Creating markets for recycled resources

Full Scale Trials of Recycled Glass as Tertiary Filter Media for Wastewater Treatment

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Final Report

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Management Summary

- The report summarises the findings of both pilot-, and full-scale trials comparing the performance of recycled glass and sand as filter medium in tertiary filtration for suspended solids removal during wastewater treatment. The trials were undertaken at three sites: the Malton municipal wastewater treatment plant operated by Yorkshire Water; Stubbins Paper Mill, Ramsbottom, operated by Georgia Pacific; and JE Hartleys food processors at Thornganby.
- Pilot trials at all three sites comparing sand, AFM (a commercial filter medium made from recycled glass) and three grades of recycled glass (coarse, medium and fine) showed that the performance of the four glass media was superior to sand, both for the amount of suspended solids removed and for the amount of influent treated, before a backwash cycle was required. Although fine glass produced the best effluent quality, there was very little difference between performances of the four glass media. Medium grade glass was selected for further studies at a pilot scale due to its superior flow properties and the amount of effluent it was able to treat prior to a backwash being required.
- Full-scale studies demonstrated that air scour was essential to improve the backwash characteristics and an optimised backwash comprised of 2.5 hours of operation followed by a backwash with 6% of the volume of treated effluent at a flow rate of 12 m^3/h and 5 minutes of air scour at 198 litres/min (a flow rate for both effluent and air of 0.45 m^3/m^2 h). The whole backwash cycle took around 10 minutes.
- The results of the full-scale trials at Malton revealed little difference in the performance of glass and sand media in terms of suspended solids removal. However the glass media had superior flow characteristics and was able to treat an additional 8 to 10% of the influent following the backwash cycle at the selected flow regime. Both glass and sand were able to remove around 75% of suspended solids from the influent provided that the influent solids concentration did not exceed 70 mg/l. Above this suspended solids concentration the performance of both media dropped rapidly. Peaks in influent suspended solids to the filter were still treated and typically a removal of 25 mg/l was achieved. Over the optimised study period, the influent to the filters had an average suspended solids concentration of 38 mg/l and a 95 percentile of 84 mg/l and an effluent with an average suspended solids of 15 mg/l and a 95 percentile of 38 mg/l was produced.
- In order to design for an average effluent solids concentration of 20 mg/l, a maximum solids loading of 0.25 kg solids/ m^3 media h is required.
- The study at Stubbin's Mill suffered due to the variable nature of the influent feed which at times had suspended solids concentrations as high as 280 mg/l. Nevertheless from those periods in the pilot-scale trials when the influent solids were low, it was possible to demonstrate that AFM and medium grade glass were more efficient at removing suspended solids and that all the glass media demonstrated better performance than sand. In the full-scale trials, there was little difference in performance between sand and glass. The medium grade glass could remove between 35 to 40

mg/l which generated an effluent with a suspended solids of around 50 mg/l. However during peak solids loads to the filters breakthrough to the final effluent occurred.

- The Hartley's study was also characterised by a period of high influent suspended solids at the start of the study with concentrations as high as 340 mg/l. Although fine grade glass generated the best effluent quality, it blinded rapidly and required frequent backwashing. All other glass media showed better removal efficiency for suspended solids than that of sand. However the medium grade was able to treat the greatest flow before blinding.
- The filters were consistently able to remove around 25 to 35 mg/l of suspended solids from the influent. Consequently in order to achieve an effluent quality of <20 mg/l (with a 95 percentile compliance) the amount of solids applied to the filters must be restricted to <0.15 kg suspended solids /m^3 h. If an effluent quality of <10 mg/l is required then the solids applied must be reduced to <0.07 kg suspended solids/m^3 h.
- An attrition study of the medium glass over a period of continuous operation lasting 42 days, showed that there was little loss of medium in the intermediate particle sizes, however the two largest particle sizes, 2,000 and 2,500 µm and lost 55% and 33% respectively. The smallest particle size (500 µm) showed a commensurate increase of 150%.
- The costs of recycled glass media are £220/m^3 as compared to £100/m^3 for conventional sand (as used in this study) or around £300/m^3 for the more specialised media used in moving bed filters. Based on the results of this study, use of recycled glass will give a 10% reduction in the amount of media required, together with the associated capital saving. The performance of the glass during backwash is more effective leading to a greater flow through at the start of the new cycle and this suggests that glass media may overcome many of the blinding problems suffered by full-scale sand filters. Finally it carries with it the benefits of using a recycled material that are difficult to quantify economically and which include: reduced CO_2 emissions, a more sustainable product, favourable publicity and positive environmental reporting.

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1.0 Introduction

1.1 Background

Aqua Enviro Ltd. specialise in the treatment of industrial and domestic wastewaters and successfully tendered for a WRAP funded project to compare the effectiveness of a range of media manufactured from recycled glass when used for the tertiary treatment of wastewater. Tertiary treatment is the last stage in the treatment process and is applied immediately prior to the effluent being discharged to watercourse. It is routinely employed for the removal of suspended solids and the organic contaminants associated with these solids, from the effluent produced during the biological treatment of domestic and industrial effluents. Its role is to ensure that the treated effluent will comply at all times with the standards that have been set by the Environment Agency to permit the discharge of the treated effluent to a receiving watercourse (usually a river, estuary or the sea). These standards are referred to as "consents" and specify three parameters: the maximum permitted flow, the biochemical oxygen demand (BOD) and the suspended solids. Other parameters may also be included depending on the sensitivity of the receiving watercourse and the environmental quality objectives in place for that watercourse. Consents for ammonia and chemical oxygen demand (COD) are common and increasingly total phosphorus and total nitrogen are included. Consents may also include, *inter alia*: iron, aluminium, pesticides and temperature.

Meeting the discharge consent is the sole purpose of wastewater treatment and the implications for failing consent are numerous, including a financial penalty levied by the courts, the attendant bad publicity (The Environment Agency website has a Hall of Shame which lists the worst offenders) and in severe cases a custodial sentence on Company Directors. Thus both the water utilities and industry invest a lot of time and efforts in ensuring plants do not exceed consent. The needs of the water utilities, (who treat largely domestic wastewater) and industry (who treat industrial wastewater) for tertiary treatment are not dissimilar despite the fact that the nature of the wastewater produced is very different.

1.1.1 Domestic Wastewater Treatment

There are around 7,500 treatment plants in the UK operated by the water companies and of these the majority (about 85%) are small plants treating populations of <5,000 people. There are only about 400 plants treating population of >10,000 people. Treating wastewater in larger plants is simpler because:

i. The daily flow rate to a larger treatment plant shows much less variation than the flow to smaller plants
ii. The variations in the composition of the sewage are much less at larger plants
iii. There are more likely to be monitoring and control equipment, together with a SCADA (supervisory control and data acquisition) system

iv. Such plants are likely to be continuously staffed
v. Effluent quality is more likely to be continuously monitored
vi. It is easier to design a large plant to produce a high quality effluent

By contrast smaller plants are more likely to give operator problems and consequently to have consent failures. Most consent failures are associated with a loss of solids in the final effluent due to poor performance of the final clarification stage of treatment. This may be a result of clarifier design and operation or the plant may simply be overloaded. However it is more likely to result from a biological problem known as filamentous bulking and foaming. This problem regularly afflicts treatment plants in the UK (and 60% of plants suffer bulking on one or more occasions each year). It is caused by the proliferation of a group of bacteria termed the filamentous bacteria and whose presence reduces the settling velocity of the biological solids in the final clarifier. As a result there is a major risk of suspended solids overflowing the final clarifier and prejudicing consent.

It is the problem of high effluent suspended solids that is tackled in this report by the application of tertiary treatment, using recycled glass as the tertiary filter medium.

Tertiary sand filtration is one traditional engineered solution to tackle the problem of high effluent suspended solids. Although this technology has proved reasonably successful, many sites have experienced problems. These have generally resulted from failures in sand backwash which have led to the sand blinding with a reduction in the flow rate through the filter. In addition there have been examples of channelling in the sand bed which has led to short circuiting with a consequent reduction in performance. Problems with backwash have been overcome by the development of continuous, moving bed backwash systems. The moving bed systems have required different mineral media based on sand but with larger diameters and a consequent higher cost. It was thought that the use of recycled glass might overcome some of the performance issues associated with sand and prove a more successful option, thus filling a large market niche, both at those sites which have problematic sand filters and for new sites that require simple, but effective tertiary treatment. However there are a number of important requirements to fulfil before this can be achieved; in particular the technology must demonstrate (in order of importance) that it:

i. provides a reliable solution to ensuring that a treatment plant always remains in consent
ii. is a cheaper whole-life solution (typically 10 to 15 years) than alternatives such as moving bed systems, membranes or increasing secondary clarification capacity
iii. is technically simple and robust without the need for skilled staff to operate
iv. can be safely used at remote sites which receive no operator attention for periods of several days
v. does not require the use of chemicals
vi. does not produce a sludge that is difficult to handle
vii. demonstrates a commitment to sustainability that will be recognised by the Environment Agency

The programme of study described in this report was designed specifically to provide answers to the above criteria.

1.1.2 Industrial Wastewater Treatment

Much of what has been written in section 1.1.1 applies equally well to the treatment of industrial wastewaters. Compliance with Environment Agency consents is essential, but problems with filamentous bacteria are probably even more pronounced in the industrial sector. The differences arise because, unlike domestic wastewaters, it is not possible to make generalisations about the nature of the flow and the composition of industrial wastewaters make each one unique. However certain sectors do have particular treatment problems and those most associated with effluent suspended solids problems are: paper industry, brewery wastewaters, food industry and chemical manufacturing.

Industrial wastewater treatment plants also tend to be larger and treat a wastewater that is much stronger, always in terms of BOD and generally in terms of the suspended solids. However industrial wastewater treatment plants are nearly always staffed every day and 24 hour staffing is not unusual, consequently it is unusual to see a high degree of automation and control at industrial sites. Thus when considering the requirements for tertiary treatment at an industrial site the technology must demonstrate (in order of importance) that it:

i. provides a reliable solution to ensuring that a treatment plant always remains in consent
ii. is a cheaper solution (typically with a 3 to 4 year payback period) than the alternatives
iii. is robust
iv. fits in the available footprint on-site
v. does not require the use of chemicals
vi. does not produce a sludge that is difficult to handle
vii. has no odour associated with it
viii. demonstrates a commitment to sustainability that will be recognised by the Environment Agency

Again the research undertaken in this study tender proposal was designed specifically to provide answers to the above questions.

1.2 Outline of Research Programme

The research programme was undertaken in two stages with the first stage designed to evaluate the performance of BSI PAS 102 grade fine, medium and coarse glass to that of AFM and conventional sand (1–2mm) in a pilot scale operation (5 l/min). The second stage was to select the best performing recycled glass medium for larger scale (10 m^3/h) trials involving an optimisation of the backwash requirements, again in direct comparison to sand.

Performance evaluation of the test media was to be undertaken based on:

i) solids removal, and;

ii) the amount of effluent processed before a backwash was required.

Although there are a number of ways to express solids removal, all with advantages and disadvantages, for the purpose of this study it was considered that the simplest technique was to estimate the total amount of solids removed for a given suspended solids loading (determined as the product of the volume of effluent applied and its suspended solids concentration) prior to the filter clogging and requiring a backwash. Although this does not necessarily select the medium which produces the best effluent quality it does ensure selection based on the most economic performance. Consequently this was adopted in both the first and second stage trials.

Filter clogging was measured by the backpressure required to maintain the operating flow rate across the filters and thus this was an indirect measure of the headloss across the filters. At a predefined headloss the filters were deemed to require a backwash. The volume of effluent processed during each cycle was measured and this provided the information necessary to evaluate media performance under item ii) above.

The project was also designed to identify any other benefits that might derive from the use of recycled glass as a filter media, when applied to the tertiary treatment of domestic and industrial wastewater for solids removal. If successful and glass proves a viable option as a tertiary filter medium, the project could make a significant contribution towards the WRAP glass programme target of placing 150,000 tonnes/annum of recycled glass into high value markets.

In view of the need to answer specific questions for both the domestic and industrial effluent sector, research was undertaken at three sites: a domestic wastewater treatment plant and two manufacturing industries, one in the paper and the other in the food sector. The latter two sites were selected for a number of reasons: the importance of these two sectors to the UK manufacturing base; the varied nature of the effluent they produce, which provides a good test of the glass medium treating a range of different effluents; the interests of the respective companies in the results of the trial with the potential for adoption of the technology if successful, and the historic good links that existed with the two companies prior to the project commencing.

2.0 Description of the Sites Selected for Glass Media Trials

2.1 Malton Wastewater Treatment Plant

Malton WwTW is a medium sized domestic sewage works operated by Yorkshire Water and receiving the wastewater from the town of Malton, North Yorkshire and surrounding area. The works treats a population equivalent of approximately 10,000 and the average flow to the works is ~5,000 m^3 /d with peak flows up to of 12,000 m^3/d. The treatment system comprises screening and grit removal, primary sedimentation and secondary biological treatment by trickling filters and solids removal of the treated effluent in radial flow secondary tanks (Figure 1). At times of high flows the secondary tanks can become hydraulically overloaded with an increase in the upflow velocity[1] which in turn leads to an increase in final effluent suspended solids as the smaller particles of humus have insufficient settling velocity to avoid being washed out of the settlement tank. In order to ensure that the site remains within its discharge consent of 35 mg/l TSS and 25 mg/l BOD, a sand filter was installed as a tertiary treatment to reduce the final effluent solids. The sand filter treats approximately 30 % of the flow, which is then returned to the final effluent pit prior to discharge to the river.

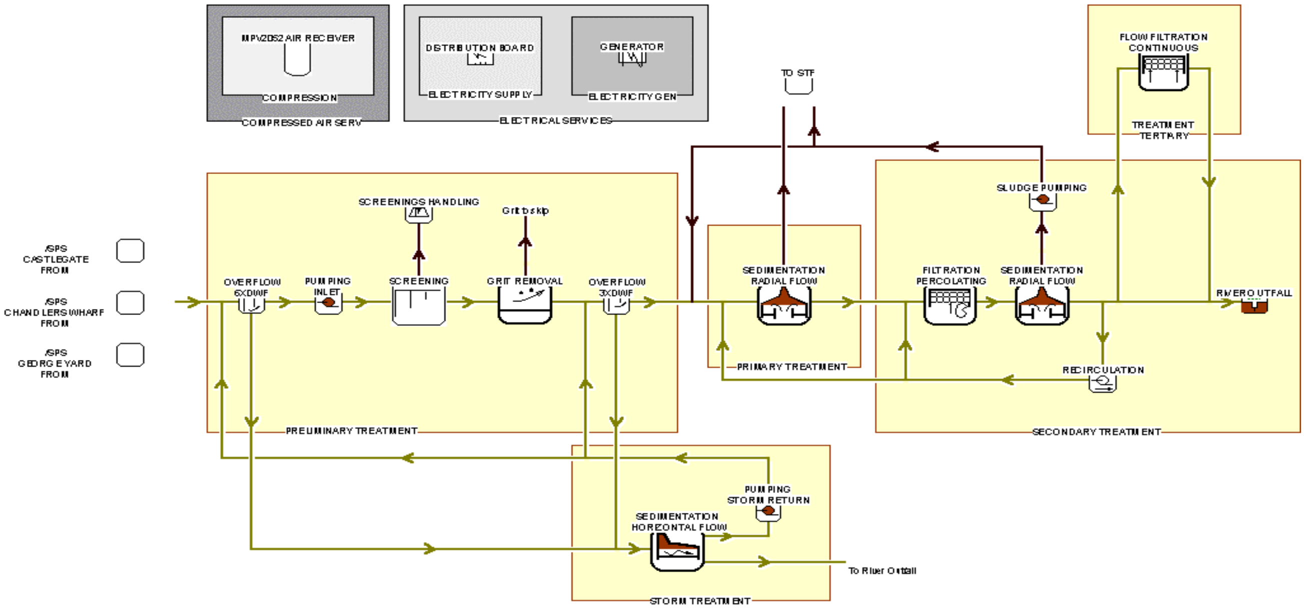

Figure 1. Schematic of Malton WwTW (reproduced courtesy of Yorkshire Water plc.)

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[1] Upflow velocity is determined as the the influent flow rate in m^3/d divided by the cross sectional surface area of the secondary tanks in m^2, thus it has units of m/h. Suspended solids are known to settle with a velocity of between 1.2 and 4.0 m/h and thus if the upflow velocity of the secondary tank is >1.2 m/h than some solids will not be able to settle and will pass into the final effluent

The Malton site was chosen as it is typical of a domestic treatment works which relies on tertiary treatment to achieve the discharge consent when operating at its limit. If the performance of the treatment plant could be improved through the implementation of a recycled glass media then this would reduce the risk of the works failing. All the water utilities operate many small plants for which tertiary treatment would be appropriate and it was anticipated that if these trials proved successful then it would produce significant interest both in Yorkshire Water and within other UK Water Companies.

2.2 Stubbins Mill, Ramsbottom

Stubbins Mill, Ramsbottom, is a tissue mill owned and operated by Georgia-Pacific GB Limited. The mill produces kitchen towels and toilet tissue from both raw and recycled paper fibres. Their current water usage is 16.26 m^3/ tonne tissue produced, compared to an industry standard of 32.5 m^3 / tonne tissue (ETBPP, 1998) and the Mill is re-using approximately 15m^3 water/tonne tissue produced. However the Environment Agency no longer favours discharge of treated effluent to sewer and is requiring that Georgia-Pacific consider new treatment options to reduce the effluent discharge, by further increasing water re-use. It is a condition of their IPPC application to report on the potential for using tertiary treatment on the site and Aqua Enviro Ltd. were contracted to conduct a feasibility study into the possible options to improve the effluent quality and permit the re-use of more water within the mill.

Currently the primary treatment system is situated at the mill and comprises Algas™ filters and settlement. The settled wastewater is then pumped to a separate treatment works for secondary treatment and this is sited approximately 800m away on the opposite side of the road. Secondary treatment comprises three biotowers, two of which treat the wastewater for re-use within the mill and the third discharges to sewer. Effluent from all three biotowers receives a final clarification stage. The plant also has a series of redundant tertiary sand filters, which were commissioned to improve suspended solids removal following secondary treatment. However due to constant blinding of the beds and odour-related problems these are now by-passed.

