Separation and Purification Technology 65 (2009) 147–155

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

New granular materials for dual-media filtration of seawater: Pilot testing

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ARTICLE INFO

Article history:
Received 21 May 2008
Received in revised form 13 October 2008
Accepted 17 October 2008

Keywords:
Seawater pre-treatment
Dual-media filtration
Membrane desalination
Particle surface roughness

ABSTRACT

The scope of this study was to test new granular materials for dual-media bed filtration of seawater and to assess the quality of the filtrate with regard to criteria for feeding reverse osmosis desalination installations. Two different filter columns, one with the new materials (expanded clay), i.e. Filtralite NC 1.5–2.5 mm on top of Filtralite HC 0.8–1.6 mm (called *Filtralite MonoMulti* filter), and another with anthracite coal 1.2–2.5 mm on top of a sand layer 0.8–1.25 mm (called *sand/anthracite* filter), were tested in parallel operation under various conditions in the summer of 2007. Both filters exhibited similar performance, removing particulates from feed water and producing filtrates of acceptable quality for feeding RO systems (SDI_{15}, 15-min Silt Density Index, values lower than 5). The relatively high temperatures prevailing during the summer apparently favoured the formation of larger aggregates and their subsequent effective capture within the filter media. Regarding the hydrostatic head development, it was observed that the Filtralite MonoMulti column had slower head build up than the sand/anthracite column for the same duration of filtration, especially at the higher filtration velocities (10 and 15 m/h). For the lower filtration velocity tested (5 m/h) both filters demonstrated almost the same rate of head build up. Regarding the duration of filtration cycles, Filtralite MonoMulti exhibited either the same (in the cases of filtration velocities 5 and 10 m/h) or longer duration (at the highest filtration velocity tested of 15 m/h) compared to the conventional sand/anthracite filter.

A comparative assessment of data from dual-media filters tested in this as well as in previous campaigns with similar materials shows that the combination involving Filtralite NC 1.5–2.5 mm on top of Filtralite HC 0.8–1.6 mm exhibits, overall, the best performance. The latter is attributed to the rough surface texture of Filtralite grains, which are characterized by extensive crevices, with an increased capacity of retaining micro-particles and aggregates.

1. Introduction

The removal of particulate matter using granular media filters plays a critical role in seawater pre-treatment for feeding many membrane desalination installations. In general, granular media filters are a relatively inexpensive separation process for achieving a desired water quality level with respect to particulate parameters [1]. Typical particulates in seawater include clay and silt particles, microorganisms (bacteria, viruses, protozoan cysts), colloidal and precipitated humic substances as well as other natural organic matter from the decay of vegetation [2]. The common types of media used in granular bed filters are silica sand, anthracite coal and garnet or ilmenite. These may be used alone or in dual- or triple-media combinations [2]. Furthermore, granular filters can be made of a variety of natural materials. Depending on the origin of these materials they can have very different shapes, sizes and compositions. In this study, the performance is examined of new granular media obtained from a processed clay material.

Granular filter media must satisfy various specifications before they can be considered for applications. These include grain size, grain surface condition, density, particle porosity, solubility, durability, settling rate [2–4]. The void fraction of the granular bed formed by the grains is also important. The shape of the grains used in filtration media mainly depends on the origin of the material. Grains collected from river beds are usually rounded and smooth. Grains resulting from the crushing of larger pieces are jagged and angular. Although inadequately studied so far, improved performance of crushed particles over rounded grains has been demonstrated for water filtration [4–6]. For instance, the shape of the grains affects the bulk porosity of the bed, which is strongly related to the increase in head loss that results from deposits in the filter. However, systematic studies on the effect of *grain shape* on filtration are rather limited. Recently, Barton and Buchberger [5] presented such a study, dealing with one of the main capture

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doi:10.1016/j.seppur.2008.10.041

mechanisms, i.e. that of physical straining of particles and the positive effect angular grains have on filtration performance, as compared to rounded media (e.g. river sand). Regarding grain *surface roughness* effects, although intuition and recent evidence [7] suggest that they should play a significant role in filtration, there is meager information in the literature, especially for applications of the type treated here.

Regarding applications of filter media in desalination plants, it is noted that the extent and complexity of the pre-treatment systems for combating colloidal and organic fouling varies depending on site-specific conditions. A critical factor in designing pre-treatment is the possible use of an intake well, in particular a beach-well. If such an intake well exists, it is essentially part of the pre-treatment process because of the capacity of the sand (usually present at the seabed) to act effectively as a first filter medium for the suspended solids in the seawater [8]. Then, a simple form of pre-treatment by granular filter media, even without addition of coagulants, may be adequate [9]. In case of open seawater intake, reverse osmosis membranes should be protected against a variety of foulants, necessitating an extensive pre-treatment process. For example, the use of coagulants and sedimentation or flotation equipment may be necessary, followed by media filtration. Alternatively, granular media filtration can be replaced by membrane treatment such as ultrafiltration or microfiltration, e.g. [10].

