Attrition of granular activated carbon during air scour followed by water backwash and the impact on filter performance

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ABSTRACT

Backwashing of GAC has developed from backwash regimes used for sand, which has greater density and more resistance to attrition. Attrition arises from lack of grain strength and washout arises from low grain density. Loss of GAC by either means can increase costs, filter downtime and cause other operational maintenance problems. Carbon fines produced by attrition may remain in the filter bed pores and pass into the supply during filtration. To investigate the attrition of GAC during backwashing, a laboratory scale filter column system was assembled and operated. The attrition of GAC and subsequent release of fines during filtration were assessed by using a series of backwashing and filtration cycles. A particle counter was used to quantify particles generated during backwash and filtration. The average GAC attrition after 8 cycles of backwashes was approximately 0.33%. Results showed that fines were released into backwash and filtration effluents throughout the experiment.

Key words | air scour, attrition, backwashing, carbon fines, filtration, GAC, granular activated carbon

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INTRODUCTION

The filtration process is arguably one of the most important stages in drinking water treatment, particularly when considering that the nature of particles falling within the 1–200 μm size range include bacteria such as *Escherichia coli*, and protozoa such as *Cryptosporidium*. The continuous successful operation of the filtration process is therefore critical to achieving a filtrate of acceptable quality, in accordance with the code of practice or directive relevant to the country of operation.

Typically sand and/or anthracite are used as filter media. As water quality legislation has become more stringent, granular activated carbon (GAC) has been used to a greater extent as a filter or filter–adsorber medium (Cleasby 1990). This is because of its ability to remove a wide range of organic and inorganic compounds that contribute to taste and odour in the finished water, adsorb regulated synthetic organic compounds and organic matter that lead to the formation of disinfection by-products (Loper *et al.* 1985; DeWaters & DiGiano 1990). In addition, as GAC is known to become colonised with bacteria, this trend has been exploited in treatment by actively encouraging the biofilm growth on GAC and using organisms to metabolise a fraction of the organic carbon found in the water. This type of GAC is commonly known as biological activated carbon (BAC). Thus GAC performs the roles of filtration and adsorption of particulate and dissolved matter, as well as the biodegradation of organic matter.

Since the use of GAC as a filter media has been increasing, special attention has been paid to the loss of GAC caused by attrition during backwashing. Humby & Fitzpatrick (1996) used a modified BEWA (1993) accelerated backwash abrasion resistance test to examine the attrition loss of various filter media under collapse–pulsing conditions. All filter beds were subjected to a continuous period of 100 hours backwashing, which was equivalent to approximately 3 years of daily backwashing at 6 minutes per wash. Attrition was measured by collecting particles in

Table 1 | Steps in a filtration and backwash cycle (Grens & Werth 2001)

Steps	1. Filtration	2. Air scour	3. Combined air scour and water wash	4. Water wash
Duration	17 min	3 min	30 sec	15 min
Water rate	9.5 m/h	–	20.8–24.7 m/h (wood-based)	20.8–24.7 m/h (wood-based)
			35.5–37.8 m/h (coal-based)	35.5–37.8 m/h (coal-based)
Air scour rate	–	54.6 m/h	54.6 m/h	–
Bed expansion	–	–	–	25%

the wash water, drying and weighing them. Their study confirmed that attrition of GAC during backwashing was higher than anthracite and sand. They found that attrition of sand and anthracite became negligible after 30 and 50 hours, respectively, while GAC underwent attrition for the whole 100 hours. Predicted annual attrition weight loss of GAC F400[1] and F300[1] under collapse–pulsing conditions was 0.6–1.8% and 1.5–2.4%, respectively.

More recently Grens & Werth (2001) conducted pilot plant experiments to compare the durability of virgin wood-based[2] and coal-based[3] GAC when subjected to 500 cycles of backwashing with an air scour and water wash system. This corresponded to five equivalent years of backwash operation, as the plant filters were backwashed approximately every four days. A detailed account of each step in a filtration and backwash cycle used by them is listed in Table 1.

