Desalination and Water Treatment
www.deswater.com

10 (2009) 80–86

Effective depth, initial head loss and backwashing criteria as the key factors of burned oil palm shell (BOPS) granular filtration

Ahmad Jusoh[a*], A. Nora'aini[a], A.G. Halim[b], W.N. Norsani[c]

[a]*Department of Engineering Science, Faculty of Science and Technology,* [c]*Department of Maritime Technology, Faculty of Maritime Studies and Marine Science, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Malaysia*
Tel. +60 (9) 6683344, +60 (9) 6683622; Fax +60 (9) 6694660; email: ahmadj@umt.edu.my, sunnyg@umt.edu.my
[b]*Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*

Received 28 August 2008; Accepted in revised form 10 March 2009

ABSTRACT

These studies are mainly focused on effective depth, initial head loss and backwashing criteria that have been identified as the key factors in relation to the fundamental parameters and also, indicated possible operation performance. Granular filter media used in this study are limited to burned oil palm shell (BOPS) and sand. The study on the bed depth in relation to effluent over influent turbidities ratio (C_e/C_o) has been found to exhibit an exponential relation which showed a strong correlation coefficient ($R^2 = 0.9$) for different effective sizes of BOPS (ES, 1.0–2.5 mm) and sand (ES, 0.4–0.9 mm). By approximating relatively constant C_e/C_o for both BOPS and sand at different effective sizes, an exponential equation ($R^2 = 0.98$) is proposed to link all effective bed depths. This enabled a determination of the effective depth of BOPS and sand media which were not executed in the experiment. Initial head loss of single media of BOPS and sand which involved comparison of different models, such as Ergun and modified Kozeny–Carmen equations with experimental results, at different flow rates, showed a good agreement with modified Kozeny-Carmen equation for non-sphere. In backwashing criteria, studies that showed the relation between the difference in granular settlement velocity with backwashing water velocity, confirmed that the best combination of dual-media are sand of ES = 0.5 mm with UC of 1.5 and BOPS of ES = 1.0 mm with UC of 1.3.

Keywords: Effective depth; Initial head loss; BOPS; Sand

1. Introduction

Filtration is a process commonly used for the removal of particulate matter in water and wastewater treatment. Granular filter media was found effective for removing particulate of a wide range of sizes up to 50 μm [1] that readily exists in water. Most surface waters contain microorganisms such as algae, viruses, pathogens, sediment, clay, colloidal humic compounds and other organic and inorganic particulate matters.

The process design of granular filters requires a selection of several design variables, including the type and size of filter media, the optimum or effective depth of media, the superficial filtration velocity, and the backwash rate. Selection and design considerations for depth filters are based on the knowledge of types of filter media that are available, general understanding of the filtration performance characteristics and an assessment of process variables controlling depth filtration.

Initially, the hydraulic issues relevant to the design of a filtration unit or system include head loss through

---

[*] Corresponding author.

Presented at EuroMed 2008, Desalination for Clean Water and Energy Cooperation among Mediterranean Countries of Europe and the MENA Region, 9–13 November 2008, King Hussein Bin Talal Convention Center, Dead Sea, Jordan.

a clean filter bed (commonly known as initial head loss) and the fluidization or expansion of the filter bed during backwashing.

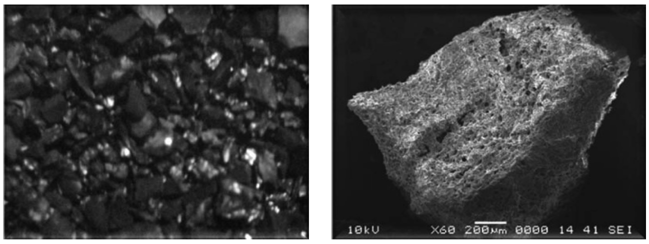
A filter has to be backwashed after the head loss reaches a maximum condition of about 2.5–3.0 m. It is normally indicated by the development of a negative pressure or a breakthrough of suspended particles [2]. At the end of the filter run, filters are backwashed by the action of a reverse flow or upward flow with an appropriate flow rate to flush out deposited material from the bed, but the flow cannot be so high that the filter media is flushed out of the filter bed. The three primary methods for backwashing filters are (1) water only, (2) air scour followed by water wash and (3) combined air and water wash [3]. The most effective method of backwashing filters is combined air and water at "collapse pulsing" [4–6].