The general objective of the present study is to assess and compare the efficiency of the new Filtralite (MonoMulti) dual-media filters with a more typical dual-media filter consisting of anthracite coal on top of a sand layer. Media with the trade name "Filtralite" are processed (expanded) clay products with high porosity and quite rough grain surfaces. Specifically, the main goal is to assess a new Filtralite MonoMulti filter, consisting of Filtralite NC 1.5–2.5 mm on top of Filtralite HC 0.8–1.6 mm, in comparison to a dual-media filter consisting of anthracite coal 1.4–2.5 mm on top of a sand layer 0.8–1.2 mm, for the pre-treatment of seawater to achieve a water quality that meets the criteria for feeding reverse osmosis desalination plants. A key criterion for this assessment is the 15-min Silt Density Index (SDI) value of the filtrate, used as feed water to RO desalination plants. To perform a reliable comparison of the two different media filters, two pilot filter columns operated in parallel with the same feed water and under the same conditions. The pilot system was constructed in a previous phase of this study [11] within the facilities of TATE&LYLE, in Thessaloniki, Greece. Seawater, obtained through an open intake, was used in this study.

2. Materials and methods

2.1. Feed water

The feed to the pilot unit was seawater employed in the industrial plant to cover cooling needs. The seawater is obtained from an open intake in the Thermaikos Gulf in the vicinity of the plant. A slip-stream from the main supply line serving the plant was used to cover the needs of the study. A physicochemical analysis of the raw seawater is presented in Table 1.

It may be observed that TDS are close to 38,000 mg/L. It is also important to note that preliminary quality measurements indicated turbidity close to 1–2 NTU, although seasonal or more frequent fluctuations would naturally exist, as will be also discussed subsequently. Moreover, a very high SDI of the raw seawater was measured. Essentially complete plugging of the microfilters of the SDI test was taking place after the first 3 min of testing. Given that the seawater supply is through an open intake, this is not completely surprising as discussed in Section 1. Finally, ultraviolet absorption at 254 nm and dissolved organic carbon (DOC) measurements with feed water samples showed that specific ultraviolet light absorbance (SUVA), which is defined as the ratio of the UV absorbance to the DOC concentration, was less than 3 L/mg C m^{-1} for all samples during the entire experimental period. Thus, it appears that the feed water is characterized by a low humic acid fraction (generally low-DOC water) and hence relatively low removal of DOC may be expected (20–50%) [2].

2.2. Filter materials

The granular bed filtration applied in this study was based on dual media. Either *Filtralite MonoMulti* (consisting of Filtralite NC 1.5–2.5 mm on top of Filtralite HC 0.8–1.6 mm), or anthracite coal, on top of sand layer, were used as filter media in two columns operating in parallel. In both beds the depth of the bottom layer (Filtralite HC or sand) was 50 cm, while the top 70 cm layer was Filtralite NC 1.5–2.5 mm in the first column and anthracite coal in the second column. The Filtralite NC particles, in the dry form, tend to float when first immersed in water, due to air trapped in the pores, but later sink as they become wetted and air is removed. For this reason, before filling the filter column, these particles are kept in water for 2 weeks. Additionally, to inhibit the possible biological growth, a disinfectant (sodium metabisulfite) is used during this 2-week soaking period. Filtralite materials are commercially avail-

Table 1
Raw seawater physicochemical analysis.

Parameter		Cations, mg/L	
pH	8.1	Na^+	12.8×10^3
Conductivity, μS/cm	49×10^3	K^+	533
TDS[a], mg/L	38×10^3	Ca^{2+}	487
Total hardness, °F	615.8	Mg^{2+}	1.2×10^3
Carbonate hardness, °F	15.3		
Non-carbonate hardness, °F	600.5		
Alkalinity, M, mg/L $CaCO_3$	152.5		
SDI_{2min}[b]	~38		
Trace elements, mg/L		**Anions, mg/L**	
B	4.8	Cl^-	21.2×10^3
Cu	0.4	HCO_3^-	186
Fe	1.3	SO_4^{2-}	30×10^2
Mn	0.5	NO_3^-	2.87
Zn	0.2	NO_2^-	<0.01
		PO_4^{3-}	<0.46

[a] Total dissolved solids.
[b] 2-min Silt Density Index.

Table 2
Characteristics of filter media [12].

Parameter	Sand	Anthracite	Filtralite	Filtralite NC
Particle size range, mm	0.8–1.25	1.2–2.5	0.8–1.6	1.5–2.5
Bulk density, kg/m^3	1550	730	700 ± 75	235 ± 75
Particle density, kg/m^3	2650	1400	1650 ± 150	720 ± 150
Effective size (d10), mm	0.9	1.55	0.9	1.7 ± 0.3
Coefficient of uniformity	<1.5	1.3	<1.5	<1.5
Particle porosity, %	–	–	40	73
Filter bed void fraction, %	43	48	62	67

able products. The characteristics of different filter materials are summarized in Table 2.

2.3. Coagulants

During the testing period a polyaluminum chloride coagulant was used with the trade name PACA16 and specifications included in Table 3. The optimal dosage of the coagulant (1.8 mg Al/L) employed in this work was established during a previous phase of this study [11].

Table 3
Technical specifications of polyaluminum chloride (PACA16) coagulant.

Analysis	Specification limits	Actual value
Al_2O_3%	15 ± 0.6%	15.1
pH (50%)	1.5–2.5	1.7
Basicity	–	30%
Density	1.330–1.380 g/cm^3, 20 °C	1.351 g/cm^3

2.4. Pilot unit

In Fig. 1 a schematic diagram of the pilot unit is shown, designed to meet the objectives of the study.

The feed water was pumped to a 30-L coagulant mixing vessel, sized to obtain a retention time of 3–5 min. Then the coagulated seawater flowed by gravity to the two filters operating in parallel. Two 3.2-m long pipes made of PVC with a diameter of 0.1 m were employed as filter columns. The total depth of filter media was 1.2 m while the available space above the beds allowed the build-up of the necessary head for constant flow rate, regardless of filter plugging. The pilot unit is described in more detail elsewhere [11].