GAC bed depth reductions from their study implied that at the full-scale plant it was equivalent to annual losses of approximately 3% for the wood-based and 2% for the coal-based GAC, both within the range typically observed in water treatment plants (Cleasby 1990). The annual loss for coal-based GAC (2%) was, however, consistent with the maximum losses reported by Humby & Fitzpatrick (1996) for F400 and F300 (1.8% and 2.4% per year, respectively).

Jeong & Fitzpatrick (2000, 2001) improved on previous studies by using a Met One WGS 267 on-line particle counter to determine continuously the particle size distribution in the effluent of GAC F400 backwash water. They also evaluated GAC attrition due to three different backwash regimes as shown in Table 2. From Table 2 it was evident that introducing air scour caused much greater attrition than water-only backwash, confirming that the latter was intrinsically a weak cleaning process. Another key finding from their study using a particle counter was that most particles created by attrition during backwashing were in the range of 2–5 μm, measured by the particle counter (particles below 2 μm were not measured). Particles in this size range correspond to the size of *Cryptosporidium* oocysts and could cause confusion between the passage of such pathogenic particles and carbon fines during filtration.

The filter ripening period has long been identified as a cause for concern with respect to particulate passage into the filtrate, especially following cryptosporidiosis outbreaks such as those in Milwaukee in 1993, North London in 1994 and the latest in Glasgow in August 2002. It is well documented that filter ripening is the result of two components, i.e. the interface with the influent, which is thought to be caused by the need for particles to build up on media grains to subsequently act as collectors for other particles in the influent (Clark *et al.* 1992), and the presence of backwash water remnants in the filtration system (Amirtharajah & Wetstein 1980). The backwash water remnants consist of three components: (a) backwash water in the under-drain and connecting pipe work (T_U), (b) backwash water within pores of the media (T_M) and (c) backwash water remaining above the filter media up to the

[1] Calgon Carbon Corporation, Pennsylvania, USA.
[2] Bio-Nuchar 90, Westvaco Corporation, USA.
[3] F820, Calgon Carbon Corporation, Pennsylvania, USA.

Table 2 | Backwash regimes used and attrition losses of GAC F400 in the laboratory scale filter column studies of Jeong & Fitzpatrick (2001)

	1. Intermittent water wash	2. Air scour followed by water wash	3. Combined air scour and water wash
Duration	15 min	15 min	15 min
Air scour rate	–	7.6 m/h	7.6 m/h
Water wash rate	15.3 m/h	15.3 m/h	3.1 m/h
Time of air scour	–	5 min	–
Time of water wash	10 min[a]	10 min	–
Bed expansion	20%	20%	–
Attrition loss after 10 washes[b]	0.01% wt	0.17% wt	0.20% wt

[a]Followed by 5 minutes resting such that total duration was 15 minutes.
[b]Attrition losses had been divided by 8. In Jeong & Fitzpatrick (2001), the size of particles determined by the particle counter were taken in error as the radius of a particle in their calculations to convert particle count to weight. This was corrected as particle sizes counted by the particle counter indicate the diameter of the particles.

level of the backwash water overflow weir (T_F) (Amirtharajah & Wetstein 1980). This implies that particles produced by the attrition of media may remain in the backwash remnants and be present during ripening, particularly for light and friable media such as GAC (Fitzpatrick 2001).

Research in the last few years has shown that carbon fines from GAC and BAC filters were released into the water filtrate (Camper *et al.* 1987; Stringfellow *et al.* 1993). Unlike sand, carbon fines combine large surface area with a high affinity for adsorbable contaminants (e.g. pesticides) and bacteria. Several authors have demonstrated that GAC fines found in the filter effluent were colonised by bacteria that were markedly resistant to disinfection by chlorine (Camper *et al.* 1986; Stewart *et al.* 1990). Therefore, questions have arisen about the potential health risks as these carbon fines may have attached biofilms that may harbour pathogens and settle in the drinking water distribution system.