In view of their recent problems with wastewater treatment, the need for an effective alternative tertiary treatment solution together with the experience Aqua Enviro Ltd. have gained on-site, it was a most appropriate choice for the WRAP glass media trials. In addition if the project proved successful, Georgia-Pacific would be keen to implement full-scale tertiary glass filtration, thus creating a demonstration facility for other users within the paper industry.

2.3 J. E. Hartley, Thorganby

The J E Hartley site is located near Thorganby in North Yorkshire. The site processes vegetables for freezing and typically a flow of around 200m^3/day is produced. Treatment consists of a mixing and balancing tank, two sequencing batch reactors (SBRs), a final effluent storage tank and tertiary sand filtration to further reduce the suspended solids. The site has struggled periodically to meet its final effluent consent as the nature of the influent to the treatment plant changes with each seasonal crop processed. The site has an EA consent for solids of 30 mg/l and it relies heavily on tertiary treatment to maintain compliance. Once again there is the potential for this food processing company to implement full-scale glass filtration on site subject to a successful trial.

3.0 Materials and Methods

3.1 The Pilot-rig

The initial trials at each of the three sites were undertaken in identical test rigs each of which comprised five filters with a diameter of 0.2m and a height of 0.9m. The filters were designed for operation in a downflow mode and backwashed by reversing the flow up through the media by manual operation of the control valves. To maintain an even flow and pressure across each of the five filter vessels, a restrictor plate was fitted to the outlet of the service flow enabling delivery of a fixed flow of 5l/ min to each filter. The pump was a Jet Flow 100 with a nominal capacity of 100 l/min, thus enabling a variable backwash. The rigs have an air entrainment valve which meant that a more vigorous flow could be applied during backwash to increase solids release; however it should be noted that this was not equivalent to an air scour. The filter vessels were filled with support media of glass beads with a diameter of 3 - 12mm, in place of the pea gravel support media that is routinely used as bedding for sand medium. Each filter vessel was packed with approximately 20kg of filter medium. This provided a residence time within the vessel of between 2 and 2.4 minutes. The filter rigs were fitted to a trailer for ease of transportation and access during the trial, with bespoke suction and delivery pipework at each site (Figure 2).

Figure 2. The five trailer-mounted filter units in the pilot trials

The feed pipe for the existing sand filter takes water from the final effluent tank and this was the source of influent for the five filters. Pressure gauges measured both influent and effluent pressure across the filter. Flow meters were also fitted to each filter to measure the volume treated. Hourly readings of pressure and flow were taken from each filter during operation.

Initially the influent was passed through the filters at a flow rate of 0.3 m^3/h, until the pressure at the filter outlet dropped below 3 psi. At this point the flow was reversed and backwashing carried out to remove solids that have accumulated on the filter medium and return the media to its original state. In order to achieve maximum agitation of filter media during the backwashing period, the influent flow to all the filters was stopped and the combined flow was pumped through the filter being backwashed. The backwash cycle was repeated four times for each backwash. The material from the backwash was collected and approximately 20l removed to form a composite sample in order to determine the amount of solids produced and to assess visually whether any medium was lost during backwash.

At the start of the study the filters were operated with continuous 24 hour operation and with regular flow and pressure readings recorded manually during the working period. However on a number of occasions the filters would clog overnight and thus it was not possible to calculate the volume of feed that had passed through them before a backwash was required. Consequently the outlet pressure was continuously monitored over a number of cycles to determine the typical times taken for the outlet pressure to drop to 3 psi. Depending on the type of medium, the filters could be operated for between 30 and 100 hours before backwash was required. Once this was determined, filters were operated on a timed service/backwash cycle.

3.2 The Large-scale Filter Apparatus

3.2.1 The Filters

Six identical filters vessels were employed in the full-scale trials with two at each site. They comprised mild steel vessels with a heavy duty galvanized coating complete with the interconnecting pipework necessary for filter operation and backwashing. They had a height of 2100mm with an internal diameter of 750mm which gave an effective area for filtration of 0.44 m^2 (Figure 3). Each filter was designed to treat a variable flow of up to 10m^3 /h with a backwash rate of up to 20 m^3. The filters had valves for the manual selection of service or backwash flow. The service and backwash valves were 50 mm ball valves constructed from phosphor bronze and mounted on 50mm diameter pipework. Influent distribution system was via a pipe grid with 0.5mm slots and positioned at the top of the filter vessel above the media bed. A similar distribution system was located at the base of the vessel to collect the filtered influent. Each filter was also fitted with pressure gauges and flow monitors to measure inlet and outlet pressure and to measure the volume of treated effluent leaving the filter. The filters were both fed from a common centrifugal pump, although each filter was capable of independent operation.

The system also included an aerator loop on the pump outlet which was capable of delivering an aerated flow in either duty or backwash mode. An air vent was also incorporated into the system to allow a manual venting of the filter vessel and thus preventing air locking (Figure 4).

Figure 3.. The full-scale filters as installed at Malton

3.2.2 Pumps

The pumps for each pair of filters were cast-iron, self-priming, centrifugal pumps powered by a 4 kW motor. They were fitted with a 150mm diameter open impeller with a shut valve condition of 3 bar and a duty point of 20m^3/h. The absorbed power at the duty point was approximately 3kW. The pump was on a separate base plate assembly from the main filter vessels and fitted with an isolator and weather cover. A drain and priming valve was also fitted to each pump.

3.2.3 Pipework

The suction pipework to the pump and the discharge from pumps to filters was of 50 mm MDPE. Sample points for influent and effluent were provided by means of a 13mm galvanized loop system fitted with appropriate valves to allow sampling to be undertaken at a common point by reversing the direction of flow.

3.2.4 Air-scour operation

The backwash cycles included a period of aeration delivered by a 1.5 hp compressor fed by a 13mm flexible hose into the drain valve at the bottom of each filter. The compressor was able to deliver 198 l air/min at a maximum pressure of 8 bar.

3.2.5 Systems Operation

Three operational modes were available, namely:

1. Service flow

Water was fed from the pump to the filter and a 3-way valve routed the flow to the top of the vessel. The regulating valve was adjusted on set up to give a fixed flow during service operation. The filters were operated in a downflow mode whereby laterals at the base of the vessel collected the filtered water and fed

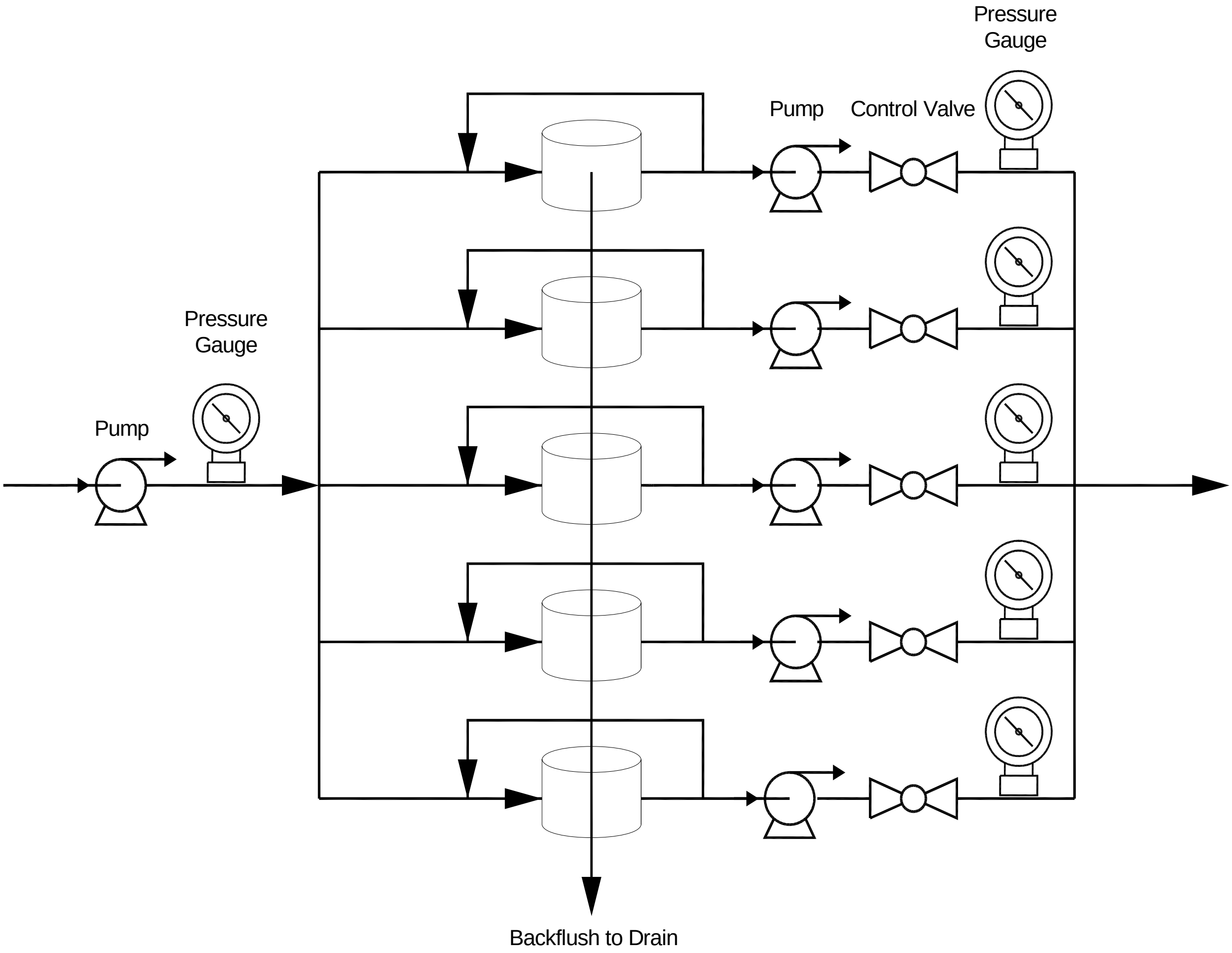

Figure 4.. Schematic diagram of the full-scale filters

it via the distribution pipework through the flow meter and into a clean water capture and sampling tank, or back to the sump.

2. Backwash flow

The 3-way valve switched the system into backwash mode and also set the flow rate required for the backwash cycle. Backwash was carried out in an upflow mode.

3. Rinse flow

The rinse flow was an emergency option and not part of the routine filter operation. It utilised a clean water supply to the inlet of the pump and available to aid in filter recovery following a shock solids load. It was carried out in upflow mode following service and backwash modes. A drain valve was fitted to the bottom of each vessel and the rinse cycle could also be carried out with the rinse liquor passing straight to drain at the bottom of each filter vessel.

3.2.6 Media

The media placed into each of the units was supplied by AllGlass reprocessors. The lower third of the filter vessel was placed with 100 kg of support material consisting of 3 - 13mm glass beads produced from clear cullet. The actual filter medium comprised 0.5mm – 1.5mm glass particles regulated as PAS 102 Medium grade. This material was also manufactured from clear glass cullet and there was approximately 650kg in each filter. The material was supplied in 25kg bags and packed using a funnel through the inspection hatch at the top of the vessel. Media removal could be achieved by removing the access cover at the bottom of the vessel. Care was taken to fill the filter to only 2/3rds capacity to allow for bed expansion during the backwash cycle. In order to minimise any media loss from the filters, the critical upflow velocity at which the media became fluidized was determined (Section 4.2 and Appendix 1) and the flow rates applied during the service, backwash and rinse cycles were always less than this critical velocity.

3.2.7 Backwash

During the course of the pilot-scale studies, it became apparent that the backwash cycle was not efficient and that it would be necessary to optimise this during the full-scale trials in order to evaluate the performance of the sand and glass media for suspended solids removal. Consequently a large number of trials were undertaken in order to determine the efficacy of various cycle times, recycle rates and the impact of air scour addition. The Malton site was chosen as the test site to undertake the changes as it demonstrated the most consistent effluent quality in terms of its suspended solids concentration. The changes that were undertaken in order to optimise the backwash are summarised in Table 1. Basically there were three distinct operating periods, the first period trialled the five pilot-scale filters and selected the most appropriate medium for the large-scale studies, the second period was the large-scale studies comparing the solids remove performance of the selected medium with sand and a backwash cycle that employed only final effluent with no air scour, the third period utilised a backwash of both final effluent and air-scour.

The time required for the backwash cycle was a function of the amount of flow required to achieve backwash. Traditionally this is expressed as the percentage of the flow processed by the filter since the last backwash, and is usually in the range 2 to 8%. The maximum flow for backwashing was fixed at 12 m^3/h to ensure that there was no media carryover (Appendix 2) and thus the backwash time was calculated from the equation:

$$T = \left\{ \frac{\left(Flow_{T_{360}} - Flow_{T_0} \right) x \ {}^{p}\!/_{100}}{12 \ m^3 / h} \right\} x \ 60$$

Where:

T = Backwash time (min)

$Flow_{T360}$ = Total Flow (m^3) processed at the end of the cycle (in this case a 3 hour cycle).

$Flow_{T0}$ = Total Flow (m^3) processed at the start of the cycle

P = Percentage of processed flow required for the backwash cycle (in the range 2 to 8%)

The protocol used for undertaking the backwash is summarised in Figure 5 and the results from this part of the study are reported separately in Appendix 1.

At the time the backwash was being optimised, it was also recognised that if the backwash velocity was too high, there was the danger of media loss in the backwash water. Consequently a series of small-scale experiments were undertaken concomitantly with the backwash optimisation trials, to determine the optimum backwash flow rate without the bed volume fluidising and media carry over occurring. The laboratory study measured the particle size distribution, porosity and specific gravity using glass taken from the Malton filter (medium grade) and these parameters were used to characterise the headloss and to determine the required backwash velocities for filter cleaning, based on the equations presented by Metcalf and Eddy (2003). A worked example with the full procedure and the supporting data is contained in Appendix 2.

Table 1.. Sequences of changes to the cycle times, influent flow rate and backwash cycle, initially undertaken at Malton in order to optimise the backwash and then adopted at the other sites

Event	Key Event	Operating Change
Period 1 (02/12/04 – 19/01/05)	**Pilot-Trials**	
A		Backwash every 5 hours until liquor is clear
B		Backwash in response to headloss, 3% backwash flow
Period 2 (24/01/05 – 18/02/05)	**Full-scale Trials** Backwash for 2.5 minutes only No air scour	
C		Backwash using 3% of daily flow at end of 6-hour cycle
D		Backwash using 3% of flow at 180 and 360 minutes
E		Backwash using 6% of flow at end of 6-hour cycle
F		Backwash for 15 min at beginning of cycle and with 6% of flow at end of cycle
G		Backwash using 6% of flow at 180 and 360 minutes
Period 3 (01/03/05 – 02/06/05)	**Air-scour Introduced**	
H	Backwash cycle 2.5 min followed by: Air scour at 0.45 m^3 air/m^2 media min.	Filter flow rate set to 6 m^3/h and backwash with 6% of flow at end of 6-hour cycle
I		Cycle time reduced to 4 h
J		Flow rate increased to 10 m^3/h and cycle time reduced to 2.5 h
K		Cycle time increased to 4 hours

🟩 Valve \ tap OPEN.

🟥 Valve \ tap CLOSED.

1 = Influent feed valve
2 = Outlet valve
3 = Bypass valve
4 = Backwash outlet valve

BACKWASHING IS CRITICAL

Backwash each filter INDIVIDUALLY (ALL OTHER FILTERS SHOULD BE CLOSED OFF) for 5-minutes, then switch back to normal operation on the individual filter for 5-minute. REPEAT THIS 3 TIMES AT LEAST. Backwashing to take place on separate filters when removal rates for suspended solids are negative.

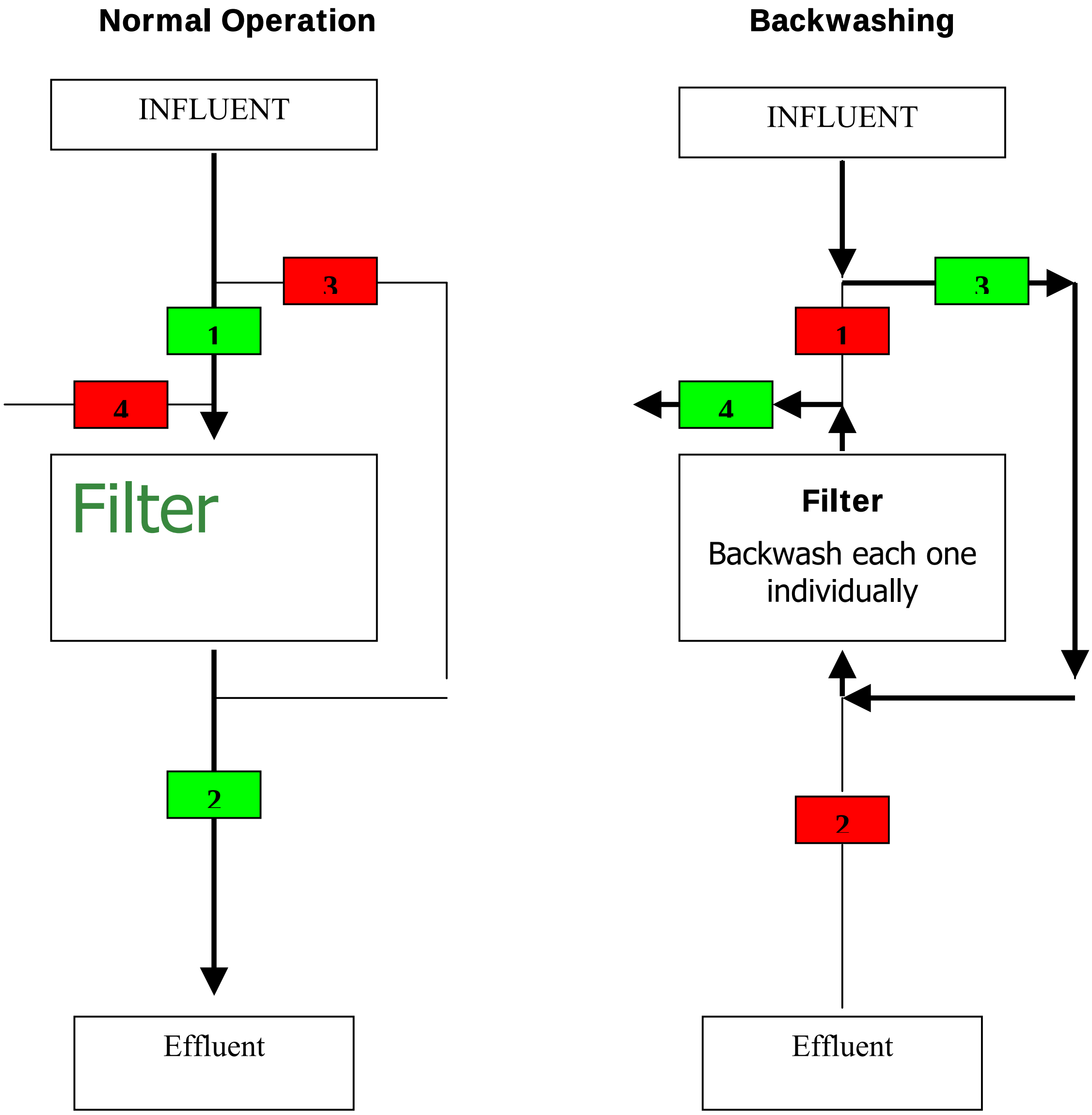

Figure 5.. Backwashing procedure for the full-scale filters

3.3 Sample Collection and Storage

Samples of the influent to, and the effluent from, each filter were collected regularly with no more than an hour between consecutive samples. The samples were either stored in cool boxes (4ºC) or refrigerated to keep the temperature as low as possible to prevent degradation prior to analysis.

