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Assessment of clogging phenomena in granular filter media used for stormwater treatment

Analyse du phénomène de colmatage des filtres granulaires utilisés pour le traitement des eaux pluviales

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RÉSUMÉ

La conductivité hydraulique des filtres granulaires et son évolution au cours de temps sont les paramètres clés pour la conception de tels systèmes. Les études précédentes montrent que le colmatage des filtres granulaires est lié aux caractéristiques du filtre et du débit entrant. Cet article, basé sur une expérience en laboratoire, vise à déterminer l'impact des caractéristiques physiques du filtre ainsi que du débit d'entrée sur le colmatage et par conséquent leur influence sur le rendement épuratoire. Alors que la forme et la rugosité des grains ont un effet limité sur la performance des filtres, le taux d'infiltration semble avoir une influence majeure sur leur performance. Les autres facteurs qui peuvent agir sur le colmatage d'un filtre granulaire comprennent, d'une part, la granulométrie, la porosité, la structure et la compaction du filtre et, d'autre part, les caractéristiques de l'eau pluviale influente, telles que sa concentration, la granulométrie des matières en suspension et son taux de chargement. Des recherches supplémentaires permettront une meilleure compréhension du phénomène de colmatage dans les filtres granulaires, surtout dans le cadre de l'assainissement des eaux pluviales.

ABSTRACT

Hydraulic conductivity of granular filter media and its evolution over time is a key design parameter for water treatment systems based on such media. Existing studies on clogging suggest that the hydraulic performance is specific to the nature of filter media and characteristics of inflows. This article, using a laboratory-based approach, aims to study the effect of physical characteristics of filter media and flow through rate on the clogging phenomenon and its inter-relationship with treatment performance. While shape and smoothness of filter media grains had limited effect on the performance of most filter media, it was found that the water flow through rate affected performance of all media significantly. Other variables that may influence the clogging phenomenon were also identified: filter media characteristics (porosity, structural strength of grains); packing of filter grains; stormwater inflow characteristics (concentration, particle size distribution); filter design (particle size) and loading state. Further experimentation with these variables will give better understanding of the clogging phenomenon in granular filters, particularly in the context of stormwater treatment.

KEYWORDS

Stormwater, porous pavement, filter media, hydraulic permeability, clogging, harvesting, treatment, performance, hydraulic conductivity

1 INTRODUCTION

Hydraulic conductivity of infiltration-based systems depends on a range of factors such as influent flow rate and its characteristics, particle size of the filter media, antecedent moisture conditions in the filter media, and the nature and extent of clogging of media (Raimbault et al 1999, Scholz and Grabowiecki 2007, Yong et al 2008). Other factors that may affect hydraulic conductivity could include the density and depth of roots and the type of vegetation, in case of the vegetated filters (however, the focus of this study is on non-vegetated filters). Many authors have recognised that clogging of filter media is a significant problem that affects the hydraulic and treatment performance of systems based on such media (Metcalf and Eddy, 1972; Siriwardene et al, 2007; Hatt et al, 2008). The development of a clogging layer leads to increased overflows, and long periods of ponding, resulting in a range of concerns - from public safety to aesthetics, health, hygiene and reduction in operational efficiency (Le Coustumer et al 2007). Existing studies on clogging suggest that the hydraulic performance is specific to the nature of filter media and characteristics of inflows (Perez-Paricio, 2001; Mays and Hunt, 2005; Skolasinska, 2006; Changhong, 2008).

Granular media filters can be incorporated in a wide range of systems such as porous pavement based systems that harvest and treat stormwater. However, specific studies to assess the hydraulic and treatment performance of filter media in context of stormwater treatment have been rarely undertaken. Further, limited work to-date has been done to understand the clogging phenomenon and inter-relationship between reduced hydraulic permeability of such systems and their treatment performance.

The main purpose of this research is thus to understand the process of clogging in filter media used in stormwater treatment systems and the inter-relationship between clogging phenomenon and treatment performance in these systems, using a laboratory-based approach. The following hypotheses have been identified for investigation based on literature review:

- physical characteristics of the media material such as its shape (angularity) and smoothness have a significant impact on the rate of clogging and treatment performance, and
- the influent flow rate through the filter system impacts its clogging and treatment performance.