The intention of this research is therefore to investigate further the attrition of GAC media during backwashing and the subsequent release of fines generated by backwashing during filter ripening.

MATERIALS AND METHODS

Filter media

The filter medium tested throughout all experiments was virgin, coal-based GAC Filtrasorb® 400[4] (F400). GAC characteristics relevant to this study are shown in Table 3. The media size range, maximum uniformity coefficient and effective size were taken from the manufacturer's specification. The density was determined previously by Jeong & Fitzpatrick (2000) using the Mercury Intrusion Porosimetry method. Virgin GAC F400 of 1400 g (dry weight) was loaded into each filter column for all experimental runs. To ensure the dry weight of the media, GAC was dried in an oven for 24 hours at 120°C and weighed after cooling. Before being placed in the columns, the GAC was allowed to soak in water for approximately 24 hours. This was necessary to ensure that air was removed from the pores of the media.

Experimental apparatus

All experiments were conducted by using two identical laboratory scale filter columns to allow for duplication and repeatability assessment of each experiment. The experimental apparatus configuration is illustrated in the schematic diagram (Figure 1). Each filter column was made of transparent cast acrylic with 5 mm wall thickness, 100 mm internal diameter and 0.8 m height measured from the bottom of the base plate. Each column had a backwash water outlet at 0.95 m above the base plate. Below the base plate was the under-drain system, which was 0.13 m in height. The under-drain was connected to the column via a proprietary dome type filter nozzle. Air and water could be supplied into each column via connections at the base of the under-drain and through the filter nozzles.

A Met-One[5] digital particle counter model WGS-267 was connected to the backwash and filtration effluents for on-line particle measurements throughout the experiment. The particle counter was capable of reading particles in the range of 2–400 μm in six specified size channels. These channels were 2–3 μm, 3–5 μm, 5–7 μm, 7–10 μm,

[4]Calgon Carbon Corporation, Pennsylvania, USA.
[5]Met-One, Oregon, USA.

Table 3 | GAC particle characteristics

Type	Size range (mm)	Maximum uniformity coefficient	Effective size (mm)	Density (kg/m³)
Granular coal based F400	0.425–1.7 (−4%/+5%)	1.9	0.55–0.75	1208.8

10–15 μm and >15 μm. There was a coarse pre-filter of 350 μm used in order to prevent clogging of the particle counter. Therefore the maximum particle size counted by the particle counter would be 350 μm, assuming that all particles >350 μm were trapped by the pre-filter.

Particle count units, sampling period and interval were standardised for the entire experiment as follows: number of particle counts per millilitre (count/ml), 30 seconds and 1 minute, respectively. The sampling period and interval were selected taking into account recommendations by the manufacturer and the need to provide continuous representative count data for the experiment.

Influent water characteristics

The source of water supply for the experiment was London tap water. Average daily values of influent water quality recorded during the study are listed in Table 4. The experimental programme was conducted during the summer period from June to August 2003. Water temperature did not vary significantly throughout the study. There was, however, a difference between filtration and backwash water temperature. Though both were from the same source of supply, filtration water was in the mixing tank and header tank before passing through the filter columns. The retention time in these two tanks resulted in the filtration water temperature being influenced by the room temperature of the laboratory.

Backwash and filtration procedures

The backwash arrangement of air scour followed by water was used in this research since this is still the most widely used backwash regime in the water industry in the UK. Prior to backwash and filtration cycles, the filter media was fluidised to 20% bed expansion (18–23 m/h) for 5 hours. This was to remove any fine particles present in the media. All the fine particles obtained during the subsequent filtration and backwash experiments would thus be due to attrition.

After the removal of fines, the filter column was subjected to 20 hours of low rate filtration (3 m/h). This was carried out for comparison purposes with biological GAC experiments, which have not been included in this paper.