3.4 Analytical Techniques

All samples were analysed for their suspended solids concentration using the gravimetric analysis as outlined in Standard Methods (AWWA 1998). Other determinands were analysed as appropriate and these included chemical oxygen demand (COD) using the reflux/titration method, 5-day biochemical oxygen demand in the presence of allylthiourea ($BOD_{5(ATU)}$) using dissolved oxygen measurements (AWWA, 1998) and turbidity using a Hanna turbidimeter.

4.0 Properties of the Glass Media

4.1 Traditional Filtration for Tertiary Treatment

Historically, tertiary treatment was considered as *the further treatment of biologically-treated sewage by removing suspended matter to enable the effluent to comply with a standard more restrictive than 30:20 before discharge to a body of water* (IWPC, 1974). By removing the suspended matter, it was recognized that a large amount of organic material associated with these suspended solids, would also be removed and thus the wastewater could be brought into consent. Increasingly however, tertiary treatment also requires the removal of ammonia, nitrogen and phosphorus and this cannot be achieved simply by suspended solids removal, but requires some biological activity within the tertiary treatment unit. This is often called advanced treatment to distinguish it from the simple requirements of tertiary treatment. For a tertiary treatment process based around filtration, to be commercially viable it must meet a number of requirements, in particular that the:

- effluent from the tertiary filter meets the effluent quality standards.
- media-loading rate to achieve this performance is compatible with competing media.
- filter can treat a similar solids loading to its competitors before blinding and clogging.
- media can be backwashed over a similar time period and using a similar backwash regime as its competitors.

There are a large number of ways in which granular filter media such as sand, can be used in the tertiary treatment of wastewaters but the major configuration of filters are either pressure filters or gravity filters. The former are designed to operate at filtration velocities of up to 20 m/h and with headlosses of up to 9m before solids breakthrough, whereas gravity filters operate with filtration velocities in the range 5 to 15 m/h and headlosses of 2.4 to 3 m (Vesilind and Rooke, 2003). This experimental study employed pressure filters and the experimental design was set up to assess the above four criterion. All parameters for each filter were identical and thus a direct comparison of performance could be made based on effluent quality and cumulative solids removal.

4.2 The Glass Media Used in this Study

Four glass media were evaluated in this study and operated in direct comparison to the conventional sand medium routinely used in tertiary treatment. The four media were all recycled glass products supplied to a PAS 102 grade structure. The PAS 102 grades are 0, which is a fine media with a particle size of 0.2 - 1mm Amber glass 1 is a medium grade media of particle size 0.5 - 1.45mm and clear glass 2 is a coarse media with particle size 1.5 - 2.5mm clear glass. Finally a highly processed recycled glass known as Active Filter Media was also trialled (Table 2). AFM is supplied by Dryden Aqua with a particle size of 0.5 – 1.1mm. It has been evaluated in detail as a tertiary filtration medium for wastewater treatment and found to demonstrate mechanical, catalytic, oxidative and surface adsorption phenomena (Dryden Aqua, 2004).

Table 2. Properties of the Media used in this study

Properties	**Medium**				
	Fine glass	**Medium glass**	**Coarse glass**	**AFM**	**Sand**
Supplier	AllGlass	AllGlass	AllGlass	Dryden Aqua	Marshalls
Cost (/m^3)	220	220	220	980	120
Particle size (mm)	0.2 - 1.0	0.5 – 1.45	1.5 – 2.5	0.5 – 1.1	1- 2

4.3 Attrition Studies on the Glass Media

In order to establish the physical stability of the glass media for long term operation in a tertiary filter a small-scale filter unit was established on the laboratory bench (Figure 6). This was designed to simulate as closely as possible, the continuous operation of the full-scale filter units used in this study. It involved 6 hours of feeding with tap water, followed by a period of 20 minutes of backwashing which incorporated 2 minutes of air scour. The unit had a closed loop feeding arrangement simply required the feed reservoir to be topped up occasionally.

Figure 6.. Bench-scale filter to measure the attrition of the glass media under continuous operation

The stability of the media was measured by sieve testing with sieve sizes appropriate to the media under tests. Samples were taken every week for testing and then replaced in the filter after completion of the test. There was some degradation of the glass medium observed after a period of 2 weeks operation when it was noticed that the larger particle sizes were reduced with a concomitant increase in the amount of smaller particles (Table 3). This reduction continued throughout the attrition period and although there was no change in particle size distribution for the medium range of particles this does not demonstrate that they were not degraded as it is likely there was a trickle down of particle sizes during the degradation process.

Table 3. Particle size distribution for coarse glass after six weeks of continuous operation

Sieve Size (µm)	**Particles passing sieve (%)**						
	Time from Start of Study (weeks)						
	0	1	2	3	4	5	6
2,500	18	14	18	10	15	7	8
2,000	31	28	23	18	22	12	20
1,700	13	23	16	13	16	11	16
1,400	16	15	15	21	18	20	22
500	22	21	27	36	28	49	33

Thus at the start of the attrition study 51% of the particles were in the range 500 to 1,700 µm and at the end of the study 71% were in this range. However the percentage of particles > 2,500 µm had reduced from 18% to 8% and the percentage of particles <500 µm had increased from 22 to 33%.

5.0 Results of the Pilot and Full-scale Studies

5.1 Malton Wastewater Treatment Works

5.1.1 Introduction

The pilot rig was installed on site on 25th November 2004 and located next to the final effluent sump (Figure 7). This is adjacent to the current Dynasand tertiary treatment system (labelled tertiary treatment on Figure 1) which draws its feed from the sump. The tertiary treated effluent from the Dynasand is returned to a chamber where it is mixed with the remaining effluent and discharged to river.

Figure 7. The pilot rig comprising of five filter unit and sited at Malton WwTW.

5.1.2 Operation and Performance of the Pilot Apparatus

Samples of the influent to, and the effluent from the filters were taken at the same time so that the performance of the filter could be assessed. The influent samples were analysed for COD and TSS and over the duration of the phase one study, the TSS only varied between 18 and 45 mg/l (Table 4).

Table 4. Variation in composition of the influent to the filters over the first part of the study period

Parameter	Suspended solids (mg/l)	COD (mg/l)
Average	34.1	102.5
Max	45.0	143.0
Min	18.0	51.0

In order to determine the contribution of the solids to the COD in the effluent, these two parameters were plotted. Although there was no linear relationship between the two parameters (and this is generally observed for samples of final effluent) the concentration of COD was always greater than that of the suspended solids. For all of the samples taken during the study, the average effluent COD concentration was three times the average suspended solids concentration. Samples were also taken of the backwash liquor in order to determine the optimum time for backwashing to be carried out. The concentration of solids in the backwash liquors and the time required between backwashing varied between the different filters reflecting the characteristics of the different glass media.

The performance of the different media was assessed by reference to the amount of effluent that could be treated by the filter before a backwash was required and also to the total amount of solids removed by the filter during treatment of this flow. The fine glass medium showed the best solids removal and could remove around 19.5 mg/l and thus it produced the better effluent quality. However as illustrated in Figure 8, it was the first medium to blind and after 28 hours, when it had processed around 15 m^3 of influent, it required a backwash.

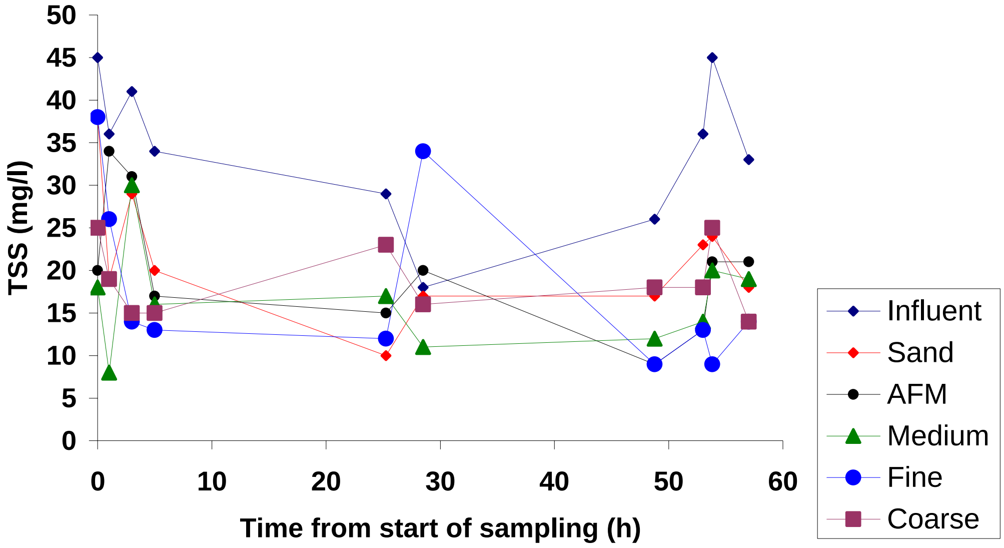

Figure 8. The performance of the five media treating and identical influent

By contrast the medium glass was able to treat around 55 m^3 and sand 35 m^3 without blinding (Figure 9).

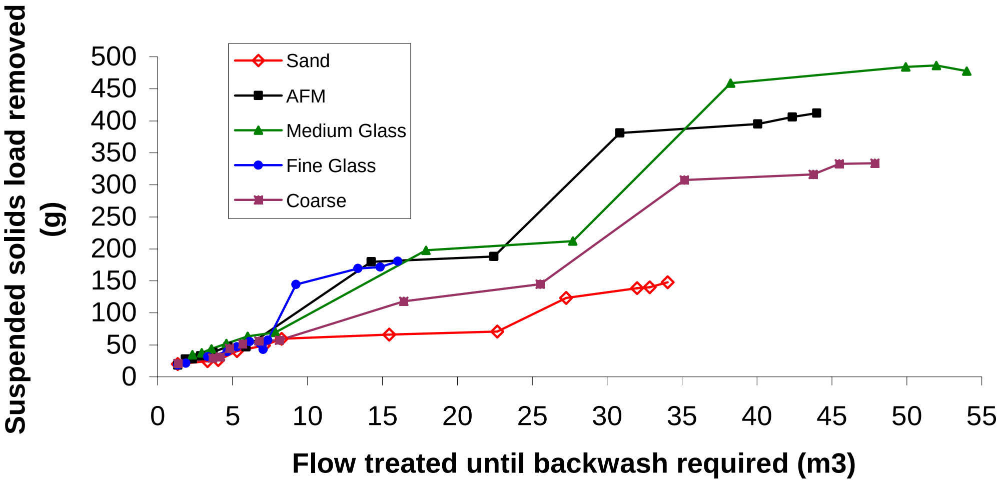

Figure 9. The performance of the five media evaluated in the pilot trial at Malton

Thus in terms of the total solids load removed before backwash, the medium grade glass was the best performing glass media, although there was very little difference between AFM, coarse and medium glass both in terms of the amount of solids removed from each m^3 of influent applied and the concentration of solids removed (Table 5). The sand medium demonstrated the worst performance both for solids removal and after the fine sand, the flow treated before blinding.

Table 5. Performance of the five media based on solids removal before backwash was over the period 26/11/04 – 17/01/05 and ranked based on solids load removal

Rank	**Media**	**Solids concentration removed (mg/l)**	**Flow treated before backwash (m^3)**	**Solids load removed (kg)**
1	Fine	19.5	15	0.29
2	Medium	15.6	55	0.86
3	Coarse	13.0	50	0.65
4	AFM	12.9	45	0.78
5	Sand	9.9	35	0.35

In addition to ability to remove suspended solids all the media were assessed for COD removal (Table 6). It was anticipated that the amount of COD removed would be a function of the suspended solids removed and any COD removed attributable to the organic fraction of the suspended solids. However the ratio of solids removed to COD removed was very different for each medium. Whereas sand and medium glass were similar with a ratio of 1.0, AFM and fine glass both had a ratio of 1.4 and the coarse glass showed the highest COD removal, and was able to remove 2.4 mg of COD for every mg of solids removed. This suggests that the different glass media have variable binding properties for soluble organic material, but this phenomenon was not investigated further in this study.

Table 6. Overall removal efficiencies of the five media for COD and suspended solids

	Influent	Filter 1 Sand	Filter 2 AFM	Filter 3 Medium Glass	Filter 4 Fine Glass	Filter 5 Coarse Glass
COD (mg/l)	109.7	100.5	91.3	92.4	84.3	78.0
% COD Removed	-	8.4	16.8	15.8	23.2	28.9
TSS (mg/l)	32.9	23.0	20.0	17.3	13.4	19.9
% TSS Removed	-	30	39.2	47.4	59.3	60.5

5.1.3 Operation and Performance of the Full-scale Test Rigs

Two full-scale filters were installed at the Malton WwTw (Figure 10) packed with medium grade glass and sand medium to allow a direct comparison of the performance of these media under identical operating conditions. The filters were operated as described in section 5.1.2 and a series of trials to optimise the backwash cycle were carried out as described in Table 1.

Figure 10. The two full-scale filters at Malton WwTw, one packed with sand medium the other with medium grade glass

Suspended Solids Removal

During the first four weeks of the full-scale trials the filters were operated without air-scour but with varying backwash conditions, whilst the backwash cycle was being optimised (Table 1). Their performance was monitored throughout this period for the removal of suspended solids and there was little difference in performance between the sand and glass media (Figure 11). Clearly the effluent quality depended largely on the quality of the influent, as suspended solids peaks in the influent also appeared as peaks in the effluent. It appears from inspection of Figure 11 that the filters were able to remove around 25 mg/l of suspended solids, or 70% of the influent solids and for much of the time when the influent solids were around 35 to 40 mg/l, the effluent from the filter was < 10 mg/l. However on those occasions when the influent solids increased to 95 mg/l the effluent quality also increased to about 65 mg/l.

During the final operating period an air scour was introduced to the backwash cycle (Period 3, Table 1) and during this period the influent to the filters was much more variable on an hourly basis, although without the high suspended solids peak that was observed in Figure 11. Following the optimisation of the air scour, the filters were again able to remove consistently around 25 mg/l from the influent to the filters (Figure 12). During Period 3 the 95 percentile of the influent suspended solids was 84 mg/l and both filters were able to reduce this to around 37 mg/l (Table 7).

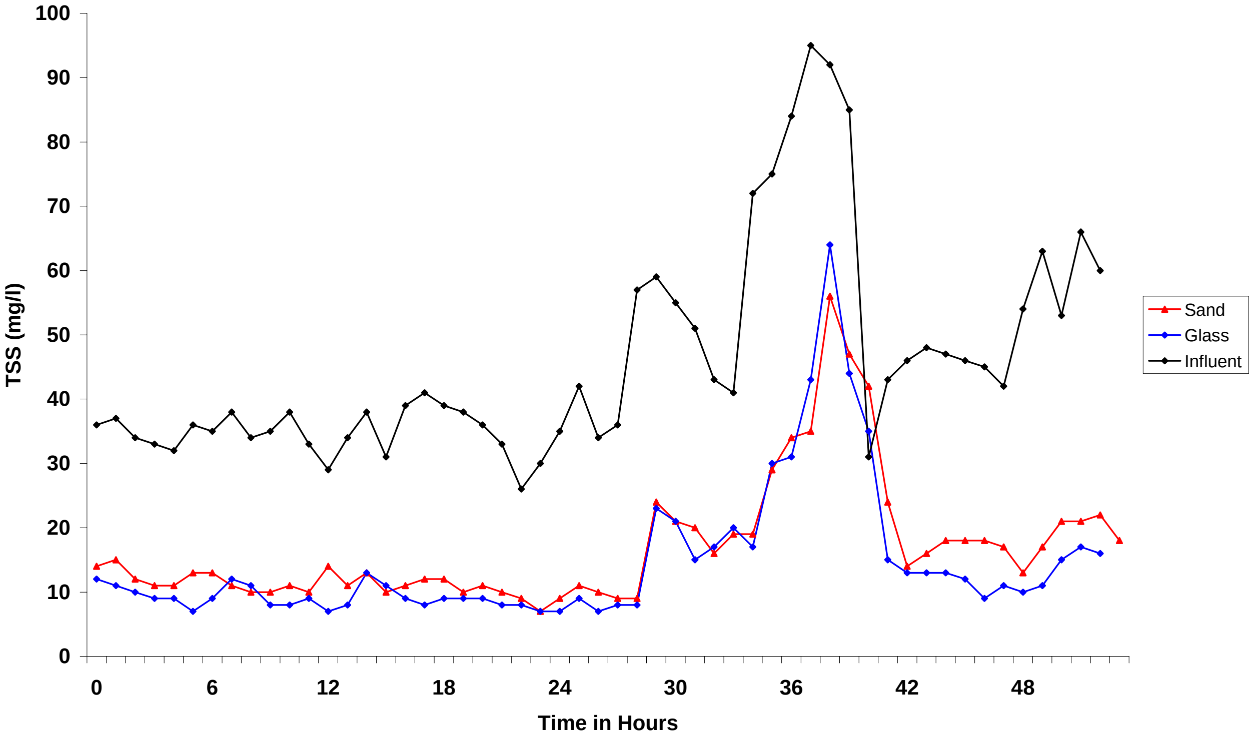

Figure 11. Performance of the full-scale filters during the period when backwashing was achieved without air scour. The data in this Figure is from Period 2 E (Table 1) but performance during the other periods was similar.