Filtration velocities of 5, 10 and 15 m/h, within the filters during normal operation were investigated. After a period of operation, referred to as a filter cycle, the filters become clogged by the retained particulates and require cleaning. The latter is performed by backwashing, using an upward high flow rate of seawater (60 m/h), resulting in a bed expansion of about 10–15%. Data on

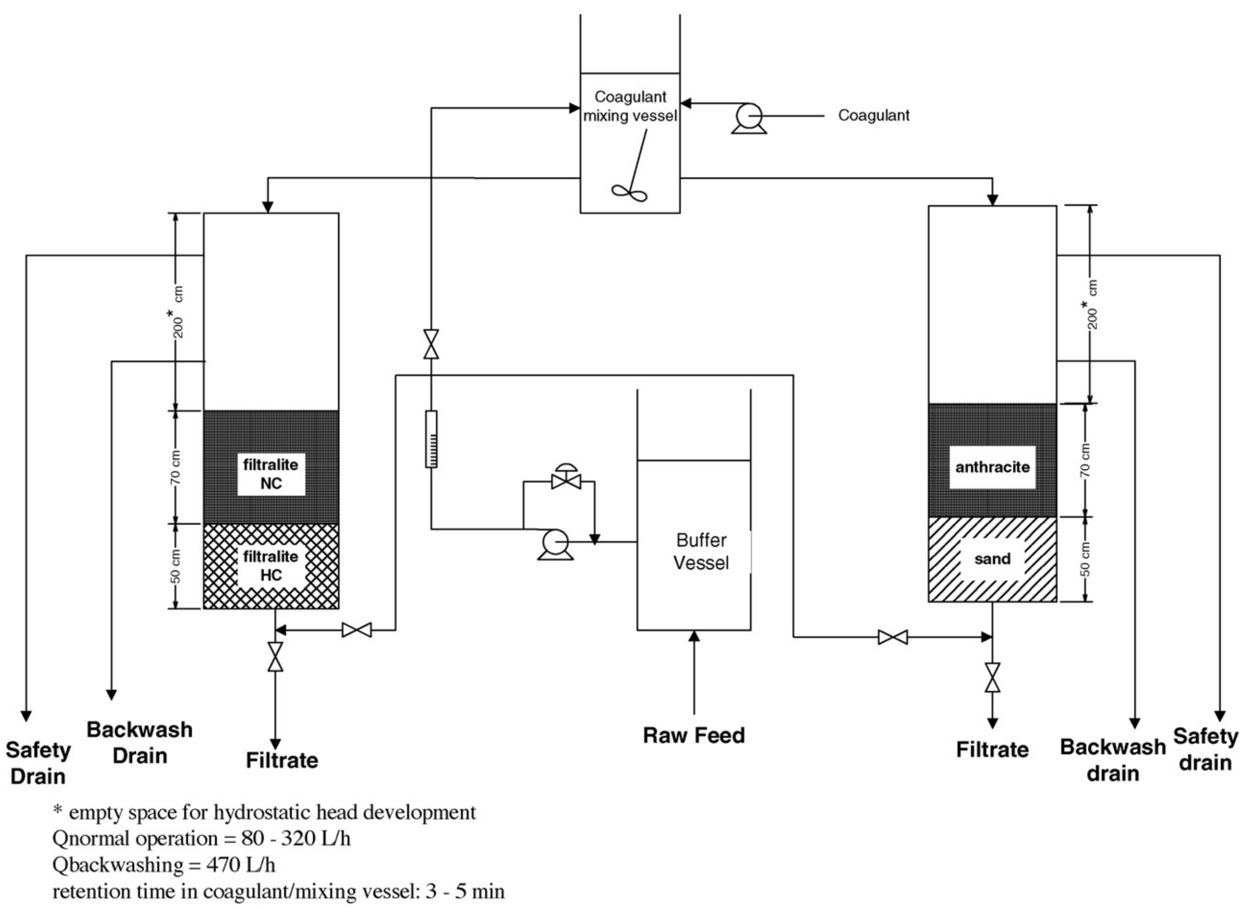

Fig. 1. Schematic diagram of pilot unit.

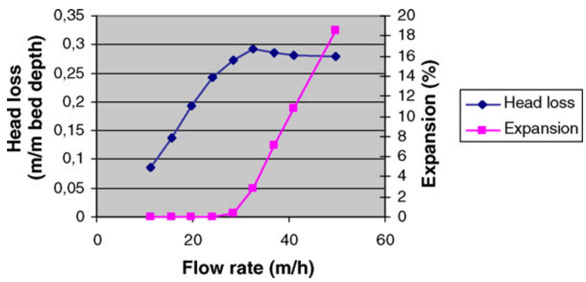

Fig. 2. Backwash head loss and expansion for Filtralite MonoMulti at 14 °C.

the performance of the Filtralite material regarding expansion during backwashing, obtained by maxit Group AB, Norway [12], are available. In Fig. 2 typical backwash head loss and expansion curves for filtralite MonoMulti dual media are presented. Data on expansion of each component of the dual filtered media (not presented here due to space limitations), compared to the data of Fig. 2, show that the onset of dual-media expansion is determined by the properties of the heavier component and the incipient dual bed fluidization velocity is near that of the heavier material (Filtralite HC 0.8–1.6 mm).

