

## Use of filterability index in granular filtration: effect of filter medium type, size and shape

Selda Yiğit Hunce, Elif Soyer and Ömer Akgiray

### ABSTRACT

Ives' Filterability Index (FI) was employed to evaluate silica sand versus crushed recycled glass as a rapid filter media. The presence of past studies comparing these two media allows an evaluation of the applicability and utility of the FI concept as a simple and quick preliminary test for the assessment of different media to be used in water filtration. The present tests also allow an evaluation of the effect of shape on filter performance.

**Key words** | crushed glass, Ives' Filterability Index, porosity, rapid filtration, silica sand, sphericity

Selda Yiğit Hunce  
Elif Soyer  
Ömer Akgiray (corresponding author)  
Department of Environmental Engineering,  
Marmara University,  
Istanbul,  
Turkey  
E-mail: omer.akgiray@marmara.edu.tr

### INTRODUCTION

Solids removal efficiency of a granular filter depends largely on the characteristics of water which are in turn influenced by processes used for conditioning the water such as coagulation-flocculation, clarification, and the addition of an oxidant. The main concern of an operator in a water treatment plant is the selection of the most efficient coagulant and coagulant aid and their dosages under a variety of conditions. These may include changes in quality of an existing water source or a decision to switch to a new supply. On the other hand, the design of a new water filter unit may require consideration and evaluation of different types of media and their properties in addition to the quality of the water to be treated.

It is well known that effective operation of granular filters requires appropriate pretreatment. Systems to be included in pretreatment steps depend on raw water quality and turbidity. General water quality limits and type of pretreatment required vary for different filter types. In a direct filtration treatment train which includes coagulation, flocculation and filtration without a separate sedimentation basin, all solids are removed in filtration and the raw water turbidity should be less than 80 Nephelometric Turbidity Units (NTU) (Castro *et al.* 2005). In the process called in-line filtration, the treatment scheme does not include a flocculation basin. In these systems flocculation occurs in the

conduit between rapid mixing and the granular filter, in the water column above the filter media, and within the filter media. Raw water turbidity for in-line filtration systems should be less than 20 NTU (Castro *et al.* 2005). In both direct filtration and in-line filtration, filter beds must be designed to include increased floc storage capacities. Although deeper dual- and mixed-media filters allow the treatment of high turbidities (i.e. 20 and 80 NTU as given above), direct filtration and in-line filtration are generally employed for higher-quality waters with a turbidity of 10 NTU or less, with occasional spikes up to 40 NTU. In treatment plants which include conventional filtration, raw water is treated through coagulation, flocculation and clarification followed by rapid filtration. Maximum raw water turbidity can be as high as 3,000 NTU.

Whenever metal salts are applied in water treatment, a number of parallel and sequential reactions occur. Reaction products and effectiveness of the coagulation process depend on raw water quality and turbidity. Jar testing is required for coagulant/coagulant aid selection and determination of dosages. Typical dosage of alum or aluminum sulfate ranges from 10 to 150 mg/L. It is commonly used in hydrated form as  $\text{Al}_2(\text{SO}_4)_3 \cdot x\text{H}_2\text{O}$ , where  $x$  is usually 14 or 18. Typical dosages of ferric sulfate  $[\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}]$

and ferric chloride [ $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ ] range from 10 to 250 mg/L and 5 to 150 mg/L, respectively (Crittenden *et al.* 2005).

Organic polymers or polyelectrolytes are generally used together with metal coagulants to promote the formation of larger and more shear-resistant flocs. Low dosages of high molecular weight polymers (0.005–0.05 mg/L) can be added before granular filtration and to the backwash water to improve filter performance. Care should be exercised in selecting the appropriate dosage of polymer to prevent formation of mudballs that may be difficult to remove during backwashing (Crittenden *et al.* 2005).

Filter efficiency is determined by physical characteristics such as grain size, shape, porosity, and bed depth/media grain size ratio. Kawamura (2000) suggests using  $L/d_e$  ratio for the design of filter beds where  $L$  is the depth of the filter bed (mm) and  $d_e$  is the effective size of the filter medium.  $L/d_e$  ranges between 1,000 and 2,000 for different filter beds: 1,000 for ordinary mono-medium sand and dual-media beds, 1,250 for regular tri-media beds (coal, sand, and garnet), 1,250 to 1,500 for coarse deep mono-medium beds in which  $d_e$  is 1.2 to 1.4 mm, and 1,500 to 2,000 for very coarse mono-medium beds in which  $d_e$  is 1.5 to 2.0 mm. It is also emphasized that pilot studies are recommended in the selection of filter depths when the medium is larger than 1.5 mm. Kawamura (2000) also recommends using  $L/d_e$  ratios that are increased by 15% to achieve filtered water turbidities less than 0.1 NTU.