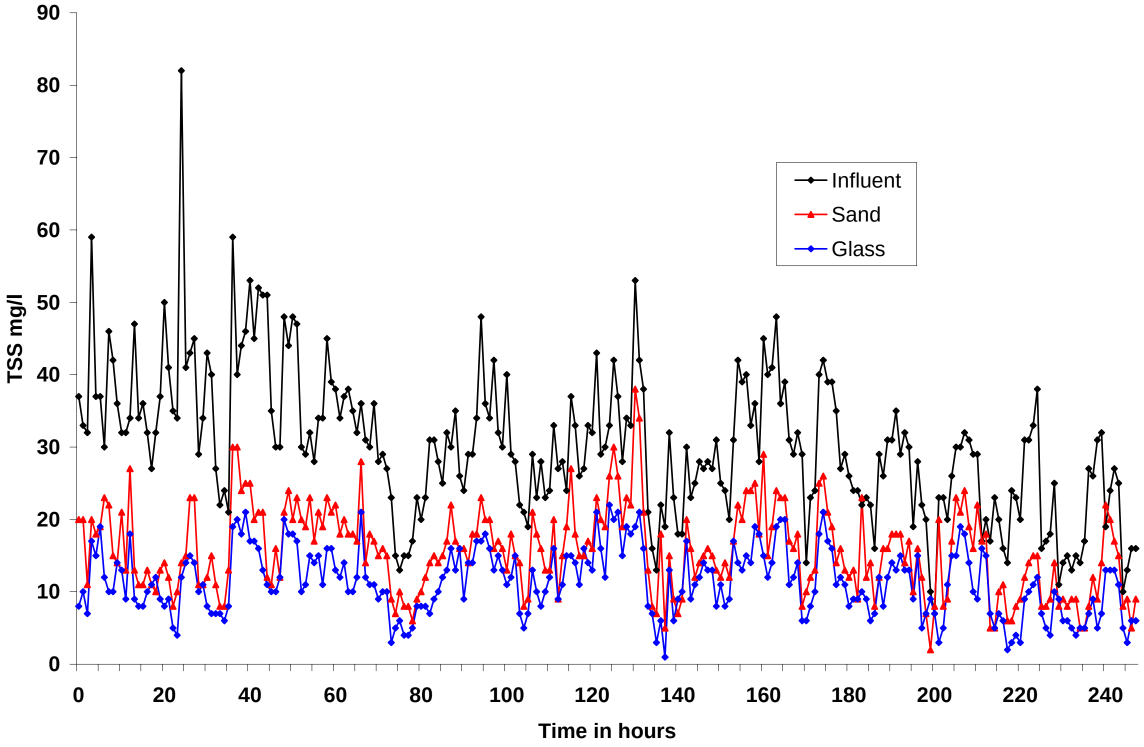

Figure 12. Performance of the filters during Period 3 H - K when air scour was incorporated and the backwash was optimised

During each cycle it was noticed that the flow rate through the glass medium filter following backwash was higher than through the sand filter, when all other operating conditions were identical (Figure 13). Thus at the end of a service run the glass filters had treated about 10% more flow than the sand filter.

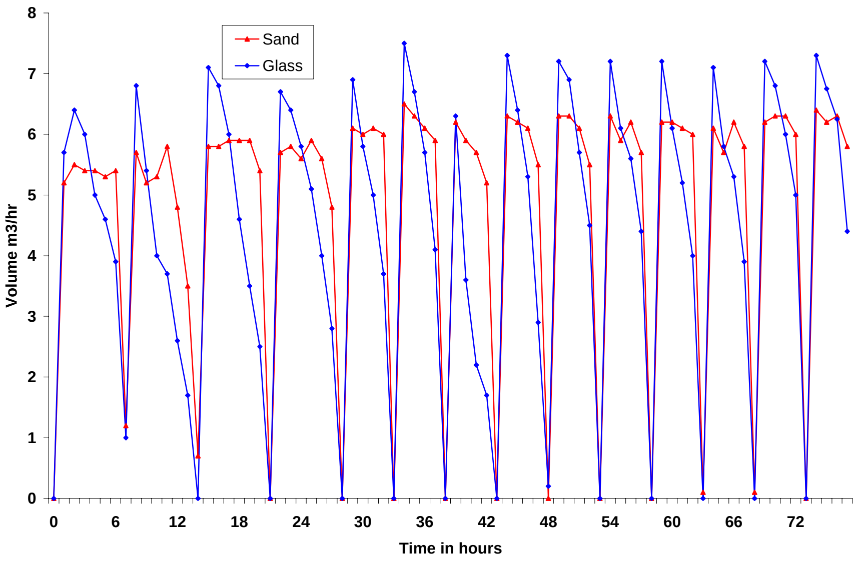

Figure 13. Flow rate through the filters for an optimised, 6-hour cycle with air scour

Table 7. Performance of the filters during Period 3 with an optimised backwash cycle

Parameter	**Suspended solids (mg/l)**		
	Influent	**Effluent from Sand**	**Effluent from Glass**
Average	46	17	15
95 percentile	84	37	38
Maximum	95	56	64
Minimum	26	7	7

When the performance of the filters was analysed with respect to the percentage removal of suspended solids (Figure 14) it was clear that a removal of around 75% could be achieved for influent solids concentrations up to 70 mg/l. However above this concentration there was a rapid deterioration in performance.

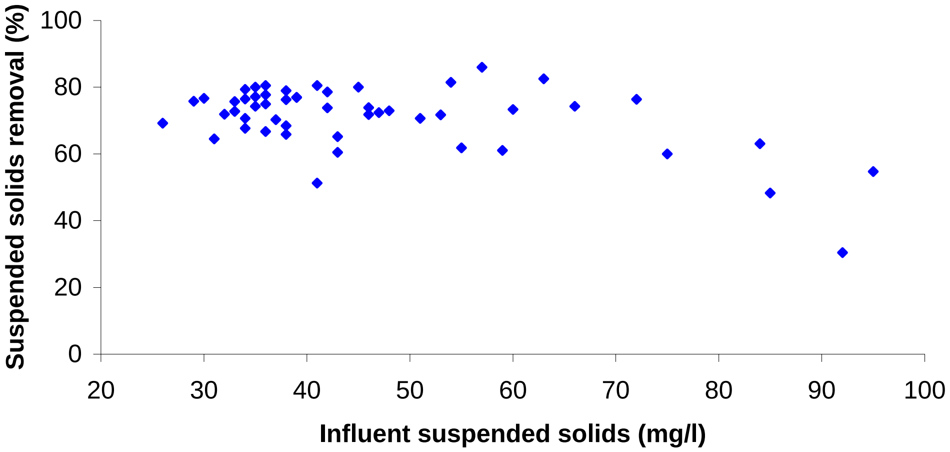

Figure 14. The influence of the influent suspended solids concentration on the performance of the glass filter medium

The performance of the filters was then analysed in order to establish a design solids loading rate (Figure 15) and it was noted that in order to ensure an average effluent suspended solids concentration of less than 20 mg/l, it was necessary to keep the loading rate to less than 0.25 kg solids/m^3 media h.

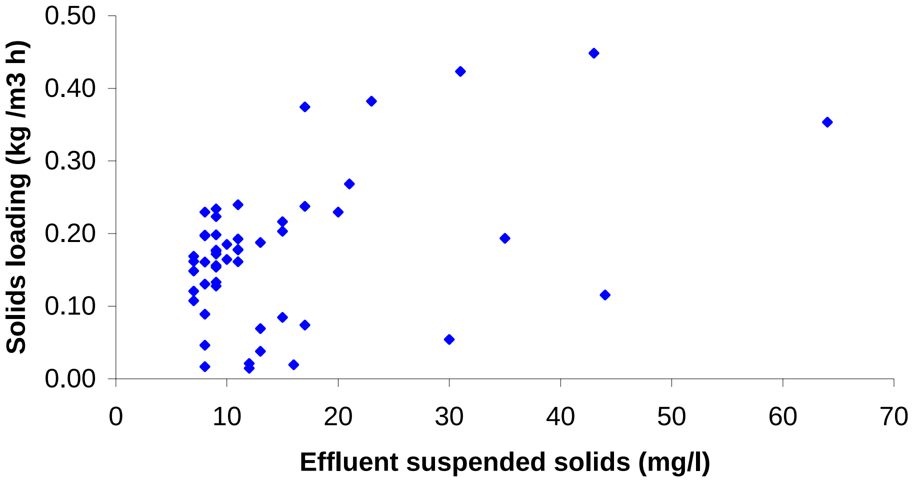

Figure 15. The influence of the solids loading rate to the glass filter medium on the effluent suspended solids concentration

Whereas the media solids loading rate is used to determine the amount of media required for the filter, the depth to which the media is placed is calculated from the upflow velocity (Figure 16). A clear relationship between upflow velocity and filter performance was not established at Malton, however provided that this parameter is <15 m/h then a suspended solids removal of 20 mg/l or better can be achieved. Above this value filter performance starts to deteriorate.

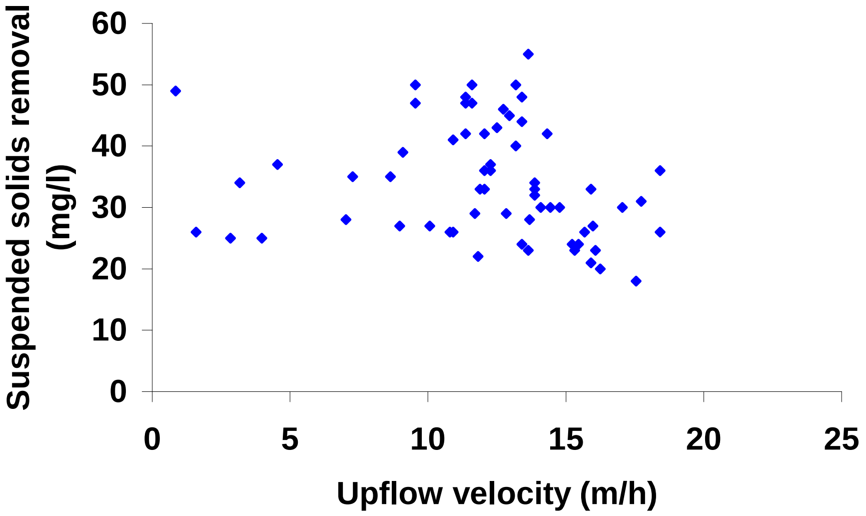

Figure 16. The effect of increasing the upflow velocity on filter performance

5.2 Stubbins Mill, Ramsbottom. Georgia Pacific

5.2.1 Introduction

The trial at Stubbins Mill was undertaken over a period of 127 days between 16th November 2004 and 23rd March 2005 with the the first stage involving the pilot-rig, which was installed on 15th November 2004.. The rig was located at the secondary treatment plant, close to the filtrate return sump (Figure 17). The experimental study followed a similar pattern to that described for the Malton site as summarised in Table 1. Operational decisions for the Stubbins Mill filters were made based on the results obtained at Malton and all data from Stubbins Mill were analysed in the context of the findings obtained from the other two sites. The filters were commissioned with the five media as described in Section 5.1.2. The rig was positioned to permit an influent sample to be taken from the sump, prior to the sand filter by-pass, and the filter discharge was also directed back into the sump. As the steam in Figure 17 suggests, the temperature of the influent wastewater is quite high, averaging slightly below 40°C.

Figure 17. The pilot rig employed at the Stubbin's Mill site

The wastewater was typical of that from an industrial process with a much higher concentration of COD and suspended solids than that of the Malton site (Table 8). There was also a high sulphide concentration in the biotowers that produced an average of 2.7 mg sulphide/l in the filtrate return sump. The sulphides produce corrosion on site and metal work appears heavily oxidised. After just a few hours of operation at this site the metal components of the rig also appeared tarnished.

Table 8. Variation in composition of the influent to the filters during the pilot plant study

Parameter	Suspended solids (mg/l)	COD (mg/l)
Average	103	653
Max	267	1,287
Min	31	363

5.2.2 Operation and Performance of the Pilot Apparatus

Once the rig had been primed, influent was pumped continuously and simultaneously through each of the 5 filters. Flow and pressure readings were taken every half hour for the first day's operation and influent and effluent samples taken every hour. At the end of the day, each filter was backwashed individually for 2 minutes and the backwash water sampled. A routine of continuous filter operation was established, with hourly pressure readings and samples taken during the working day and unattended operation at night. Initially backwashing was initiated when the effluent pressure fell below 3 psi, however, as with the Malton site, this was changed to a fixed cycle of service flow and backwash after problems with filter blockage during unattended periods. Each filter was backwashed for 2 minutes and the backwash directed to a storage vessel in order to permit a composite sample of the backwash to be taken after each backwash cycle (Figure 18).

Figure 18. Backwashing filter 4 to the backwash storage vessel.

The operational period permitted around fifty service flows to be passed through the filter and Figure 19 illustrates one such flow from the end of one backwash period through five hours of service flow to the next backwash cycle. This Figure demonstrates that after 250 minutes of flow the performance of the fine glass medium was deteriorating. Analysis of data from all of the trials demonstrated that AFM was the most efficient medium and on average over the study period was capable of removing 34.8g of solids per m^3 of flow for a feed wastewater which had a suspended solids concentration in the range of 34 to 233 mg/l. The effluent quality with AFM as the medium and under the initial operating conditions, had an average suspended solids concentration of 72 mg/l and a range of 36 to 177 mg/l. It is also worth noting that the AFM, fine and medium glass all performed better than the sand medium (Figure 20).

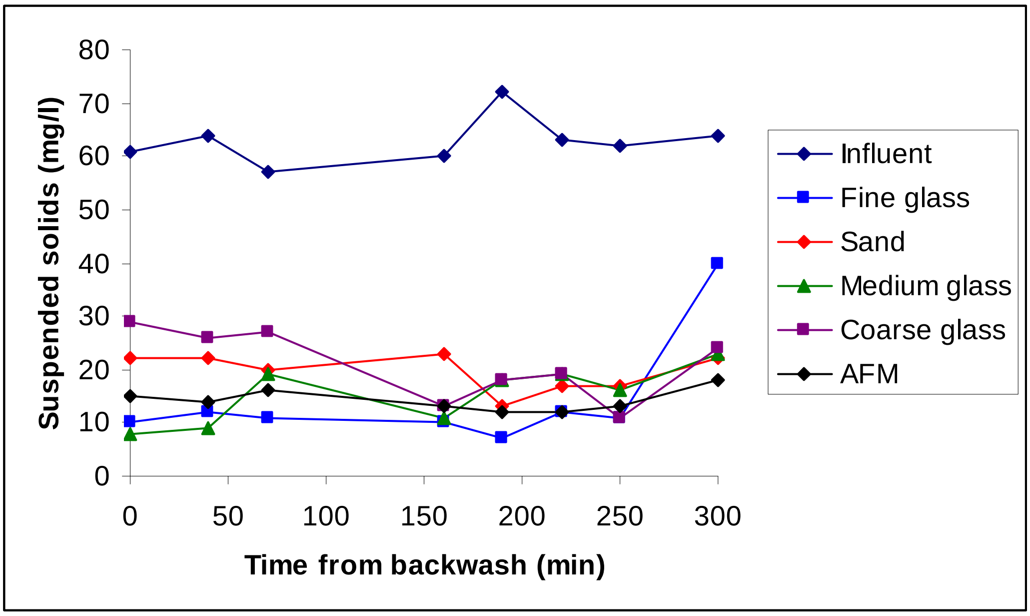

Figure 19. Typical solids removal during Period 1A between 17/11/04 to 12/01/05

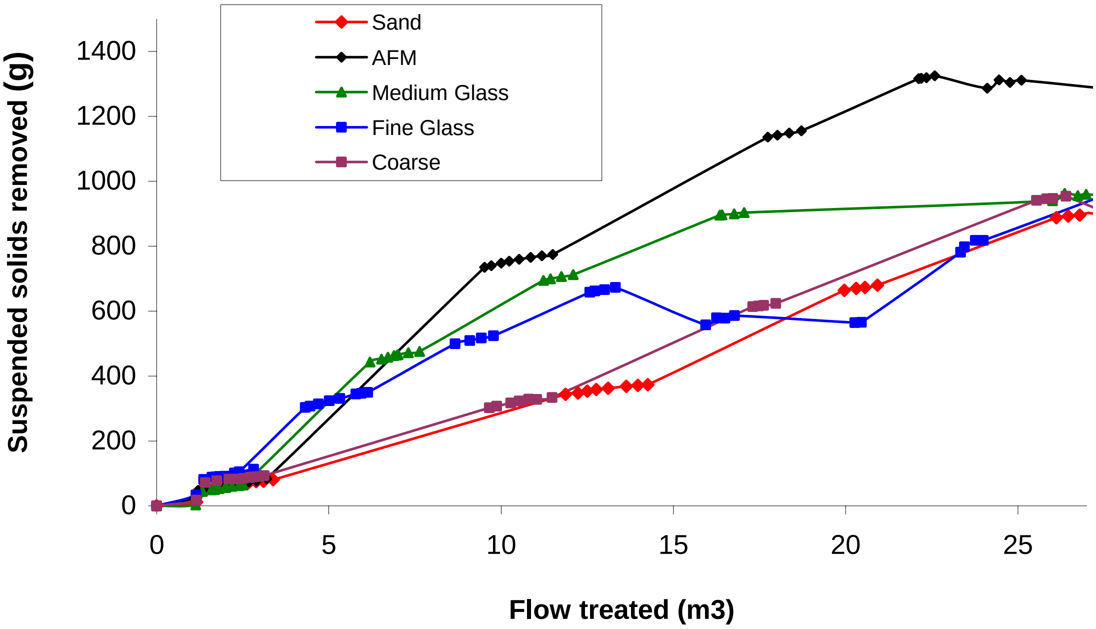

Figure 20. Cumulative removal of suspended solids over the period 17/11/04-10/12/04

Table 9 summarises the comparative performance of the five media types and when performance was assessed by the volume of flow they were able to process before a backwash cycle was required, it was observed that whereas the fine glass clogged most rapidly and able to treat only 13.3 m^3 of wastewater other glass media could treat in the range of 22.6 m^3 (AFM) to 26.4 m^3 (medium and coarse glass); sand was the best performing medium treating 27.1 m^3. However it is also clear from Table 9 that differences in performance between each of the four glass media were only slight and probably not statistically significant. By contrast there was a big difference in the performance of the sand medium which removed 33% less solids than the AFM. It should also be noted that the performance of the pilot-scale rigs was assessed solely upon the ability of the different media to remove suspended solids. Although results from backwashing in terms of the propensity for the different media to blind have been taken into account the backwash regime at this stage was not optimised.