Stratification is one of the common phenomena that occur after backwashing of rapid filter due to different settling velocities of individual grains of filter media depending on size or diameter. The smallest particles fluidize most and rise to the top, while the largest particles fluidize less and settle near the bottom of the bed. Stratification contributes adverse effects on the filters performance, especially as small grains near the top cause deposited material to be concentrated in the first few centimeters of the bed as well as development of excessive head loss. Therefore, to minimize a stratification problem, a proper selection of filter media with a low uniformity coefficient, UC, of about 1.3–1.4 is recommended [7] (UC is the ratio of granular diameter at 60% passes over the diameter at 10% passes). This design strategy is most important and must be considered in selection of a dual-media filter such as BOPS and sand.

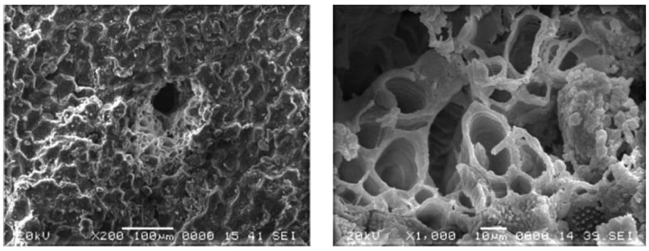
2. Material and methodology

Burned oil palm shells (BOPS) are prepared from oil palm fruit shells that is a solid waste by-product from oil palm factories and abundantly available. Palm shells were burned in a furnace at about 300°C and then ground into granules before being sieved to establish a particle size distribution curve. A sample of BOPS and its morphology under scanning electronic microscope with enlargements of 60×, 200× and 1000× is shown in Fig. 1. The effective sizes (ES) (ES is the diameter at 10% passes) for sand were 0.4, 0.5, 0.6, 0.8 and 0.9 mm, and for BOPS were 1.0, 2.0 and 2.5 mm respectively. Both sand and BOPS have the same uniformity coefficient of 1.5. The example of a size distribution curve of BOPS with an effective size of 1.0 mm and a uniformity coefficient of 1.5 is shown in Fig. 2. The size limit of individual media of BOPS and sand at selected effective sizes could be determined by using a corresponding distribution curve. They are shown in Table 1.

The effective sizes for a dual-media filter of BOPS : sand were limited to 1.0 mm : 0.5 mm, 2.0 mm : 0.5 mm and 2.5 mm : 0.5 mm only. The specific gravity of sand and BOPS were 2.65 and 1.30, respectively.



Original SEM enlargement 60x



SEM enlargement 200x SEM enlargement 1000x

Fig. 1. A sample of BOPS and its morphology under scanning electronic microscope.

Table 1
The size limit of BOPS and sand (the smallest and the biggest sizes)

Effective size (ES), UC = 1.5	The smallest size $P_{10} - 0.2\,(P_{60} - P_{10})$		The biggest size $P_{60} + 0.8\,(P_{60} - P_{10})$	
Sand	%	Size, mm	%	Size, mm
0.4	9.60	0.35	33.6	0.75
0.5	15.2	0.45	43.2	0.95
0.6	21.6	0.56	55.6	1.20
0.7	27.6	0.65	61.6	1.40
0.8	34.8	0.77	66.8	1.70
0.9	38.6	0.85	72.6	1.85
BOPS				
1.0	28.0	0.90	36.00	2.00
2.0	63.6	1.90	97.60	5.60
2.5	73.0	2.30	100.0	10.0

The effective depth experiments were carried out by using settled water of 2–5 NTU, as influent to a filter column of different depths of media. The turbidity of influent and effluent at each depth were recorded after the filtration process had reached steady state (i.e., after about 30 min). The filtration processes were continued at different depths until the effluent turbidity indicated a constant value.

