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PARAMETERS OF FILTRATION PROCESS ON MULTI-MEDIA FILTER BEDS

Major geometrical, hydraulic and technological parameters have been analysed. The experiments involved double-media and triple-media filter beds. The methods for measuring the parameters of interest were determined and discussed to assess the effect of retaining solid-phase particles on the filter bed.

The following parameters were studied: permeability, shear stress, velocity gradients, and head loss gradient. These parameters made it possible to determine the depth of the zones of the highest ability to retain solid-phase particles. But the same parameters were insufficient to quantify the mass and volume of the retained particles.

Attempts are also made to assess the filtering properties of the flocs retained in the bed. This feature is best described by such parameters as compressibility and resistivity. Knowing the values of the compressibility and resistivity coefficients, as well as the mass and energy balance, it is possible to derive the expression for hydraulic losses, relating them to the geometry of the bed, and to the hydraulic and technological parameters of the rapid filtration process.

NOTATION

A – constant, $A = \frac{1}{3}\left(1-\sqrt{\frac{1}{3}}\right)$,

B – constant, $B = \frac{1}{3}\left(1+\sqrt{\frac{1}{3}}\right)$,

C, D – coefficients of regression in eq. (5),

c_s – concentration of suspended solids, $\mathrm{g \cdot m^{-3}}$,

d_g – grain diameter of filter bed, m,

D_C – coagulant dose, $\mathrm{g \cdot m^{-3}}$,

H – depth of filter bed, m,

K – Kozeny–Carman constant,

s – compressibility index,

t – time of filtration (duration of the process), h,

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v_f — filtration rate, $m \cdot h^{-1}$,
V_M — mass capacity, $kg \cdot m^{-2}$,
V_p — volume capacity (volume of suspended particles retained per unit volume of filter bed), $m^3 \cdot m^{-3}$,
W_ε — coefficient of bed porosity,
α_{R_0} — specific resistance of solid particles retained in filter bed, $m \cdot kg^{-1}$,
ΔC — colour differences between influent and effluent, $g\ Pt \cdot m^{-3}$,
ΔT — turbidity differences between influent and effluent, $g \cdot m^{-3}$,
ΔH — unit depth of filter bed, m,
$\Delta P, \Delta P_0, \Delta P_s$ — increment of hydraulic losses in fresh bed and in bed polluted with solids, $N \cdot m^{-2}$,
ε_0 — bed porosity,
η — dynamic viscosity coefficient, $Ns \cdot m^{-2}$,
ϱ — water density, $g \cdot m^{-3}$,
ϱ_{fl} — floc density, $g \cdot m^{-3}$.

1. INTRODUCTION

The ever increasing water demand has made rapid filtration a vital part of the systems for water treatment and renovation. The need for more efficient filtering processes has directed our attention to the analysis of the phenomena involved. Both theory and engineering practice have substantiated the effectiveness of filtration processes making use of multi-media filter beds. Beds built of more than one filter medium utilize the principle of *reverse filtration*. This means that water passes from the coarse-grain medium to media with finer grain sizes, thus increasing the bed