2.5. Laboratory and on site measurements

Three water samples were collected on a daily basis. One sample was collected from the buffer vessel and the other two from the filtrates of the Filtralite MonoMulti and sand/anthracite columns in order to compare the quality of raw untreated water with that of filtered water. The temperature and turbidity of the three samples were measured on site with a thermocouple (OMEGA, Model HH23) and a turbidimeter (HF Scientific Inc., DRT-15CE), respectively. Measurement of SDI was also performed on site, according to ASTM standard test method D 4189-87 using Millipore membrane filters, 47 mm in diameter, gridded, with a mean pore size in the range of $0.45 \pm 0.02\,\mu$m. To perform these measurements, filtrate was collected from each column in 30-L vessels and fed to the SDI filtration apparatus through a pump at controlled 30 psig pressure.

Other parameters measured on a daily basis in the laboratory were pH (Metrohm, 744), conductivity (Metrohm, 712), UV absorption at 254 nm with Shimadzu UV-visible spectrophotometer UV-1700 (for the determination of aromatic organic compounds [2,13,14]) and total organic carbon (TOC) with Shimadzu TOC-5000A analyzer. Additional measurements, including concentration of total suspended solids (TSS) [15], were made on selected samples.

3. Results and discussion

3.1. Pilot tests: operating conditions and data

The pilot unit operated for a total time period of 4 weeks, from 16th of July to 10th of August 2007. The operation was continuous throughout the week and was interrupted during the weekends.

The temperature of the feed water during the experimental period was on the average close to 27 °C, fluctuating from 24.8 to 31.4 °C. The feed water turbidity varied between 1.0 and 4.5 NTU, but for most of the time it was around 1.5 NTU. Filtration velocity was the parameter investigated regarding its effect on the quality of filtrate.

Reference pilot tests were performed first, *without coagulant addition*. Three filtration velocities, 5, 10 and 15 m/h, were tested. In all cases, there was a noticeable turbidity removal (from 1.4 NTU of feed water down to 0.4 NTU for filtrates from both filter columns) but SDI values in both filtrates were extremely high, i.e. the product water quality was not satisfactory with respect to RO feed water criteria. UV absorption at 254 nm, which is a measure of existing aromatic organic compounds in the samples, or those having conjugated double bonds, showed a small improvement between feed water and both filtrates. Furthermore, TOC reduction was determined in filtrates from Filtralite MonoMulti (varying from 13 to 18%) and from the conventional sand/anthracite filter (varying from 4 to 22%). Finally, no hydrostatic head build-up was measured in both columns for the duration of filtration cycle (up to 24 h). These reference tests without coagulant addition clearly suggest that an effective coagulant is absolutely necessary if good filtrate quality is to be consistently produced.

Table 4 summarizes the pilot data from filter operation with PAC coagulant addition to seawater under various flow velocities tested. When operating at the lowest *filtration velocity of* 5 m/h, *with 1.8 mg Al/L coagulant dosage*, the feed water temperature ranged from 25 to 27.7 °C. It is noted first that turbidity measurements showed that, after 20 min from the beginning of operation, filtrate turbidity was reduced down to 0.1 NTU and this low turbidity value remained constant even after 45 h of continuous filtration through both filters. Filtration through the Filtralite MonoMulti column produced water with measurable 15-min SDI values, in the range of 2.9–3.5, whereas the 15-min SDI values for sand/anthracite column were in the range of 2.6–4.2. It must be pointed out that a longer filtration cycle was observed at this low filtration velocity, without a need for backwashing. Indeed, both filtrates appeared to be of acceptable quality for feeding RO systems, regarding 15-min SDI values, even after 45 h of continuous filter operation. TOC removal as a result of the filtration through Filtralite MonoMulti column was in the range of 41–57.5% while TOC removal observed for filtration through the sand/anthracite column varied from 6 to 64%. Furthermore, dissolved natural organic matter (DNOM) removal, estimated by absorbance measurements at 254 nm for feed water and filtrates, was in the same range of 36–47% for both filtrates. Finally, regarding the head build-up, it was observed that both columns showed a relatively slow head development; i.e. for Filtralite MonoMulti column it was estimated to be 0.33 MWC/d (meters water column/day), which is slightly lower than that estimated for sand/anthracite column (on average 0.39 MWC/d).

For operation at higher *flow velocity* (10 m/h), it is noted that during the first 30 min of filtration through both filters, filtrate turbidity decreased down to 0.2 NTU (which implies a short "ripening" time for both filters) and remained constant for 24 h of filtration. The short ripening time is further reflected in the SDI_{15} measurements. Thus, filtrates, either from Filtralite MonoMulti bed or sand/anthracite bed, which were collected only after 50 min from the beginning of filtration, had SDI_{15} values of 4.3 and 4.0, respectively. The following days, filtrates from both columns were collected after filtration times 1300–1390 min from the start of filtration cycle and SDI_{15} values were as low as 2.8 for Filtralite MonoMulti or 3.2 for sand/anthracite. No particle breakthrough was observed during the 24-h filtration cycle, something that was also observed during previous campaigns performed during a summer period [11]. As already mentioned, this fact could be attributed to the good performance of the coagulant as a result of the relatively high prevailing temperatures in this campaign. Most likely, much larger and better adhering flocs could be formed, thus facilitating their effective capture within the filter media. This is expected since the rate of floc formation and the efficiency of primary particle removal are found to increase as the temperature increases [2,16]. TOC removal achieved by the Filtralite MonoMulti column was in the range of 0–46% and 0–37% by the sand/anthracite column. Furthermore, DNOM removal, estimated by absorbance measurements

Table 4
Measured parameters for both columns at 5, 10 and 15 m/h flow velocity and 1.8 mg Al/L coagulant.