The clean bed or initial head loss experiments were run in a filter column at a flow rate of 5 m/h and total bed depth of 0.9 m with selected effective sizes for mono-

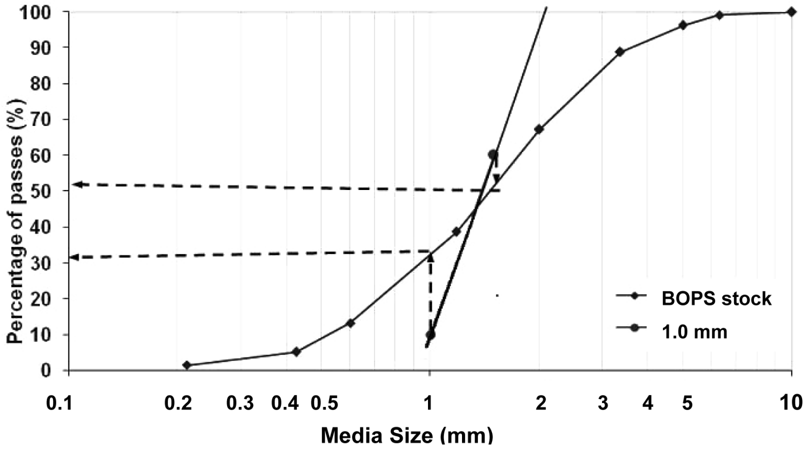


Fig. 2. Size distribution curve for BOPS at ES of 1.0 mm and UC of 1.5.

media BOPS and sand. The initial head loss at different depths was recorded by using manometers (installed at 10 cm interval) after the filtration process had reached steady state. The experiment of initial head loss was continued for mono-media BOPS and sand at selected effective sizes.

3. Results and discussion

3.1. Effective depth

The effective depth of filter media is defined as the minimum depth that will produce the best water quality of effluent after passing through a filtration unit. Since excessive depth might cause excessive head loss or early development of negative pressure as well as incur a high cost due to extra usage of filter media, the determination of an accurate effective depth for each type of media at the specified effective sizes and uniformity coefficient becomes primarily very important.

The experimental results in determining the effective depth for mono-media filters of BOPS and sand at different effective sizes are shown in Fig. 3. This figure shows that every curve flattens out at a specific depth which depends on the types of media as well as the effective sizes. The equations for every curve with its own correlation coefficient, R^2, are shown in Table 2.

The experimental data for the determination of the effective depth indicates a very strong correlation coefficient of R^2 which is in the range of 0.90–0.99. Therefore, the point at which the gradient (i.e., dy/dx) of each curve approaches to zero is considered to be the effective depth for the selected media. The best fit common line that con-

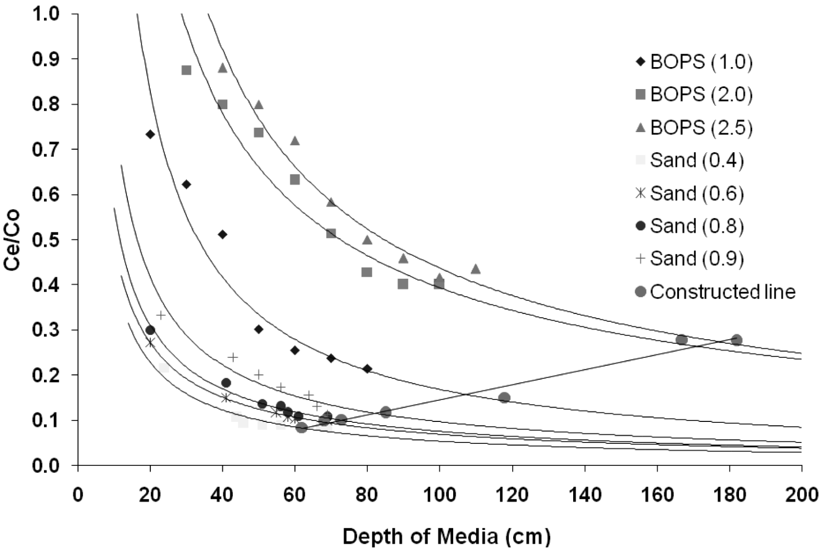


Fig. 3. A determination of effective depth for mono-media BOPS and sand at selected effective sizes.

Table 2
The line equation for BOPS and sand media at specified ES, effective depth and their correlation coefficient, R^2

