Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.928234

55 (2015) 1712–1724
August

Taylor & Francis
Taylor & Francis Group

Characterization of polystyrene granules as granular media filters

Juliana Marques Schöntag*, Maurício Luiz Sens

Programa de Pós-Graduação em Eng. Ambiental, Universidade Federal de Santa Catarina, Bairro Trindade, Florianópolis/SC CEP 88040-900, Brasil, Tel. +55 (48) 37219883, +55 (48) 37219470; emails: juschontag@gmail.com (J.M. Schöntag), mls@ens.ufsc.br (M.L. Sens)

Received 12 September 2013; Accepted 20 May 2014

ABSTRACT

The need for water production is increasing in urban populations. In conventional water treatment plants, the filters are backwashed by treated water, which represents high long-term costs. In order to obtain a highly effective production of water with a subsequent reduction in production costs, it was proposed to feature a granular filter element with low density and its potential to provide a down-flow rapid filter, which can represent a reduction in the volume of water used for backwash. The polymer used for this purpose appears to be favorable; in addition, there are possibilities of recycling this material. A velocity of 6.08 m/h for a 50% expansion was demonstrated, which is very low compared to conventional filter elements (i.e. sand and anthracite). So, this element has shown great potential in reducing the volume of water during the backwash process, as observed using mathematical models. The final quality of the filtered water still needs to be analyzed. However, the permeability coefficient was determinate at $1.79 \times 10^{-5} \pm 2.87 \times 10^{-6}$ m/s being satisfactory as filtration. The outlook is that it may become an option for element filtration in down-flow rapid filters for water treatment.

Keywords: Down-flow rapid filtration; Backwashing models; Granular media filters; Low density; Effective production

1. Introduction

In large cities, with increasing populations, water consumption has increased not only by individual demand, but by industrial needs as well. With the increasing levels of pollution in the sources of supply, the prices of treated water are being incremented according to the difficulties encountered, such as the enlargement of treatment plants for higher flow rates and the expansion of water supply networks. To assist in the production of potable water at reasonable costs and optimize production, this study was conducted to acquire a new filter element with the prospect that there may be a reduction in water used for backwashing the filters in the production process. The reduction in water use may also result in lower backwashing time and related energy consumption reductions. The performance of different media filters (sand, anthracite, and garnet) were studied already [1], but did not evaluate the density of the material with the amount of water consumed during the backwash process. The use of granular synthetics as a water treatment filter is not widely explored, but exists [2]. In Norway, there is the Skull red water treatment plant. This plant has direct downward filtration technology with triple layer filters (two layers of different plastic media and a

*Corresponding author.

layer of sand). This plant supplies 10% of the population of Oslo since 1994 and is still in operation. Synthetics are expensive compared to conventional filter elements such as sand, anthracite, and garnet (easily extracted from nature), so there would be a long-term economic advantage. There is also the possibility of using recycled materials for this purpose; however, further studies must be administered, particularly regarding the durability thereof.

To get to that stage, it is necessary to characterize the filter element, the energy required for its proper performance and other elements involved in the process, such as water quality.

However, the aim of this study was to characterize the polystyrene (PS) granules as a media filter, especially the density and performance during the backwash. Because it is a lightweight material, it is believed that low velocities are required during ascensional cleaning, to achieve high porosities, turbulence, hydrodynamic shear stress, and shear rate, which ease the cleaning process and could possibly generate savings in the process.

Experiments to obtain the characteristics of the material such as grain size, initial porosity, density, and hardness, as well as acidic and caustic resistances were performed. Additionally, expansion tests were realized for this material, in order to obtain the mathematical model constants to simulate the performance during backwashing, such as the minimum fluidization rate, settling velocity, and the sphericity coefficient, among others. Thus, it was possible to simulate the physical mechanisms, with an amendment (hypothetical) of the superficial velocities without an experimental comparison. The permeability coefficient was also determinate, according to the physical aspects of the material. Currently, physical–chemical aspects of the water or the filter material were not considered, because it is a theoretical analysis and it is the first observation of the use of this material for this purpose.

2. Materials and methods

2.1. Material characterization

During the selection process, the objective was to find a lightweight material with low density. Therefore, polymers became the best candidates. Other polymers were observed, such as acrylonitrile butadiene styrene, polypropylene, and the same PS, but the granulometry available on the market was larger, as 6 mm, which is unfavorable. PS granules were selected because they displayed similar characteristics (geometry and shape) of sand; they are light, inert, and commercially available. PS is displayed in Fig. 1 below.

Fig. 1. Polystyrene granules.

To verify that a material is capable of constituting a filter, it has to be characterized by the following criteria: size, sphericity, porosity, hardness, density (which in this case needs to be lower, or a little higher than that of water), and present acidic and caustic resistances.

The granulometric test was performed on material [3] as shown in Fig. 2 and Table 1, where are results are obtained by the granulometric curve.

The initial porosity was determined according to the methodology of AWWA [4] and through this same calculation, the density of the material was extracted. The porosity reached 0.382 ± 0.00045, with a relative error of 0.11% and a specific density of 1.046 ± 0.0005 kg/cm, with a relative error of 0.05%. The hardness was determined in the UFSC laboratory of Materials Engineering and reached a value of 15.2 ± 1.15 HV (Vickers), with a relative error of 7.6%.

The caustic and acidic resistances were evaluated with HCl e NaOH (1%) [5], and presented a loss of 0.18 and 0.07%, respectively. In addition to the physical and chemical characteristics of the material, expansion tests were performed.

For the experimental expansion test, a transparent acrylic column with a 60 mm diameter and a height of 2 m was used. It was built with a level chamber and three levels were positioned to control head loss during expansion. To test the backwashing, the material was placed in a column with water (wet).

The element was supported by pebbles and stones with granulometrics between 19 and 1.6 mm and was placed on a 20 cm layer of material, as shown in the photographs of the expansion test and PS on the support layer in Fig. 3. The PS granules crossed the support layer somewhat, but not to the point of jeopardizing the operation of the system. The initial

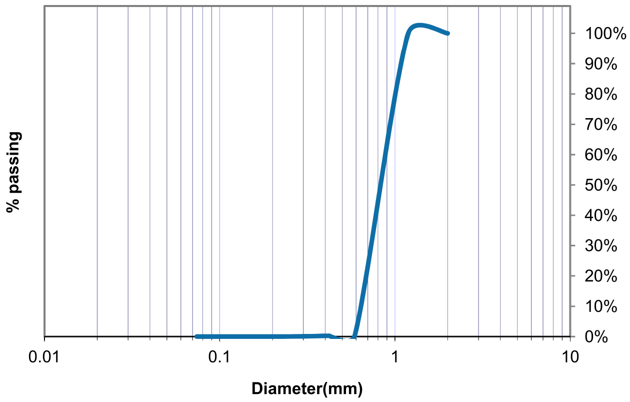

Fig. 2. Granulometric curve PS.