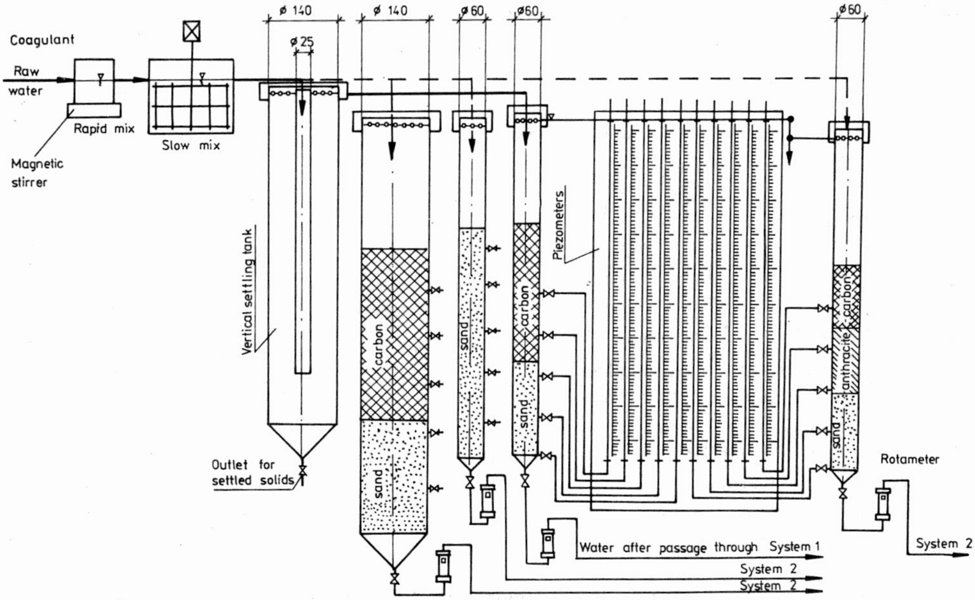

Fig. 1. Experimental system

Table 1

Grain size

	Double-media bed		Triple-media bed		
	Sand	Carbon	Sand	Anthracite	Carbon
d_{10} m	0.45×10^{-3}	0.7×10^{-3}	0.7×10^{-3} 0.8×10^{-3}	1.3×10^{-3} 1.08×10^{-3}	1.1×10^{-3} 1.0×10^{-3}
d_{60} m	0.65×10^{-3}	1.7×10^{-3}	1.05×10^{-3} 1.2×10^{-3}	1.05×10^{-3} 1.68×10^{-3}	1.8×10^{-3} 2.6×10^{-3}

capacity to retain pollutants. In this way, the filtration cycle may be extended and pressure drop can markedly be decreased. Most of the experimental works reported in the literature [1], [2] deals with the identification and modelling of the phenomena involved in the filtration process, as well as with optimization problems. Having these in mind, it seems advisable to determine experimentally the relations that occur among grain size, hydraulic parameters and technological parameters.

The objective of the study reported in this paper was to analyze all those phenomena involved in filtration on multi-media beds that are of prime importance to the efficiency of the process. Thus, consideration is given to the structural parameters which both contribute to the volume and mass capacities of the filter beds and influence the compressibility of the flocs retained by them.

2. SCOPE AND METHODS OF INVESTIGATION

The filtration process was investigated in the experimental system shown in fig. 1. The granulometry of the filter beds is given in tab. 1. The experiments were run with three types of samples including coagulated river water, artificially turbidified water

Table 2

Parameters of suspension

Sample	Composition of flocs	Floc density, max and min ϱ_{fl}, $\mathrm{kg \cdot m^{-3}}$	Water content in flocs U_{fl}, %
River water	$Al(OH)_3$ + turbidity (20–50 g/m^3) + colour (30 – 40 g Pt/m^3) + suspension (20–100 g/m^3)	1004.07 1008.77	99.25 98.46
Turbidified water	$Al(OH)_3$ + turbidity (15 g/m^3) + colour (20 g Pt/m^3) + suspension (15 g/m^3)	1002.48 1003.02	99.52 99.43
Reservoir water [5]	$Al(OH)_3$ + turbidity (2.7–3.2 g/m^3) + colour (30 g Pt/m^3)	1002.72	99.48

and water from a storage reservoir, respectively. Filtration rates varied from 5.0 to 15 m/h. The composition of the precipitated suspension is given in tab. 2. The measurements included hydraulic losses and physicochemical composition of the investigated water before and after passage through the filter. Hydraulic losses were measured at the bed depth every 1–2 h. Hydraulic loss head was determined during passage of tap water for filtration rates ranging between 5.0 to 20.0 m/h.

3. DISCUSSION AND INTERPRETATION OF RESULTS

Water flow through the filter beds was estimated in terms of the relation between filtration rate and hydraulic loss head gradient. The straight-line behaviour of the plot (fig. 2) is an indication of laminar flow in the whole range of the investigated filtration rates. This finding enabled us to make use of the relations and equations describing the laminar flow of water through a granular filter bed [3].

