Experimental study on carbon removal in biological aerated filters

G. Farabegoli, A. Carucci*, G. Gandolfo**, E. Rolle** and P. Viotti****

* Department of Geoengineering and Environmental Technologies, Faculty of Engineering, University of Cagliari, Piazza d'Armi, 09123 Cagliari, Italy (E-mail: *carucci@unica.it*)

** Department of Hydraulics, Transportations and Roads, Faculty of Engineering, University of Rome "La Sapienza", 18 via Eudossiana, 00184 Rome, Italy (E-mail: *geneve.farabegoli@uniroma1.it*; *giu.gan@katamail.com*; *enrico.rolle@uniroma1.it*; *paolo.viotti@uniroma1.it*)

Water Science and Technology **Vol 48 No 11–12 pp 235–242** © IWA Publishing 2003

Abstract The aim of the present work was to evaluate the performance of a pilot-scale BAF in terms of removal of organic matter and suspended solids to obtain a highly polished effluent. The first part of the research was the evaluation of the optimal filter media for a full scale BAF. Mechanical and biological tests were performed over four materials: glass, plastic, pozzolan and expanded clay (Arlita) and the results obtained showed that the plastic spheres and the Arlita particles were the optimal materials for both the mechanical and biological requirements. Hence, a down-flow pilot scale BAF was set up in the laboratory to treat a synthetic medium. As filter media first plastic spheres and then Arlita spheres were used. Carbon removal studies were carried out at several influent COD concentrations, specific removal efficiency and COD profiles along the height of the filter were determined and used to analyze the process. Validation and calibration of a mathematical model formulated for carbon removal, were also performed by using the experimental data obtained. The results showed that this system allows us to achieve the more strict limits on final effluent.

Keywords Biological aerated filter (BAF); biomass; carbon removal; filter media; mathematical model

Introduction

Recently, the need of reducing plant areas and reactor volume, the increase of the management costs for wastewater treatment, and the necessity to improve the performances of the existing plants to comply with the more strict effluent standards of Italian law (D.Lgs.152/99) regarding COD, nutrients and suspended solids, have led us to consider the advantages of the attached growth biomass treatment processes compared to the suspended biomass one. The attached biomass reactors can remove simultaneously organic matter, suspended solids and organic and ammonia nitrogen. In particular a biological aerated filter (BAF) can entrap the particulate COD and the solid particles that are successively removed by a backwash step, while the soluble COD is degraded by microorganisms growing on the filter media (Grady *et al*., 1999). The aim of the present work was to evaluate the performance of a pilot scale BAF in terms of removal of organic matter and suspended solids to obtain a highly polished effluent. This research is part of a wide project aimed at optimizing and modelling the performances of attached biomass processes. The first part of the research was the evaluation of the optimal filter media and of the design criteria of full scale BAFs. Hence, during the second part of the research, a down-flow pilot scale BAF was set up in the laboratory to treat a synthetic medium. Furthermore the validation of a mathematical model, formulated for carbon removal (Viotti *et al*., 2002), was also performed by using the experimental data obtained.

Methods

Description of the lab scale and the pilot scale BAFs

The four lab scale BAFs are Plexiglas cylinders of 20 cm height, 9 cm internal diameter and 10 cm filter media height. The synthetic influent (whose composition is presented in Table 1) is applied to the top of the filters while oxygen is supplied by blowing air through a porous stone located at the bottom of the filter. Sludge coming from the oxidation process of a real wastewater treatment plant of Rome with 450 mg SST/l and 320 mg SSV/l was used as seed.

The pilot scale BAF is a plexiglas cylinder of 1.8 m height, 15 cm internal diameter and 80 cm filter media height. Eight liquid sampling points are placed from 5 to 75 cm, every 10 cm, along the filter bed height and four solid sampling points are at 10, 30, 50 and 70 cm from the bottom of the filter bed. The synthetic influent, the same for the four lab scale BAFs, is applied to the top of the filter and passes downward through the media to an effluent collection system. Oxygen is supplied by blowing air through four porous stones located at the bottom of the filter bed, in order to keep DO concentration always around 2 mg/l. Sludge coming from the oxidation process of a real wastewater treatment plant of Rome with 450 mg SST/l and 380 mg SSV /l was used as seed.

The carbon removal process is carried out by the microorganisms that grow attached to the filter packed media. The biomass growth produces an increase of the biofilm thickness and a decrease of bed porosity. Consequently the head loss over the filter bed increases reaching a maximum level that makes necessary a backwashing phase. This phase is performed with air, to detach the excess biomass, water and air, in order to fluidise and expand the filter bed volume of 15–20% and only water to transport the detached biomass out of the filter. The influent feed, the aeration system and the backwashing phase are managed by a controller box connected to a computer. Since a backwashing phase is required once a day, this controller starts and stops at a prefixed time the influent pump, the air compressor and the backwashing water pump.