Types of media (mm)	$f(x)$	$f'(x)$	Equation	X (cm)	R^2
BOPS ES = 2.5	$y = 18.703x^{-0.8154}$	$dy/dx = -15.250x^{-1.8156}$	(1)	182	0.96
BOPS ES = 2.0	$y = 12.304x^{-0.7476}$	$dy/dx = -9.1998x^{-1.7476}$	(2)	167	0.94
BOPS ES = 1.0	$y = 16.099x^{-0.8154}$	$dy/dx = -15.930x^{-1.9895}$	(3)	118	0.94
Sand ES = 0.9	$y = 6.3683x^{-0.9089}$	$dy/dx = -5.788x^{-1.9089}$	(4)	85	0.90
Sand ES = 0.8	$y = 4.2644x^{-0.8746}$	$dy/dx = -3.730x^{-1.8746}$	(5)	73	0.98
Sand ES = 0.6	$y = 3.4698x^{-0.8490}$	$dy/dx = -2.946x^{-1.8490}$	(6)	68	0.99
Sand ES = 0.4	$y = 3.3202x^{-0.8933}$	$dy/dx = -2.966x^{-1.8933}$	(7)	62	0.90

nects all the tangent points (i.e., dy/dx at the same gradient) is called "constructed line of the effective depth". This constructed line fitted well with all the tangent points with a strong correlation coefficient, R^2 equal to 0.98. The line equation is given as follows:

$$y = 0.0489\, e^{0.0099x} \quad (8)$$

This new finding enables an effective depth for monomedia BOPS and sand that are commonly used effective sizes to be obtained from Fig. 3 by using an interpolation method. For instance, the effective depth of sand at ES of 0.5 mm and BOPS at ES of 1.5 mm are 65 and 145 cm, respectively. The effective depth of sand and BOPS are comparable to those found by Castro and Martin, [8]. It is found that larger effective sizes result in higher effective depth. Consequently, BOPS media with a higher porosity ($\varepsilon_o = 0.49$) and effective sizes produces a higher effective depth compared to the sand media ($\varepsilon_o = 0.4$). It is clearly indicated that sand with lower porosity and effective sizes produces a better quality effluent of less than 0.1 NTU water at lower effective depth compared to BOPS media (i.e., 0.15 – 0.27 NTU for ES = 1.0–2.5 mm).

In designing a dual-media filter of BOPS : sand, the combination of the individual media of BOPS and sand must follow the guide line of the determined effective depth as shown in Fig. 3. As a general rule, the combination of dual-media filter could be in the range of 100% BOPS : 0% sand, X% BOPS : (100 – X)% sand up to 0% BOPS : 100% sand. However, a commonly used ratio of dual-media filter of anthracite : sand can be adopted for the dual-media filter of BOPS:sand with a value in the range of 60–40% BOPS : 40–60% sand [9,10].

In order to recommend an appropriate overall depth of media to be used in the design, an extra depth of about 20% over the effective depth should be considered to overcome a washout filter media as well as some media damages that might occur during repeated backwashing processes [9].

3.2. Initial head loss

When water passes through porous granular media, energy losses occur due to friction (or flow resistance) of fluid and surface of media. Furthermore, losses could also occur due to continuous contraction and expansion experienced by the fluid as it passes through the non-uniformity of voids in the media. The flow patterns through granular media are extremely complex and the prediction of initial head loss as well as operational head loss requires various strategies and approaches. However, this section only focuses on the prediction of initial head loss as an indicator to the performance of the operational head loss or the performance of the filtration efficiency.

The hydraulics of the initial head loss will depend on several variables, including porosity of filter bed, depth of filter, diameter of media grains, shape factor of granular media, superficial velocity and fluid characteristics such as dynamic viscosity, density of fluid and acceleration due to gravity. It can be expressed as Eq. (9):

$$h_L = F(\varepsilon, L, d, \xi, V, \mu_W, \rho_W, g) \quad (9)$$

The fluid characteristics are temperature dependent and a typical average temperature for Malaysia is about 25°C. A typical initial head loss by Kozeny–Carmen for a granular sphere considering all the variables mentioned above in Eq. (9) is shown as follows:

$$h_L = \frac{K_k V \mu_w (1-\varepsilon)^2}{\rho_w g \varepsilon^3 d^2} L \quad (10)$$

The first term of Eq. (11) is the head loss due to viscous forces. However, Ergun [11] introduced an additional head loss due to inertial forces as indicated by the second terms of this equation as follows:

$$h_L = \kappa_V \frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu_w V L}{\rho_w g d^2} + \kappa_I \frac{(1-\varepsilon)}{\varepsilon^3}\frac{V^2 L}{gd} \tag{11}$$