Date	Parameter											
	Turbidity, NTU			SDI_{15}			TOC, mg C/L			Head build-up, MWC/d		
	F.W.	M/M	S/A	F.W.	M/M	S/A	F.W.	M/M	S/A	F.W.	M/M	S/A
U = 5 m/h and 1.8 mg Al/L												
31/07/07	1.7	0.1	0.1	–	3.2	4.2	3.3	1.7	1.2	–	0.41	0.53
01/08/07	1.7	0.1	0.1	–	2.9	3.0	3.4	1.6	3.2	–	0.40	0.47
02/08/07	2.0	0.1	0.1	–	3.2	2.6	4.0	1.7	2.3	–	0.27	0.29
03/08/07	1.3	0.1	0.1	–	3.5	3.3	2.7	1.6	1.6	–	0.22	0.27
U = 10 m/h and 1.8 mg Al/L												
24/07/07	0.7	0.1	0.1	–	3.7	4.1	2.4	2.4	2.4	–	0.64	1.42
25/07/07	0.7	0.1	0.1	–	4.3	4.0	2.5	1.8	2.1	–	–	–
26/07/07	1.8	0.1	0.1	–	2.9	3.2	2.4	1.3	1.5	–	0.87	1.28
27/07/07	0.9	0.1	0.1	–	2.8	3.3	1.9	1.2	1.2	–	0.86	1.23
U = 15 m/h and 1.8 mg Al/L												
07/08/07	3.3	0.1	0.2	–	3.7	–	2.1	1.4	1.5	–	2.06	3.00
08/08/07	4.6	0.1	0.3	–	3.8	NM[a]	2.8	1.4	1.6	–	–	–
09/08/07	3.8	0.1	0.1	–	4.6	2.9	2.2	1.5	1.4	–	2.46	3.42
10/08/07	2.5	0.1	0.1	–	4.7	3.5	2.7	1.5	1.7	–	2.96	3.13

F.W.: feed water; M/M: filtrate from MonoMulti column; S/A: filtrate from sand/anthracite column; MWC/d: meters water column/day.
[a] NM: not measurable.

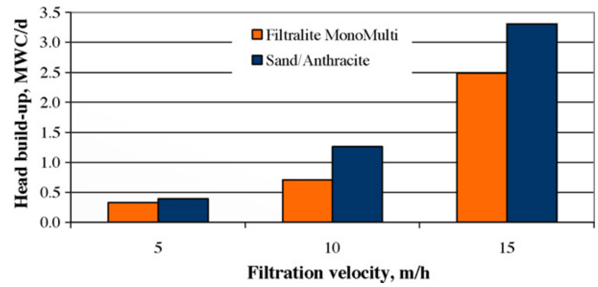

Fig. 3. Head build-up development in two dual-media columns as a function of filtration velocity.

at 254 nm for feed water and filtrates, was in the range of 23–47% and 15–41%, for the Filtralite MonoMulti and the sand/anthracite column, respectively. Finally, regarding the head build-up development during the filter cycle when both filters operated at 10 m/h filtration velocity with coagulant dosage of 1.8 mg Al/L, the Filtralite MonoMulti column was on average 0.79 MWC/d whereas the sand/anthracite column exhibited a greater head build up (on average 1.3 MWC/d).

The ripening time for both filters was quite short (∼30 min) even for tests performed at the highest *flow velocity of* 15 m/h. The high filtration rate (15 m/h) led to shorter filtration cycles which may be explained as follows. First, operating at this high filtration velocity resulted in the plugging of the filters in a relatively shorter time period. Furthermore, particle breakthrough was observed during filtration of feed water from sand/anthracite column after 17 h of continuous operation. These two factors necessitated backwashing both filters twice a day and collecting samples for SDI measurements at shorter time intervals. It should be pointed out that the Filtralite MonoMulti column could operate efficiently, regarding the RO quality criteria, at this high filtration velocity even after 20 h of continuous filtration producing filtrate with SDI_{15} value below the acceptable limit of 5. On the other hand, the sand/anthracite column could not be operated for so long because particle breakthrough was observed, degrading filtrate quality for feeding RO systems, as evidenced from SDI_{15} values reported in Table 4 (days 07/08 and 08/08 when the samples were collected after 20 and 17 h of continuous operation, respectively). When the samples for SDI measurements were collected after 1 or 3 h from the beginning of filtration, both filtrates appeared to be of acceptable quality for RO systems, based on measured SDI_{15}. Regarding TOC, filtration through Filtralite MonoMulti column caused TOC removal in the range 32–50% and filtration through the sand/anthracite column from 29 to 43%. DNOM removal from filtration through both filters was in the same range of 30–45%. Finally, head build up development during filtration through Filtralite MonoMulti column was estimated to be on average 2.49 MWC/d while during filtration through sand/anthracite column it was higher (on average 3.18 MWC/d).

In Fig. 3, the head build-up development is presented as a function of filtration velocity. It is evident that at the lower filtration velocity examined, both filters exhibit similar head build up. However, for the higher filtration velocities tested, the rate of head build up in sand/anthracite filter is greater than the rate in Filtralite MonoMulti filter.

3.2. Overall assessment of experimental results

In this section, a brief overall assessment is made of the performance of all filter media tested in this study, by employing the same pilot unit. Tables 5–7 summarize experimental data obtained

Table 5
Comparison in performance of dual filter media tested during all experimental campaigns (U = 5 m/h).