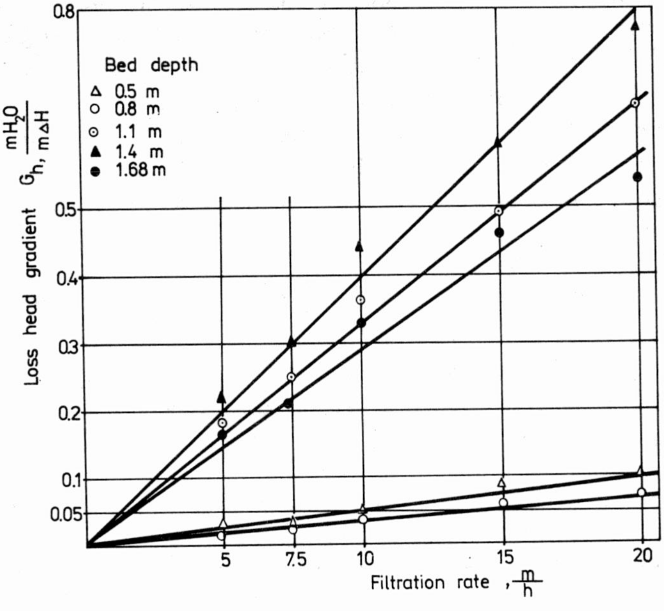

Fig. 2. Relation between filtration rate and gradient of hydraulic loss head G_h

3.1. VOLUME CAPACITY OF FILTER BEDS

The term *volume capacity* is used here to denote a certain part of bed porosity occupied by the particles of the suspension in the course of the filtration cycle. For the purpose of interpretation, volume capacity was related to some decision parameters included in the following general equation:

$$V_p = V_p \left[d_g, \varepsilon_0, \eta, \varrho, v_f, \frac{\Delta P_s}{\Delta H}\left(\frac{\Delta P_0}{\Delta H}, c_s, t\right)\right] . \tag{1}$$

To define the particular form of eq. (1), the authors of this report availed themselves of the Kozeny–Carman model. Volume capacity was calculated by making use of the hydraulic loss values related to time and bed depth. Owing to its simple formula and high reliability, the Kozeny–Carman model is convenient and workable.

Thus, volume capacity was evaluated by virtue of [4]

$$V_p = \sqrt[3]{-\frac{1}{2W_\varepsilon^3}(W_\varepsilon - A)(W_\varepsilon - B) + \frac{1}{6W_\varepsilon}\sqrt{(27W_\varepsilon - 4)/3W_\varepsilon}} + \sqrt[3]{-\frac{1}{2W_\varepsilon^3}(W_\varepsilon - A)(W_\varepsilon - B) - \frac{1}{6W_\varepsilon}\sqrt{(27W_\varepsilon - 4)/3W_\varepsilon}} + \varepsilon_0 - \frac{1}{3W_\varepsilon} \tag{2}$$

where A and B take constant values, and W_ε is a coefficient of bed porosity.

Table 3

Volume capacity related to the duration of the filtration process

Filtration rate m/h	Media	Volume capacity as a function of time m^3/m^3					
		$t = 3$ h	$t = 9$ h	$t = 12$ h	$t = 15$ h	$t = 16$ h	$t = 18$ h
5.0	carbon	0.220	0.277	0.283	0.287	0.288	0.292
	anthracite	0.060	0.163	0.180	0.195	0.197	0.196
	sand	0.005	0.070	0.098	0.120	0.122	0.125
10.0	carbon	0.142	0.219	0.244	–	0.260	–
	anthracite	0.060	0.119	0.117	–	0.146	–
	sand	0.038	0.110	0.133	–	0.160	–
15.0	carbon	0.138	–	0.211	0.211	–	0.233
	anthracite	0.057	–	0.122	0.129	–	0.132
	sand	0.027	–	0.107	0.123	–	0.137
5.0	carbon	0.095	0.167	0.184	0.195	–	0.203
	anthracite	0.040	0.113	0.138	0.155	–	0.163
	sand	0.021	0.045	0.072	0.095	–	0.112
10.0	carbon	0.036	0.150	0.163	0.174	–	0.184
	anthracite	0.014	0.099	0.126	0.142	–	0.148
	sand	0.020	0.054	0.086	0.103	–	0.105
15.0	carbon	0.098	0.158	–	–	–	–
	anthracite	0.052	0.115	–	–	–	–
	sand	0.025	0.080				

The calculated results are listed in tabs. 3 and 4. Analysis of the data included there enables the following generalizations to be made:

1. Increase of filtration rate brings about the decrease of the volume occupied by solid phase particles in the top layer (carbon) and the increase of the occupied volume in the lower layers (anthracite, sand).
2. Volume capacities of triple-media filters are inversely proportional to filtration rate.
3. The degree of utilizing the dynamic porosity of the filter bed decreases with the increasing filtration rate.