2 METHODS

2.1 Experimental setup

To investigate the above hypotheses in the context of stormwater filtration, several filtration media were combined with porous/permeable pavement based systems in a testing column, wherein granular filters are located underneath a porous pavement to create an effective treatment train and treated stormwater is then collected from the outlet of column.

The different granular filter media selected in this study include: Zeolite, Scoria, Riversand and Glass beads (polymer material) (see Figure 1). These filter media were selected based on the differences in shapes of their particles, roughness and their treatment potential (based on industry experience), with the aim being to try to get a relatively wide range of characteristics, to allow the influence of these characteristics on clogging to be tested. A uniform particle size of 2mm has been selected for assessments at this stage as fine filter media have better treatment potential (Al-Anbari 2008). Figure 1 depicts the differences in physical characteristics of these media. Zeolite particles are the most angular and glass beads most spherical; scoria particles are the roughest of all media and glass beads are the smoothest and; glass beads are the least porous whereas scoria is the most porous material.

Figure 1: Photographs of the filter media grains (from left to right: zeolite, scoria, riversand and glass beads)

In order to test the hypotheses listed in Section 1, experimental columns of 150mm diameter with different designs were constructed using the different filter media. The influence of flow rate through

the system was tested by providing restricted and unrestricted outflow conditions. In the columns with unrestricted flow, the outlet diameter was 79 mm (hence leading to zero pressure conditions at the outlet) as compared to the restricted columns wherein the outlet diameter was 10mm.

Figure 2 shows the basic design of the experimental column and the details of the design are given in Table 1. Coarse gravel provided on the top of the filter media helps dissipate the energy of flowing water (as would occur in real-world conditions). The fine gravel layer provided at the bottom acts as a drainage layer and prevents migration of the filter media and hence clogging of the outlet pipe.

A minimum of five replicates of each column design have been built to allow statistical comparison of each treatment. Initially a high variance in performance was observed amongst the replicates and hence more replicates were tested for some of the designs. In total, 48 columns were built, encompassing different filter media and outflow conditions, as listed below:

- Zeolite: Unrestricted flow columns- 6 replicates; Restricted flow columns- 8 replicates
- Scoria: Unrestricted flow columns- 5 replicates; Restricted flow columns- 6 replicates
- Riversand: Unrestricted flow columns- 5 replicates; Restricted flow columns- 6 replicates
- Glass beads: Unrestricted flow columns- 6 replicates; Restricted flow columns- 6 replicates

Material	Depth (mm)	Remarks
Coarse stones	50	Simulates a porous pavement
Fine filter media	300	2mm sized grains of Zeolite/Scoria/ Polymer glass beads/River sand
Fine gravel	50	Drainage layer
Outflow type	-	Restricted/Unrestricted outflow

Figure 2: Basic design of experimental columns

Table 1: Details of columns

2.2 Experimental procedures

To ensure that the filter media was clean prior to testing, it was either washed initially in column during construction or the columns were dosed with 100 litres of potable water (equivalent to 45-50 pore volumes of the media). Flow rates were measured three times at regular intervals to determine the initial infiltration rates of media when potable water is passed through. At the end of the cleaning process, a water quality sample was taken and analysed for total suspended solids (this result was termed as Background TSS).

The columns were dosed with semi-synthetic stormwater, instead of using natural stormwater because of the high volume required for tests and also to ensure fairly consistent composition of inflow for the experiments. This stormwater was prepared in a 1400L tank using tap water and sediment harvested from a stormwater pond, sieved to select particles less than 1000µm in diameter. This size range was selected to represent real practice, as particles coarser than this size range are likely to settle down in the catchment before the stormwater reaches the filtration system, even with limited or no pre-treatment. This approach has been used in earlier studies to investigate the clogging phenomenon (e.g. Siriwardene et al 2007, and Siriwardene et al 2008).

The concentration of sediment was targeted at 150mg/l (based on typical stormwater concentrations from a review of international data (Duncan, 1999) and was maintained at a constant concentration for each experiment by a mixer in the stormwater tank. This concentration represents a range likely to be observed in typical field conditions (Duncan 1999, Fletcher et al 2003). Within experiments, the TSS concentration of the stormwater ranged between 125 and 290 mg/l. All filter media of particular design (restricted or unrestricted) were tested simultaneously to ensure that same stormwater was applied to

all media, thus avoiding artefacts due to varying concentrations between treatments.