Name	Filter media (Top)	Bottom layer	Campaign	Tempera-ture, ^{0}C	Particle porosity of filter media	SDI_{15}	TOC removal, %	DNOM removal, %	Head build up, MWC/d
U = 5 m/h with 1.8 mg Al/L									
S/A	Anthracite 1.2-2.5 mm	Sand 0.8-1.2 mm	Winter 2006	10	NDA*	3.4 - 5.6	-	-	0.4
S/F	Filtralite MC 1.5-2.5mm	Sand 0.8-1.2 mm	Winter 2006	10	MC 1.5-2.5: **52%**	3.4 - 4.8	-	-	0.3
S/A	Anthracite 1.2-2.5 mm	Sand 0.8-1.2 mm	Summer 2006	27	NDA*	3.3 - 5.0	11 - 46	12.5 - 20	1.0
S/F	Filtralite MC 1.5-2.5mm	Sand 0.8-1.2 mm	Summer 2006	27	MC 1.5-2.5: **52%**	3.5 - 5.7	15 - 40	12.5 - 15	0.8
Filtralite MonoMulti	Filtralite NC 1.5-2.5mm	Filtralite HC 0.8-1.6 mm	Summer 2007	27	NC 1.5-2.5: **73%**	2.9 - 3.5	41 - 57.5	36 - 47	0.3
S/A	Anthracite 1.2-2.5 mm	Sand 0.8-1.2 mm	Summer 2007	27	NDA*	2.6 - 4.2	6 - 64	36 - 47	0.4
S	Sand 0.4-0.8 mm	Sand 0.4-0.8 mm	Autumn 2006	20	NDA*	1.8 - 2.5	8 - 29	24 - 69	3.2
S/F	Filtralite MC 0.8-1.6 mm	Sand 0.4-0.8 mm	Autumn 2006	20	MC 0.8-1.6: **48%**	1.9 - 2.7	8 - 33	19 - 77	0.5

* NDA : No Data Available

in this phase of the work as well as in previous campaigns, which are presented elsewhere [11].

It will be pointed out first that, before data evaluation, one should take into consideration the seasonal temperature variation in this region of Mediterranean Sea, resulting in a variable quality of raw feed water (e.g. in terms of turbidity, algal content). The effect of temperature on filter performance was already discussed and it was concluded that during the summer and autumn campaigns, when the seawater had higher temperature, the quality of filtrates was better (judged by the measured turbidities and SDI_{15}) than that of filtrates obtained during the winter campaign. It was suggested that the relatively high feed water temperatures apparently favour the formation of large and relatively strong aggregates, after coagulant addition, resulting in their effective capture in the filter media. This observation is also supported by the fact that during the winter campaign smaller head loss was measured (compared to summer) when applying dual-media filtration in raw seawater, at the various filtration velocities tested.

By inspecting the data in Tables 5–7, one can make a comparative assessment of the performance of three dual-media filters; i.e., *Filtralite MonoMulti*, consisting of Filtralite NC 1.5–2.5 mm on top of Filtralite HC 0.8–1.6 mm, *Filtralite/sand*, consisting of Filtralite MC 1.5–2.5 mm on top of a sand layer (0.8–1.2 mm) and the conventional dual media *anthracite/sand* of the same grain sizes as Filtralite/sand. It will be noted that these dual media have the same grain size in their top layers; additionally, their bottom layers have practically the same size, with Filtralite HC having slightly larger maximum size. However, there is a significant difference in the type of material (alumino-silicates versus anthracite at the top, and alumino-silicates versus silica sand at the bottom) and, perhaps more important, in the macro-porosity and *surface texture* of these particulate materials. Scanning electron microscopy pictures of the new materials used in Filtralite MonoMulti filter are included in Fig. 4(a) and (b), which clearly show the differences in the surface texture of various particles. Regarding the top layers, the particle surface texture is evidently related to the porosity of the original material, with the most porous NC 1.5–2.5 mm particles (Fig. 4(b)) characterized by a very rough surface with a lot of crevices; at the other extreme, the least porous anthracite particles exhibit smooth surfaces (Fig. 5(b)). Similarly, for the bottom layer, the non-porous quartz sand particles (Fig. 5(a)) are quite smooth compared to the porous Filtralite HC 0.8–1.6 mm grains (Fig. 4(a)). It is also appar-

Table 6
Comparison in performance of dual filter media tested during all experimental campaigns (U = 10 m/h).

Name	Filter media (Top)	Bottom layer	Campaign	Temperature, °C	Particle porosity of filter media	SDI_{15}	TOC removal, %	DNOM removal, %	Head build up, MWC/d
U = 10 m/h with 1.8 mg Al/L									
S/A	Anthracite 1.2-2.5 mm	Sand 0.8-1.2 mm	Winter 2006	10	NDA*	4.4 - 5.0	-	-	0.6
S/F	Filtralite MC 1.5-2.5mm	Sand 0.8-1.2 mm	Winter 2006	10	MC 1.5-2.5: **52%**	4.4 - 5.9	-	-	0.5
S/A	Anthracite 1.2-2.5 mm	Sand 0.8-1.2 mm	Summer 2006	27	NDA*	3.3 - 5.5	19 - 46	12 - 29	1.9
S/F	Filtralite MC 1.5-2.5mm	Sand 0.8-1.2 mm	Summer 2006	27	MC 1.5-2.5: **52%**	3.1 - 5.4	8 - 36	8 - 29	1.6
Filtralite MonoMulti	Filtralite NC 1.5-2.5mm	Filtralite HC 0.8-1.6 mm	Summer 2007	27	NC 1.5-2.5: **73%**	2.8 - 4.3	0 - 46	23 - 47	0.8
S/A	Anthracite 1.2-2.5 mm	Sand 0.8-1.2 mm	Summer 2007	27	NDA*	3.2 - 4.1	0 - 37	15 - 41	1.3
S	Sand 0.4-0.8 mm	Sand 0.4-0.8 mm	Autumn 2006	20	NDA*	2.5 - 4.7	5 - 41	30 - 50	7.6
S/F	Filtralite MC 0.8-1.6 mm	Sand 0.4-0.8 mm	Autumn 2006	20	MC 0.8-1.6: **48%**	2.1 - 3.7	5 - 26	30 - 50	1.3