Table 1
Granulometric characteristics PS

Spherical polymeric polyestyrene		
Characteristics	Results	E (%)
Minimum size	0.52 ± 0.03 mm	5.7
Maximum size	1.25 ± 0.05 mm	4
Effective size	0.66 ± 0.014 mm	2.1
Uniformity coefficient	1.36 ± 0.024	1.7
Media grain diameter	0.87 ± 0.04 mm	4.6

permeability and its progress were not analyzed at that time. The performance of the material during its expansion was evaluated and the theoretical behavior was analyzed during backwashing.

The fluidization test was conducted thrice. The filter bed with 20 cm describes a head loss curve (Fig. 4) and the large standard deviations in the region near the minimum velocity of fluidization. Therefore, the experimental results were compared with the model suggested by Wen and Yu [6] using Eq. (1).

$$Vmf = \frac{\mu}{\rho_w deq}\left(\sqrt{(33.7)^2 + 0,0408G_a} - 33.7\right) \tag{1}$$

where Vmf = minimum velocity of fluidization, G_a = Galileo number, given by $G_a = deq^3 g\rho_w(\rho_s - \rho_w)/\mu^2$, μ water viscosity to 25℃, ρ_w = water density of 25℃, ρ_s = specific density of material, and deq = equivalent diameter oxf granules.

According to the Wen and Yu model [6], the minimum velocity of fluidization of the material is 0.248 ± 0.16 mm/s (0.89 m/h). This value is within the standard deviation presented by the experimental result. The test result also shows fluidization at a velocity of 1.69 mm/s (6.08 m/h), which was achieved by an increased expansion of approximately 50% as shown in Fig. 5.

To determine the sphericity of the material, a pressure drop was observed during the expansion tests and its value was determined by the calculation based on the Ergun equation, which is valid for fixed and expanded beds, where $K_I = 150$ and $K_V = 1.75$ for fixed beds and $K_V = 1$, for expanded beds, for adjustment values, on Eq. (2):

(a) (b)

Fig. 3. (a) Acrylic column and level chamber built with level markers that indicate head loss during the expansion test (b) the support layer of the material under analysis.

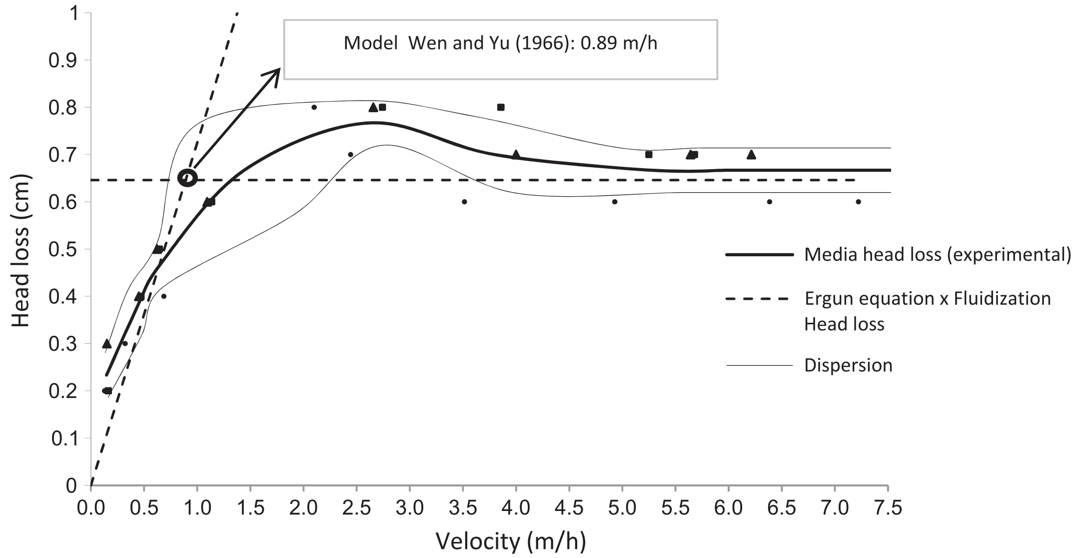

Fig. 4. Experimental results of the head loss curve according to fluidization velocity by the Wen and Yu model [6].

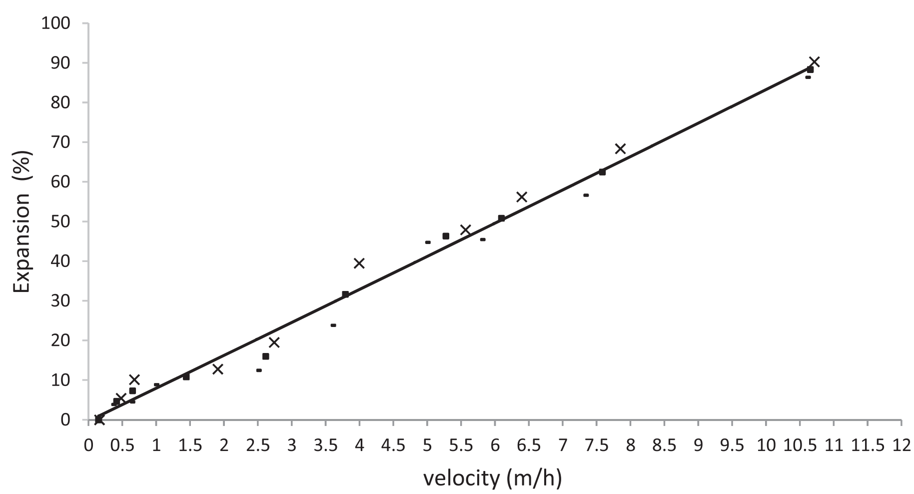

Fig. 5. PS expansion test (Expansion (%) x velocity (m/h)).

$$h_L = K_V \frac{(1-\varepsilon)^2}{\varepsilon^3 C_e^2} \frac{\mu L V}{\rho_w g deq^2} + K_I \frac{1-\varepsilon}{\varepsilon^3} \frac{LV^2}{C_e g deq} \quad (2)$$

where K_V = head loss coefficient due to viscous force; K_I = head loss coefficient due to inertial force; ε = porosity; L = depth of granular media; V = superficial velocity; g = acceleration to gravity; d = media grain diameter, and C_e = sphericity coefficient. This material reached a value of 0.96 ± 0.086, with a relative error of 4%. In fact, if the value of the sphericity of the material is set to 1, then the results are not changed significantly.