Due to the time and cost constraints, it was necessary to compress the timescale of the experiments. To do this an analysis of Melbourne's historical rainfall data (last 10 years) was conducted as below:

- Total rainfall - 512mm/yr (BoM, 2009)
- Total rainfall contributing to runoff - 422mm/yr (based on 10 years of rainfall/runoff simulations with an initial loss of 1mm)
- Total number of events contributing to runoff- 72/yr
- Average amount of rainfall during each event- 5.9mm

To determine an appropriate dosing volume we assumed that a stormwater filter of this type would represent around 0.3% of its catchment area. Given that the column has an area of 0.017m^2 (there with a catchment area equivalent to 6m^2) 30L per column was calculated for each dosing. Similar approaches have been used in the past to test and design different stormwater filters and pavements (for instance, Hatt et al., 2007; Bratieres et al., 2008).

Using this regime, the columns were dosed twice a day and usually a constant head (to top of column) was maintained during each dosing session. The outflow rates were monitored regularly and the infiltration rate of each column was estimated using Darcy's law. Composite water quality samples were obtained both for inflow and outflow to assess the amount of sediment load applied and removed by the experimental filters and hence the treatment performance of the filters could be estimated. Since hydraulic conductivity (and hence the infiltration rate) has been observed to vary with the temperature of water (because of its viscosity), a temperature correction is applied to report standard value at 20°C .

The experiments have been 'compressed in time', where months of operational life of the systems are compressed to several days due to time constraints. However, the effect of drying and wetting regimes on the clogging phenomenon will be investigated in future experiments, wherein the filters shall be allowed to dry for sometime between the two dosing rounds and performance changes shall be assessed.

2.3 Data analysis

The data were analysed for trends to investigate the impact of the key variables related to the hypotheses made. Statistical analysis such as calculation of median, range of observations, inter-comparison of replicates, linear regression and statistical significance assessments have been carried.

For all the results presented, the variables - Infiltration rate, Total volume of stormwater passed (measured as Equivalent litres with a concentration of 150mg/l) and Treatment efficiency ($\text{TSS concentration of inflow} - \text{TSS concentration of outflow} / \text{TSS concentration of inflow} * 100$) have been reported as median value and 95 % confidence interval (95% CI) of all the replicate columns of a given design. Statistical analysis to test the statistical difference between the different groups of results has been carried out using unpaired t-tests, with significance accepted at $p=0.05$. Comparison of the performance of replicates of each design has also been done to assess the coefficient of variation for each design, as against the observed median value.

The hydraulic conductivity of each column was calculated, to assess the permeability/clogging performance, using the constant head method (ASTM international D 2434-68) and as per Darcy's Law:

$$k = \frac{h}{A_s} \frac{Q}{H} \dots\dots\dots \text{Equation 1}$$

Where, k is the hydraulic conductivity

Q is volumetric flow rate (measured at the outlet of the column (m^3/s))

A_s is cross-sectional area of the column (m^2)

H is the total hydraulic head across the filter and

h is the length of the filter media whose hydraulic conductivity is being tested

Since hydraulic conductivity has been observed to vary with the temperature of water (because of its viscosity), a temperature correction is applied to report standard value at 20°C.

$$k_T = k_\theta \frac{\eta_\theta}{\eta_{20}} \dots \dots \dots \text{Equation 2}$$

where, k_θ is the coefficient of permeability measured at a given temperature,

η_θ is the dynamic viscosity of water, at the measured temperature, θ , and η_{20} the dynamic viscosity at a standard temperature of 20°C. The equation works to be

$$k(\text{at } 20^\circ\text{C}) = ((-0.0239 \cdot \theta + 1.571) \cdot k_\theta) / 1.005 \dots \dots \dots \text{Equation 3}$$

The treatment performance was measured as the difference in total suspended solids concentration (TSS) between the inflow and outflow of the filters and equals:

$$\text{Treatment efficiency} = 100 \cdot \frac{(\text{Inflow TSS concentration} - \text{Outflow TSS concentration})}{\text{Inflow TSS concentration}}$$

3 RESULTS AND DISCUSSION

3.1 General trends in clogging and treatment performance

Evolution of infiltration rate with the volume of stormwater passed through and the evolution of treatment efficiency with decline in Infiltration rate are presented for Riversand and Scoria in Figure 3. It is evident that the infiltration rate decreases steadily over time as more stormwater is passed through the filter media.