* NDA : No Data Available

ent that the natural sand particles have suffered surface erosion that has resulted in their smooth rounded shape, as opposed to the more irregular Filtralite HC grains obtained by breakage of larger particles.

By comparing *summer 2006* data for *anthracite/sand* and *Filtralite-MC/sand*, listed in Tables 5–7, it is concluded that, regarding SDI values and TOC/DNOM removal, the performance is generally similar for all three velocities tested. However, the Filtralite-MC/sand filter exhibits systematically smaller rate of head build-up. Similarly, for the summer 2007 campaign, *anthracite/sand* and *Filtralite-NC/Filtralite-HC* filters exhibit generally similar performance regarding SDI values and TOC/DNOM removal. However,

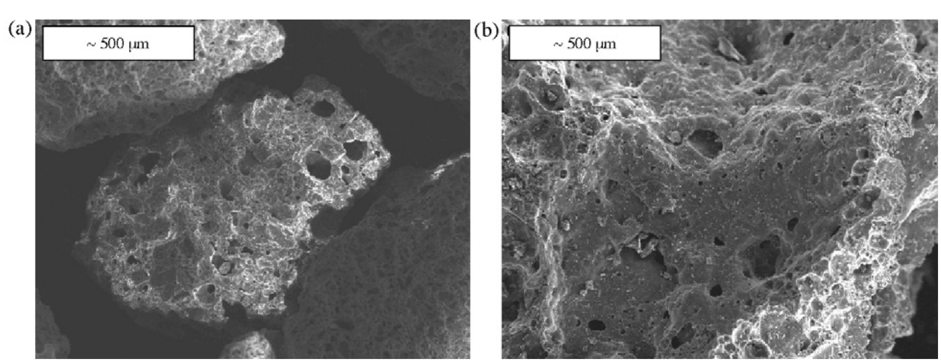

Fig. 4. SEM images of (a) Filtralite HC 0.8–1.6 mm and (b) Filtralite NC 1.5–2.5 mm with magnification 80×.

Table 7
Comparison in performance of dual filter media tested during all experimental campaigns (U = 15 m/h).

Name	Filter media (Top)	Bottom layer	Campaign	Temperature, ^{0}C	Particle Porosity of filter media	SDI_{15}	TOC removal, %	DNOM removal, %	Head build up, MWC/d
U = 15 m/h with 1.8 mg Al/L									
S/A	Anthracite 1.2-2.5 mm	Sand 0.8-1.2 mm	Winter 2006	10	NDA*	-	-	-	-
S/F	Filtralite MC 1.5-2.5mm	Sand 0.8-1.2 mm	Winter 2006	10	MC 1.5-2.5: **52%**	-	-	-	-
S/A	Anthracite 1.2-2.5 mm	Sand 0.8-1.2 mm	Summer 2006	27	NDA*	3.3 - 5.6	12 - 31	13 - 22	4.0
S/F	Filtralite MC 1.5-2.5mm	Sand 0.8-1.2 mm	Summer 2006	27	MC 1.5-2.5: **52%**	3.6 - 6	16 - 37	9 - 20	3.6
Filtralite MonoMulti	Filtralite NC 1.5-2.5mm	Filtralite HC 0.8-1.6 mm	Summer 2007	27	NC 1.5-2.5: **73%**	3.7 - 4.7	32 - 50	30 - 45	2.5
S/A	Anthracite 1.2-2.5 mm	Sand 0.8-1.2 mm	Summer 2007	27	NDA*	2.9 - 3.5	29 - 43	30 - 45	3.2
S	Sand 0.4-0.8 mm	-	Autumn 2006	20	NDA*	1.7 - 4.1	5 - 47	35 - 79	14.5
S/F	Filtralite MC 0.8-1.6 mm	Sand 0.4-0.8 mm	Autumn 2006	20	MC 0.8-1.6: **48%**	1.5 - 3.7	20 - 37	35 - 79	2.3

* NDA : No Data Available

the *Filtralite-NC/Filtralite-HC* filter exhibits significantly smaller rate of head build-up for all three velocities tested. Finally, by comparing the data for *Filtralite-NC/Filtralite-HC* (summer 2007) with those for *Filtralite-MC/sand* (summer 2006), it is noted that the performance of the former is better in terms of SDI values and TOC/DNOM removal, as well as in respect of the smaller head build-up, for all three velocities tested. Based on the above comparative assessment, it may be concluded that the *Filtralite-NC/Filtralite-HC* dual filter performs better compared to both *Filtralite-MC/sand* and *anthracite/sand*, all of them comprised of very similar grain sizes. The better performance of the *Filtralite-NC/Filtralite-HC* dual filter may be rooted in the aforementioned greater particle porosities of both the top and the bottom layers, compared to the other two media combinations. As outlined above, the higher porosity appar-