Filter media and their characteristics, filter depth, suggested coagulant dosages for different operating conditions and for different types of water sources are well documented in many references. Although these reflect the results of significant amount of data and experience and are helpful in design and operation of filters, a parameter or an index indicating performance of the system considered would be very convenient to use.

As emphasized by Cleasby (1969), who explained the need for and reviewed past attempts at the development of such an index, the standardized filtration time test using membrane filters has drawbacks of inadequacy in indicating particle removal or head loss development in a granular filter. The Filter Performance Index (FPI) proposed by Gamet and Rade-mecher was modified by the AWWA Task Group by introducing a limiting factor for the duration of a filter run. FPI is given by the following equation and the length of a

filter run in this equation is the time before observing any deviation from a preset effluent quality (Cleasby 1969):

$$\text{FPI} = \frac{(\text{filtration rate}) (\text{filter run length})}{\text{head loss at the end of run}}$$

A similar index was then suggested by Cleasby (1969):

Filterability Index

$$= \frac{\left( \begin{array}{c} \text{particle removal along a certain depth} \\ \text{specific deposit accumulated at the same depth} \end{array} \right)}{\text{head loss}}$$

Several years later a different expression with the same designation was proposed by Ives (Ives 1978). A unique setup was designed for operators to conduct the test and compare relative values of the Filterability Index (FI) within the framework of an experimental matrix. The Ives' FI is defined as follows:

$$\text{FI} = \frac{C}{C_0} H \frac{1}{V T}$$

Here  $C$  = filtrate quality,  $C_0$  = inlet water quality,  $H$  = head loss (m),  $V$  = filtration rate (m/h),  $T$  = length of filter run (h). This index has been used by several researchers to assess the effectiveness of filtration (Amirtharajah & Trusler 1986; Graham *et al.* 1992; Cikurel *et al.* 1996; Kang *et al.* 1999; Tchio *et al.* 2003; Jiao *et al.* 2016; Soyer 2016; Jiao *et al.* 2017; Schöntag *et al.* 2017).

Pilot-scale testing of filter media such as silica sand and crushed recycled glass has been reported in previous studies (Yüksel *et al.* 2002; Aksoğan *et al.* 2003; Yüksel *et al.* 2003; Soyer *et al.* 2010, 2013). Especially when new and different media, unconventional rates and/or different coagulants are planned, pilot testing is indispensable for the collection of data to be used in filter design. Pilot tests, however, can be time-consuming and relatively expensive. The FI concept is therefore very attractive as it can obviate the need for weeks or months of preliminary testing when for example unconventional media types or specifications are considered. Unfortunately, the usefulness and validity of the Ives' FI have not been studied to a satisfactory extent so far in the literature. It is therefore still not clear if this index can serve as a simple and inexpensive measure of filtration effectiveness in a capacity similar to that served by the jar test for coagulation and sedimentation. The main motivation for this research was therefore to investigate

the usefulness of the Ives' Index for the stated purpose. Towards this end, this study focuses on the applicability of the Ives FI concept to the comparison of crushed glass and sand media. These two types of medium were selected as they were previously studied and compared extensively in pilot-scale tests by the authors. The presence of such past pilot scale experience with the media to be tested allows a more meaningful evaluation of the FI as a useful simple tool for filter performance assessment.

## METHODOLOGY

### Preparation of filter media

Silica sand was obtained from a water treatment plant located in Istanbul. Recycled glass material obtained from a glass factory was crushed in a jaw crusher to reduce the average size of particles from several centimeters to millimeter-scale. Five different fractions of sand and crushed glass were prepared using a Ro-Tap sieve shaker (Retsch AS200 tap). The sieving process was carried out in accordance with ASTM standards (ASTM C136/C136M-14, 2014). Further crushing and sieving were conducted when the amount of glass material retained in the sieves was insufficient. Glass particles obtained during this repeated-crushing process were observed to have slightly different shapes than the particles prepared by crushing only once. Sharp edges were abraded and rounded during repeated crushing. Therefore, glass fractions obtained by crushing once and twice were not mixed and named as 'crushed glass (CG)' and 're-crushed glass (ReCG),' respectively. Each fraction was thoroughly cleaned, labeled and stored prior to

characterization experiments. The overall procedure applied for the preparation of glass fractions is given in Figure 1. The fractions of sand, crushed glass, and ReCG that were prepared and tested in this study are 1.40–1.18 mm, 1.18–1.00 mm, 1.00–0.85 mm, 0.85–0.71 mm, and 0.71–0.60 mm (sieve sizes are written with the format 'passing sieve size – retaining sieve size'). Samples of 1.00–0.85 mm size fractions of sand, CG and ReCG are shown in Figure 2(a).