Table 4

Volume capacities of triple-media filter beds

Filtration rate v_f m/h	Volume capacity of filter bed m^3/m^3	Utilization of dynamic porosity %
5.0	0.196	51.0
10.0	0.186	48.1
15.0	0.164	41.7
5.0	0.173	50.6
10.0	0.164	47.0
15.0	0.114	33.5

The percentage of utilized bed porosity varies from one filter medium to another. Thus, the rise in filtration rate made the degree of utilization drop in the upper layers (carbon, anthracite) from 63.4% (at $v_f = 5$ m/h) to 49.2% (at $v_f = 15$ m/h) for carbon and from 47.5% to 37.9% for anthracite (at the same filtration rates). In the sand layer, the degree of utilization increased from 36.7% (at a filtration rate of 5 m/h) to 45.2% (at 10 m/h), and from there decreased to 39.3% (at 15 m/h).

The contribution of volume capacity to the dynamic porosity of the double-media filter amounted to 55.5% and 24.5% for carbon and sand, respectively. The highest values of the volume occupied by the suspended matter retained in the bed were measured in the upper zones of each media up to a depth of ~ 0.1 m.

The filtration cycle may be divided into periods of significant increment in the volume of solid-phase particles and periods of a slight increment or maintenance of the values achieved. Maximum increment per unit time was found to occur in the initial stage of the filtration cycle in the surface zone of each medium. Thus, the increment fell in the range 3.03×10^{-2}–11.1×10^{-2} m^3/m^{3}h for carbon, 0.367×10^{-2}–5.77×10^{-2} m^3/m^{3}h for anthracite, and 0.667×10^{-2}–3.75×10^{-2} m^3/m^{3}h for sand.

Periods of minimum increment, zero-increment and decrement in the volume of suspended matter retained in the upper zones occurred between 12 and 18 h of duration at filtration rates of 5 and 10 m/h. When filtration rate amounted to 15 m/h, volume increment was considerable even at the end of the filtration cycle. The lack of continuity in the increment of volume occupied by the solid phase may be an indication of a transport fluctuation of particles in the bed during filtration.

3.2. MASS CAPACITY OF FILTER BEDS

The efficiency of the filtration process and the duration of the filtration cycle depend on the bed capacity.

It is a well-known fact that suspended matter arising from precipitation shows limited structural strength and, consequently, insufficient compressibility of flocs. And that is why such parameters as volume capacity and floc density do not describe adequately the mass of solids retained in the filter bed. Taking these into account, we have also determined the mass capacity of the bed, which seems to be among the major technological parameters. *Mass capacity* is defined as the mass of solid phase retained in a unit volume of the bed in the course of the filtration cycle. Moreover, mass capacity is a function of many variables and may be written as

$$V_M = V_M\left(d_g,\ \varepsilon_0,\ v_f,\ t,\ c_s,\ \frac{\Delta P_s}{\Delta H},\ \varrho_{fl},\ \text{water composition}\right). \tag{3}$$

To determine the mass capacity of the filter bed, the mass balance was established in terms of influent and effluent suspended solids' concentration.

Analysis of the mass balance of river water and knowledge of water composition enabled the following equation to be derived [4]:

$$c_s = 0.234\,D_c + 0.254\,\Delta C + 1.982\,\Delta T. \tag{4}$$

Using equation (4), it was possible to determine the mass capacity of the filter bed even for such filtration cycles that involved no mass balance analyses.

It has been found that there exists a correlation between the values of the solids' mass retained throughout the filter bed and the measured values of hydraulic losses. The correlation takes the form [4]

$$\frac{\Delta P_s}{\Delta H}(t) - \frac{\Delta P_0}{\Delta H} = C\left(V_M(t)\right)^D. \tag{5}$$

For the coefficients C and D determined by virtue of eq. (5), the distributions of suspended solids mass at particular bed depths were established by making use of eq. (5) and the unit values of hydraulic losses occurring at these depths. The calculated data are given in tabs. 5 and 6, and in fig. 3.

Analysis of the results listed there leads to the following generalizations:

1. Mass capacity of double- and triple-media filters depends on filtration rate, grain size and water composition, and ranges between 2.06 and 17.2 kg/m^2.