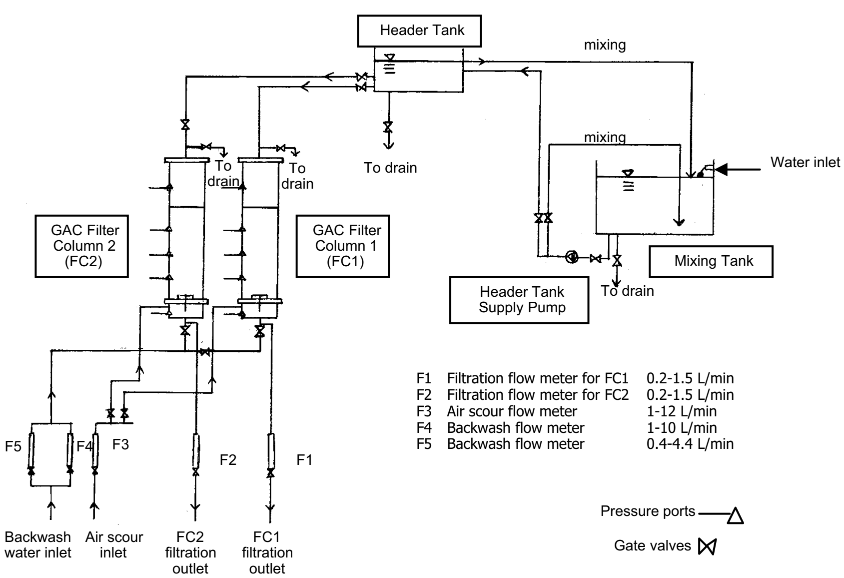

Figure 1 | Schematic diagram of the filter column apparatus used in the laboratory study.

Table 4 | Water quality for backwash and filtration water

Parameter	Range
Filtration water temperature	26–28.5°C
Backwash water temperature	22–24°C
pH	7.2–8.0
Free chlorine residual	Nil
Conductivity[a]	540–560 μS/cm
Turbidity	0.22–0.35 NTU

[a]Potable meter, Hanna Instruments, Italy.

Following the 20-hour low rate filtration, the starting filter bed heights were measured and the study began by alternating backwash and filtration cycles. A detailed account of steps in the filtration and backwash cycle is as follows:

1. The water level in the filter column was lowered to approximately 200 mm below the backwash water outlet.
2. Air-scour of the GAC bed for 5 minutes at 11.5 m/h.
3. Water-only backwash for 10 minutes at 20% bed expansion (backwash rate was 18–23 m/h).
4. Allow approximately 1–2 minutes for GAC media to settle after backwashing.
5. Clean water filtration at 5.85 m/h for 30 minutes.

A total number of 8 cycles (from steps 1 to 5) were repeated in this study.

GAC attrition calculation

Calculation of GAC attrition followed an earlier approach by Jeong & Fitzpatrick (2000, 2001), that is, by converting particle counts per millilitre (count/ml) to volume/ml, and then weight/ml, by assuming a particle density and spherical particles. Although it was impossible to measure particles finer than 2 μm by using the particle counter, it was assumed that the generation of carbon fines from attrition smaller than this size would not contribute significant media loss in terms of percentage weight loss. These fine particles could be significant in terms of their large surface area and capacity for carrying organic matter and bacteria.

For consistency, the density used for GAC F400 was 1208.8 kg/m^3, which was obtained using Mercury Intrusion Porosimetry (Jeong & Fitzpatrick 2001). Results from this research could thus be compared to those from Jeong & Fitzpatrick (2000, 2001). The geometric mean particle sizes of 2.5 μm for 2–3 μm, 4 μm for 3–5 μm, 6 μm for 5–7 μm, 8.5 μm for 7–10 μm, 12.5 μm for 10–15 μm and 70 μm for 15–350 μm were used.