### Particle size, density and shape characterization

Particle densities of fractions were measured by a water displacement technique using pycnometer bottles. The volume equivalent diameter of fractions were calculated by i) counting and weighing 500 grains of each fraction, ii) calculating the volume of one grain using its particle density, iii) equating the volume of one grain to the volume of equivalent sphere. Particle sphericity, which is one of the most widely used parameters for defining shape of an irregular material, was determined by collecting the fixed-bed head loss data for each fraction and using the Ergun equation (Ergun 1952; Cleasby & Fan 1981; Soyer & Akgiray 2009).

### Filterability apparatus

FI apparatus developed by Armfield Co. was used in the experiments (Figure 2(b)). The setup included a Perspex column of 4 cm internal diameter and 7 cm length. Filter material to be tested is placed into the column and is supported by a 100  $\mu\text{m}$  stainless steel screen which is fitted to the bottom of the column. The filter column receives flocculated water from a 1.5-L conical reservoir. Filtration rate and

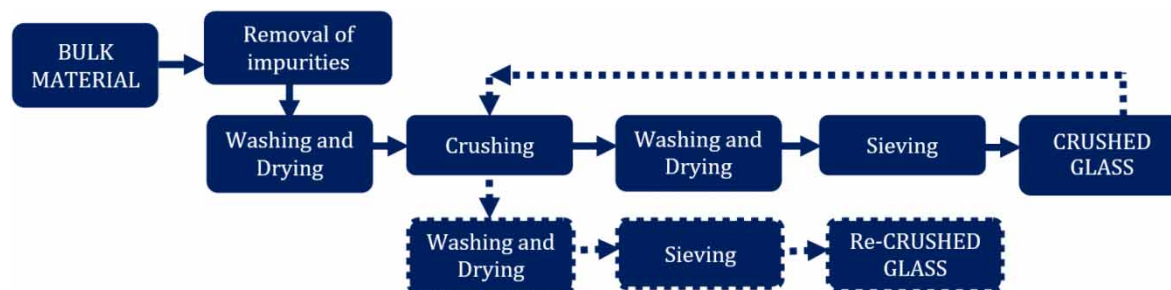
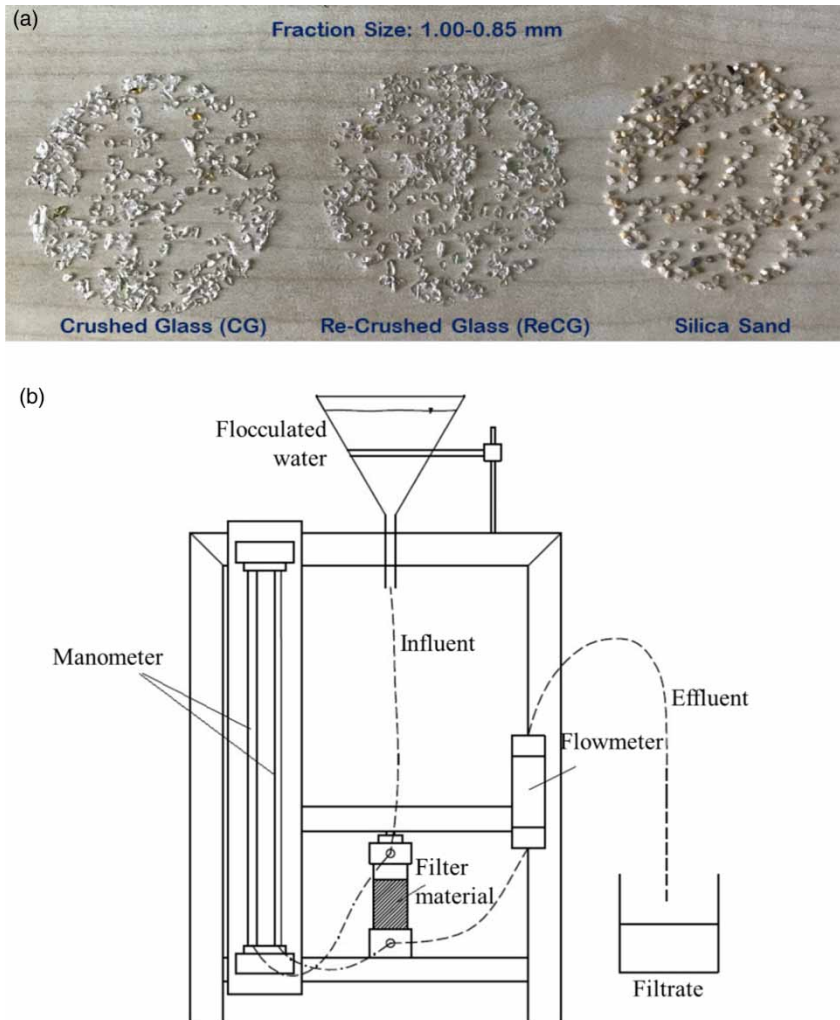