Table 9. Performance summary of all five filters during the period 1A (02/12/04 – 8/12/04)

Rank	Media	Solids concentration removed (mg/l)	Flow treated before backwash (m^3)	Solids load removed (kg)
1	AFM	21.7	22.6	1.88
2	Medium	21.6	26.4	1.86
3	Fine	34.8	13.3	1.86
4	Sand	17.6	27.1	1.76
5	Coarse	14.0	26.4	1.40

In addition to the removal of suspended solids it was also anticipated that the filters would remove other contaminants such as BOD, COD and possibly ammonia. Although there was some removal of organic material measured as COD (Table 10) this was not high, at around 2% of the total COD load. However when expressed in terms of suspended solids removal, there was on average 0.7 mg of COD removed for every 1 mg of suspended solids removed. This suggests that much of the COD in the Stubbin's Mill effluent was soluble and that for other effluents, in particular domestic effluents, where much of the COD is particulate the percentage COD removal would be much higher.

Table 10. The impact of suspended solids removal on the effluent COD

	Influent	Filter 1 Sand	Filter 2 AFM	Filter 3 Medium Glass	Filter 4 Fine Glass	Filter 5 Coarse Glass
COD (mg/l)	660.26	641.83	643.9	649.08	652.57	634.57
% COD Removed	-	2.79	2.48	1.69	1.16	3.89
TSS (mg/l)	100.46	76.67	72.48	71.78	71.39	74.09
% TSS Removed	-	23.68	27.85	28.55	28.94	26.25

In January of 2005 operational problems were experienced with the feed pump to the rig. However by this stage it was thought that adequate evidence had been collected to select the best medium for the second stage trial and so pilot-scale testing ceased and operation of the full-scale units commenced.

5.2.3 Operation and Performance of the Full-Scale Test Rigs

Full-scale units were delivered to site in the week commencing 17th January, with operation commencing on January 24th 2005. The objectives of the second stage of the trials were to: i) confirm the results of the earlier studies at full-scale, ii) investigate the addition of air scour to enhance backwash, and; iii) optimise filter performance and establish future design criteria.

When the performance of the two types of medium were compared for their solids removal ability (Figure 21) it was apparent that there was very little difference between them and both media were typically able to remove between 50 to 60% of the influent suspended solids to generate an effluent between 50 to 60 mg/l. However the influent showed wide variations in quality and at times the influent solids were as high as 280 mg/l and routinely above 200 mg/l. Bearing in mind that the filters at Malton showed a maximum solids concentration of 70 mg/l before performance deteriorated, the filter efficiency at Stubbin's Mill remained high and a removal of as much as 80% of the peak solids load was achieved. Clearly however under these circumstances the additional solids loading would contribute to media clogging with deterioration in performance following the peak load. This was demonstrated by the gradual deterioration in effluent quality from a relative constant value of 50 mg/l to 60 mg/l after a period of sustained high suspended solids loading.

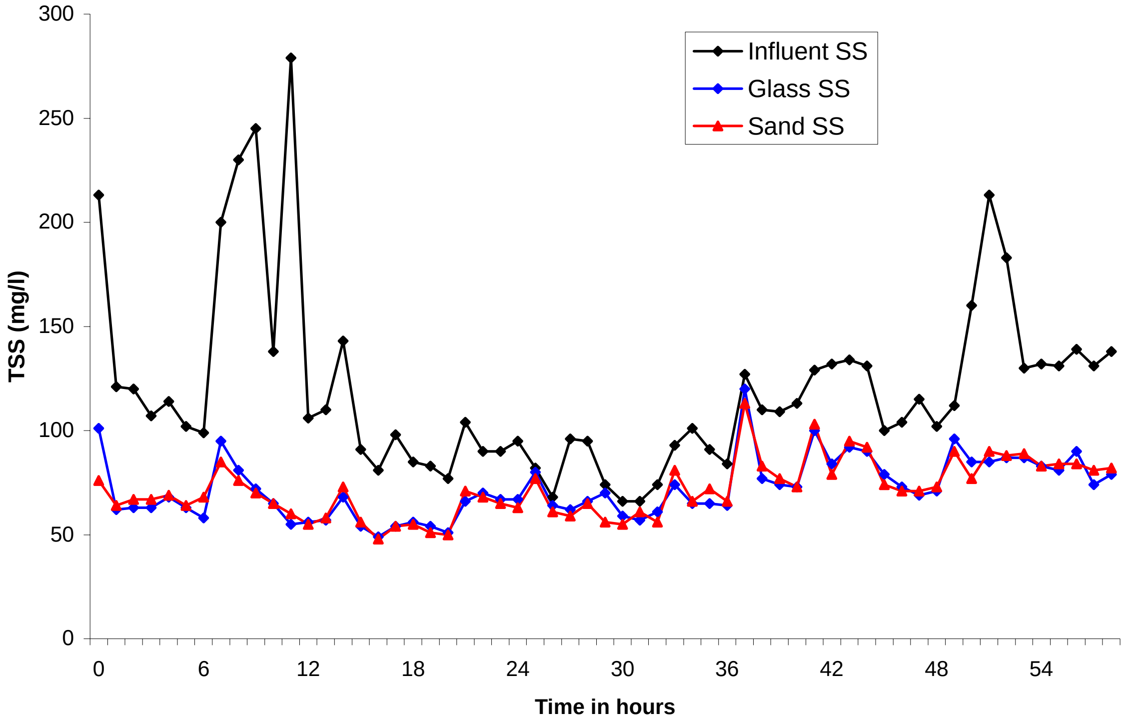

Figure 21. Effluent suspended solids concentration following the onset of a solids peak to the filters

Although the initial experiments utilised a backwash that involved only pumped recirculation of influent flow, the results from the Malton site had demonstrated that that filter performance would be improved by incorporation of air scour and thus for the last period of the trials, backwash involved both air scour and recirculation with treated effluent.

Under these conditions there was a marked improvement in the backwash which resulted in a more consistent filter performance and consequent effluent quality which averaged around 50 mg/l (Figure 22). Again there were no discernible differences between the performance of the sand medium and that of the glass, although this was helped by the influent which did not show the large peaks in suspended solids that had characterised the first period of the study. The amount of solids removed for each m^3 of flow applied was also quite consistent with a value between 350 to 400 g solids removed/m^3 applied flow.

A feature of the influent from this site over the period of operation when the filters were optimised, was the high influent suspended solids which averaged 130 mg/l (Table 11). Clearly the filter was not intended to treat such a high solids but it is was nevertheless gratifying to note that even with an average influent concentration of 90 mg/l and peaks of 250 mg/l, the filters were able to achieve solids removals of 41% (glass) and 36% (sand).

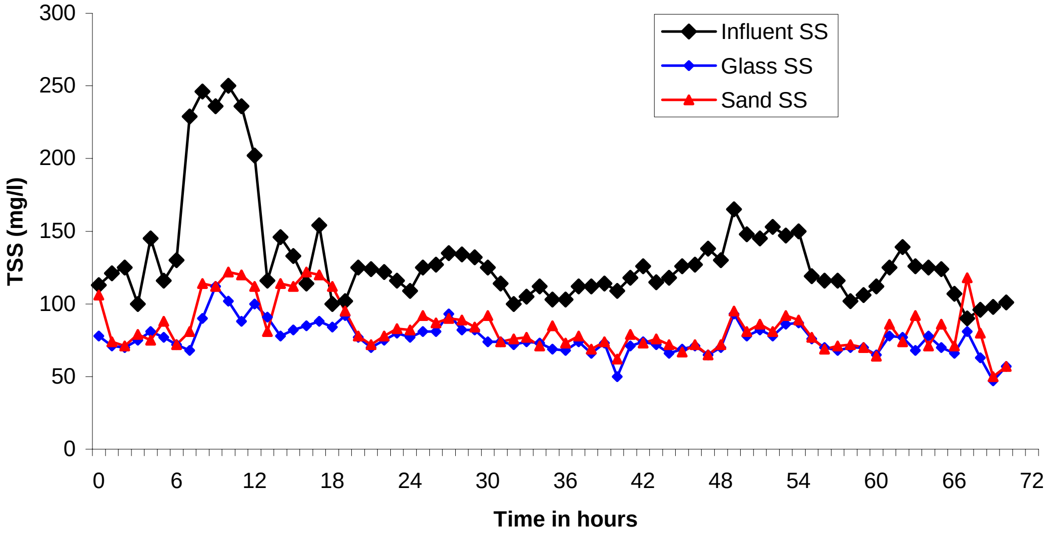

Figure 22. Effects of incorporation of air scour into the backwash cycle on the removal of suspended solids, for a backwash cycle time of 6 hours

For Stubbin's Mill an analysis of the suspended solids removal showed that as the flow rate increased, although the total amount of solids removed also increased there was a reduction in the efficiency of solids removal as shown in Figure 23, with the highest removal occurring at upflow velocities <10 m/h

Table 11. The performance of the filters over the optimised study period

Parameter	**Suspended solids (mg/l)**		
	Influent	**Effluent from Sand**	**Effluent from Glass**
Average	130	84	76
95 percentile	232	119	93
Maximum	250	122	112
Minimum	90	50	47

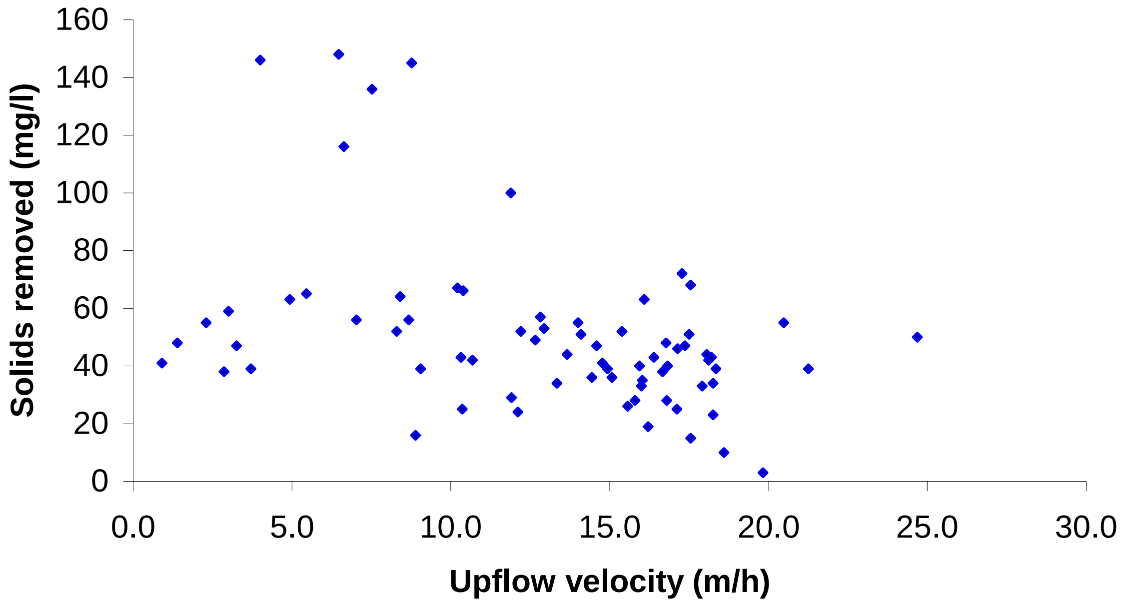

Figure 23. The influence of the upflow velocity of the removal of suspended solids

5.3 J E Hartley, Thorganby. York

5.3.1 Introduction

The pilot apparatus was installed on November 22nd with full operation commencing on 25th November. The feed to the filters was taken from the final effluent tank prior to the sand filters and the discharge from the filters passed to a drain in the yard which then fed it back into the effluent treatment system (Figure 24). As with the other two sites. the filters were initially operated continuously, but after blockage during unattended period, they were operated during the daytime only with pressure and flow readings taken hourly during the operational period.

Figure 24. The pilot rig at JE Hartleys

Historic operating and performance data for the Hartley's treatment plant suggested that the solids concentration would not exceed 100 mg/l and indeed the existing onsite sand filter was designed to remove solids between a concentration of 40 and 80mg/l. However over the operating period from November to December, the suspended solids in the feed to the filters were much higher with an average of 291 mg/l; on occasions the solids were in excess of 400 mg/l (Table 12). By contrast the COD concentration was not unusual and generally much less than the suspended solids. This shows that the suspended solids were largely inorganic and their origin is unknown.

Table 12. Variation in composition of the influent to the filters during the pilot plant study

Parameter	**Suspended solids (mg/l)**	**COD (mg/l)**
Average	291	151
Max	441	431
Min	90	59

5.3.2 Operation and Performance of the Pilot-rig

Immediately after commissioning the filters performed well, removing up to 50 mg/l suspended solids (Figure 25). However in the first two weeks the influent solids averaged 140 mg/l and the backwash cycle was not able to remove all of the solids removed by the filters. Consequently performance deteriorated rapidly. On the 9th December the influent solids concentration was 420 mg/l and although filters were able to reduce this to around 130 mg/l, the solids that accumulated on the filter then broke through on subsequent days. This meant that on a number of occasions there were negative solids removal from the filters (Figure 26) and so it was not possible to express filter performance in terms of a cumulative solids removal, in a similar way to the Malton and Stubbin's Mill sites.

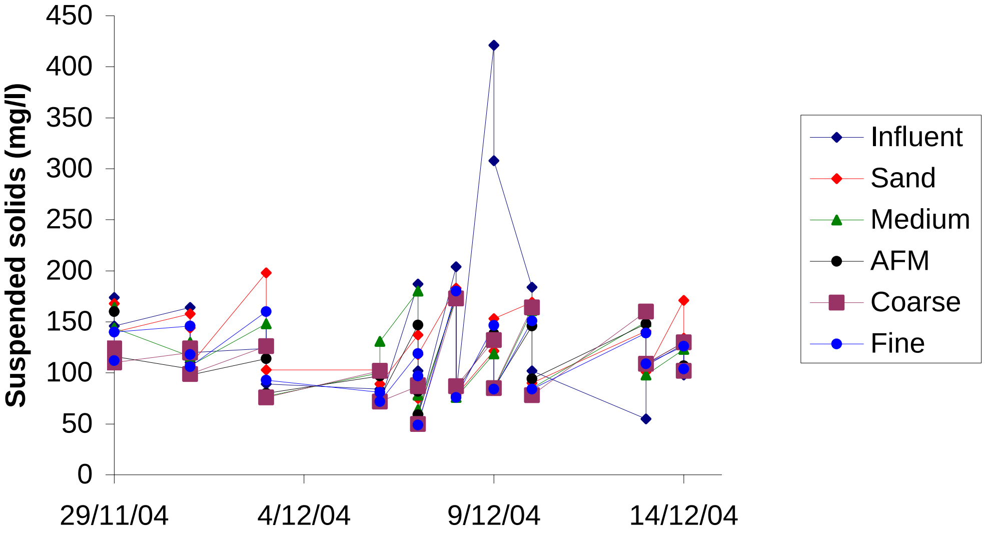

Figure 25. The start-up of the pilot-rig until the first shock load of solids

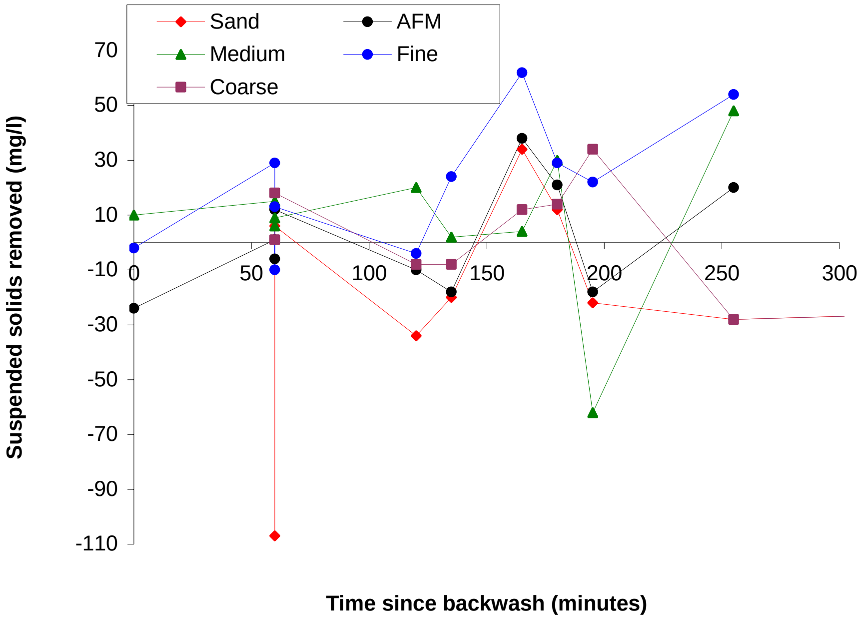

Figure 26 Suspended solids removal during the early months of the study when the influent solids exceeded 300 mg/l

After the 2004 Christmas period, the feed wastewater to the rigs improved and during January 2005 the suspended solids concentration was below 30 mg/l. The filters were emptied and repacked with fresh media and during this operation, it was noted that large quantities of solids were compacted within the filter and that the backwash had not been efficient. However even with the repacked filters and the low effluent suspended solids, performance was not as good as the other two sites (Figure 27) and it was apparent from visual inspection that much of the solids in the Hartley's effluent had a very small particle size and was not amenable to filtration. Again the COD of these solids was low showing that they are not the typical suspended solids generated during wastewater treatment. Consequently decisions as to the most appropriate medium for further work at this site were made on a paucity of data compared to the other sites. However what data was available confirmed the results obtained at both Stubbin's Mill and Malton. Fine glass was able to produce the best effluent quality but it soon blinded following a backwash when the effluent quality would deteriorate rapidly (Figure 28).