Table 5

Mass capacity of the filter bed for the filtration of river water after coagulation

Filtration rate v_f m/h	Depth of filter medium m	Type of filter medium	Grain size		Mass capacity of filter medium kg/m²	Mass capacity of filter bed kg/m²
			$d_{10} \times 10^{-3}$ m	d_{60}/d_{10}		
5.0	0.3	carbon	1.1	1.6	0.7832	2.6877
	0.3	anthracite	1.3	1.5	0.4381	
	0.4	sand	0.7	1.5	1.4663	
10.0	0.3	carbon	1.1	1.6	0.7409	3.0958
	0.3	anthracite	1.3	1.5	0.4456	
	0.4	sand	0.7	1.5	1.9093	
15.0	0.3	carbon	1.1	1.6	1.2806	5.1008
	0.3	anthracite	1.3	1.5	0.5643	
	0.4	sand	0.7	1.5	3.2628	

2. The joint influence of grain size and filtration rate on mass capacity as well as the existing interrelations make it impossible to distinguish the contribution of each factor separately. At an appropriate choice of the grain size, the increase of filtration rate from 5.0 to 15 m/h brought about an increase in the mass capacity of the filter bed (tab. 5).

3. When the grain diameter in the sand layer (d_{10}) is larger than that recommended for the effluent from the coagulation process ($d_{10} = 0.75 \times 10^{-3}$m), increasing the filtration rate above 10 m/h accounts for a decrease in the mass capacity of the filter bed (tab. 6).

Table 6

Mass capacity of the filter bed for the filtration of reservoir water after coagulation

Filtration rate v_f m/h	Depth of filter medium m	Type of filter medium	Grain size		Mass capacity of filter medium kg/m²	Mass capacity of filter bed kg/m²
			$d_{10} \times 10^{-3}$ m	d_{60}/d_{10}		
5.0	0.3	carbon	1.0	2.6	0.6515	2.0601
	0.3	anthracite	1.08	1.56	0.7060	
	0.4	sand	0.80	1.5	0.7026	
10.0	0.3	carbon	1.0	2.6	1.1684	3.7771
	0.3	anthracite	1.08	1.56	1.0464	
	0.4	sand	0.80	1.5	1.5623	
15.0	0.3	carbon	1.0	2.6	0.6976	2.1350
	0.3	anthracite	1.08	1.56	0.5789	
	0.4	sand	0.80	1.5	0.8585	

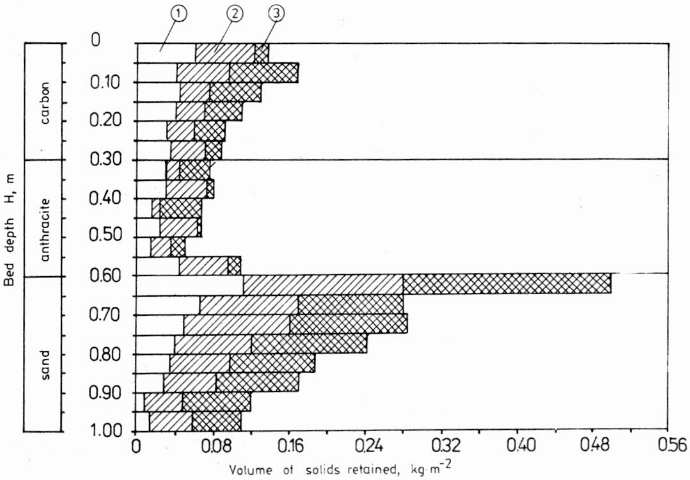

Fig. 3. Distribution of suspension mass as a function of bed depth and duration of filtration process ($v_f = 10$ m/h)

1 – $t \in \langle 0{,}3\,\mathrm{h}\rangle$, *2* – $t \in \langle 3\,\mathrm{h}, 9\,\mathrm{h}\rangle$, *3* – $t \in \langle 9\,\mathrm{h}, 16\,\mathrm{h}\rangle$

It was quite easy to evaluate the effect of water composition on the mass capacity of the filter bed because the spectrum of properties of the precipitated solid suspension was wide. On estimating this effect, two characteristic events were taken into account, i.e., 1) water of high turbidity with considerable content of suspended solids, 2) intensely coloured water as well as water without suspended solids.

