equation. Then the Kozeny-Carman equation in a modified form can be written as:

$$H = \frac{180\,.{\sim}Q\,.\,\mu\,.\,(1 - f_m)^2.\,L_2}{A_e\,.\,\varrho\,.\,g\,.\,f_m^3\,.\,d_{pmf}^2} \quad \ldots \quad \ldots \quad (7)$$

where L_2 = pebble/sand bed depth.

The micro-porosity, f_m, and the d_{pmf} values evaluated for three different types of sands are given in Table I.

TABLE I. VALUES OF MICRO-POROSITY (f_m and d_{pmf}) FOR DIFFERENT SANDS (pebble porosity f_2 = 0.36)

	Sand grade 8/16 (d_{10} = 1.03 mm)	Sand grade 16/30 (d_{10} = 0.56 mm)	Sand grade 22/44 (d_{10} = 0.38 mm)
f_m d_{pmf}	0.486 1.25 mm	0.465 0.68 mm	0.420 0.46 mm

The headloss values calculated by substituting the above values in equation (7) are given in Table II against the experimentally-determined values for comparison.

EXPERIMENTAL PROGRAMME

During the laboratory experiments, the following design and operating questions had to be answered in relation to pebble matrix filtration:

TABLE II. CALCULATED HEADLOSS VALUES USING A_e, f_m AND d_{pmf} IN MODIFIED KOZENY-CARMAN EQUATION

Q (l/min)	H (mm) exp.	H (mm) calc.
Pebbles + sand (8/16) *L_2 = 750 mm; at 15°C*		
0.40	10	10.0
0.50	12	12.5
0.55	13	13.9
0.70	19	17.7
0.90	25	22.7
1.00	29	25.2
Pebbles + sand (16/30) *L_2 = 750 mm; at 14°C*		
0.40	42	40.0
0.50	52	50.0
0.55	59	55.0
0.70	79	70.0
0.90	103	90.1
1.00	116	100.0
Pebbles + sand (22/44) *L_2 = 775 mm; at 13°C*		
0.40	133	131.5
0.50	166	164.4
0.55	183	180.8
0.70	242	230.1
0.90	312	295.9
1.00	354	328.9

(i) What is the depth and media size of the pebble matrix?
(ii) What is the depth of the sand infilling?
(iii) What is the size of the sand grading?
(iv) What is the rate of flow (approach velocity)?
(v) How does the concentration change with depth and time?
(vi) How does the headloss change with depth and time?
(vii) What are the cleaning procedures?

Bearing in mind these questions, experimental investigations were conducted on a laboratory-scale filter unit comprising a 244-mm ID, 1.30-m long Perspex column with sampling and manometer points. Filtration velocities of 0.50, 0.72, 1.17 and 1.56 m/h, with SS concentrations in the raw water ranging 100–5000 mg/l, were tested. The filtrate quality was monitored continuously using a HACH-Ratio turbidimeter and pen-recorder. A summary of the results from various experiments, using different inlet concentrations, flow rates, sand sizes, and depths of media, carried out to determine the best design for pretreating London tap water containing kaolin clay, is given in Table III.

At a filtration velocity of 0.72 m/h with fine sand (d_{10} = 0.38 mm) the filter produces an effluent containing less than 1 mg/l SS even with as high as 1000–5000 mg/l SS at the inlet. At all the above-mentioned filtration rates a filtrate quality of less than 25 mg/l SS has been achieved, and a typical graph showing the variation of filtrate quality with time is shown in Fig. 4.