Figure 1 | Preparation steps of crushed glass (CG) and re-crushed glass (ReCG).



**Figure 2** | Glass and sand particles of 1.00–0.85 mm fraction (a) and Filterability Index setup (b).

filter bed head loss are measured with the help of a flow-meter and a water manometer, respectively.

### Raw water preparation

Raw water samples used in the filtration experiments were prepared by mixing kaolin clay stock solution with tap water. The turbidity of resulting samples was around  $8.75 \pm 0.4$  NTU. High intensity sonication (Bandelin Sonopuls HD 3220) was used to help dispersion of the clay particles. A target raw water turbidity slightly less than 10 NTU was selected because 10 NTU is normally the suggested maximum limit for direct filtration (Cleasby & Logsdon 1999). It should be remembered that the experimental setup

employed in this study has a design suitable for mimicking direct filtration (Ives 1978). Furthermore, the settled water turbidity (i.e. the turbidity of the water entering the filters) is normally below 10 NTU in conventional treatment that includes sedimentation (Tobiason et al. 2011).

### Pretreatment conditions and filtration rates

Filterability experiments were conducted with three different size fractions (0.85–0.71 mm, 1.00–0.85 mm and 1.18–1.00 mm) of each material. The experiments were repeated at two different flow rates (5 and 10 m/h) for each fraction. Raw water was coagulated using alum  $[\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}]$ . The effect of dosage was studied (for one fraction of each

material and at 10 m/h) by adding alum at four different concentrations: 25, 50, 75, and 100  $\mu\text{M}$  Al, which correspond to 8.3, 16.7, 25, and 33.3 mg/L as  $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ , respectively. Following rapid and slow mixing stages, the sample was filtered (bed height = 5.5 cm and column diameter = 40.14 mm). 1 L of sample was flocculated by rapid mixing for 30 seconds and slow mixing for 10 minutes in all the experiments. The conditions selected here are within the range of design detention times that are commonly employed in coagulation-flocculation (typical mechanical rapid and slow mixing units are designed to have detention times of 10–60 seconds and 10–30 minutes, respectively, cf. Delphos & Letterman 2012). Following the protocol proposed by Ives (1978), the following data were recorded when the volume of filtered water was 1 L: total head loss, elapsed time to collect 1 L of filtrate, and average turbidity of the filtered water.

### Bed porosity

Filter bed porosity was calculated using the formula:

$$\text{porosity} = 1 - [\text{particle volume} / \text{bed volume}].$$

Bed volume is found by multiplying cross sectional area of the column and bed depth. Volume of particles in the column is calculated using the mass of particles and particle density. An easily reproducible technique was developed to determine the required amounts of silica sand, CG and ReCG. Each filter medium was loaded into the filter cell of the filterability apparatus up to a marked level (5.5 cm). Air bubbles entrapped between the particles were removed by stirring the material with a glass rod. The filter cell was placed in a large container containing water during this process so that water penetrating from the bottom support sieve filled the spaces between the grains. Material in the cell was shaken manually every time a new spoon of sample was loaded to compress it. Then, all the material was carefully removed and dried in an oven at 103–105 °C.