The infiltration rates for Riversand and Scoria columns with unrestricted flow decreased from an initial value of about 54000 mm/hr and 780000 mm/hr respectively to a completely clogged state (with infiltration rate of almost 0mm/hr) on passage of 170 litres and 315 litres of stormwater (refer Figure 3). However, columns with a restricted outflow had a lower initial infiltration rate (Riversand- 16000 mm/hr and Scoria- 14000 mm/hr). Similar trends in clogging and evolution of treatment performance were observed for other filter media and column designs.

The evolution of treatment performance in Riversand and Scoria filters with the change in infiltration rates (and hence with the volume of stormwater passed through) is presented in Figure 3. It was observed that for columns with unrestricted flow, treatment efficiency at the start was lower for all the filters (ranging between 49 and 58% i.e. an effluent TSS of 63 to 76mg/l against an influent TSS of 150mg/l) and it improved consistently as the filters became clogged (ranging between 86 and 92% at the end for filter life i.e. an effluent TSS of 12 to 21mg/l against an influent TSS of 150mg/l), thus reducing their effective hydraulic conductivity. Similar trends in treatment performance were observed for Zeolite and Glass beads. As the filters clog, the detention time of stormwater within the filter media increases and this improves the removal rate of suspended solids. Further the formation of clogging layer enhances the removal efficiency of fine sediment particles because of the reduced pore space within the media grains. Further, the deposition of sediments within the voids of filter media may effectively diminish any grain shape differences, thus reducing or eliminating any performance differences, such as treatment efficiency,

This indicates the effects that changes in hydraulic performance on account of clogging could have on treatment performance of pollutants, especially sediments which have a special significance for stormwater treatment application.

Figure 3: Evolution of Infiltration rate with the volume of stormwater passed and Evolution of Treatment performance with the decline in Infiltration rate in Riversand and Scoria

3.2 Comparison of performances of filter media

The results comparing the performance of four filter media are illustrated in Figure 4a and 4b. This figure provides box plots for: initial infiltration rates, total volume of stormwater treated prior to clogging and overall treatment efficiency of the four media tested in two different sets of flow conditions.

The limited differences observed in the initial infiltration rates of the media may be attributed to the re-packing of the filter media grains as water first passes through them. While the volume of stormwater treated by zeolite, riversand and glass beads is comparable, it was observed that scoria treated more stormwater with comparable treatment efficiency (Figure 4a, 4b). Further, all filter media start treating stormwater with equal effectiveness once they start getting clogged irrespective of any difference in their physical characteristics (Figure 3).

The results of the statistical analysis (Table 2) also suggest that there is limited difference in the performance of zeolite, riversand and glass beads. However, scoria differs from the other three media in some ways (refer bold values in Table 2a, 2b).

The difference in behaviour of Scoria is possibly because of its porous nature and/or the change in the size of the media grains and their packing arrangement (we hypothesise that they may break into smaller fractions with the passage of stormwater). Therefore, the effects of media porosity and disintegration of particles to a smaller size on clogging phenomenon need to be investigated further.

An analysis of the rate of decline of infiltration rate with the volume of stormwater passed through indicates that the rate of decline was slowest for scoria (Figure 3). Among replicates, it was observed that the coefficient of variation in observations was greatest for glass bead columns, which could be attributed to the material's properties (for example floating because of its relatively low density),

surface tension effects (being a polymer material) and consequently its packing. A high coefficient of variation within replicates indicates that it may be difficult to predict the performance of such a material accurately and hence poses a challenge for designers.

It was also observed that the amount of suspended solids that remain within the different filter media (the background TSS) does not vary much except for Scoria wherein the average TSS was found to be 4-20 times higher than the other media. This also suggests that Scoria material leaches initially and that this possibly affects its apparent initial treatment performance. Again, the relatively porous and fragile nature of scoria, results in a high proportion of resident fine material.