Therefore, the authors would like to introduce a similar additional head loss due to inertial forces to the Kozeny–Carmen initial head loss equation by adding a second term to the sphere and non-sphere Kozeny–Carmen as shown by Eqs. (12) and (13) as follows:

$$h_L = \frac{K_k V \mu_w (1-\varepsilon)^2}{\rho_w g \varepsilon^3 d^2} L + \kappa_I \frac{(1-\varepsilon)}{\varepsilon^3}\frac{V^2 L}{gd} \tag{12}$$

$$h_L = \frac{K_k \xi^2 V \mu_w (1-\varepsilon)^2}{\rho_w g \varepsilon^3 d^2} L + \kappa_I \frac{(1-\varepsilon)}{\varepsilon^3}\frac{V^2 L}{gd} \tag{13}$$

The experiments to monitor initial head loss for mono-media BOPS and sand were carried out at a flow rate of 5.0 m/h and the results are shown in Fig. 4. These results clearly indicate that the modified Kozeny–Carmen equation of non-sphere gives the best fit to the experimental data for all mono-media BOPS and sand at a flow rate of 5 m/h. It can be concluded that the shape factor of non-sphere contributes an additional effect to the initial head loss.

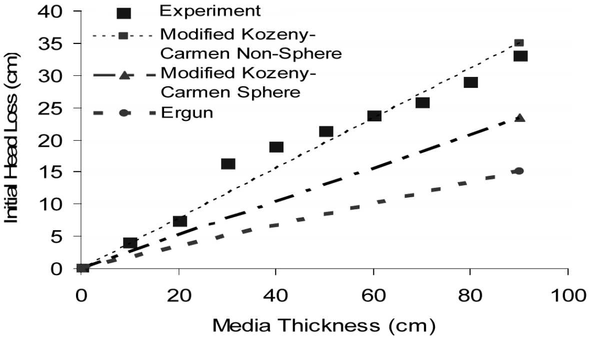
In addition, the predicted as well as the experimental initial head loss for mono-media BOPS was rather small, i.e. in the range of 0.0–4.8 mm at 0–0.9 m depth and at a velocity of 5 m/h. However, the initial head loss for mono-media sand was 7 times higher than that of the mono-media BOPS at the same depth of media and velocity (i.e., initial head loss of 0.0–33 cm). This indicates that mono-media BOPS could operate at a longer operational time for the filter as compared to mono-media sand as BOPS has a lower initial head loss as well as a slower development operational head loss.

3.3. Backwashing

The performance of gravity or rapid filtration directly depends on the effectiveness of the backwashing process. The effectiveness of backwashing for dual-media filter of BOPS : sand depends on the density or specific gravity of each media and a combination of the selected sizes (effective size) which later on effect the settling velocities of the two types of media as clearly shown by Eqs. (14) and (17).

$$V_S = \frac{g\rho_W (Gs - 0.997) d^2}{18\mu_W} \tag{14}$$

(a) Initial Head Loss, Sand ES = 0.5 mm, V = 5 m/h



(b) Initial Head Loss, BOPS ES = 1.0 mm, V = 5 m/h

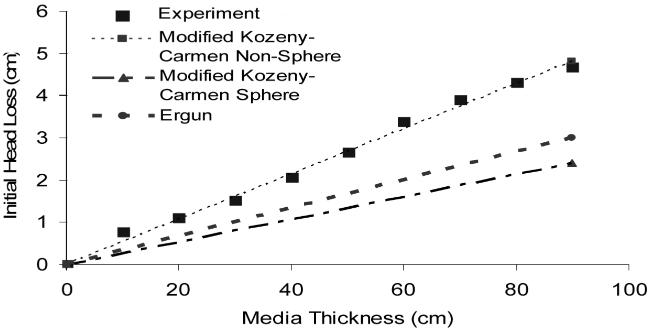


Fig. 4. Initial head loss vs. depth of media at V = 5 m/h (a) mono-media sand (b) mono-media BOPS.