## RESULTS AND DISCUSSION

Filter bed porosities determined according to the procedure given above are shown in Figure 3. It should be noted that

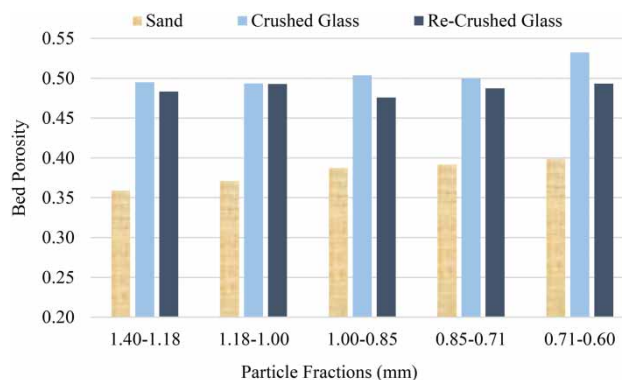
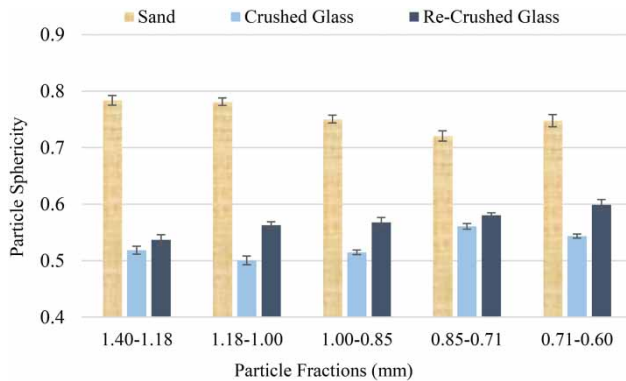


Figure 3 | Filter bed porosity of sand, crushed glass and re-crushed glass particles.

fixed-bed porosity depends on a number of factors (such as how the bed is prepared, absence or presence of vibrations during preparation, particle to column diameter ratio) and does not have a unique value for a given material. The numbers reported in Figure 3 resulted from the preparation method described earlier and correspond to nearly the most compact beds (lowest porosities) obtainable for each material. It may be noted that the porosity of a full-scale filter is difficult to measure accurately and that there is evidence indicating that full-scale filters usually have lower porosities than pilot-scale filters (Trussell *et al.* 1999). It should also be remarked that the most important point here is that all the beds in this study were prepared using exactly the same steps, resulting in similar bed compactness for all the beds. Since fixed-bed head loss (conductivity) strongly depends on porosity, preparing different beds in different manners (some beds in loose condition, others in more compact forms) could possibly lead to misleading conclusions. In this research, the method used to remove bubbles from the bed resulted in compact beds, although compacted beds were not specifically targeted (all the beds could, for example, be in a loose condition as long as they were all prepared using the same method). Based on Figure 3, the following observations can be made: In general, crushed glass has higher porosities than silica sand (0.36–0.40). This is consistent with the fact that crushed glass has a lower sphericity than silica sand (see Figure 4). It is well known that bed porosity increases with decreasing sphericity (Foust *et al.* 1960). Furthermore, ReCG has slightly lower porosities (0.48–0.49) than those of glass crushed once (0.49–0.53) and this is also consistent with

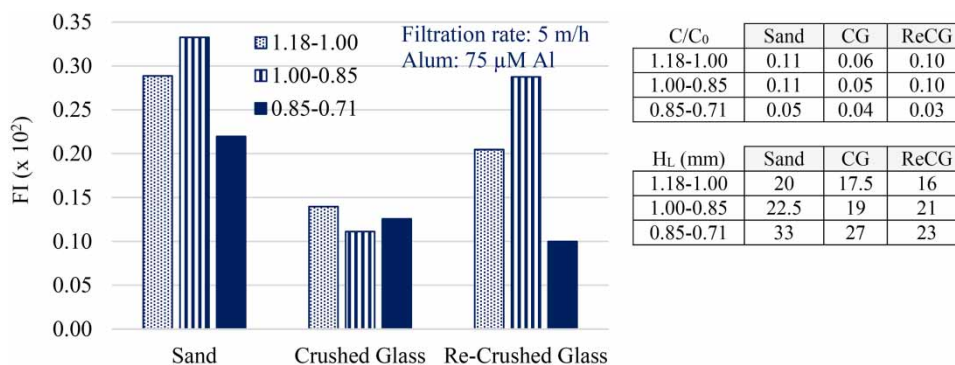


**Figure 4** | Particle sphericities of sand, crushed glass and re-crushed glass particles.

the higher sphericity of ReCG. With regard to the effect of particle size on porosity, the following were observed. Focusing on the sand fractions, it is seen that larger sizes lead to slightly lower porosities. The same trend is not apparent for the glass fractions. It may be noted that the column diameter to particle diameter ratio  $D/d$  varied between nearly 30 to about 60 in these measurements and the effect of wall on porosity is negligible in this range (Pottbacker & Hinrichsen 2017). The variation observed for sand may be partially explained by the fact that the sphericity of sand increased with size (Figure 4), and higher sphericities may have led to lower porosities. For crushed and ReCG fractions, on the other hand, an opposite trend in sphericity is observed. Based on this, it could be expected that the porosity of glass fractions would increase with increasing size, but such a trend is not observed. This finding may be related to the method of preparing the beds (which involved manual shaking instead of a standardized mechanized vibration technique) and requires further investigation.