Figure 4a: Comparison of performance of four filter media with 'unrestricted outflow'

Figure 4b: Comparison of performance of four fine filter media with 'restricted outflow'

Initial Infiltration rate				Total volume of stormwater passed			Overall treatment efficiency		
	Scoria	River sand	Glass beads	Scoria	River sand	Glass beads	Scoria	River sand	Glass beads
Zeolite	0.37	0.06	0.39	0.35	0.85	0.68	0.09	0.96	0.29
Scoria	–	0.03	0.13	–	0.25	0.58	–	0.05	0.00
River sand	–	–	0.46	–	–	0.53	–	–	0.24

Table 2a: p-values of t-tests for performance of filter media with 'unrestricted outflow' (Pairs with significant differences are shown in bold)

Initial Infiltration rate				Total volume of stormwater passed			Overall treatment efficiency		
	Scoria	River sand	Glass beads	Scoria	River sand	Glass beads	Scoria	River sand	Glass beads
Zeolite	0.01	0.93	0.53	0.08	0.07	0.58	0.64	0.00	0.93
Scoria	–	0.11	0.02	–	0.03	0.15	–	0.17	0.68
River sand	–	–	0.58	–	–	0.05	–	–	0.01

Table 2b: p-values of t-tests for performance of filter media with 'restricted outflow' (Pairs with significant differences are shown in bold)

3.3 Impact of flow restriction on performance of filters

The impact of variation in flow rates (on account of flow restriction provided in filter) on the performance of filters was also evaluated by varying the outflow conditions, as discussed in Section 2.1. T-test results (Figure 5) suggest that there is no statistical difference in the volume of stormwater passed before clogging occurred, between the two types of experimental columns - with and without restriction for all filter media types.

The comparison of performance of filters under the two sets of flow conditions further suggests that flow restriction:

- Reduces the initial infiltration rate of the filters. For instance, zeolite filters with unrestricted flow had infiltration rates of about 62000mm/hr as against filters with restricted flow which had infiltration rates of about 16500mm/hr only (refer Figure 4a and 4b). This lower initial infiltration rate in restricted columns is because of the smaller outlet size, which restricts the rate at which water flows through the media initially.
- Improves the volume of stormwater treatment by the filter media as shown in Figure 5.
- Improves the treatment efficiency of all filter media, as shown in Figure 6, owing to lower flow rate through the outlet and hence increased residence/contact time within the filter media (UR- Unrestricted columns, R- Restricted columns)

Figure 5: Total volume of stormwater treated by each filter

Figure 6: Treatment Efficiency of different filter media

The high variability in the results indicate that there could be other parameters that affect the hydraulic performance of such systems based on natural filter media and hence the clogging phenomenon. Further experiments will be conducted to analyse the influence of variables such as the filter particle strength, filter particle porosity and effect of the drying and wetting regimes on the hydraulic performance of these filters.

4 CONCLUSIONS

Clogging of granular filters as stormwater is passed through them has been studied. As expected, the reason for the decrease in infiltration rate is the deposition of sediment in the voids between filter media particles. Analysis of comparative performance of filter media suggests that filter media characteristics such as shape and smoothness affect the performance of filter media in a limited way. While zeolite, glass beads and riversand were capable of treating comparable volume of stormwater before clogging, it appears that scoria may be able to treat a greater volume with comparable treatment efficiency, although these differences were not statistically significant. However, shape and smoothness of the media cannot explain entirely the clogging phenomenon. Other parameters such as porosity of grains, reduction in size of media grains and/or the nature of packing arrangement over time need further investigation.

There is some evidence that low flow through rates improves the overall performance of the filter system as the total volume of stormwater treated during the filter life increases; the treatment efficiency of filters with restricted outflow was also found to be greater than for filters with unrestricted flow rates.

Whilst we have demonstrated the effect of flow rate and media physical characteristics on clogging and treatment performance, more experiments are needed to understand more precisely the clogging phenomenon in granular filters. Further experiments will be conducted to analyse the influence of filter design (such as filter media particle size, depth of filter, layering arrangement with particles of different sizes, compaction of the media during construction); stormwater inflow characteristics (such as

concentration, particle size distribution of sediment and inflow rate) and drying and wetting regimes. These results will further our understanding of the clogging phenomenon of granular filters and its effect on treatment performance, with the ultimate aim being to build a model which predicts the hydraulic and treatment performance of filters, along with their lifespan. One of the main applications of such a tool would be in improved design of water treatment systems based on such granular filters, particularly for stormwater filtration for ecosystem protection or the supply of filtered stormwater for harvesting purposes.

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