As with Cleasby and Fan [7], the terminal settling velocity for this material was determined through an experimental test with a glass column with water of 23.8°C, and two marks counted the percolation time for individual grains. This terminal settling velocity achieved was 10.1 ± 1 mm/s (32.65 m/h), with a relative error of 9.9%.

With the results of the characterization of the material, it is possible to equate through mathematical models the behavior of the material during the backwash. The PS material was compared with materials already known and studied, such as sand and anthracite, as in Table 2 [7].

where V_t is the terminal settling velocity and Ret is the Reynolds number relative to the terminal settling velocity. Low values of the settling velocity of the PS beads showed that the material density is slightly higher than that of water. It can be concluded from this, that the duration of backwashing can be impaired, thus requiring a longer time for completion of the process.

In the equations presented by Turan et al. [8] and Naseer et al. [9] (presented below) for the simulation of the physical parameters of the backwash in conventional media, sand and anthracite were used. Through this parameter, it is possible to identify the influence of density during the backwash and other physical parameters of PS granules. In these equations, values relative to permeability are not entered. This does not mean that this amount is not relevant, as they influence this step in the process. However, the purpose is to follow the model suggested by these authors. The permeability parameters were not considered at this time, but were investigated in a second stage.

With initial porosity determined by the AWWA method [4], the superficial velocity variation was assigned with values ranging from 0 to 83.3 mm/s (300 m/h). It was possible to calculate the theoretical porosity of the material during cleaning (backwashing). The idea was to observe the backwash performance with increasing backwashing expansion, i.e. increasing porosity. Obviously, there are differences between the porosity of clean and dirty media filters. Based on this, the variation of porosity was analyzed because of the initial porosity of maximum value, i.e. 100%.

2.2 Backwashing models

The models presented by Turan et al. [8] and Naseer et al. [9], describe the behavior of the media filter during backwashing. In fact, the efficiency of backwashing depends on other aspects: the physical–chemical parameters, the number of active sites, and the specific surface of the grain, but the suggested models only consider the physical parameters.

When subjected to different superficial velocities during backwash, the material reaches different degrees of expansion and different porosities. Using this parameter as a variable, equations were extracted by the responses to the hydrodynamic shear turbulence and the velocity gradient of PS granules was used as a filter medium.

To succeed in solving the proposed equations, the physical constants of the material were sought out. Subsequently, there were related variables of porosity and solid fractions, obtained through of the superficial velocities assigned among 0–83.3 mm/s (0–300 m/h). Thus, it was necessary to follow the reasoning suggested by the authors [8–10] to get the answers of the physical parameters of backwashing. For all simulations, a temperature of 25˚C was considered.

Expansion models of the fluidized bed: the correlation of Richardson and Zaki [11] is widely utilized to describe the characteristics of fluidized beds for spherical grains, according to Eq. (3).

$$\frac{V}{V_i} = \varepsilon^n \tag{3}$$

where V is the superficial velocity, V_i is the interception velocity, n is the expansion coefficient bed, and ε is the fluidized porosity bed.

Cleasby and Fan [7] found that the non-spherical grains of the bed behave differently during the backwashing process compared with spherical particles, and reached the following Eq. (4):

$$\frac{V_i}{V_t} = 0.91\psi^{-0.4} \tag{4}$$

where V_t is the terminal settling velocity and ψ is the grain sphericity.

The superficial velocity of the fluidized bed is always greater than the fixed bed. When the volume of the grains in the filter is constant, the fixed and fluidized beds can be described as Eq. (5):

Table 2
Physical properties of the media filter

Materials	Size (mm)	Specific density (g/cm)	Porosity	*deq* (mm)	Sphericity	V_t (cm/s)	Ret
Sand*	1.00/0.84	2.65	0.467	1.006	0.73	12.58	143
Anthracite*	1.68/1.41	1.73	0.597	1.516	0.46	6.95	118
Anthracite*	0.853/0.699	1.46	0.564	0.815	0.64	3.94	35.7
PS spheres (averaged)	1.25/0.52	1.046	0.382	0.87	0.96	1.01	8.99

*Data extracted from Cleasby and Fan [7].

$$\frac{L}{L_0} = \frac{(1-\varepsilon_0)}{(1-\varepsilon)} \tag{5}$$

L is the depth of expanded bed, L_0 is the depth of fixed bed, ε_0 is the porosity of fixed bed, and ε_0 is the porosity of expanded bed.

The expansion coefficient with spherical grain can be described as Eq. (6):

$$n = \left(4.45 + 18\frac{deq}{D}\right)\mathrm{Re}_\mathrm{t}^{-0.1} \quad \text{for } 1 < Re < 200 \tag{6}$$

According to Cleasby and Fan [7], non-spherical grains can be described as Eq. (7):

$$n = \left(4.45 + 18\frac{deq}{D}\right)\mathrm{Re}_\mathrm{t}^{-0.1}\psi^a \quad \text{for } 15 < Re < 200 \tag{7}$$

where $a = -2.9237\psi^{0.884}\mathrm{Re}^{-0.363}$ and $\mathrm{Re} = \frac{\rho_\mathrm{w} V_\mathrm{t} deq}{\mu}$, and D = column filter diameter.

These conditions are validated for a backwash with laminar flow.

Power dissipation during backwash: As previously discussed, the efficiency of backwashing not only depends on physical parameters, but also on the physical–chemical parameters, the number of active sites, and the specific surface of the grain, among others. However, the suggested models only consider the physical parameters. In this case, the physical parameters of the grain, which constitute the bed, are size, density, superficial velocity, porosity, and the type and amount of material deposited during filtration.

The velocity gradient and hydrodynamic shear are very important to make provision for optimal cleaning. Camp presented the velocity gradient for laminar flows in 1964 as $\tau = \mu G$ (where τ is the shear stress and G is the average shear rate). As the backwash process usually occurs in a regime transition states, the gradient can be written as Eq. (8):

$$G = \left(\frac{P_\mathrm{d}}{\mu(1+C)}\right)^{0.5} \tag{8}$$

where P_d is the power dissipation and C is the dissipation coefficient of turbulence during total dissipation energy.

The energy equation of backwash flow can be described as Eq. (9):

$$\tau\frac{du}{dy} = \left(\alpha_1\rho_\mathrm{w}V_*^3/KL_\mathrm{m} + \beta\alpha_1\rho_\mathrm{w}V_*^3/KL_\mathrm{m} + \rho_\mathrm{w}V_*^3/Ky\right)\varepsilon^{(n-1)} \tag{9}$$

where β represents the random motion of grains and $\alpha_1 = {V_\mathrm{i}}/{V_\mathrm{t}}$ is a coefficient related to grain characteristics [12].