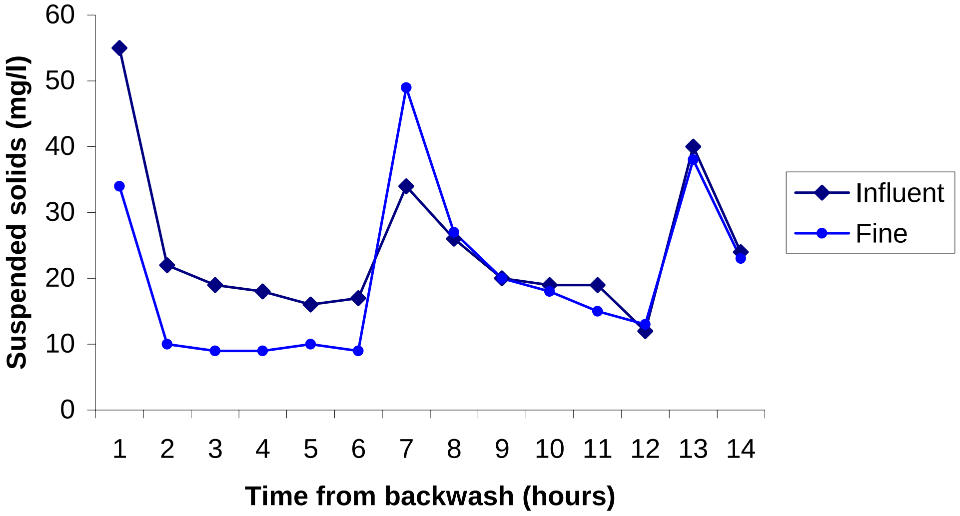

Figure 27. Performance of fine medium showing the rapid deterioration in solids removal following backwash

There was little difference between the medium glass, coarse glass and AFM in terms of solids removal efficiency, although medium glass had a slightly better performance. All three media were able to treat a greater volume of influent than the fine glass, before a backwash was required and sand showed the worst performance.

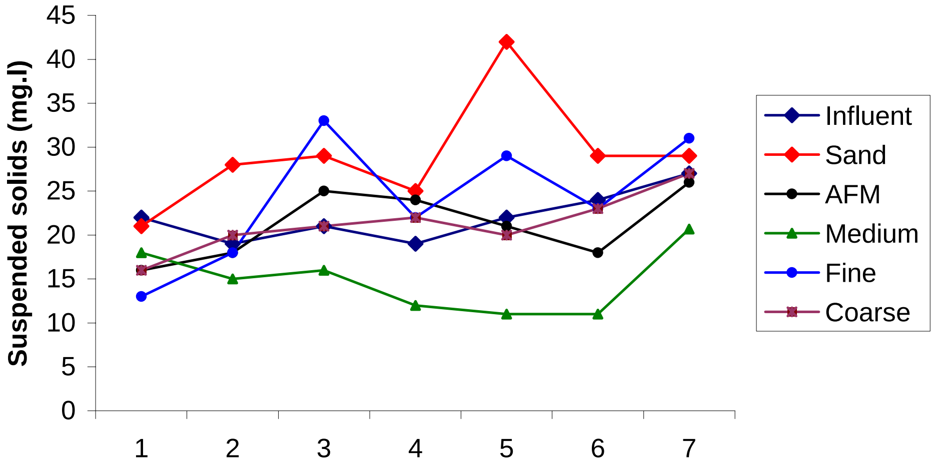

Figure 28. Suspended solids removal following backwash when the influent solids were more sTable

5.3.3 Operation and Performance of the Full-scale Test Rigs

The full-scale rig was installed on site on the 01/03/05 and operation began on the 03/03/05. Unlike the other two sites, the full-scale trials involved only a single filter packed with medium grade glass with no sand filter for comparison. The filter feed was taken from the final effluent storage tanks which were designed to feed the existing on-site sand filters. As the upstream biological treatment system was a sequencing batch reactor with a batch discharge mode of operation, the filter was designed to sample and operate immediately after the SBR's discharged, because the final effluent storage tanks emptied rapidly and before the next SBR discharge, thus leaving no time to process the effluent.

The experimental programme at Hartley's followed a similar pattern to that at Malton with the optimisation of the backwash regime demonstrating similar improvements to the filter performance. However following on from changes to the Hartley's treatment system in early January the solids concentration in the influent to the filters dropped dramatically and varied over the range 2 to 56 mg/l with the peaks appearing early in the study (Figure 29). The filter was able to remove a small amount of solids from the peaks, but the effluent suspended solids still increased whenever there was an influent peak. The media was able to remove on average about 40% of the influent solids to produce an effluent with an average suspended solids of 9 mg/l. It seems likely that the characteristics of the final effluent in terms of its suspended solids concentration and very small particle size are the reason why removal was not as good as either Malton or Stubbin's Mill.

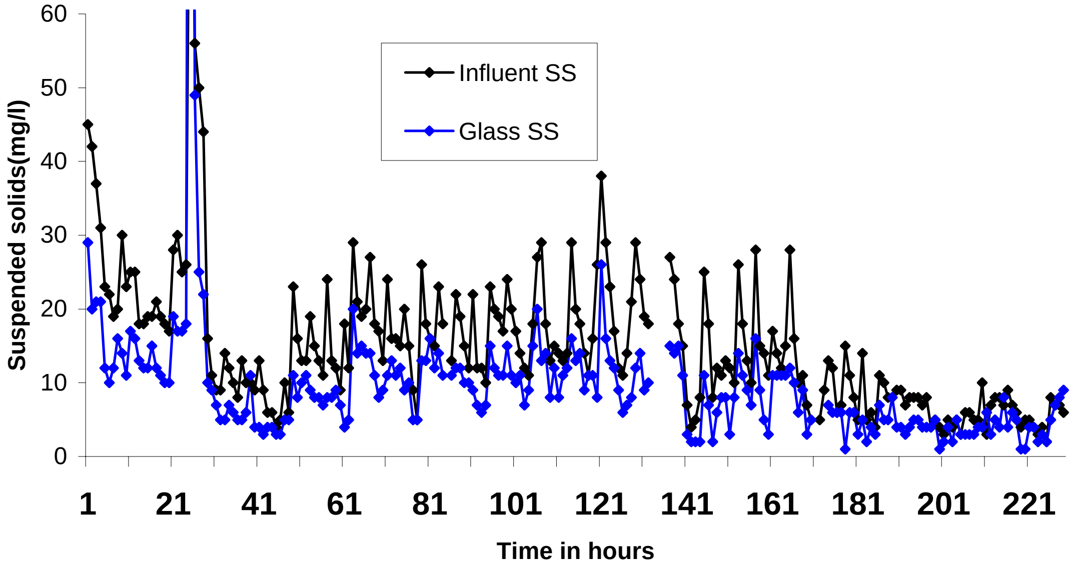

Figure 29. Total suspended solids levels over time with air scour throughout the trial

The full -scale filter was operated over a narrow range of flow rates between 1.7 to 7.1 m^3/h but with 95% of the time the flow set at 5.0 m^3h. This meant it was not possible to explore the relationship between the upward flow velocity and the efficiency of solids removal. However when the performance of the filter was analysed in terms of its solids loading there was a clear relationship between this parameter and the effluent suspended solids concentration (Figure 30). As the solids loading to the media increased the effluent suspended solids also increased in a linear fashion and in order to achieve a suspended solids concentration of <20 mg/l a solids loading of <0.14 kg solids/m^3 media is required. In order to achieve an average effluent suspended solids of 10 mg/l, which is equivalent to a typical 20 mg/l suspended solids consent with a 95 percentile compliance, an applied solids loading of <0.07 kg solids/m^3 medium h is required (Figure 30).

Over the optimised study phase at Hartley's the filter performance is summarised in Table 13 and this demonstrates that the filters would have met an Environment Agency consent of <20 mg/l suspended solids at a 95 percentile compliance, compared with a compliance in the absence of the tertiary filter of 29 mg/l.

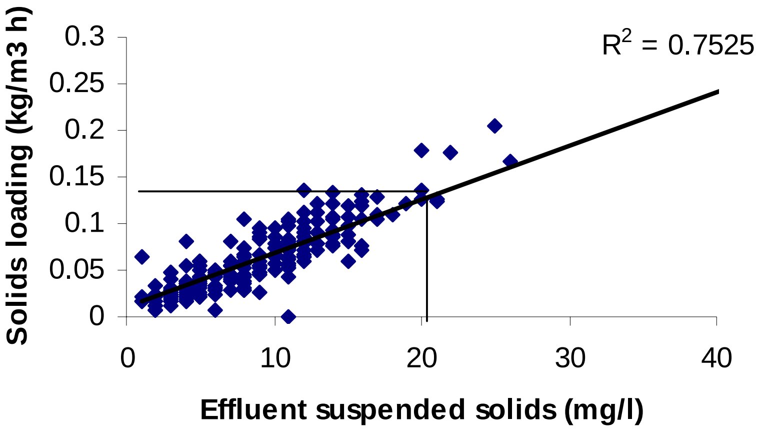

Figure 30. The effects of the media solids loading rate on the filter performance

Table 13. Summary of glass medium performance over the duration of the full-scale trial at Hartley's

Parameter	**Suspended solids (mg/l)**	
	Influent	**Effluent from Glass**
Average	15	9
95 percentile	29	18
Maximum	56	49
Minimum	2	1

6.0 Discussion

6.1 Interpretation and Discussion of the Pilot-scale Studies

The aim of the first stage of the project was to determine whether a glass medium could demonstrate similar solids removal efficiency to sand, which is the traditional medium of choice for tertiary filters. If this was the case, the aim was then to identify the most suitable of the four glass media for further studies at full-scale. Two of the trial sites demonstrated quite clearly that glass media was more effective at solids removal than sand, but it was also clear that the performance of individual medium was a function of the nature of the influent and the backwash regime. That was most apparent from the studies at the Hartley's site which were largely unsatisfactory as a result of the high influent suspended solids, averaging 291 mg/l before Christmas and on occasions over 440 mg/l. This has shown the limitations in the tertiary media as clearly they are unsuitable for effluents which are likely to demonstrate such wide variations in suspended solids.

Despite these caveats, there were a number of conclusions that could be drawn from the pilot-scale studies. Broadly speaking as the media size increases there is:

1. an increase in the volume of wastewater that can be processed before a backwash cycle is required
2. a reduction in the amount of suspended solids removed for each m^3 of flow
3. a reduction in the total amount of suspended solids removed

Thus fine glass was able to produce a better effluent quality than the other three media evaluated but suffered because it blinded rapidly and its performance soon deteriorated. Although the other three glass media did not produce such a high quality effluent, they could treat more than double the volume of influent before blinding. Of these three, medium glass produced the better effluent quality removing only slightly less suspended solids (about 4 mg/l or 20%) than fine glass, but it was able to treat 117% more flow. AFM had very similar solids removal properties to medium grade glass but the latter was able to treat slightly more flow (17%) than AFM before backwash was required. The sand medium was able to a treat similar volume before backwash as medium glass and AFM, but it removed 23% less solids from this volume.

Based on these findings the medium glass was selected for the second stage of study.

All three sites demonstrated a problem with backwashing although it was most acute at the two industrial sites, Stubbin's Mill and Hartley's, due to greater fluctuations in the influent solids. Ideally backwash should remove all the accumulated solids so that the cleaned medium has a flow and headloss comparable to the virgin medium. Although this was achieved at Malton this was never achieved at Hartley's and achieved only sporadically at Stubbin's Mill. It was essential to resolve this problem during the full-scale studies

By removing suspended solids a tertiary filter is also able to remove the BOD, COD and nitrogen associated with these suspended solids. However it was thought that the glass media might also show additional removal of these parameters by for instance, binding to the charged glass surface or by microbial activity resulting from biofilm formation around the medium. Whereas the former mechanism would be expected to show a large removal in the early days of the trial the latter would take some time to develop in response to the growing biofilm. In the event there was little evidence for significant additional soluble organic removal not associated with particulates removal and it was the coarse glass that demonstrated the best performance. It might be expected that an extended trial would provide more opportunity for a biofilm to develop and so the potential for additional organic and nutrient removal cannot be ruled out from these trials alone.

6.2 Interpretation and Discussion of the Full-scale Studies

The performance of the full-scale filters was better at all three sites than corresponding results obtained during the pilot trials and demonstrated the ability of the glass filter medium to polish secondary effluent to a standard that allows it to meet a tight suspended solids discharge consent. At both sites the glass medium showed a superior performance to that of sand although the differences were not as great as observed in the pilot studies. This may be due to the optimisation of backwash which enhanced the performance of the sand medium more than that of the glass.

However optimisation of backwash by the provision of an air scour did permit the glass medium to process more flow for each cycle following a backwash, than the sand medium, when operated under identical conditions. Although this varied considerably both between sites and at the same site, depending on the concentration of the influent solids, on average across all the sites the glass medium was able to process up to 10% more flow than the sand medium. This is a distinct advantage as many sand filters fail because of a propensity to blind following a shock solids-loading and this blinding is not ameliorated by the routine backwash regime. The ease with which the glass medium was backwashed even after a period of high solids loading, suggests that this problem will be much reduced, if not completely alleviated with glass media.

The optimised backwash cycle that was established at Malton also proved effective at Stubbin's Mill and permitted the filter to be returned to a similar flow rate at the start of each cycle, with no headloss apparent. Under these conditions the filters were able to remove suspended solids with a removal efficiency of up to 65% and it was possible to achieve an average effluent suspended solids concentration of 50 mg/l for an influent suspended solids in the range 100 to 150 mg/l. Whilst not as good as the 80% efficiency that could be achieved at Malton the final effluent quality proved very dependant on the influent to the filters and performance was much better if the influent solids was <70 mg/l. At Stubbin's Mill there was a much higher suspended solids concentration in the influent feed which at times was in excess of 200 mg/l. When the influent solids were in excess of 70 mg/l, peaks in influent to the filters were mirrored by peaks in effluent solids. A similar picture was noticed during trial of the AFM glass (Dryden Aqua, 2004) where pilot scale trials at three sites concluded that "AFM can cope with high solids loading without any adverse effect on effluent quality". However, inspection of the site data shows that the influent solids concentration was routinely <70 mg/l at these three sites. At times when it exceeded this value the effluent quality also deteriorated.

At Hartley's the concentration of suspended solids in the influent was so low that the filters were not challenged and it was difficult to say conclusively that the backwash regime had been optimised for this particular site. Consequently it was not possible to demonstrate a relationship between the filter performance and the solids loading rate or upward flow velocity.

As with the pilot trials, the performance of the full-scale tertiary filters depended both on the concentration and nature of the influent suspended solids. In the original site selection procedure, the sites selected had similar effluent qualities in terms of their suspended solids, based on historic performance data for a long period prior to the trials commencing. By choosing these three sites, it was hoped that any differences in the performance of the filter between the sites, could thus be attributed to differences in the nature of the suspended solids. In the event however there were marked differences over the trial period between the solids in the influent (Table 14).

Table 14. Summary of average filter performance at the three sites

Site	**Average Influent TSS (mg/L)**	**Average TSS Removal (%)**	
		Glass	**Sand**
Malton	46	67	63
Stubbins Mill	130	41	35
Hartleys	15	40	-

The Hartley's site averaged only 15 mg/l and a removal of 40% was returned. The Malton site averaged 46 mg/l and demonstrated 67% removal, and the Stubbin's Mill site had an influent of 130 mg/l with an average removal of 41%. Under these circumstances it is difficult to draw any conclusions as to how the influent to the filter is likely to affect its performance. It is quite reasonable to comment though, that there is no evidence to suggest that the effluents from industrial treatment plants are any less amenable to treatment with glass media than the effluents from domestic plants. What these results do demonstrate is a key message that when selecting and designing tertiary filters, although published design data provides a guide to likely filter performance and will give indicative filter sizings, pilot trials are essential to ensure an optimized filter design and guarantee consent conditions are met.

Tertiary filters are generally designed based on a solids loading rate (in kg/m^3 d) which determines the volume of the medium required to treat a given flow rate of influent, and the upward flow velocity (in m/h) which determines the area of media required. The upward flow velocity determines how long the influent to the filter remains in contact with the medium (effectively the hydraulic retention time) and as the upward flow velocity increases the hydraulic retention time decreases. Increasing the upward flow velocity also increases the suspended solids load to the filter, however this latter parameter also changes even when the flow rate is constant, if the suspended solids in the influent also change. Knowing the volume of media and its area the filter depth can then be calculated. In this study the media loading rate necessary to achieve an average effluent suspended solids of 20 mg/l was found to range from 0.14 kg/m^3 h for the Hartley's site to 0.22 kg/m^3 h for the Malton site, whereas the Stubbin's Mill site demonstrated that an upflow velocity of <10 m/h is necessary to achieve the same effluent quality.

One issue that was present from the start of the study was the problem of achieving backwash by recycling of treated effluent. The consumption of backwash water is highly dependent on the concentration of the suspended solids on the influent and typically single media filters would use between 1 and 2% of the volume treated. However it proved very difficult to fully fluidise and scour the beds used in this study without recourse to prohibitively large volumes of backwash water. But the inclusion of an air scour was able to alleviate this problem and ensure good release of trapped and compacted particulate material from the bed. The final optimized backwash rate employed an effluent flow rate of 0.45 m^3/m^2 min which is compatible with the typical design figures used for backwashing single-medium sand filters based on experiences in N. America (Table 15) and somewhat less than the rates recommended for a water only backwash of a similar sized medium (Table 16). The water backwash lasted around 2.5 minutes and used 3% of the total volume treated on the filter. The air scour rate of 0.45 m^3 air/m^{2}min was considerably less than that employed in typical single-medium sand filters (Table 15) and may account for the negligible loss of media observed during the study.