Weight/ml could then be converted to weight/min by multiplying the former by the backwash flow rate. As particle counts were recorded every minute during the 10 minutes of water wash, the total weight of fines generated from attrition during backwashing could then be summed up and the percentage of attrition loss could be obtained by dividing this total weight with the initial GAC weight of 1400 g loaded on the filter column.

RESULTS AND DISCUSSION

Particle count data for raw water

To evaluate the presence of background particles in the water supply source and laboratory system, particle count data were recorded for the mains supply, and backwash and filtrate water from the filter columns without GAC filter media (empty columns). These results are presented in Table 5. Data presented were average values of 20 records, with a sampling period of 30 seconds and an interval of 1 minute. Data from previous studies conducted in the same laboratory are also included.

Particle count data for the mains supply is consistent with the counts obtained by Thurston (2003) conducted in the same laboratory; the highest counts were in the 3–5 μm size range. Backwash water counts recorded by Jeong & Fitzpatrick (2001) were higher than the FC1 and FC2 backwash water counts, which was unexpected given that both studies used the same source of water supply for backwashing; this difference may have been caused by the accumulation of residual filtrate particles in the under-drains during the studies of Jeong & Fitzpatrick (2001) that were not removed during backwashing events. The particle

Table 5 | Particle count data (count/ml) for raw water, i.e. mains supply, backwash water and filtrate water (FC = filter column)

	2–3 μm	3–5 μm	5–7 μm	7–10 μm	10–15 μm	>15 μm	>2 μm (total)
Mains supply	15.3	21.8	4.5	4.4	1.7	1.2	48.8
Backwash water FC1	21.1	23.9	3.8	5.8	2.4	0.5	57.5
Backwash water FC2	16.1	22.3	8.8	7.9	1.2	1.2	57.6
Filtrate water FC1	330.0	398.3	68.9	54.1	8.7	2.7	862.7
Filtrate water FC2	309.5	391.4	59.3	39.6	6.6	1.7	808.2
Backwash water count (Jeong & Fitzpatrick 2001)	87.2	102.6	16.9	16.4	5.6	2.0	230.7
London tap water count (Thurston 2003)	14.3	31.6	4.0	3.5	0.8	0.3	54.3

counts in the filtrate water for both columns used in this study were higher than the backwash water counts, indicating that water flowing through the columns picked up particles through the tanks and the influent supply piping system.

Particle count data in the backwash water for all the backwash experiments presented subsequently were assumed to be solely that of carbon fines since allowance was made (deductions) for the background particles in the water. However, for the case of the filtration tests, the reported particle counts in the filtrate water were the actual values measured without any adjustments; it was assumed that the background particles from the influent supply system would be substantially removed by the GAC during filtration.

Particle count data during 8 backwash and filtration cycles

Figures 2–5 show plots of particle count versus time during 8 backwash and filtration cycles using filter column 1. Plots of particle count data from filter column 2 are not included in this section as they illustrate similar patterns and repeat-