In this equation, the left-hand side represents the energy produced by Reynolds stress and the right-hand side represents the power necessary to suspend the grains in unit volumes, the rate of energy removal due to random motion of suspended grains such as rotation, rectilinear motion relative to the fluid, and the power dissipated by a turbulent motion of the liquid phase. If the regime is laminar flow, these items are underrepresented.

The von Karman universal constant flow with suspended particles, K and Monin–Obukhov length, L_m, are given, respectively, as in Eqs. (10) and (11):

$$K = \frac{K_0}{(1+2(1-\varepsilon))} \tag{10}$$

$$L_\mathrm{m} = \frac{V_*^3}{KgV_\mathrm{t}({\rho_\mathrm{p}}/{\rho_\mathrm{w}} - 1)(1-\varepsilon)} \tag{11}$$

where K_0 Von Karman universal constant for pure water flow is 0.4 and $(1-\varepsilon)$ is the fraction solids or concentration. In addition, the specific density of fluid and grain mixture ρ_a and the friction velocity V_* are represented in Eqs. (12) and (13). V_* is used to describe shear-related motion in moving fluids [13]:

$$\rho_\mathrm{a} = \rho_\mathrm{w}(1 + (\rho_\mathrm{p}/\rho_\mathrm{w} - 1)(1-\varepsilon)) \tag{12}$$

$$V_* = (g\rho_\mathrm{w}(\rho_\mathrm{p} - 1)(1-\varepsilon)D/4\rho_\mathrm{w})^{0.5} \tag{13}$$

Energy dissipation parameters: The model presented by Turan [8] was developed to describe the influence among different types of filter materials with regard to the energy dissipation parameters such as hydrodynamic stress, velocity gradient, turbulence dissipation coefficient (Ca), and turbulence parameter ($Ca^{0.5}/\mathrm{Re}$) in backwashing filters. Thus, the velocity gradient was developed as Eq. (14):

$$G = 8V_*(\ln(\rho_\mathrm{w}V_*D/23.2\mu) - 1)/KD \tag{14}$$

Using the energy dissipation equation for backwashing filters, the hydrodynamic stress can be obtained by Eq. (15):

$$\tau_\mathrm{a} = \rho_\mathrm{w}V_*^2\varepsilon^{(n-1)}((\alpha D/6L_\mathrm{m}) + 1) \tag{15}$$

where the coefficient α is show in Eq. (16):

$$\alpha = \alpha_1(1+\beta) = 7V_i/V_t \tag{16}$$

If Eq. (8) is arranged in average arithmetic, the turbulence dissipation coefficient Ca can be calculated as Eq. (17):

$$Ca = (\tau_a/\mu G - 1) \tag{17}$$

The turbulence parameter ($Ca^{0.5}/\mathrm{Re}$), describes the effect of the turbulence in the liquid phase, calculated as Eq. (18):

$$Ca^{0.5}/\mathrm{Re} = (\tau_a/\mu G - 1)^{0.5}/\mathrm{Re} \tag{18}$$

where $\mathrm{Re} = {}^{\rho_w Vdeq}/_{\mu}$, V is the superficial velocity, and deq is the equivalent diameter of the grain.

2.3. Permeability coefficient

The permeability coefficient was determined in accordance with the Kozeny–Carman equation, as shown in Eq. (19).

$$K_k = \frac{(\Delta H/L).\rho_w.g.\varepsilon^3}{2\mu.(1-\varepsilon)^2.S_e^2.V_\infty} \tag{19}$$

where K_K = Kozeny coefficient; ΔH = Head loss (m); L = depth of granular media (m); ρ_w = water density (kg/m^3); g = acceleration due to gravity, 9.81 m/s^2; ε = porosity; μ = water viscosity; S_e = specific surface area, m^{-1}; and V_∞ = superficial velocity (m/s).

To find the head loss variation, it is necessary to simulate the filtration with a pilot filter. The filter was constructed of stainless steel with a 20 cm square section, using the medium filter with PS granules (Fig. 6).

The relation L/d (layer's height/specific diameter of the grain) was approximately 1,426 [14]. The operation rate was 208 ± 1.01 m^3/m^2.d with variable hydraulic load. The raw water source Peri Lagoon (Santa Catarina/Brazil), reaches a reservoir and is conducted by a constant level chamber with a pump. This level chamber has a hole which leads the water (already with an established flow) until the rapid mixing unit, which receives the polyaluminum chloride coagulant at a dosage of 1.08 mg Al^{3+}/L and a gradient rate of 1,200 s^{-1}. The parameters were defined in bench tests (jar-test). The employed technology treatment was a direct filtration (coagulation–filtration). Then, after coagulation, the water was referred to a second-level chamber, which feeds into down flow filters. The filter runs were completed when the head loss reached 2 m, which were controlled by piezometers. At the end of the filter runs, backwashing was performed using the following steps:

(1) The air was introduced into the bottom of the filter bed, with a rate of 20 NL/min and a pressure of 8 kgf/cm for 5 min;
(2) After 5 min of air, the wait time had an interval of 1–2 min (to ensure no loss of material);
(3) After step 2, water was introduced in an upward flow for 22.8 m/h for 10 min. The expansion of the material reached 200%;
(4) The wait time was 1–2 min apart and steps 1, 2, and 3 were repeated for a total of 36 min of backwashing.

With this process, the material was visually clean and the backwash water was visually clear.

Nine (9) backwash procedures were performed (between filter runs) according to the procedure described. Based on this performance, the backwash process was possible. However, the timings of the air and water applications and their velocities should be better analyzed and their values should be optimized.

3. Results and discussion

The objective of this study was to characterize the PS granules as possible filter elements for rapid filtration, compared to sand and anthracite. Currently, the physicochemical parameters were not evaluated, only the physical parameters were characterized, i.e. the particle size, density, hardness, acid, and caustic resistance. By obtaining these values, and following the mathematical models presented by Turan et al. [8] and Naseer et al. [9], it was possible to calculate the porosity, hydrodynamic shear stress and turbulence. This suggested that the superficial velocity with values between 0 and 83.3 mm/s (300 m/h) and the expansion coefficients were also calculated by Eqs. (6) and (7). The results relative to superficial velocity and calculated porosity are shown in Fig. 7.

Fig. 7 illustrates an influence of the filter media on the backwash rates necessary for the fluidizing medium. It is noticed that the lighter grains should have a lower velocity for backwashing. While PS spheres need 2.2 mm/s (7.9 m/h) (expansion between 65 and 85%) to achieve porosity of 0.72 approximately, the sand needs 50 mm/s (180 m/h) for the same function. The deflections shown refer to a cumulative error of experimental results.