TABLE III. Suitable Operational Ranges for PMF

Conc. of inlet clay (mg/l)	Depth		Approach velocity V_a (m/h)	Run time (T hours) t_c or t_h	Headloss at T hours (mm)
	L_2 (mm)	$L_1 + L_2$ (mm)			
Sand 8/16†					
500	610	770	0.72	14 (t_c)	25
500	840	1020	0.72	34 (t_c)	65
500	840	1020	1.17	10 (t_c)	45
Sand 16/30†					
500	310	620	0.72	18 (t_c)	145
500	750	1020	0.72	60 (t_c)	615
500	750	1020	1.17	16 (t_c)	320
1000	750	1020	0.72	28 (t_c)	635
1000	750	1020	1.17	12 (t_c)	330
2000	750	1020	0.72	12 (t_c)	340
2000	950	1300	0.72	18 (t_c)	415
500	950	1300	0.72	116 (*)	1500
Sand 22/44†					
500	340	640	0.72	35 (t_c)	628
1000	340	640	0.72	16 (t_c)	562
500	750	1020	0.72	44 (t_h)	1080
500	750	1020	1.17	25 (t_h)	1020
500	750	1020	1.56	19 (t_h)	1240
1000	750	1020	0.72	27 (t_h)	1297
1000	750	1020	1.17	14 (t_h)	1332
5000	750	1020	0.72	9 (t_h)	1260

where:

† = passing and retaining British Standard sieves
t_c = breakthrough by filtrate quality (limit = 25 mg/l)
t_h = run limit by headloss (limit = 1500 mm)
(*) = ($t_c = t_h$)

As a final test the PMF was put in sequence before the SSF (Fig. 5) to prove the whole system. During these experiments the PMF was operated at 0.72 m/h (sand grade 22/44) with 5000 mg/l SS at the inlet, and the filtrate was used to feed the SSF. Under these conditions the PMF produced a filtrate containing less than 1 mg/l SS for most of the run but, due to occasional peaks (similar to the peaks in Fig. 4), gave an average value of less than 5 mg/l SS. The SSF performed satisfactorily at 0.18 m/h, producing a filtrate containing below 0.5 mg/l SS (see Fig. 6) with only 300-mm headloss after three weeks.

Filter Cleaning by 'Drainage and Backwash'

Good cleaning was achieved by two drainage cycles followed by backwashing to expand the sand into the pebble pores above; firstly, by draining down the filter (approx. drainage velocity 7–10 m/h) and refilling it with raw water, and draining down again, the majority of the deposit (>70%) was removed leaving the free pebble bed completely clean. Then by reverse-flow washing (50 m/h), the sand was fluidized to occupy the spaces between the pebbles.

Several cleaning processes have been investigated

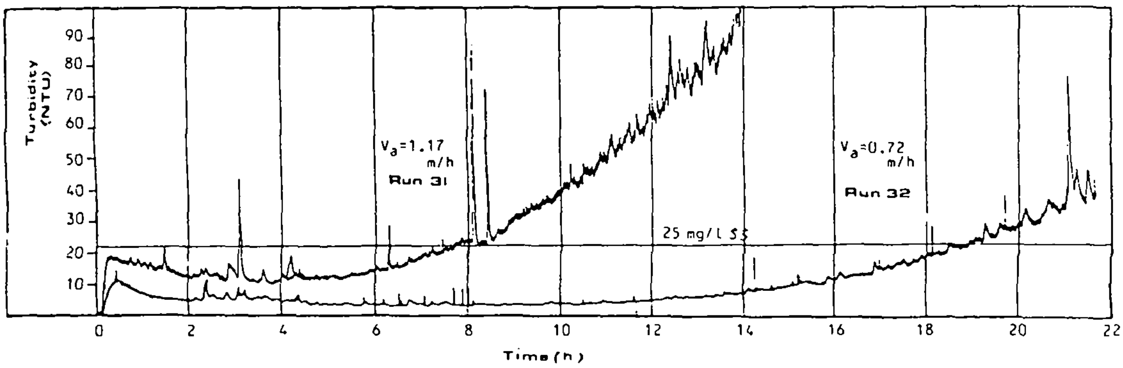

Fig. 4. Variation of filtrate turbidity with time for PMF

Headloss at T hours (mm)
25
65
45
145
615
320
635
330
340
415
1500
628
562
1080
1020
1240
1297
1332
1260