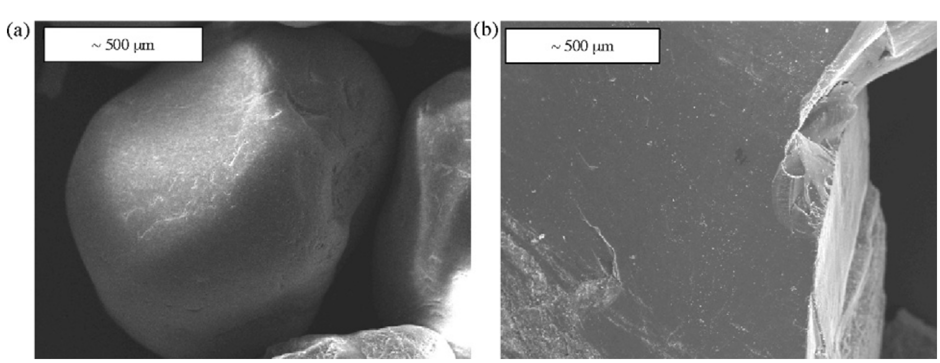

Fig. 5. SEM images of (a) sand grains 0.8–1.2 mm and (b) anthracite 1.2–2.5 mm with magnification 80×.

ently influences the grain shape and, perhaps more importantly, the surface texture leading to very rough grain surface with crevices. It is likely that the latter facilitate the retention of deposited flocs, in a way shielding them from the action of flow shearing forces that tend to re-suspend them.

4. Conclusions

The performance of a dual-media filter consisting of a layer of Filtralite NC 1.5–2.5 mm grains on top of Filtralite HC 0.8–1.6 mm was compared with a typical dual-media filter consisting of sand and anthracite. Seawater, obtained through an open intake was made available for the study. In this paper results are presented which were obtained during an experimental campaign under the fairly high temperatures prevailing in the summer of 2007 in this particular region of the Mediterranean Sea. This campaign is a follow-up of a previous phase of the study where the performance of a single medium filter was compared with that of dual-media filtration first, and another where dual-media filtration with two different filter media (Filtralite 1.5–2.5 mm and anthracite of the same grain size) was employed during two experimental campaigns; one was carried out at relatively low temperatures prevailing during the winter, and another at high temperatures prevailing during the summer.

As in the previous campaigns, attention was focused on filtrate quality parameters relevant to feeding RO membrane desalination systems. In this campaign various filtration velocities inside the filters were investigated in order to identify conditions for optimal filter performance. It was demonstrated that in most cases, filtrate of good quality for feeding RO systems (judged by relatively low SDI_{15} values) was obtained by both types of media with the particular type of the raw feed water.

During the previous phase of the study, it was shown that polyaluminum chloride (PACl) at a concentration of 1.8 mg Al/L gave satisfactory results, in terms of filtrate quality, and acceptable duration of the filtration cycles; thus, the same coagulant type and dosage was also applied in this work. The relatively high feed water temperatures in this summer campaign (on average 27 °C) apparently favoured the formation of large and strong aggregates, resulting in their effective capture inside the filter material. This improved efficiency of the coagulant was also observed even at the highest tested velocity (15 m/h). The filtration cycles, for all the flow velocities tested, were determined by the available free space above filter materials for hydrostatic head build up and not by the appearance of particle breakthrough. The only exception was during the operation of anthracite/sand column at the highest filtration velocity when particle breakthrough was observed after 17 h of continuous operation. On the other hand, it was observed that for operation at 5 m/h filtration velocity, both columns could run without the risk of breakthrough for more than 45 h. When operating at double that flow velocity (10 m/h) no particle breakthrough was observed after 24 h of continuous operation for both filters.

Both filters, i.e. Filtralite MonoMulti, consisting of Filtralite NC 1.5–2.5 mm on top of Filtralite HC 0.8–1.6 mm, and sand/anthracite filter, with anthracite grains on top of a sand layer, demonstrated a similar performance in removing particulates from the seawater as well as in reducing SDI_{15}. Turbidities close to 0.1 NTU and SDI values lower than 5, or even close to 3, could be obtained from both filters, thus producing filtrate water of fairly good quality. Comparing the two filters, it was observed that under the flow velocities tested (i.e. 5, 10 and 15 m/h) both demonstrated a fairly similar performance regarding filtrate turbidity measurements and 15-min SDI values. The major difference between the two filters was the rate of head build-up especially for the higher filtration velocities tested. Thus, when operating at 10 or 15 m/h filtration velocity, sand/anthracite filter demonstrated a greater rate of head build up in comparison to Filtralite MonoMulti filter which resulted in shorter filter runs and consequently demanded more frequent backwashing.

A comparative assessment of data from all dual-media filters tested in this as well as in the previous campaigns shows that the combination, involving Filtralite NC 1.5–2.5 mm on top of Filtralite HC 0.8–1.6 mm, exhibits, overall, the best performance. The improved performance of this dual filter medium is attributed to the rough surface texture, with crevices that tend to better retain flocs. The rough particle surface is due to the rather high porosity of these Filtralite materials.

Acknowledgements

Thanks are due to TATE & LYLE for the permission to install and operate the pilot unit in their industrial plant of Thessaloniki, Greece. In particular the plant general manager, Dr. Ioannis Thiokas, and engineers S. Kipritzis and L. Pseftakis are thanked for their hospitality and help. In addition, thanks are due to Prof. M. Mitrakas of the Department of Chemical Engineering, University of Thessaloniki, for critical suggestions during the design phase of the pilot unit and during the initial phase of tests, and to Mr. A. Lekkas for expert technical support.

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