Sphericity values obtained from fixed-bed head loss data in conjunction with the Ergun equation are found to be as follows: Silica sand: 0.72–0.78, Re-crushed-glass: 0.54–0.60, Crushed glass: 0.51–0.56 (Figure 4). Each of these values is based on at least fifteen separate measurements. It is seen that sand fractions have higher sphericities compared to the glass fractions. This finding is consistent with the measurements previously reported for crushed glass fractions obtained with a different crusher and with a different set of sieves (Soyer & Akgiray 2009). ReCG fractions always have higher sphericities than glass fractions crushed only once. This finding is also consistent with the visual observation of the mentioned fractions: it was visually apparent that glass crushed twice was more rounded and has a smaller proportion of sharp edges and elongated particles. A similar observation was made in an earlier work (Soyer & Akgiray 2009). There is some variation in sphericity values obtained with different fractions of the same material. This is expected and is consistent with previous observations (Cleasby & Fan 1981; Soyer & Akgiray 2009).

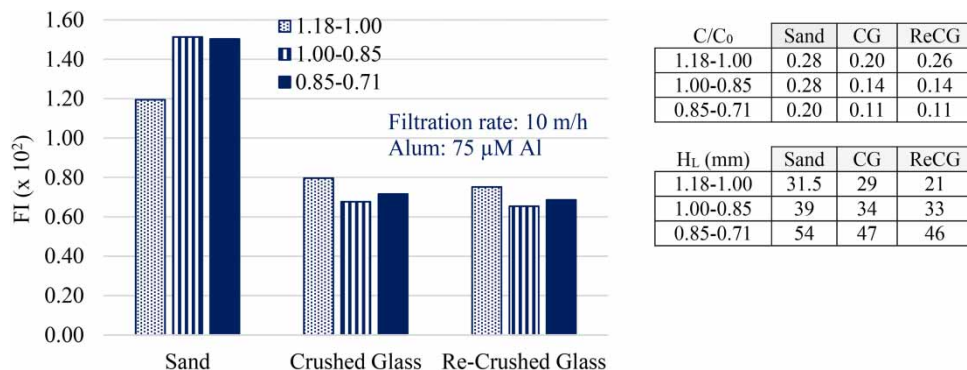
Filterability experiments were conducted with three different size fractions (0.85–0.71 mm, 1.00–0.85 mm and 1.18–1.00 mm) of each material. Filterability was measured according to the method described by Ives (1978). The experiments were repeated at two different flow rates and the results are reported in Figures 5 and 6. Observed values of head loss ( $H_L$ ) and effluent quality ( $C/C_0$ ) are also reported in these figures. An examination of the bar diagrams on the left side of each figure shows that better (i.e. lower) FI values were obtained with the glass fractions. One of the most striking effects of rate increase from 5 to 10 m/h is that the FI



**Figure 5** | Filterability Index of materials (5 m/h filter rate and 75 µM Al coagulation).

$C/C_0$	Sand	CG	ReCG
1.18-1.00	0.11	0.06	0.10
1.00-0.85	0.11	0.05	0.10
0.85-0.71	0.05	0.04	0.03

$H_L$ (mm)	Sand	CG	ReCG
1.18-1.00	20	17.5	16
1.00-0.85	22.5	19	21
0.85-0.71	33	27	23



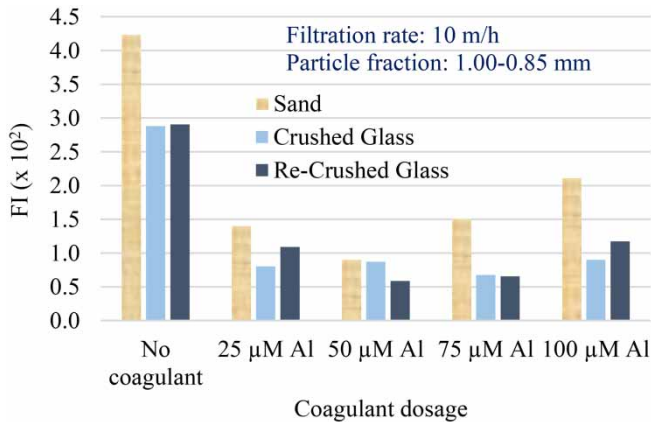
**Figure 6** | Filterability Index of materials (10 m/h filter rate and 75 µM Al coagulation).