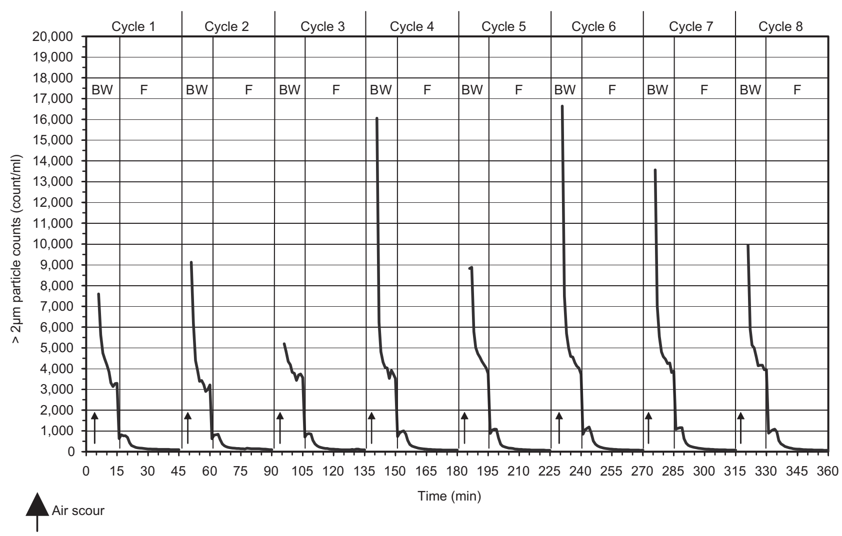

Figure 2 | The variation of total particle counts (>2 μm) for 8 successive clean bed backwash (BW) and filter ripening cycles (F).

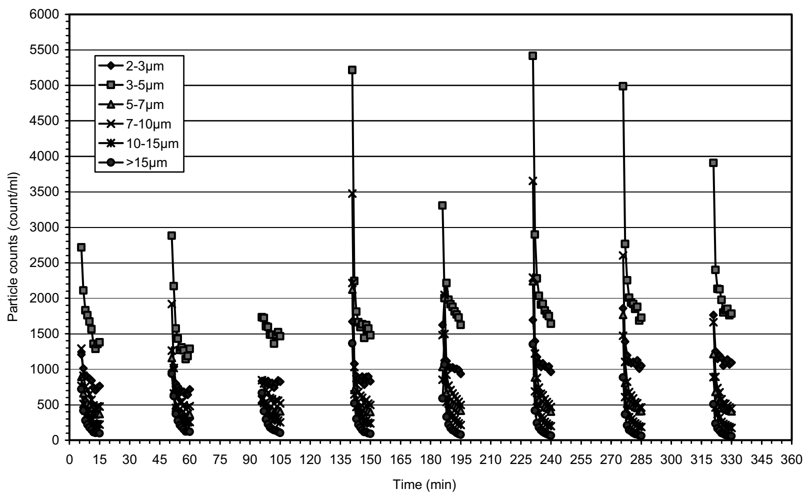

Figure 3 | The variation of differential particle counts for 8 successive backwash cycles (filtration data omitted).

ability. Figure 2 shows the $>2\,\mu m$ total particle counts for all backwash and filtration cycles. It can be seen that, during each backwash and filtration cycle, there was an initial peak of particle counts during backwash that reduced rapidly to a half within 5 minutes and a filter ripening peak that reduced and stabilised thereafter during the 30 min filtration. During the experiments it was observed that the peak of particle counts during backwashing could be easily missed out. Initial peaks dropped very quickly within the first 3 minutes of backwashing. After air scouring, some air bubbles were trapped within the media bed. These air bubbles were released into the backwash effluent once the subsequent 10 min water-only backwash started. When the backwash effluent containing air bubbles passed through the particle counter during the 30 seconds sampling period, it generated errors in the sensor of the particle counter. Though air bubbles only appeared during the first few minutes of the water-only backwash, peaks of particle counts could fail to be recorded. Therefore it was difficult to identify the trends of the peak after each cycle.

Figure 3 presents the differential particle counts during 8 backwashes (filtration count data were removed in the plot for clarification). Particle counts during each backwash cycle indicate that backwashing by air scour followed by