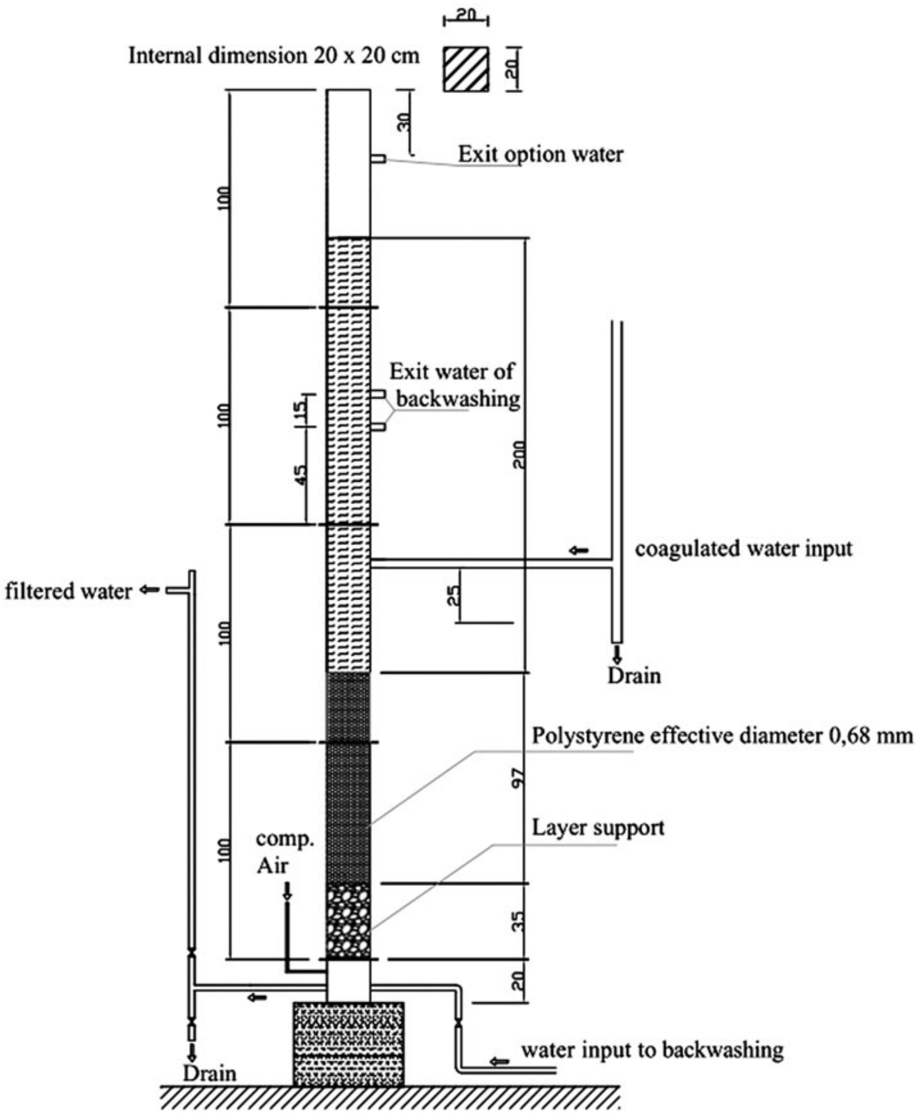

Fig. 6. Scheme of the pilot filter with PS granules as filter element (cm).

Once the porosity was determined, according to the change of surface velocity, the hydrodynamic shear stress was calculated. However, to arrive at their values, it was necessary to first determine the friction velocity, the α coefficient, and the Monin–Obukhov length. The results were related to the porosity calculated, shown in Fig. 8.

The hydrodynamic shear contributes to the detachment of the material adhering to the grains during filtration, and breaks the flakes that were formed during filtration, facilitating backwashing. In Fig. 8, a singular behavior appears between materials. It is believed that the hydrodynamic shear values are smaller with smaller porosities, because the friction between the particles is smaller due to low turbulence. The Fig. 8 presents its apex with porosities between 0.7 and 0.8 and increased porosity, the particles move away, thus, reducing the friction and the hydrodynamic shear stress.

Additionally, as seen in the results shown, PS beads have lower hydrodynamic shear stress, low velocity and high expansion (when compared to sand and anthracite). In this case, the deviation is so small that it is indistinguishable from the average. Thus, depending on the characteristics of the raw water to be filtered, the material retained by the filter and its amount, this agitation will not be sufficient for the detachment of particles. Therefore, this process will require a supplement for this task (e.g. introduction of air).

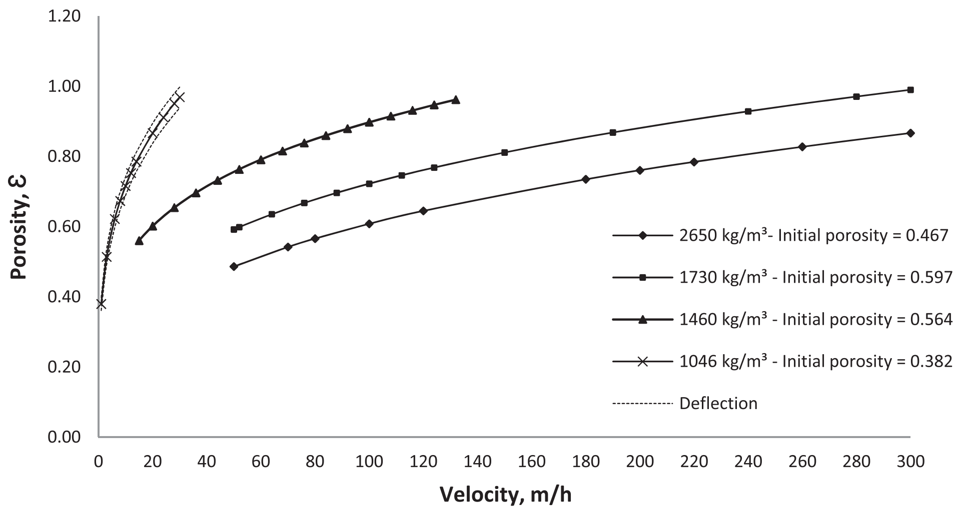

Fig. 7. The porosity calculated of the expanded bed vs superficial velocity of materials with different specific densities.