values increased nearly five-fold. This means that higher rates result in poorer filtrate quality and/or higher head loss values. While both of these effects are consistent with filtration theory (Crittenden *et al.* 2005), more insight can be gained by examining the effluent quality and head loss values reported on the right side of each figure. For the sand fractions, it is seen that effluent turbidity increased by a factor of 3 to 4, whereas head loss increased by a factor of 1.5 to 2. For the once-crushed glass fractions, effluent turbidity increased by a factor of 2.5 to 4, whereas head loss increased again by a factor of approximately 1.5 to 2. For the ReCG fractions, effluent turbidity increased by a factor of 1.5 to 3, whereas head loss increased by a factor of nearly 1.5 to 2. Note that for a clean bed the head loss would be increased at least by a factor of two when velocity is doubled (Ergun 1952). In the present situation, however, the state of the bed (i.e. the amount and morphology of the accumulated dirt in the bed) is different at the end of the runs with the two rates. These considerations show that the increase in FI values results mostly from effluent quality deterioration when rate is increased.

The effect of the choice of the medium can be seen when each figure is examined within itself (Figures 5 and 6). As noted above, crushed glass yields better FI values with both rates. A number of researchers have noted that the use of angular (low sphericity) media results in improved performance (Trussell *et al.* 1980; Kawamura 1999), whereas others hold that ‘rounded particles produce clearer water than angular ones’ (Baylis *et al.* 1971; Hudson 1981). It may be noted that an angular medium (crushed glass) and a relatively round medium (silica sand) are compared here. Since

the two media have the same size in each comparison, the new data presented here may be relevant to the further assessment of this point. An examination of Figures 5 and 6 shows that smaller head loss values are obtained with the use of crushed glass instead of silica sand of the same size. This finding is consistent with the pilot-scale measurements carried out previously using graded media (Soyer *et al.* 2010). What is different here is that effluent quality is also observed to be better when crushed glass is used, whereas Soyer *et al.* (2010) found that effluent quality with crushed glass was only slightly better than or equivalent to the quality obtained with silica sand. It should be emphasized that the conditions and the scale of the tests in the two studies are different (sieved fractions instead of graded media are used in the present study) and exact agreement is not expected. Be that as it may, the current findings together with those reported by Soyer *et al.* (2010) indicate that angular media is indeed more effective in rapid filtration.

The effect of coagulant dosage was studied at the fixed rate of 10 m/h and a fixed size 1.00–0.85 mm and the results are displayed in Figure 7. The leftmost group of three bars shows the FI values when no coagulant was used, i.e. in the roughing filtration mode. Focusing on the sand filter first, it is seen that there is a significant improvement in performance as a result of the use of a coagulant. It can also be seen that the FI values continue decreasing until an alum dosage of 50 µM Al (16.7 mg/L as Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>·18H<sub>2</sub>O) and then the FI values start to increase. Similar trends are observed for the glass media. For crushed glass the minimum FI is observed at 75 µM Al,



**Figure 7** | Filterability Index of materials (10 m/h filter rate and 1.00–0.85 mm fraction).

whereas the minimum occurs at 50 μM Al for ReCG. The difference in FI values for 50 μM Al and 75 μM Al, however, is small for the latter and it may be argued that the optimum dosage is near 75 μM Al for both glass media. It is possible, however, that a dosage between 50 μM Al and 75 μM Al may be optimal for all three materials. Overall, glass media give equivalent or better FI values than those obtained with silica sand. This is consistent with the pilot scale results previously obtained with different coagulant types (alum and ferric chloride) and dosages at a similar flow rate (Soyer et al. 2010).