Table 7

Effect of water composition on mass capacity and volume capacity

Composition of water	Mass capacity of filter bed kg/m^2	Volume capacity of filter bed m^3/m^3
Turbidity 15 g/m^3 Colour 20 g Pt/m^3 Suspended solids 15 g/m^3 $Al(OH)_3$ 7.03 g/m^3	3.0958	0.18606
Turbidity 20–50 g/m^3 Colour 30–40 g Pt/m^3 Suspended solids 20–100 g/m^3 $Al(OH)_3$ 2.04 g/m^3	17.1980	0.20945
Turbidity 2.7–3.2 g/m^3 Colour 30 g Pt/m^3 Suspended solids 0 $Al(OH)_3$ 2.9 g/m^3	3.7771	0.16433

During filtration of those water samples (after coagulation) it became obvious that the mass capacities differed significantly from one multi-media filter to another, even though the difference in volume capacity among them was much less pronounced. The data of interest are listed in tab. 7.

Filtration of water samples with high suspended solids content (event 1) accounted for very high mass capacities, which were several times as high as those achieved with water samples referred to as event 2. The difference in volume capacity between these events was either equal to, or lower than 21.5%.

3.3. COMPRESSIBILITY OF FLOCS

On estimating the floc compressibility for the pollutants retained in the filter beds, we used the classical definition of the compressibility index which takes the form [4]

$$\alpha_R = \alpha_{R_0}\left(\frac{\Delta P_s}{\Delta H}\right)^s. \tag{6}$$

On analyzing the problem of interest [4], as well as taking into account the hydraulic properties of the filter beds and considering the mechanism governing the filtration process, the following equation was derived:

$$\frac{\Delta P_s - \Delta P_0}{V_M \, \Delta H \, v_f \, \eta} = \alpha_{R_0}\left(\frac{\Delta P_s}{\Delta H}\right)^s. \tag{7}$$

Equation (7) enables evaluation of s and α_{R_0}. It defines the relation among the process parameters v_f, $\Delta P_0/\Delta H$, V_M, viscosity η, and the s and α_{R_0} values. The equation, furthermore, makes it possible to determine the s and α_{R_0} values not only for the whole of the filter bed, but for particular depths as well. The calculated results are given in tab. 8 and fig. 4. Analysis of these data leads to the following conclusions:

1. At the end of the filtration cycle, the values of the compressibility for the

Table 8

Compressibility factor and resistivity of flocs for the whole of the multi-media filter bed

Type of bed	Compressibility index s	Resistivity of flocs α_{R_0} m kg^{-1}
Carbon–anthracite–sand bed	from 0.421 to 0.663	from 2.82×10^6 to 4.73×10^7
Carbon–sand bed, the authors'own study	0.177	1.32×10^8
Carbon–anthracite–sand bed	from 0.468 to 0.785	from 6.89×10^5 to 3.77×10^7

multi-media filters under study amounted to $s \in \langle 0.177; 0.785 \rangle$, whereas those of solids resistivity fell in the range $\alpha_{R_0} \in \langle 6.89 \times 10^5; 1.32 \times 10^8 \rangle$ (tab. 8).

2. The values of s and α_{R_0} were influenced by filtration rate and by the composition of the suspension retained in the bed. As the rate of filtration increased, so did the compressibility index for the flocs. This took place as long as the suspension was retained in the bed. At higher filtration rates ($v_f = 15$ m/h), the floc compressibility value decreased and the flocs of the suspension were washed away from the bed.