Table 15. Air and water backwash rates for single-medium sand (Dahab and Young, 1977)

Effective Size (mm)	**Backwash Rate**	
	Water (m^3/m^2 min)	**Air (m^3/m^2 min)**
1.00	0.41	6.7
1.49	0.61	13.1
2.19	0.82	19.8

Table 16. Degremont (1991) Guidelines for single-medium filters (sand or anthracite) backwashed with water only

Effective Sand Size (mm)	**Backwash Rate (m^3/m^2h)**
0.35	0.42 – 0.58
0.55	0.66 – 0.83
0.75	0.92 – 1.17
0.95	1.17 – 1.50

7.0 Benefits from Selecting Recycled Glass as a Filter Medium

The aim of this study was to evaluate the performance of recycled glass as a tertiary filter medium, and compare this to the performance of the more traditional sand medium when operated under the same conditions. The results have shown clearly that recycled glass is a superior medium both in terms of its solids removal ability and its ease of backwash. However the technical case alone is not enough to ensure the commercial viability of recycled glass in this application, unless a clear business case can be made for its selection. The business case is not decided exclusively on cost issues (although of course this is usually the most import factor) and many other aspects of the process, some of them difficult to quantify, will play a part.

From a Water Company perspective the most important consideration is that the tertiary treatment option selected will ensure consent is met. In this respect, past experiences with sand have not always been successful and many filters have suffered problems with blinding and fouling. As a consequence the new generation of sand filters are either continuous backwash filters or deep bed filters, both of which were developed to overcome backwash problems. The former utilises a bed of sand that is continuously removed from the bottom of the filter vessel by an air lift or screw pump. This is then washed, the solids separated and the sand returned to the top of the vessel. The latter employs a deep bed of 1.2 to 2.0 m depth with a rounded sand of around 2mm diameter that is backwashed daily with a powerful air and water wash (Rundle, 2005). But there are many older assets employing sand medium that are either redundant or performing well below expectations, and which might be uprated with glass medium and brought back into service. As recycled glass has proved more amenable to backwashing it is likely that the problems experienced with sand will be either minimised or reduced completely.

Where new assets are required and a decision has to be made between recycled glass, or some other process options, clearly the superior performance of the glass media will be a key factor. But perhaps more importantly as Water Companies now strive to include the principles of sustainable development in their business practices, this unique feature of recycled glass will be more important. One important aspect of achieving more sustainable engineering practices is that companies shall, wherever possible, minimise their use of non-renewable resources and substitute these with renewable or recycled material. Indeed environmental considerations were central to the water resource plans that water undertakers prepared for the 2004 periodic review process. The recently adopted Strategic Environmental Assessment (SEA) Directive has included water companies' water resource plans in its indicative list of plans and programmes subject to SEA and it is inevitable therefore that demonstrating sustainable practices will play a greater part of the next periodic review in 2009.

Water Companies along with other quoted industries, are also subject to shareholder pressure and major shareholders, in particular fund managers, demand that Environmental Reporting forms a key part of a company's annual statement. The substitution of a non-renewable resources with recycled material demonstrates a clear and measurable commitment to more sustainable practice.

There are some examples where recycled materials are specified because of their environmental benefits alone and recycled paper is a good example of this. Historically the quality of recycled copier paper was not as good as paper made from virgin pulp and its retail price was significantly higher than virgin material, yet many companies were (and still are) prepared to pay this extra price, for the publicity associated with using recycled paper. It is such an approach that will best serve the recycled glass market. It is a good product, indeed a better product than sand but most importantly it demonstrates the right environmental credentials, and this should be the main focus of any marketing message.

8.0 Conclusions

Glass filter media made from recycled glass is able to remove suspended solids from both the effluents of domestic and industrial activated sludge plants, when employed in a tertiary treatment mode. The performance of glass media was at least as good, and generally better, than the traditional sand medium employed in tertiary filters. For an influent that has a suspended solids concentration of 70 mg/l or less, then up to 70% removal of suspended solids can be achieved and a consent of < 20 mg/l is possible. Above this figure the performance deteriorates and influent solids peaks appear as effluent solids peaks. Despite this even at average influent concentrations of 130 mg/l it is possible to achieve 40% solids removal and thus produce an effluent of < 80 mg/l. In this way a two stage treatment process becomes a possibility for treating influents with a high suspended solids concentration.

The optimised backwash requirements for glass media were established and although both an air scour and a backwash with treated effluent are required, the magnitude of these is no greater than similar figures quoted for tertiary sand filters.

For a typical domestic wastewater treatment plant where the suspended solids in the effluent would not be expected to exceed 50 mg/l an effluent suspended solids of <20 mg/l was achieved with ease using a solids loading rate of <0.22 kg/m^{3}h.

9.0 Further Work

This study has shown clearly that recycled glass is able to achieve removal of suspended solids from the final effluent from a wastewater treatment plant when employed as a tertiary filtration medium. The glass – media demonstrated this ability both in a small- and a large-scale pilot-plant. Although this study was comprehensive it is inevitable that it will throw up questions that should be answered prior to marketing the media as a viable competitor to sand and such questions generally focus on the needs to optimise performance and thus reduce site footprint and operating costs. For the glass media there are two key areas that require further work, namely:

i) the potential to further optimise the backwash cycle by the application of continuous, moving bed backwash. Such systems, for instance the Dynasand® and Astrasand® filters (Chan and Barbadillo, 2005), continuously bring media to the surface of the bed using an air lift system, where is can be backwashed and then returned to service without the need to remove a filter from the flow train. Such an option should be evaluated using glass media in order to assess if further improvements can be achieved

ii) the opportunity for exploiting either mixed media beds or two stage filters, in response to the nature of the influent and the requirements of the consent. It was apparent from this study that fine media could generate an effluent with a very low suspended solids concentration, but was restricted with the solids loading it could handle. By contrast coarse media could treat a much higher influent suspended solids concentration without blinding, but with a reduced effluent quality. Thus where the influent has a high suspended solids concentration there is a need for a medium with a high proportion of coarse glass (or a first stage roughing filter of coarse glass) and where a low effluent suspended solids concentration is required there is a need for a bed with a high proportion of fine media (or a second stage polishing filter of fine glass). Further work is required to define the performance and kinetics of mixed or two-stage beds to permit their design for a given set of influent and effluent conditions

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Appendix 1

Determination of Backflush Flow-rate Necessary to Avoid Media Loss

1) Introduction

It was apparent during both the pilot- and the full-scale trials that the efficiency of operation depending on achieving a good removal of suspended solids from the glass media during the backflush cycle. Optimisation of backflush can be a long process as there are several variables: the period of operation between backflush; the volume of water used in the backflush; the backflush flowrate; the air scour flow rate and the time allocated for air scour. In addition it is important during the backflush cycle to ensure that it is not so vigorous that it entails excessive media loss and the filters should operate with an annual media loss of <2%. The value of the maximum backflush flow rate before media loss occurs can be determined from small-scale studies into the fundamental properties of the medium and this section describes the work that was undertaken to assess these fundamental parameters.

2) Determination of Backflush Flow-rate Necessary to Ensure Avoid Media Loss

The backflush flow rate that will result in a loss of media depends on the particle size distribution of the media and the finer the particle size, the more likely they are to be lost at lower backflush rates. The laboratory study measured the particle size distribution, porosity and specific gravity using glass taken from the Malton filter (medium grade) (Table 1).

Table 1. Properties of the medium glass filter media

Parameter	**Data**
Size (Geometric mean) (d_p)	70% (0.84mm), 30% (0.42mm)
Porosity (α)	0.48
Specific gravity, g/ml (S_p)	2.63

These parameters were used to characterise the headloss and to determine the required backwash velocities for filter cleaning, based on the equations presented by Metcalf and Eddy (2003). However the Malton glass was unusual in that there were effectively only two particle sizes, with 70% of the particles having a diameter of 0.84mm and 30% having a diameter of 0.42mm (Table 1).

Table 2. Cumulative frequency distribution for the medium grade glass medium

Sieve aperture (mm)	**Geometric mean (mm)**	**% Glass Retained**	**Cumulative % passing**
1.70		0.0	100
1.40	1.54	0.3	99.7
0.50	0.84	69.9	29.8
0.36	0.42	29.2	0.6
0.30	0.33	0.5	0.1
0.11	0.18	0.1	0.0

This lack of variation in particle size distribution meant that it was not possible to determine the coefficient of uniformity of the glass particles and so a different approach was taken which required a determination of the clean water headloss (in other words the headloss without media) for the packed medium. In order to calculate this, a number of filter runs were undertaken at different service flows and the flow rate (m^3/h), volume of flow treated (m^3) and volumetric area loading (m^3/m^2 min) was measured (Table 2). A number of calculations were then undertaken with this data involving four stages as summarised below:

Table 2. Clearwater headloss measured over each of the different backwash cycles

Cycle	**Run**	**Treated volume m^3**	**Flow m^3/h**	**Load m^3/m^2.min**	**V_s m/s**	**Clear-water headloss, m**	**Operational headloss (m)**	**Total Headloss (m)**
1 (6 hours)	1	31.6	5.3	0.20	0.0033	0.992	1.631	2.623
	2	24.2	4.0	0.15	0.0025	0.736	1.529	2.265
	3	30.5	5.1	0.19	0.0032	0.960	1.631	2.591
	4	30.8	5.1	0.19	0.0032	0.960	1.529	2.489
2 (4 hours)	1	21.4	5.4	0.20	0.0034	1.024	1.529	2.553
	2	24.0	6.0	0.23	0.0038	1.155	1.529	2.684
	3	13.8	3.5	0.13	0.0022	0.643	1.835	2.478

	4	21.9	5.5	0.21	0.0035	1.057	1.631	2.688
	5	24.3	6.1	0.23	0.0038	1.155	1.427	2.582
	6	23.3	5.8	0.22	0.0037	1.123	1.631	2.754
	7	22.5	5.6	0.21	0.0036	1.090	1.631	2.721
	8	22.1	5.5	0.21	0.0035	1.057	1.427	2.484
	9	25.0	6.3	0.24	0.0039	1.189	1.019	2.208
	10	24.7	6.2	0.23	0.0039	1.189	1.631	2.820
3 (2.5 hours)	1	23.8	9.5	0.36	0.0060	1.906	0.408	2.314
	2	24.1	9.6	0.37	0.0061	1.941	0.306	2.247
	3	22.4	9.0	0.34	0.0057	1.080	0.612	1.692
	4	24.5	9.8	0.37	0.0062	1.976	0.306	2.282
	5	22.8	9.1	0.35	0.0058	1.836	0.510	2.346
	6	24.6	9.8	0.37	0.0062	1.976	0.306	2.282
	7	24.0	9.6	0.36	0.0061	1.941	0.306	2.247
	8	24.4	9.8	0.37	0.0062	1.976	0.102	2.078
	9	24.9	10.0	0.38	0.0063	2.012	0.102	2.114
	10	24.5	9.8	0.37	0.0062	1.976	0.102	2.078
	11	23.9	9.6	0.36	0.0060	1.906	0.306	2.212
	12	24.4	9.8	0.37	0.0062	1.976	0.204	2.180
	13	25.1	10.0	0.38	0.0063	2.012	0.102	2.114
	14	24.9	10.0	0.38	0.0063	2.012	0.102	2.114
	15	24.0	9.6	0.36	0.0061	1.941	0.306	2.247
	16	23.3	9.3	0.35	0.0059	1.871	0.510	2.381
	17	24.0	9.6	0.36	0.0061	1.941	0.306	2.247
	18	25.0	10.0	0.38	0.0063	2.012	0.102	2.114
	19	24.3	9.7	0.37	0.0061	1.941	0.204	2.145
	20	25.1	10.0	0.38	0.0063	2.012	0.102	2.114
	21	24.9	10.0	0.38	0.0063	2.012	0.102	2.114
	22	22.3	8.9	0.34	0.0056	1.766	0.204	1.970
	23	24.5	9.8	0.37	0.0062	1.976	0.102	2.078
	24	24.0	9.6	0.36	0.0061	1.941	0.102	2.043
	25	24.9	10.0	0.38	0.0063	2.012	0.102	2.114
	26	25.0	10.0	0.38	0.0063	2.012	0.102	2.114
	27	24.2	9.7	0.37	0.0061	1.941	0.204	2.145
	28	25.1	10.0	0.38	0.0063	2.012	0.102	2.114
	29	25.2	10.1	0.38	0.0064	2.047	0.102	2.149

	30	25.3	10.1	0.38	0.0064	2.047	0.102	2.149
	31	24.8	9.9	0.38	0.0063	2.012	0.102	2.114
4 (4 hours)	1	37.6	9.4	0.36	0.0059	1.871	0.204	2.075
	2	38.4	9.6	0.36	0.0061	1.914	0.408	2.322
	3	37.3	9.325	0.35	0.0059	1.871	0.408	2.279
	4	39.7	9.925	0.38	0.0063	2.012	0.306	2.318
	5	38.5	9.625	0.36	0.0061	1.941	0.408	2.349
	6	38.2	9.55	0.36	0.0060	1.906	0.306	2.212
	7	39.4	9.85	0.37	0.0062	1.976	0.102	2.078
	8	38.4	9.6	0.36	0.0061	1.914	0.306	2.220
	9	38.9	9.725	0.37	0.0062	1.976	0.306	2.282
	10	40.1	10.025	0.38	0.0063	2.012	0.102	2.114
	11	39.9	9.975	0.38	0.0063	2.012	0.102	2.114
	12	39.7	9.925	0.38	0.0063	2.012	0.204	2.216
	13	39.9	9.975	0.38	0.0063	2.012	0.102	2.114
	14	40.0	10	0.38	0.0063	2.012	0.000	2.012
	15	39.9	9.975	0.38	0.0063	2.012	0.102	2.114
	16	38.8	9.7	0.37	0.0061	1.914	0.306	2.220
	17	39.7	9.925	0.38	0.0063	2.012	0.102	2.114
	18	39.2	9.8	0.37	0.0062	1.976	0.102	2.078
	19	38.8	9.7	0.37	0.0061	1.914	0.102	2.016
	20	38.6	9.65	0.37	0.0061	1.914	0.204	2.118
	21	39.5	9.875	0.37	0.0062	1.976	0.102	2.078
	22	39.9	9.975	0.38	0.0063	2.012	0.102	2.114

Thus in order to characterize Malton's filter glass, total headloss was computed based on clear-water headloss and operational headloss. Operational headloss was calculated by means of the difference of pressure across the outlet of filter, taking account that it is a closed filter.

1) Calculate the Reynold's number for each size of glass from the equation:

$$N_R = Ø\, v_f\, d_p / \gamma$$

Where:

Ø= particle shape factor (0.73 is assumed for angular sand)

d_p= particle size mean (0.00084m) (see Table 3)

γ = kinematic viscosity (1.003×10^{-6} m^2/s at $20^{\circ}C$)

v_s= velocity of filtration calculated for each experimental run (m/s)

The velocity of filtration was calculated for each experimental run from the equation.

$$Velocity\,of\;\;filtration\;=\;\frac{F_t\,-\,F_i}{A\;x\;t}$$

Where:

F_t = volume of water treated at the end of the run (m^3)

F_i = volume of water treated at the beginning of the run (m^3)

A = Surface area of media (m^2)

t = duration of each run (h)

For example, in the first experimental run of cycle 1:

F_t = 554.3 m^3

F_i = 522.7 m^3

$F_t - F_i$ = 31.6 m^3

A = 0.44 m^2

t = 6 h

and thus the velocity of filtration is:

$$Velocity\,of\;\;filtration\;=\;\frac{554.3-522.7}{0.44\;x6}$$

$$=11.97m^3/h\;\;or\;\;0.0033m^3/\sec$$

So for a mean particle size of 0.84mm, Reynolds Number is

N_R = $0.73 \times 0.00084 \times 0.0033 / 1.003\text{x}10^{-6}$ = 2.0175

2) Calculate the Drag's coefficient (C_d) using Drag's Equation

C_d=24/N_R+3/√N_R+0.34

Cd = (24 / 2.0175) + (3/√2.0175) + 0.34 = 14.348

3) Transform C_d to the fraction of glass retained by size.

C_d*(p/ d_p)

p= fraction of glass, 0.7 or 0.3

C_d*(p/ d_p) = 14.348 * (0.7/0.00084) = 11,956

4) Calculate Headloss using Rose’s equation.

$$h=(1.067/ \O) (L v_f^2/\alpha^4 * g)\ \Sigma\ Cd*(p/d_p)$$

L=Depth of filter bed, 1.1m

g= gravity, 9.81 m/s^2

$$h = (1.067 / 0.73) \times (1.1 \times 0.0033^2 / 0.48^4 \times 9.81) * 31780 = 1.0685\text{m}$$

Each of the stages in the above calculation is illustrated in Table 3 which shows a headloss of 0.992 m. It is recognised that the calculation is estimated for open filters, whereas for Malton this is a closed filter and a closed filter headloss represents the difference between the pressure measured at the inlet and outlet.

Table 3. Stages in the calculation of the filter headloss

Geometric mean, mm	**Geometric mean, m (d)**	**Percent glass Retained**	**Fraction of glass Retained (p)**	**Reynolds number**	**C_d**	**C_d (p/d), m^{-1}**
		0.0				
1.54	0.00154	0.3	0.003	3.71	8.38	17
0.84	0.00084	69.9	0.699	2.01	14.40	12,032
0.42	0.00042	29.2	0.292	1.01	27.04	18,715
0.33	0.00033	0.5	0.005	0.78	34.35	537
0.18	0.00018	0.1	0.001	0.43	60.96	479
Sum						31,780

The clear-water headloss was then calculated for each run for the different backwash cycles that were evaluated during the course of the full-scale study (Table 3)

Operational headloss has been computed using the difference of pressure across the outlet of filter and the difference of pressure was converted to units of metres of water and computed with clear-water headloss in order to calculate the total headloss.