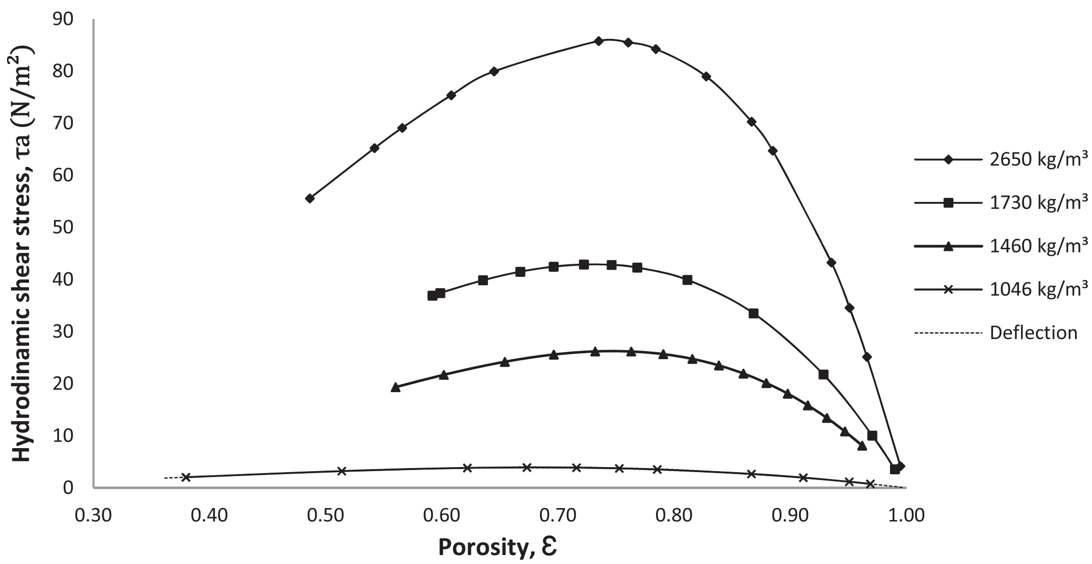

Fig. 8. Hydrodynamic shear-stress variation as a function of porosity for different media filters.

At first sight, the best material would have a higher density, because with a larger hydrodynamic shear stress and increased friction, it would release the detachment organic particles. However, this study is intended for the treatment of drinking water, and depending on the characteristics of the raw water, the use could be recommended.

With these parameters of friction velocity (Eq. (13)) and the universal constant (Eq. (10)), it is possible to calculate the velocity gradient (Eq. (14)). The results of the velocity gradient were related to fraction solids, shown in Fig. 9.

As seen in Fig. 9, the value of the velocity gradient increases with the solids fraction and the specific density of the filter material [8]. In addition, it is noticed that the lower superficial velocity will result in a higher velocity gradient. In observation of the PS beads, optimum shear conditions, or solid fraction of about 0.31 of the velocity gradient is $78\,s^{-1}$. Once the velocity gradient and hydrodynamic shear stress coefficient are determined, the dissipation of turbulence coefficient can be calculated by Eq. (17). The results were related to fraction solids and are plotted in Fig. 10.

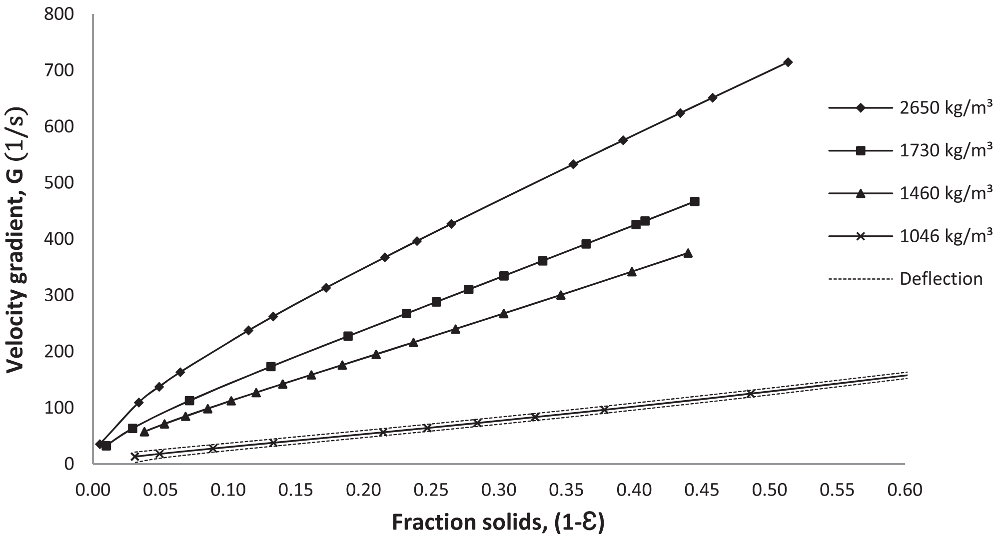

Fig. 9. Velocity gradient vs fraction solids.

The *Ca* value indicates the contribution of turbulence fluctuations for the total energy dissipation in a filter. In all cases, it is observed in Fig. 10 that the maximum amount of *Ca* is in a solid fraction of about 0.1, this coefficient decreases by increasing the fraction of solids. It was observed that for these specific cases analyzed, the higher the density of the material, the greater will be the *Ca*. This may mean that the power dissipation will be lower when the material is lighter. However, this observation needs to be further analyzed, because according to the bibliographies, the higher the density and grain size, lower will be the dissipated energy [8,9].

Finally, with the turbulence dissipation coefficient, the parameter of turbulence was determined by Eq. (18). As the other parameters, the turbulence parameters are related to the values of solid fraction. The results are shown in Fig. 11.

This parameter characterizes the effect of turbulence and its intensities. It is observed that the turbulence intensity increases by increasing the fraction of solids. In addition, the specific density increased and the size of the grains decreased. PS granules are more susceptible to turbulence when compared to anthracite and sand, which being heavier (denser) need higher velocities and larger fraction solids to achieve higher values of turbulences. In this