When Reynolds numbers of the settling velocities for BOPS and sand media fall under a transition flow regime, that is 1 < Re < 10,000 [use Eq. (15)], the most accurate formulas to calculate settling velocities are Eqs. (16) and (17). The iteration processes to obtain the exact settling velocity was carried out by using Eqs. (15), (16) and (17) until a final constant settling value was achieved. The results of the final settling velocities for BOPS and sand at the specified sizes are shown in Table 3.

$$\mathrm{Re} = \frac{\rho_W V_S d}{\mu_W} \tag{15}$$

$$C_d = \frac{24}{\mathrm{Re}} + \frac{3}{\sqrt{\mathrm{Re}}} + 0.34 \tag{16}$$

$$V_S = \left[\frac{4g(G_S - 0.997)d}{3C_d}\right]^{0.5} \tag{17}$$

A dual-media BOPS : sand of ES 1.0 mm : ES 0.5 mm is considered to be the best combination of dual-media available. From Table 3, the smallest sand size of 0.45 mm has the settling velocity of greater than 266 m/h and the largest sand size of 0.95 mm has the settling velocity of greater than 593 m/h. On the other hand, the BOPS smallest size of 0.9 mm has the settling velocity of 198.4 m/h

Table 3
Settling velocities of BOPS and sand at selected effective sizes

Sand								
Diameter (*d*), mm	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Velocity (*V*), m/h	185	266	341	411	476	536	593	646
BOPS								
Diameter (*d*), mm	0.6	0.7	0.8	0.9	1.0	1.5	2.0	2.5
Velocity (*V*), m/h	124	150	175	198	221	243	264	322

and the BOPS largest size of 2.0 mm has the settling velocity of 264 m/h. Therefore, all selected sizes of sand at ES of 0.5 mm have settling velocities of greater than the all selected sizes of BOPS at ES of 1.0 mm. There are no overlapping or inter-mixing of BOPS and sand media occurred after a backwashing.

However, if a combination of dual-media BOPS : sand of ES 2.0 mm : ES 0.5 mm (i.e. the range of size for BOPS ES 2.0 mm and UC of 1.5 is 1.9–5.6 mm), some inter-mixing of BOPS and sand might occur since BOPS with sizes greater than 2.5 mm has a settling velocity greater than the lowest sand settling velocity of about 300 m/h. Therefore, in order to minimise the percentage of inter-mixing, the uniformity coefficient for BOPS ES 2.0 mm should be lowered to about 1.2–1.3 (i.e., the biggest size of BOPS ES 2.00 mm could be reduced to 3.0–3.5 mm). Amburgey [12] utilised a dual-media of anthracite : sand with a combination at an effective size of sand 0.5 mm and UC of 1.5 with anthracite at an effective size of 1.0 mm and UC of 1.3. However, William et al. [13] used sand at an effective size of 0.62 mm and UC of 1.42 combined with anthracite at an effective size of 1.22 mm and UC of 1.34.

The fluid velocity required to keep the grains media suspended is derived from a force balance between upward forces and downward forces as shown in Eq. (18):

$$V_{up} = \left[\frac{g(\rho_P - \rho_W)d^{1.6}}{13.9\rho_W{}^{0.4}\mu_W{}^{0.6}} \right]^{0.714} \tag{18}$$

The media are normally allowed to expand up to 20–50 % with the upward velocity of water in the range of 30–60 m/h [14]. According to Chipps et al. [4], if a combination air and water was used, the velocity of scour air was from 20 to 50 m/h while the velocity of water was in the range of 7–25 m/h. As a benchmark, the upward velocity of water at 30% expansion for BOPS and sand was determined by using Eq. (18) and the overall results are shown in Table 4. From this table, the size of sand from 0.4 to 0.8 mm and BOPS from 0.9 to 2.5 mm have velocities in the range of 19–64 m/h for the 30% expansion. In other words, if the upward velocity was kept constant, the overall media would expand at about 20–50%. According to Kawamura [2] the target expansion rate for anthracite (similar to BOPS) and sand should be about 25% and 37% respectively.

4. Conclusions

Burned oil palm shell (BOPS) granules are a new filter media which has a specific gravity of about 1.3, a shape factor of 8.5 and an initial porosity of 0.49. The appropriate effective sizes of BOPS that can be used in filtering settled water are 1.0–2.0 mm with uniformity coefficient, UC = 1.2–1.5, while the best UC should be less than 1.3. The effective depth for a mono-media of BOPS with ES = 1.0, 2.0 and 2.5 mm has been established as 118, 167 and 182 cm, respectively. The effective depths for mono-media sand with ES = 0.4, 0.5, 0.6, 0.8 and 0.9 mm are 62, 65, 68, 73 and 85 cm, respectively. The best combination of a dual-media BOPS : sand should be at the ratio of 60% BOPS : 40% sand.