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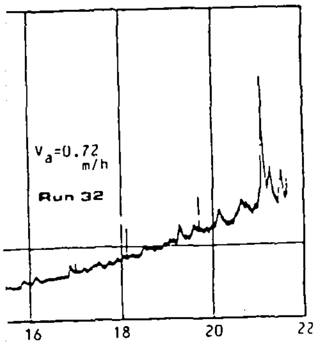
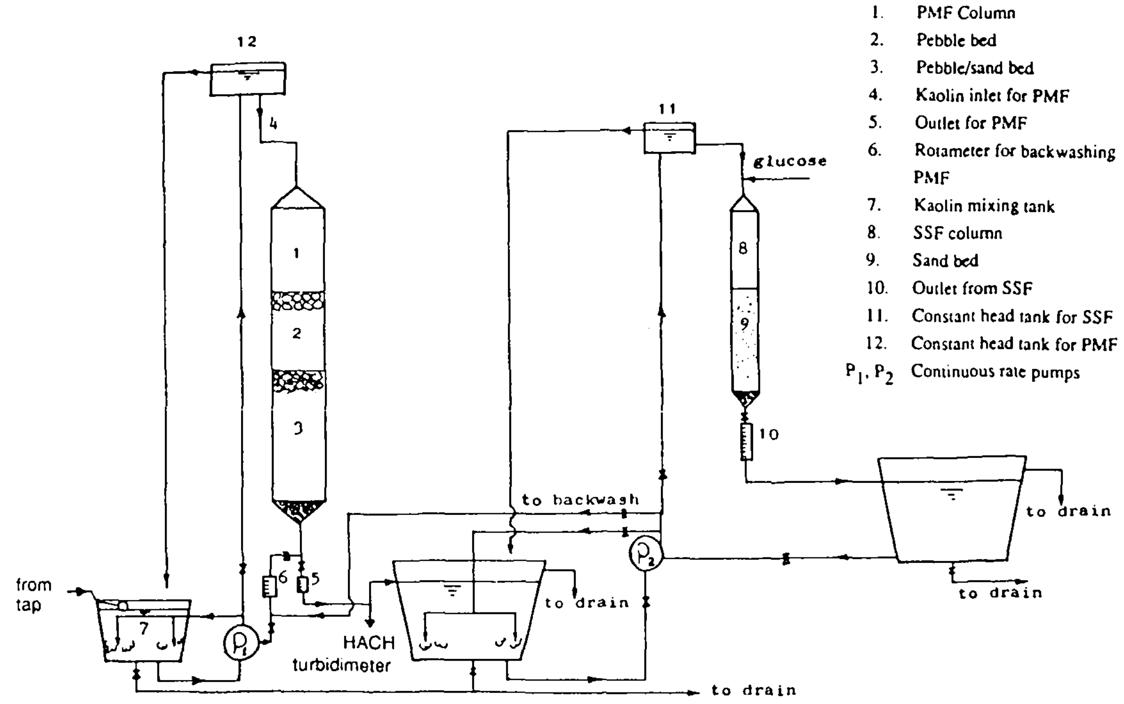


or PMF



1. PMF Column
2. Pebble bed
3. Pebble/sand bed
4. Kaolin inlet for PMF
5. Outlet for PMF
6. Rotameter for backwashing PMF
7. Kaolin mixing tank
8. SSF column
9. Sand bed
10. Outlet from SSF
11. Constant head tank for SSF
12. Constant head tank for PMF

P_1, P_2 Continuous rate pumps

Fig. 5. Pebble matrix filtration as pre-filtration to slow sand filtration

which satisfactorily incorporate the drainage and backwash technique (all with two drainages):

(i) After drainage, the filter was backwashed with clean water only. For the source of clean water, tap water, slow sand filter effluent and PMF effluent were tested as alternatives. All produced similar results with regard to washwater requirements and *initial (Kozeny) headlosses following backwashing.*

(ii) The drainage procedure was the same as in (i), but washing was first accomplished with raw water followed by clean water. This reduced the clean water consumption during backwashing by about 50%.

(iii) After draining, the filter was backwashed using only raw water (containing 500–5000 mg/l SS). This was sufficient to clean the filter of the accumulated clay so that when filtration was re-started the initial headloss was similar to that attained after washing with clean water.