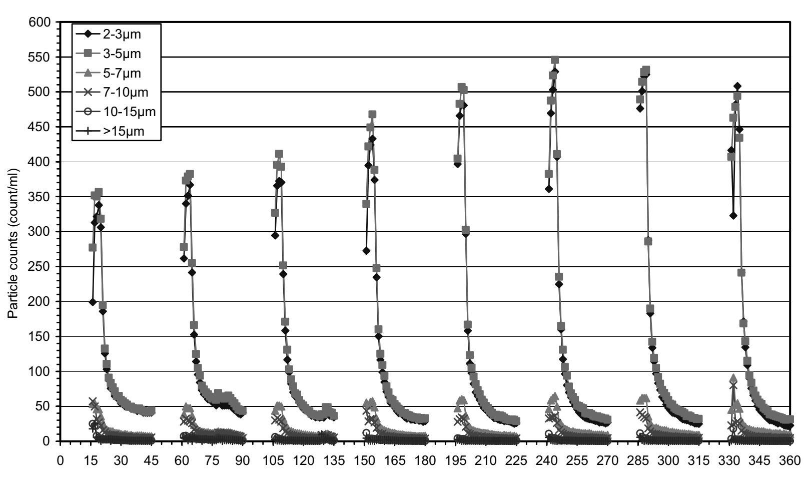

Figure 4 | The variation of differential particle counts during the filter ripening period after each successive backwash.

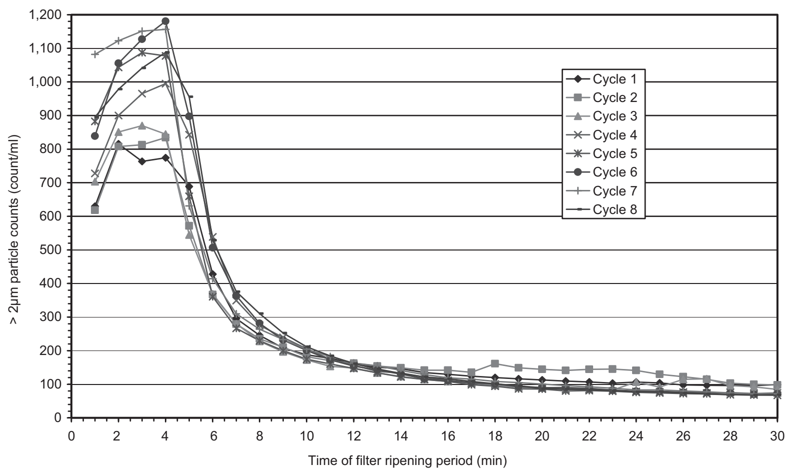

Figure 5 | The variation of total particle counts (>2 μm) during the 8 filtration cycles.

water-only generates GAC fines and attrition occurs during all 8 cycles of backwashes. From the graphs of particle counts, it can be seen that the 5 min air scour appears to be causing the wearing away of the GAC grains and producing particles. These fines generated from attrition are washed out in the subsequent 10-min water-only backwash, resulting in the initial peak of particle counts. Though particle counts drop to a lower level after the initial peak, attrition of media occurs throughout the 10-min water wash. This also indicates that backwashing by water only is a weaker cleaning process with less grain abrasion, as confirmed by previous studies (Cleasby *et al.* 1977).

From Figure 3, it is observed that more fines are generated in the 3–5 μm particle size range than for 2–3 μm during backwashing and both ranges are significantly higher than other size ranges. However, it should be noted that the particle counter is unable to measure particle sizes <2 μm. Whether more fines are created in the <2 μm size range could not be determined. Fines generated in these ranges are too small in size to pose concerns about media loss but could impact on filtered water quality, as they would have a large surface area and capacity for carrying organic matter and bacteria.

Figure 4 shows the differential particle counts during 8 filtration cycles (backwash count data were removed). There were no obvious differences between the 2–3 μm and 3–5 μm particle counts. Counts for >10 μm particle were similar throughout the 30 minutes of filtration and were insignificant compared to other size ranges.

Ripening peaks occur in all cycles of 30 min filtration (5.85 m/h) for all experiments. By comparing the empty column filtration counts in Table 5, it can be seen that particle counts during the ripening peak are much higher than the empty column filtration counts. It can therefore be concluded that particle counts during ripening peaks are GAC fines created by attrition during backwashing that remain in the column. In addition, most particles counted in the 2–5 μm size ranges are significantly higher than other size ranges, particularly during the ripening peak. This shows consistency with particle counts during backwashing where most fines generated are in the 2–5 μm ranges. This is also consistent with filtration theory where this size range has the lowest removal efficiency. However, it is noted again that no data was available for the <2 μm particles. The heights of the ripening peaks appeared to increase with each successive wash and then level off. It is thought that this levelling off would be a general tend, although further experiments are required to confirm this.