The initial head loss for mono-media BOPS ES = 1.0 mm at 0.9 m depth and velocity of 5 m/h was quite

Table 4
Upward flow velocity at various sizes for 30% expansion

Sand										
Diameter (d), mm	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Velocity (*V*), m/h	1.5	6.1	13.3	22.5	32.8	43.5	54.0	64.1	73.5	82.5
BOPS										
Diameter (*d*), mm	0.8	0.9	1.0	1.2	1.5	1.75	2.0	2.25	2.5	3.0
Velocity (*V*), m/h	16.1	19.3	22.5	28.5	36.8	43.0	48.5	53.6	58.3	66.8

low, just 4.8 cm compared to mono-media sand ES = 0.5 mm at the same depth and velocity where the head loss was 33 cm. This could be used as an indicator for the operational head loss and filter run that mono-media BOPS filter lasts 5–7 times longer than the mono-media sand filter. In the analysis of initial head loss for mono-media BOPS and sand, it was distinctly illustrated that the experimental results fitted very well with the initial head loss predicted by a modified Kozeny–Carmen equation for non-sphere. Finally, backwashing analysis confirmed that the combination of dual-media BOPS :s and (for BOPS ES = 1.0–2.0 mm, UC of 1.3 and sand ES = 0.5 mm, UC of 1.5) produces no or minimal inter-mixing of media.

Symbols

C_d — Drag coefficient
d — Diameter of media grains
e — Exponential
ES — Effective size
g — Acceleration of gravity
Gs — Specific gravity of media
h_L — Initial head loss
K_k — Kozeny factor,
K_i, K_v — Head loss coefficient due to inertial and viscous
L — Filter bed depth
P_{10}, P_{60} — Percentage of passes at 10% and 60%
Re — Reynolds number
V — Superficial velocity
V_S, V_{up} — Settling velocity and upward flow velocity
UC — Uniformity coefficient
ε_o — Initial porosity
μ_w — Water viscosity
ϱ_p, ϱ_w — Density of media and density of water
ξ — Shape factor

References

[1] S. Osmak, D. Gosak and A. Glasnovic, J. Comp. Chem. Eng., 21 (1997) 763–768.

[2] S. Kawamura, Integrated Design of Water Treatment Facilities. 2nd ed., Wiley and Sons, New York, USA, 2000.

[3] J.C. Crittenden, R.R. Trussell, D.W. Hand, K.J. Howe and G. Tchobanoglous, Water Treatment: Principles and Design, 2nd ed., Wiley and Sons, Inc., Canada, 2005.

[4] M.J. Chipps, M.J. Bauer and R.G. Bayley, Achieving enhanced filter backwashing with combined air scour and sub-fluidising water at pilot and operational scale. Filtr. Separ., January (1995) 55–62.

[5] D.G. Stevenson, Process condition for the backwashing of filter with simultaneous air and water. Water Res., 29(11) (1995) 2594–2597.

[6] J.F. Colton, P. Hillis and C.S.B. Fitzpatrick, Filter backwash and start-up strategies for enhanced particulate removal. Water Res., 30(10) (1996) 2502–2507.

[7] J.E. Amburgey, A. Amirtharajah, B.M. Brouckaert and N.C. Spivey, An enhanced backwashing technique for improved filter ripening. J. AWWA, 95(12) (2003) 81–94.

[8] K.L. Castro and S.R. Martin, Water Treatment Plant Design, AWWA, ASCE, 4th ed., McGraw-Hill, USA, 2005.

[9] S. Kawamura, Design and operation of high-rate filters. J. AWWA, 91(12) (1999) 77–90.

[10] A. Zouboulis, G. Traskas and P. Samaras, Comparison of single and dual media filtration in a full-scale drinking water treatment plant. Desalination, 213 (2007) 334–342.

[11] S. Ergun, Fluid flow through packed column. Chem. Eng. Prog., 48(2) (1952) 89–94.

[12] J.E. Amburgey, Optimization of the extended terminal subfluidization wash (ETSW) filter backwashing procedure. Water Res., 39 (2005) 314–330.

[13] G.J. Williams, B. Sheikh, R.B. Holden, T.J. Kouretas and K.L. Nelson, The impact of increased loading rate on granular media, rapid depth filtration of wastewater. Water Res., 41 (2007) 4535–4545.

[14] D.G. Hemmings and C.S.B. Fitzpatrick, Pressure signal analysis of combined water and air backwash of rapid gravity filters. Water Res., 31(2) (1997) 356–361.