Several consecutive runs incorporating this cleaning method produced similar headlosses, filtrate quality against time graphs and run times. One

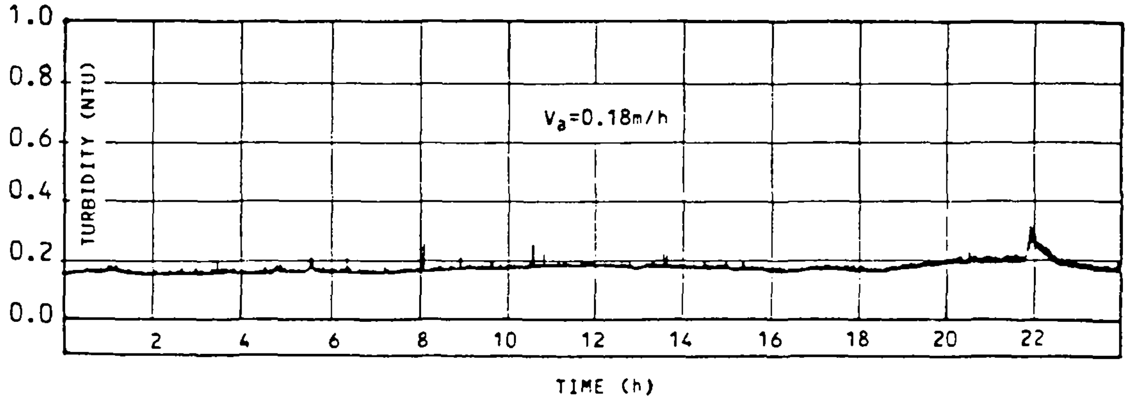


Fig.6. Continuous monitoring of filtrate quality with time for SSF
(PMF operated with 5000 mg/l SS at 0.72 m/h)
Note: the slight increase in turbidity at the end of 21 h was due to a low adjustment of the slow sand filter

advantage in this method is that there are fewer restrictions on washwater requirements, since during a monsoon period raw water is plentiful and no product water is utilized.

PRACTICAL CONCEPTS

The principal experiments utilized smooth rounded pebbles (the shape corresponding to 0.81 on the Rittenhouse[5] scale) from the seashore. As it is possible that such pebbles may not be universally available, other media (such as road materials or broken bricks) can be used. Some tests were made[6] with the same pebbles, roughened with sand and cement, and broken angular roadstones (Rittenhouse shape 0.65) of the same general size (50 mm). These tests have not yet been evaluated, but removal efficiencies appeared to be encouraging, although some modification of the cleaning procedure may be necessary. Provided that the pebble materials are not soluble in the water, and conform to the normal testing criteria for filter media[7], they can be of any inert material of density 2500 kg/m^3 or greater. With regard to the sand bed, both finer (d_{10} = 0.35 mm) and coarser (d_{10} = 1.00 mm) materials have been found to work satisfactorily under laboratory conditions, producing filtrates of extremely good quality. However, in addition to the removal efficiency, other factors such as filter run time, maximum headloss, bed depth and approach velocity have to be considered as a whole. Therefore the selection will have to depend on the above conditions, local availability of the materials and pilot-plant observations. Preliminary tests[2,8] also indicated some bacteriological quality improvement by the PMF.

When designing the PMF, as in any pretreatment process, another important factor which has to be taken into consideration is the maximum SS concentration in the river that would occur during a monsoon period. However, these monsoon turbidity SS values for rivers are not readily available in most parts of developing countries; therefore the appropriate authorities should be encouraged to collect such data in general, and more particularly during preliminary investigations of a pretreatment project. As in all sample analyses, such data should be obtained over a period to allow for seasonal changes and alterations in river flows. For example, the analysis of 2–3 years' monitoring of the Sabaki River in Kenya has been obtained[9], showing the duration in days per annum when a particular concentration of SS could, on average, be expected. This analysis (Table IV) indicates that the SS content in the Sabaki River exceeds 500 mg/l, on average, for 167 days/annum, i.e. for 46% of the time; and exceeds 1000 mg/l for 34% of the time, and occasionally exceeds 10 000 mg/l on a few days per annum.