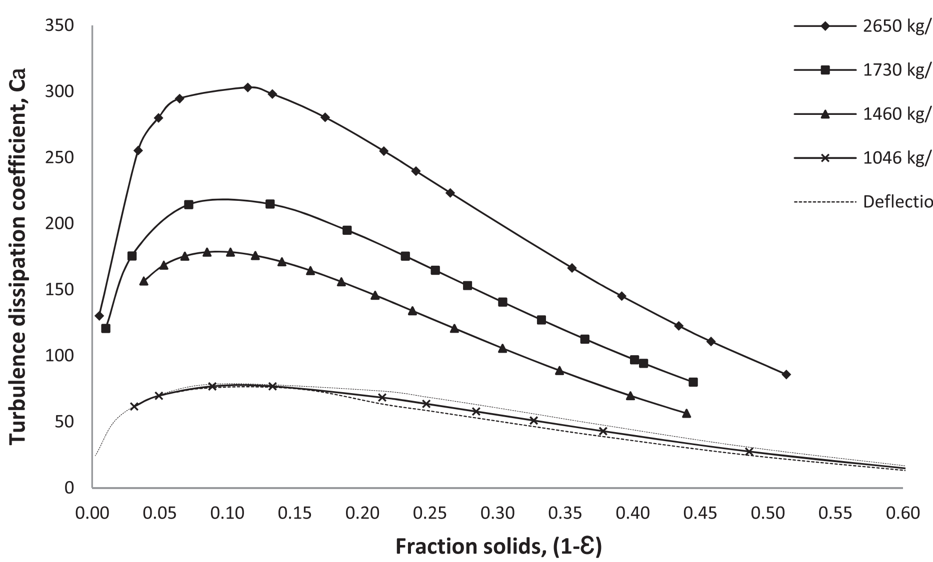

Fig. 10. Turbulence dissipation coefficient vs fraction solids.

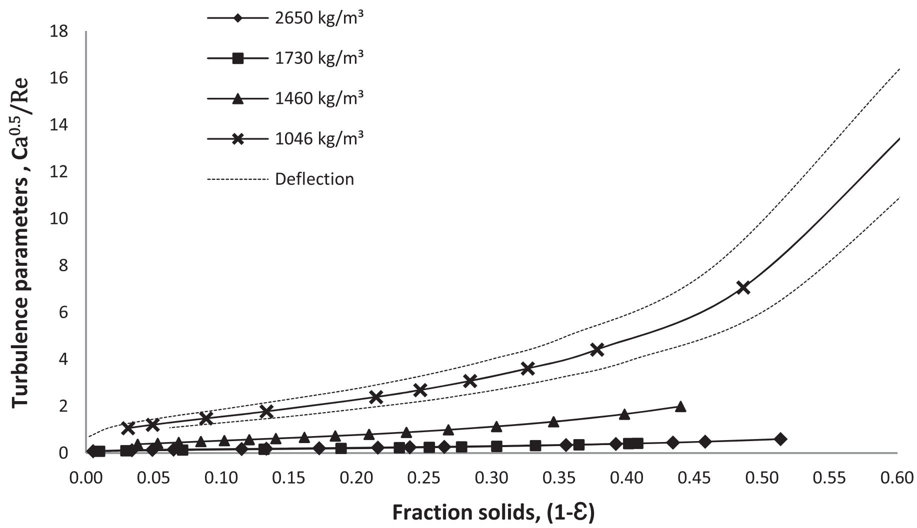

Fig. 11. Turbulence parameters vs Fractions solids.

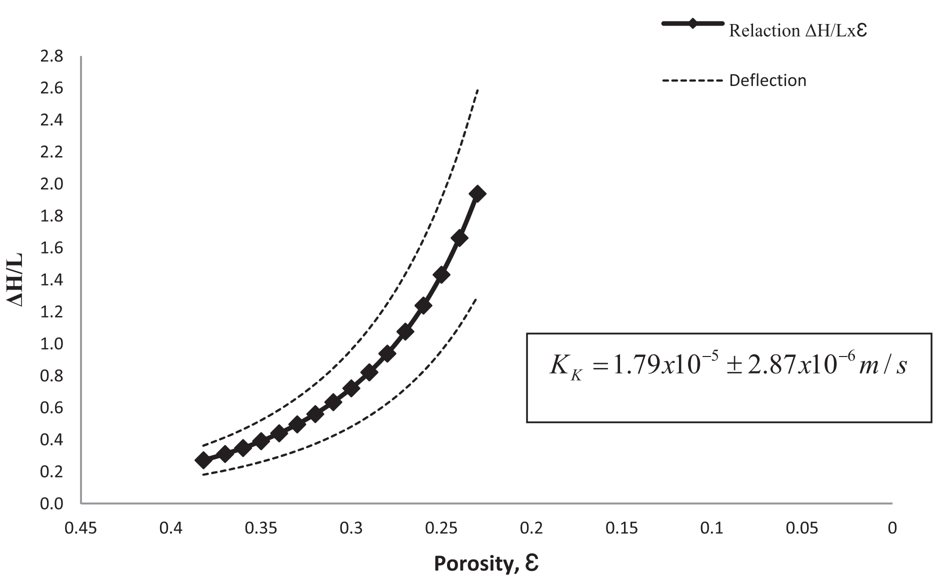

Fig. 12. Curve $\Delta H/L$ on different stages of clogging of the filter according to the permeability coefficient.

case, the greater the solid fraction and turbulence parameters, the greater the deviation. The turbulence during the backwash assists in the detachment of adhered particles during filtration. When the particles are loose and smaller, they are carried out of the filter more easily during the cleaning procedure.

To determine the permeability coefficient, the only characteristic used was the parameter of the PS material. In this case, the modeled backwashing parameters were not considered. The head loss of the clean media filter was measured at the start of each filtration, which was 10 times. At this stage, different backwash cycles and a decreased initial permeability, due to different head loss and initial porosity were considered.

For the initial porosity of 0.382 ± 0.0045, the head loss (ΔH) and thickness filter media (L) relation were 0.27 ± 0.04 m (27 ± 4 cm). Therefore, the permeability coefficient of PS granules as a media filter in water with a temperature of approximately 25℃ was calculated. Results can be seen in Fig. 12.

The permeability coefficient of this head loss variation, with the porosity decreasing due to filter clogging was $1.79 \times 10{-}5 \pm 2.87 \times 10{-}6$ m/s. The dotted line indicates the variation according to the experimental results. Compared with the coefficient of permeability of the sand (usually found), the result for the granules of PS was satisfactory, as in sand beds without fine particles, for example (with a greater than 2 mm diameter), the value of the coefficient of permeability is greater than 1×10^{-4} m/s, while in thin beds of sand (less than 0.074 mm diameter) the values found are below this value.

4. Conclusions

According to the presented models and tests, it appears that the physical characteristics of PS granules showed a capacity to be used as a filter element for down-flow rapid filters. However, the physical–chemical parameters, among others, must be analyzed. The material has a particle size similar to sand with grains approximately homogeneous. It presents a sphericity of 0.96 ± 0.086 and low roughness, which although not recommended for filtration proved valuable in the backwashing process. The material is lightweight, which was a sought-after characteristic for this study. PS granules showed minimum fluidizing velocity of approximately 0.248 ± 0.16 mm/s (0.89 m/h) in experimental expansion tests, which can bring economic benefits to cleaning systems of down-flow rapid filtration for drinking water treatment. It has significant caustic and acidic resistances, generating no by-products in water. It has a decreased hardness of 15.2 ± 1.15 HV, which corresponds to one MOH, but has a notable plasticity, so that the material does not break, but displays deformations, therefore, that feature must be evaluated for long-term use.