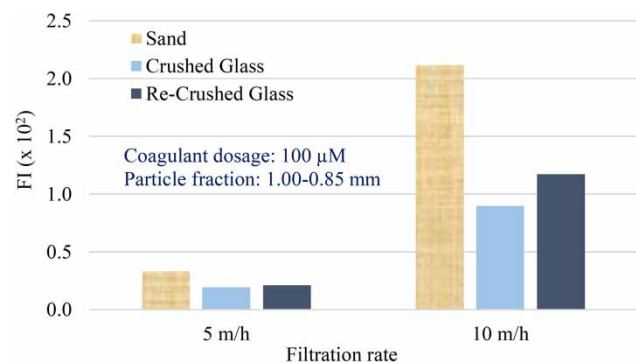
Further insight can be gained by an examination of the head loss and relative effluent quality values reported in Figure 7. It should be remembered that these are not instantaneous values; effluent turbidity values are average values based on the entire filtrate produced during an experiment and the head loss values are the total head loss values measured at the end of a run. It is seen that the effluent quality improves significantly with the use of the coagulant at the lowest dosage (compared to the roughing filtration mode) and then the quality continues improving, albeit at a lower rate with further increase in coagulant dosage until a certain point. The effluent quality starts to deteriorate after that dosage and this is observed for all three media. Similarly, the head loss increases above that observed without the coagulant as soon as the lowest dosage is employed. For the glass fractions, the head loss continues increasing at a lower rate with increasing dosage until it decreases at the highest dosage. A similar behavior is observed with sand, except that the decrease in head loss with increasing

C/C <sub>0</sub>	Sand	CG	ReCG
No coagulant	0.90	0.80	0.86
25 μM Al	0.26	0.20	0.26
50 μM Al	0.17	0.20	0.14
75 μM Al	0.28	0.14	0.14
100 μM Al	0.40	0.21	0.29

H <sub>L</sub>	Sand	CG	ReCG
No coagulant	34.5	26.5	25.0
25 μM Al	40.5	29.5	30.5
50 μM Al	40.5	32.5	31.5
75 μM Al	39.0	34.0	33.0
100 μM Al	39.5	32.5	30.5

dosage starts at a lower dosage. The increase in effluent turbidity may be explained by remembering that a shallow (5.5 cm deep) filter is used in these tests and the increased dosages may be expected to lead to the formation of increased amounts of flocs that would penetrate and pass through the bed after a certain point. If a deep filter had been used, these flocs would have been captured in lower sections of the bed and the head loss would continue increasing instead of leveling off. This point should be remembered in the application and interpretation of filterability data obtained with shallow beds.

From the results discussed above (Figure 7), it is seen that the FI value deteriorates at the highest coagulant dosage. These results were obtained with a filtration rate of 10 m/h. It is of interest to see what happens at this dosage when a lower rate is employed. Figure 8 shows the results obtained with 100 μM Al at the rate of 5 m/h together with the results



**Figure 8** | Filterability Index of materials (particle fraction 1.00–0.85 mm and 100 μM Al coagulant dosage).

at 10 m/h. It is seen that the filter performance improves drastically when the rate is decreased to 5 m/h. Most of the decrease in FI results from effluent quality improvement (Sand:  $C/C_0 = 0.11$  instead of 0.40, Crushed glass:  $C/C_0 = 0.08$  instead of 0.21, and ReCG:  $C/C_0 = 0.08$  instead of 0.29), although head loss is also less at the lower rate as would be expected. The 5 m/h rate has been the most commonly used rate historically, whereas modern rapid filters are normally designed to be operated at rates of 10 m/h and above (Tobiason et al. 2011). It is worth remembering that higher rates usually require the use of a polymer to supplement the main coagulant to achieve effective filtration.

## CONCLUSIONS

Filter material characterization and Ives' filterability experiments were carried out with three different media, namely silica sand, crushed recycled glass, and re-crushed recycled glass. The same sieved fractions, i.e. 0.85–0.71 mm, 1.00–0.85 mm and 1.18–1.00 mm, were used for all the materials. Carrying tests with the same sizes of different materials allowed the investigation of the effect of particle shape on filterability. The sphericity of glass fractions were significantly lower than that of the sand medium, while smaller differences in sphericity were observed between crushed and ReCG fractions. The findings of this research can be summarized as follows:

- Ives' FI tests showed that glass fractions yield better filter performance than silica sand. This result was confirmed in all the tests. The differences between glass crushed once or twice were smaller and therefore not conclusive. This is perhaps expected because the sphericity and porosity values for these two materials were not very different.
- There is some disagreement in the classical filtration literature regarding the effect of shape on filtration performance. The current results indicate that angular media (lower sphericity and higher porosity) perform better as filter media. This finding is consistent with the earlier results obtained via pilot-scale filtration experiments (Soyer et al. 2010).
- While the Ives' FI has become popular for educational purposes, it has not been used to a significant extent in

full-scale applications, as for example the jar test is used for coagulant selection for sedimentation. One reason for this may be that the validity and range of applicability of this index have not been sufficiently demonstrated. The present work shows that the Ives' Index yields reasonable results with a small effort compared to pilot-scale testing. More work is recommended to evaluate the applicability and extent of usefulness of this test.

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