In Figure 5 the total particle counts (>2 μm) during each 30 min filtration cycle were plotted on the same time scale. It is observed that the ripening peaks increased with increasing number of backwash and filtration cycles. The ripening peaks and duration were approximately 800–1200 count/ml and 8–10 minutes.

Table 6 shows the average time required to empty the backwash water remnants in each section of the filter column after filter backwashing, as described by Amirtharajah & Wetstein (1980), and as mentioned earlier (in the

Table 6 | Average values of backwash remnants calculation during each filtration cycle for both clean and colonised bed experiments

Backwash remnants	FC1	FC2
Underdrain, T_U (min)[a]	1.33	1.33
Media pores, T_M (min)[b]	3.08	3.61
Above media, T_F (min)[c]	3.61	3.60

[a]Backwash water in the under-drain and connecting pipework.
[b]Backwash water within pores of the media.
[c]Backwash water remaining above the filter media up to the level of the backwash water overflow weir.

introduction). Total time required for backwash water remnants to be emptied from all sections was approximately 8 minutes, based on an average bed porosity of 0.67, obtained from the measured bed volume and the density value used above. This further confirms the presumption that GAC fines created by attrition during backwashing that remain in the column are released into the filtrate during ripening.

GAC attrition

GAC attrition was very high initially, although it decreased after the initial peak, attrition occuring for the whole period of 8 backwash cycles. This was consistent with the earlier findings by Humby & Fitzpatrick (1996) and Jeong & Fitzpatrick (2001). The average total loss by attrition of GAC F400 after 8 cycles of backwashing by air scour followed by water was approximately 0.33% (see Table 7). This value is approximately double that obtained by Jeong & Fitzpatrick (2001) which was 0.17%. However, the difference could have been caused by the size of particle assumed in the attrition calculation for >15 μm ranges; 20 μm was used in the study of Jeong & Fitzpatrick (2001) and 72.5 μm in this study. These values for the highest size band were chosen to give what was thought to be the best representation for the wide range of sizes, determined by the different pre-filters used before the online counter.

CONCLUSIONS

Key findings from the laboratory scale filters are summarised below.

Table 7 | Attrition losses of F400 GAC after 8 backwash cycles

	Clean bed run 1		Clean bed run 2	
Backwash cycle no	G	%	G	%
1	0.511	0.036%	1.201	0.086%
2	0.664	0.047%	0.670	0.048%
3	0.538	0.038%	0.306	0.022%
4	0.715	0.051%	0.323	0.023%
5	0.661	0.047%	0.485	0.035%
6	0.636	0.045%	0.447	0.032%
7	0.478	0.034%	0.381	0.027%
8	0.754	0.054%	0.330	0.024%
Total	4.958	0.354%	4.142	0.296%

1. The use of air scour followed by water for the backwashing of GAC was found to generate carbon fines throughout the 8 cycles of backwashing. The majority of the fines were found to be in the 2–5 μm range, and the counts in the 3–5 μm range were greater than the counts in the 2–3 μm range.
2. Filter ripening occurs after each backwash and peaks of particle counts are attributed to carbon fines created by attrition during filter backwashing. The ripening peak of particle concentration and duration of the peak were approximately 800–1200 count/ml (>2 μm total particle counts) and 8–10 minutes.
3. Average total GAC loss by attrition after 8 cycles of backwashes from the clean bed experiments was about 0.33%. Although this value is approximately double that obtained by Jeong & Fitzpatrick (2001), the difference may be explained by the size of particle assumed in the attrition calculation for the >15 μm range.

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