It is still premature to talk about the limits of use, design, and implementation methodology, because parameters relevant to these factors are still being analyzed. However, during backwashing, special care is necessary because it is an element of low density. As verified through experimental tests, expansion low velocities are needed for the fluidization of the PS granules, which would result in smaller volumes of water during the cleaning process. However, it is necessary to check other important parameters during the backwashing process, such as the hydrodynamic shear stress, the velocity gradient, and the turbulence involved in the process of the detachment and breaking of the flakes adhered during filtration. These parameters were modeled. It was modeled that a low velocity is necessary to achieve a porosity approximated of 0.7 (expansion between 65 and 85%), or 18 times lower than the velocity applied to the sand so that it reaches the same condition of porosity during expansion. In addition, the velocity gradient needed for the same fraction of solids would be six times lower. Although lighter and smaller grains would increase the rate of turbulence in relation to the larger and heavier grains, they would present a low hydrodynamic shear-stress coefficient and low dissipation of turbulence. Depending on the features of raw water, this filter requires a support to increase the shear during backwashing, in order to break the flakes formed by the impurities retained during filtration. An applied study on what would be the best way to increase this shear is recommended. One possibility is the introduction of clean air, which would be appropriate in this case, because lower airflow would be sufficient, since it is a lightweight material. During the experiment to determine the coefficient of permeability, backwash procedures were performed after ending the course of filtration. In this backwash process, air was used to break the flakes formed during filtration and the values of the pressure drop were recorded at the beginning of each filtration process. The backwash by air apparently shows good results, but must be better analyzed.

The result of the permeability coefficient is satisfactory. Additionally, this experiment indicated that this element can be used as a filter medium and it is possible to perform backwashing, as the rate of backwash (water) needs to be large enough to drag the particles collected during filtration. These elements suggest that in order to reach an optimum backwash velocity, it is essential to know the raw water to be treated, because the dragging depends on the characteristics of these impurities retained during filtration. Additionally, low settling velocities suggest that there will be a need for more time to perform backwashing due to low velocities.

Furthermore, other parameters still need analysis for the use of this material, such as its filtration capacity by filtration index, the action of the depth of this filter, seeking the optimal thickness, and the final quality of the filtered water. A further investigation of the time necessary for backwashing, and whether the main velocity decreases the volume of filtered water used in the cleaning process will be explored.

As an advantage, the material exhibits a smaller head loss in backwashing, showing the possibility of cost reduction in the construction of cleaning systems, or with the use of pumps with less power, or the construction of lower reservoirs.

Acknowledgement

The author acknowledges the support of the FINEP/HABITARE, FAPESC/PRONEX, and Cnpq (National council of technological and scientific development).

List of symbol

Vmf	—	minimal fluidization velocity
G_a	—	Galileo number
μ	—	water viscosity to 25°
ρ_w	—	water density to 25°C
ρ_s	—	specific density of material
deq	—	equivalent diameter
K_V	—	head loss coefficient due to viscous force
K_I	—	head loss coefficient due to inertial force
ε	—	porosity
L	—	depth of granular media
V	—	superficial velocity
g	—	acceleration to gravity
d	—	media grain diameter
C_e	—	sphericity coefficient
V_t	—	terminal settling velocity and Ret is the Reynolds number relative to the terminal settling velocity
V	—	superficial velocity
V_i	—	interception velocity
n	—	expansion coefficient bed
ε	—	fluidized porosity bed
ψ	—	grain sphericity
L	—	depth of expanded bed
L_0	—	depth of fixed bed
ε_0	—	porosity of fixed bed
P_d	—	power dissipation
C	—	dissipation coefficient of turbulence during total dissipation energy
β	—	represents the random motion of grains
$\alpha_1 = {}^{V_i}/_{V_t}$	—	coefficient related to grain characteristics
K_0	—	Von Karman universal constant for pure water flow is 0.4 and
$(1-\varepsilon)$	—	fraction solids or concentration
ρ_a	—	specific density of fluid and grain mixture
V_*	—	friction velocity
K_K	—	Kozeny coefficient
ΔH	—	Head loss (m)
S_e	—	specific surface area, m^{-1}

References

[1] P. Knudsen, The effect of media selection on filtration performance, Proc. Eng. 8 (1980) 41–43.

[2] R. Fabris, C.W.K. Chow, M. Drikas, B. Eikebrokk, Comparison of NOM character in selected Australian and Norwegian drinking waters, Water Res. 42 (2008) 4188–4196.

[3] Brazilian Standard, Soil Particle size analysis. Test method, single vol., 1984, pp. 1–13.

[4] AWWA (American Water Works Association), Water Quality and Treatment. Granular Media Filtration, McGraw-Hill, New York, NY, 1999.

[5] ASTM D 543 (American Society for Testing and Material), Standard Practices for Evaluating the Resistance of Plastics to Chemical, ASTM International, West Conshohocken, PA, 1995.

[6] C.Y. Wen, Y.H. Yu, Mechanics of fluidization, Chem. Eng. Progress Sym. Series 62 (1966) 100–111.

[7] J.L Cleasby, K.S Fan, Predicting fluidization and expansion of filter media, JEED-ASCE 107 (1981) 455–471.

[8] M. Turan, E. Sabah, H. Gulsen, M.S. Celik, Influence of media characteristics on energy dissipation in filter backwashing, Environ. Sci. Technol. 37 (2003) 4288–4292.

[9] R. Naseer, A. Alhail, L. Xi-Wu, Fluidization and optimum backwashing conditions in multimedia filter, Res. J. Appl. Sci. Eng. Technol. 3 (2011) (2011) 1302–1307.

[10] N.R. Mohammed, S. Abualhail, L. Xi-Wu, Fluidization of fine particles and its optimal operation condition in multimedia water filter, Des. Water Treat. 51 (2013) 4768–4778.

[11] J.F. Richardson, W.N. Zaki, Sedimentation and fluidization: Part I, Trans. Instn. Chem. Engrs. 32 (1954) 65–73.

[12] M. Turan, Velocity gradient in filter backwashing, J. Environ. Eng. 118 (1992) 776–790.

[13] A.S. Monin, A.M. Obukhov, Buoyancy Effects in Fluids. Cambridge University Press, Cambridge, England, 1973.

[14] J. Crittenden, R. Trussel, D.W. Hand, K.J. Howe, G. Tchobanoglous, Water treatment principle and design, MWH 2 (2011) 880–932.