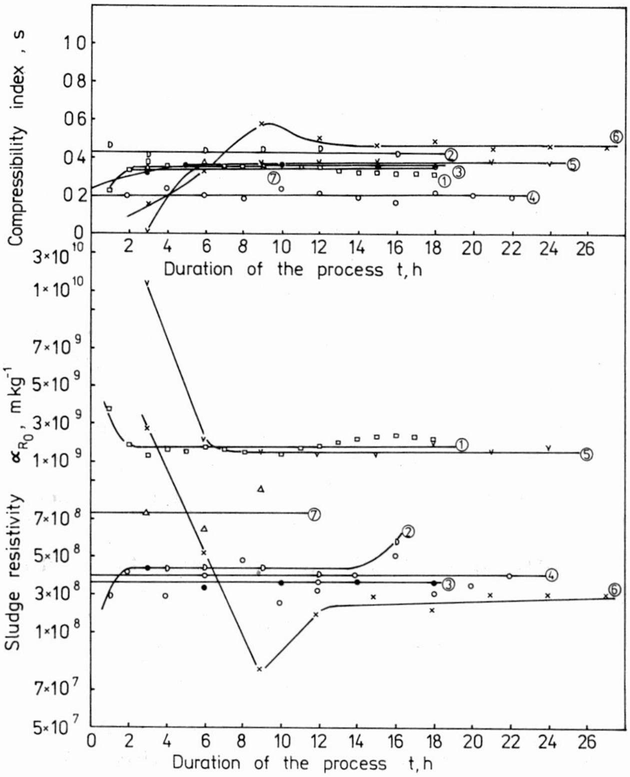

Fig. 4. Values of s and α_{R_0} versus length of the process

river water samples: *1* — $v_f = 5$ m/h, *2* — $v_f = 10$ m/h, *3* — $v_f = 15$ m/h, *4* — $v_f = 9.4$ m/h; storage-tank water samples: *5* — $v_f = 5$ m/h, *6* — $v_f = 10$ m/h, *7* — $v_f = 15$ m/h

3. Flocs generated by coagulation of water containing large amounts of suspended solids showed very low compressibility factors. When the flocs were produced by coagulation of intensely coloured water with no suspended solids, they displayed remarkably higher values of compressibility factor. This may be attributed

to the structure of the flocs built of $Al(OH)_3$ and suspended solids, which is more rigid than the structure of flocs built of $Al(OH)_3$ and coloured matter.

4. Both s and α_{R_0} were only slightly influenced by the duration of the filtration process.

5. The highest values of the floc compressibility factor ranged from 0.144 to 1.00 and occurred in the sand medium. The lowest values varied from 0.126 to 0.602 and were measured in the carbon medium.

6. The higher was the compressibility factor of the flocs retained in the bed, the higher was the mass capacity of the bed. Flocs displaying a high compressibility factor are subject to compression with the increasing pressure drop. Their volume becomes decreased, thus facilitating transport and washout.

4. CONCLUDING COMMENTS

Volume capacity and mass capacity are amongst the basic parameters of the filter bed. While volume capacity indicates the degree to which the porosity of the filter bed is utilized, mass capacity varies with each change of conditions, depending on the composition of the water under treatment.

For double- or triple-media filters volume capacity amounted to (0.3–0.5) ε_0, whereas mass capacity took the value $V_M \in \langle 2.06;\ 17.2\ \mathrm{kg \cdot m^{-2}} \rangle$. But a full and exhaustive analysis of associated phenomena requires knowledge of the mass balance. Thus, when alum coagulation was involved, the compressibility of flocs in the filter beds was defined by the compressibility index which took the value $s \in \langle 0.12;\ 1.0 \rangle$. The compressibility of flocs retained in the bed depended on the composition of the water to be treated, on the grain size of the filter media, and on the filtration rate. A correlation was also found to exist between mass capacity and compressibility factor.

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PARAMETRY PROCESU FILTRACJI NA WIELOWARSTWOWYCH ZŁOŻACH FILTRACYJNYCH

Analiza zjawisk obejmuje parametry geometryczne, hydrauliczne i technologiczne procesu filtracji pospiesznej. Badania dotyczą złóż dwu- i trójwarstwowych. Wyznaczono strefy złoża o największej pojemności. Opracowano sposób wyznaczania wartości współczynnika ściśliwości kłaczków zawiesiny zatrzymanych w złożu filtracyjnym. Stwierdzono istnienie korelacji między pojemnością masową złoża a ściśliwością kłaczków.

ПАРАМЕТРЫ ПРОЦЕССА ФИЛЬТРАЦИИ НА МНОГОСЛОЕВЫХ ФИЛЬТРАЦИОННЫХ ОТЛОЖЕНИЯХ

Анализ явлений охватывает геометрические, гидравлические и технологические параметры процесса ускоренной фильтрации. Исследования касаются двух- и трёхслоевых отложений. Определили зоны отложения с наибольшей ёмкостью. Разработан способ определения значений коэффициента сжимаемости клочков взвеси в фильтрационном отложении. Обнаружили присутствие корреляции между массовой ёмкостью отложения и сжимаемостью клочков.