The maximum backwash velocity was then determined by a six step procedure which involved:

1. Determination of the particle settling velocity (Vs) by iteration. This was achieved after four iterations using Stokes' law, Reynolds Number and Newton's equation

2. Determination of V/Vs where V is the backwash velocity equal to 0.00757 m/s. This velocity was obtained from the backwash flow rate of 12 m^3/h
3. Determination of expanded porosity $((\alpha_e)$; $\alpha_e = (V/Vs)^{0.22})$
4. Determination of p/(1-άe), where p is the fraction retained between sieves
5. Determination the expanded bed depth using the equation: $L_e/L=(1-\alpha)\ \Sigma\ (p/1-\alpha_e)$, where ά is the normal porosity of the glass medium. Porosity was determined experimentally in the laboratory and was found to be 0.489. L= depth of filter bed and measured as 1.1m
6. Determination of expanded bed depth using the equation:

$$L_e = L\ (1-\alpha)\ \Sigma(1-\alpha_e)$$

Each of the steps involved in this calculation are illustrated in Table 4.

Table 4. The steps involved in the calculation of the maximum backwash velocity

Geometric mean, mm	**Fraction of glass retained (p)**	**Percent of glass retained (p)**	**Vs m/s**	**V/Vs**	□$_e$	p/(1-□e)
		0.0				
1.54	0.003	0.3	0.230	0.033	0.472	0.006
0.84	0.699	69.9	0.137	0.055	0.529	1.484
0.42	0.292	29.2	0.063	0.120	0.627	0.783
0.33	0.005	0.5	0.046	0.165	0.672	0.016
0.18	0.001	0.1	0.018	0.421	0.826	0.008
Summation						2.296

Thus Le = (1.1 m) (1 - 0.489) (2.296) = 1.29 m

However because the expanded porosity of the largest size fraction (0.472) is less than the normal porosity of the filter material (0.489), the entire filter bed will not be expanded. It has been pointed out that:

"The expanded depth needs to be known to establish the minimum height of the wash water troughs above the surface of the filter bed." (Metcalf and Eddy, 2003).

The same procedure was then carried out to estimate the minimum flow required to ensure the expansion of filter bed since if the filter bed is expended then the washwater can clean it. Using a flow of 15 m^3/h, then V the backwash velocity is equal to 0.0094 m/s.

Table 5. Calculation of the minimum flow to ensure bed expansions

Geometric mean (mm)	**Fraction of glass Retained (p)**	**Percent of glass retained (p)**	**Vs (m/s)**	**V/Vs**	**$_e$**	**p/(1- e)**
		0.0				
1.54	0.003	0.3	0.230	0.041	0.495	0.006
0.84	0.699	69.9	0.137	0.069	0.555	1.570
0.42	0.292	29.2	0.063	0.149	0.658	0.853
0.33	0.005	0.5	0.046	0.204	0.705	0.017
0.18	0.001	0.1	0.018	0.522	0.867	0.011
Summation						2.456

Thus Le = (1.1 m) (1 - 0.489) (2.456) = 1.38 m

At this flow the expanded porosity of the largest size fraction (0.495) is greater than the normal porosity of the filter material (0.489) and so the entire filter bed will be expanded. That means a backwash flow of 15 m^3/h is enough to expand the filter bed without air. However in this study the maximum backwash flow was 12 m^3/h, and so the efficiency of filter cleanness will depend on the backwash time and the inclusion of an air scour.

Appendix 2

Optimisation of the Backflush Cycle

Introduction

Appendix 1 has demonstrated that a backwash flow rate of 15 m^3/h would fully expand the bed without the application of an air scour, however in practice due to the pump capacity it was only possible to achieve a maximum flow rate through the bed of around 12 m^3/h during backwash. Clearly therefore the bed was not fully expanded during the backwash cycle.

The effects of this can be seen during routine operation, for instance when the filters were operated on a 6 hour cycle with a backflush comprising 3% of the flow passed through the filter (Figure 1) the flow rate at the start of each cycle slowly declined such that over the 66 hours illustrated in figure 1 it had reduced from 6.75m^3/h to 5.3m^3/h.

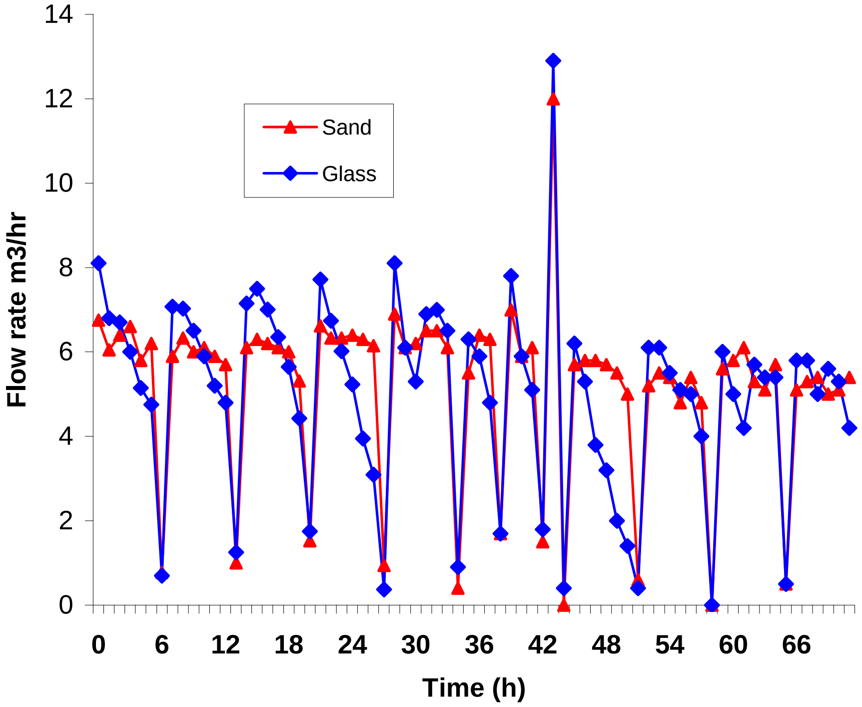

Figure 1. The flowrate through the Malton filter for a 6 hour cycle with a backwash comprising 3% of the volume treated

It had been recognised at the start of this study that one of the most expensive aspects of tertiary filter systems is the need for a backwash cycle that incorporates both high flow rate media wash and an air scour (Rogalla, 2005). It was hoped that an air scour might be avoided with glass media and consequently a number of operational modifications were investigated in an attempt to restore the flow rate to its original value, without having to resort to air scour. These involved increasing the volume of backflush water and varying the backflush time in the process cycle and the parameters investigated are summarised in table 1, section 3.2.7. However they were all ineffective and although small improvements were made it was considered essential to incorporate an air scour into the backwash. Consequently all of the full-scale filters were fitted with a 1.5 hp air compressor capable of delivering 198 l air/min.

This proved very effective and had an immediate effect on backwash performance. When measured over an operating period of 80 hours for a service flow period of 6 hours, the flow rate at the start of each cycle could always be returned to its original value of 7.2 m^3/h (Figure 2).

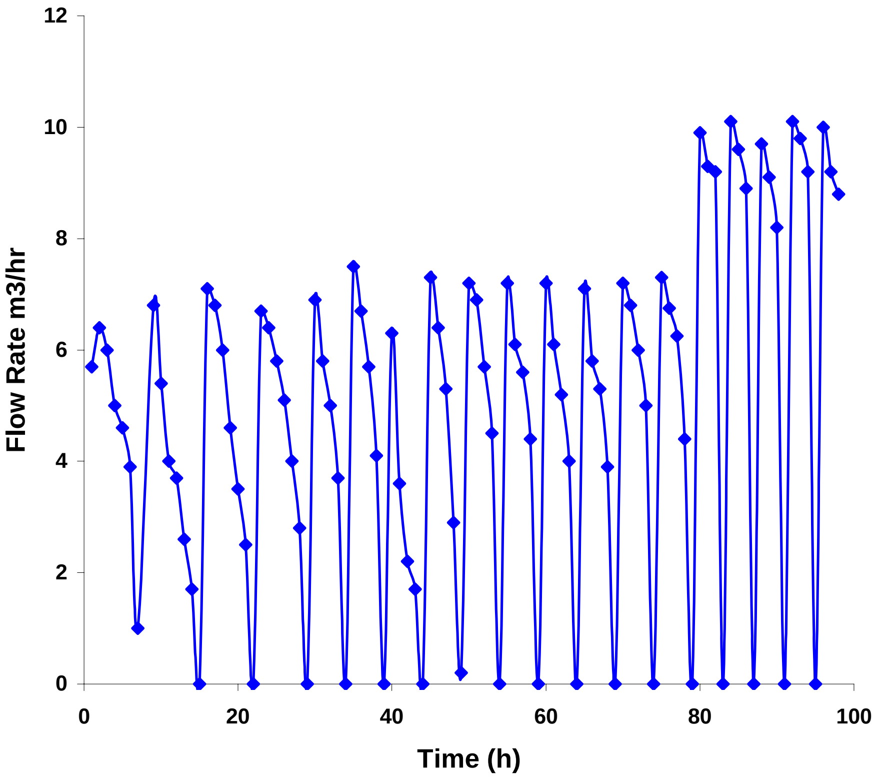

Figure 2. The effects on the flow rate through the glass filter of reducing the time between backwash periods from 6 to 2.5 hours at the Malton site

However this modification highlighted a problem with the service cycle and as figure 2 demonstrates, over the service cycle the flow rate decreased rapidly from an initial flow of 7.2 m^3/h at the start of the cycle to 4 m^3/h at the start of the backwash cycle. An attempt was made to rectify this by reducing the period between backwashes from 6 to 4 hours and then finally to 2.5 hours (Figure 2). With this regime the flow at the start of the cycle was 10 m^3/h and had reduced to 9 m^3/h when backwash was initiated. This was deemed to provide an adequate treatment period without comprising flow rate during the treatment.

When the flow rates through the glass and sand media were compared under the optimised backwash regime, performance was very similar although the glass media was able to achieve a flow rate approximately 8 to 10% higher than the sand for an identical influent suspended solids concentration. In addition, after a period of 120 hours operation the influent flow rate at the start of the cycle had shown no deterioration for either medium.

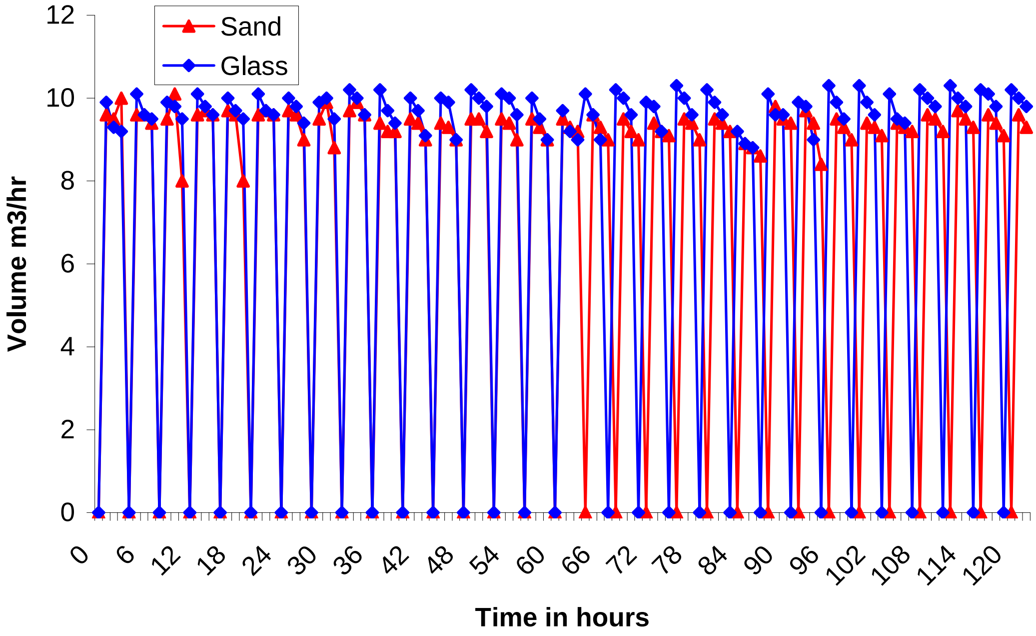

Figure 3. Flow rate through the glass and sand media under identical backwash and operating conditions at the Malton site

Once the filter at Malton was optimised at similar procedure was initiated at the other sites and at Stubbins Mill the first stage of the optimisation protocol involved an investigation of the time required to achieve an optimised backwash cycle. Initially a fixed cycle time of 6 hours was selected, based on the results from the small scale studies with a flow rate of 6 m^3/h (Figure 4).

Again the backwash cycle was clearly ineffective and it was only possible to achieve a flow rate of 5.5^3/h for sand and 3.8 m^3/h for glass. By reducing the time between each backwash to a period of 3 hours and also increasing the backwash volume to 6% the flow rate was recovered to 8 m^3/h for sand and 7.4 m^3/h for glass. When air scour was introduced (Figure 5) there was a further improvement for the glass medium which stabilised at a flow rate of 8.5 m^3/h and 6.2 m^3/h for glass.

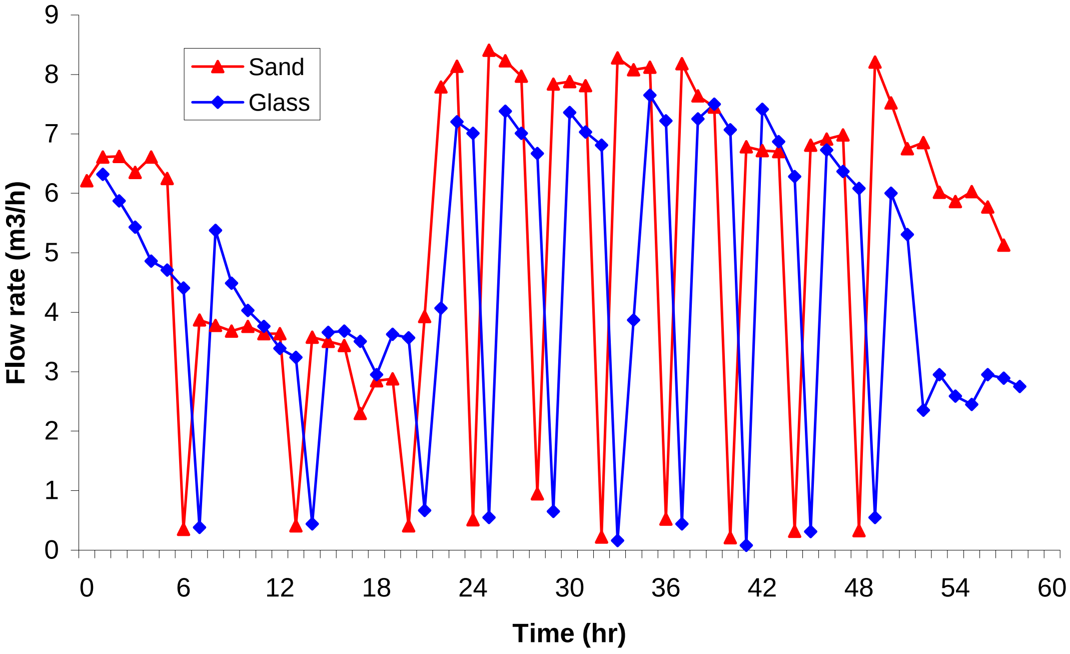

Figure 4. The effects of backwash time on the volume passing the filter. Over the first 20 hours the filter was backwashed every 6 hours, this was then followed by a 3-hour backwash cycle

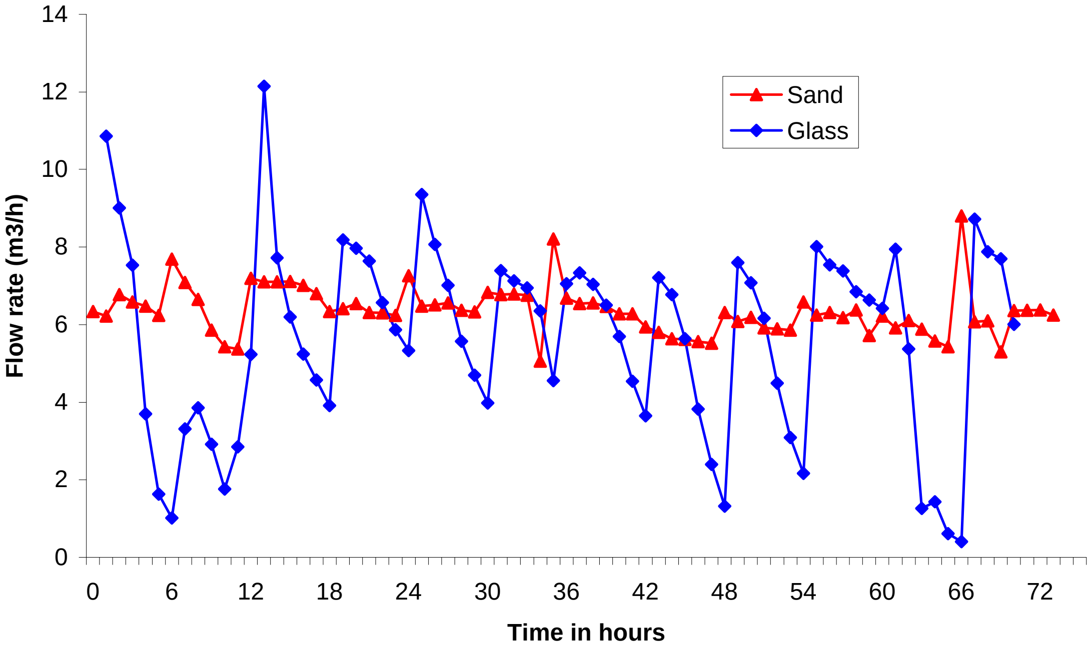

Figure 5. Inclusion of air-scour at the Stubbins' Mill site, demonstrating a recovery of the initial flow rate at the start of each cycle