TABLE IV. Suspended-Solids Analysis for Sabaki River, Kenya (1979)

Conc. of SS (mg/l)	Duration per annum	
	days	per cent
500–1 500	44	12
1 000–5 000	80	22
5 000–10 000	36	10
>10 000	7	2

It has also been shown[1] that the SS concentration varies with the river flow. Such relationships may be used to evaluate the SS loadings during the design stages of pretreatment plants in locations where no long-term records of SS/turbidity are available.

FUTURE STUDIES

It is planned to carry out pilot-plant trials in India, Tanzania and Colombia where facilities exist to pretreat river waters which supply slow sand filters. A pilot-scale unit is also being tested on a lake site in West Germany, with the object of using the high-deposit storage capacity of pebble matrix filtration for long-term (several months) operation. The process also has potential for tertiary sewage treatment, as originally conceived in the USSR, but no trials have yet been planned.

CONCLUSIONS

1. It is recommended that a maximum SS concentration of 25 mg/l should be allowed onto slow sand filters, at a filtration velocity of 0.2 m/h, for their satisfactory performance. A continuous concentration of 25 mg/l would allow a filter run of about 5 weeks at a terminal headloss of 1.0 m, producing a filtrate quality containing less than 1 mg/l SS. However, if the input SS concentration is limited to only an occasional peak of 25 mg/l, filter runs of more than 5 weeks can be expected.
2. A SS concentration of 50 mg/l in the raw water would allow a slow sand filter to operate for about 1.5 weeks under similar conditions; therefore this is not recommended.
3. The PMF can intercept high concentrations of SS (5000 mg/l) and reduce them to below 25 mg/l. In view of its simplicity in design and operation, it can be considered to be an appropriate pretreatment method to protect slow sand filters from high turbidities that occur during monsoon periods in developing countries.
4. The headloss in the PMF is considerably less than in other conventional filters, which is thought to be principally due to (a) lens-like cavities formed underneath the pebbles, and (b) boundary effects. These cavities and boundary flows create

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. KENYA (1979)

Duration per annum	
days	per cent
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36	10
7	2

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secondary (macro) flow paths, thus increasing the permeability through the bed.

5. For the evaluation of initial headlosses in the PMF, the Kozeny-Carman equation can be used in a modified form as:

$$H = \frac{180 \,.\, Q \,.\, \mu \,.\, (1 - f_m)^2 \,.\, L_2}{A_e \,.\, \varrho \,.\, g \,.\, f_m^3 \,.\, d_{pmf}^2} \qquad \ldots \qquad \ldots \qquad (7)$$

6. The following operational conditions are recommended to obtain filtrates containing less than 25 mg/l SS:
   - *(a)* With sand grade 8/16 and pebbles of approximately 50 mm size, the suitable approach velocity would be 0.7 m/h for an input concentration of 1000 mg/l;
   - *(b)* With sand grade 16/30 the filter can be operated at 0.7 m/h up to 2000 mg/l, 1.2 m/h up to 1000 mg/l and 1.5 m/h up to 500 mg/l maximum concentrations in the raw water; and
   - *(c)* With sand 22/44 it is possible to operate at 0.7 m/h up to 5000 mg/l and 1.5 m/h up to 500 mg/l.

   In all the above cases, a pebble/sand depth of 0.75–0.90 m and a total depth of 1.0–1.5 m is recommended. These recommendations are based on the kaolin/London tapwater suspensions used in this study, and require verification or amendment by pilot-scale, on-site evaluation.

7. At the end of a filter run good cleaning is achieved by two drainage cycles followed by backwashing with raw water only, to expand the sand into the pebble pores. However, backwashing the filter with clean water once a week, or fortnightly, is desirable to avoid any long-term deposits accumulating in the filter bed. A common wash rate of 50 m/h is recommended for both coarse and fine sand.

8. It would be beneficial to encourage water authorities in the developing countries to prepare a record of turbidity/suspended solids and particle size analysis for rivers during monsoon periods.

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