Measurements and analysis

During the first part of the research the following tests and relative measurement systems were performed over the four filter media: determination of the material size (sieve analysis), density (UNI 7549 part 5 and 6), porosity and specific surface area determined with MIP (Mercury Intrusion Porosimeter), minimum fluidization velocity V_{mf} (Wen and Yu and Carmen-Kozeny formulas, Kent *et al.*, 1996) and weight loss (Los Angeles test, CNR – BU No 34).

Biological parameters were measured in both parts of the research. Influent, liquid and solid along the filter bed height and effluent samples were taken and analysed for COD, Total and Volatile Suspended Solids (TSS,VSS), ammonia and phosphorus using the *Standard Methods for the Examination of Water and Wastewater* (1992). Head loss over the whole filter bed, DO, temperature and pH were monitored.

Table 1 Synthetic influent composition

Salt	Concentration [mg/l]
$C_6H_{12}O_6$	200
CH_3COONH_4	100
K_2HPO_4	22.45
$CaCl_2 \times 2H_2O$	25
$MgCl_2 \times 6H_2O$	36
$MgSO_4 \times 7H_2O$	30

Results and discussion

Lab scale results

The four materials used as media are: glass, plastic, pozzolan and expanded clay (Arlita), whose characteristics are represented in Table 2.

The size of the filter media has been chosen from literature results in the range of 5-8 mm (Kent *et al*., 1996). It has been preferred to use a spherical shape media in order to achieve optimal hydraulic conditions and a simple modeling process. Since the bed is fixed in time and space, density was chosen over 1 g/cm^3 avoiding the glass spheres because of their higher value of density and minimum fluidization velocity V_{mf}, which requires a higher energetic cost to expand the bed during the backwashing phase.

Pozzolan and Arlita have a high porosity and specific surface area that create better conditions of colonization and attachment of the biomass during the start up phase. The minimum fluidization velocity has been determined using the mathematical relations of Wen and Yu for non-spherical particles and Carmen-Kozeny for spherical particles. Pozzolan and Arlita have the lowest minimum fluidization velocity requiring the less energetic cost for backwashing but pozzolan has the highest weight loss determined with the friction and friability tests. Since plastic has the lowest weight loss and Arlita has the highest porosity and specific surface area, they can be considered the two materials chosen as the optimal BAF media, according to the mechanical tests performed.

Furthermore a number of biological tests were carried out on the four media in order to determine their suitability for the pilot scale BAF. During the start-up period the results obtained showed that Arlita removes more COD than the other media and has the highest removal rate (over 80%). The biomass growth was higher over the Arlita media that favours its colonization and attachment.

During the continuous phase the influent flow rate was 2 l/h, the Surface Hydraulic Loading (CIS) was 0.32 m/h, the Volumetric Organic Loading (COV) was 19.6 kg COD/m^3 × d and the influent COD concentration was of 260 mg/l. The highest COD removal efficiency (about 70%) was of plastic and Arlita BAFs. Pozzolan was subject to bed clogging events while Arlita needed less frequent backwash. The weight of biomass per unit of bed volume was higher in Arlita. Finally the results obtained in both mechanical and biological tests showed that plastic and Arlita media are the most suitable media for application in the pilot scale BAF.

Pilot scale results

A down-flow pilot scale BAF was set up in the laboratory to treat a synthetic medium. As filter media first plastic spheres and then Arlita ones were used.

BAF with plastic media

After a start up period of 4 days, the BAF has been fed with an influent flow rate of 5 l/h, CIS = 0.3 m/h, and with an influent COD concentration between 200 and 350 mg/l. Airflow rate was of 5 l/min (0.0.3 Nm^3/h). The results show a carbon removal efficiency of 90%,

Table 2 Characteristics of the four media

Material	Size range (mm)	Density (g/cm^3)	Porosity (m^3/m^3)	Specific surface (m^2/cm^3)	V_{mf} (m/h)	Weight loss (%)
Glass	5	2.53	0	6.28×10^{-4}	890.44	0
Plastic	6	1.93	0	5.23×10^{-4}	869.05	0
Pozzolan	2–6	1.71	0.108	0.67	88.49	13
Expanded clay (Arlita)	5–8	1.34	0.486	14.30	365.32	3

without a real concentration profile along the height of the filter. Furthermore the suspended biomass concentration was of 70–80 mg SSV/l, constant at the different filter heights; this high value means that the biofilm structure was not compact and the suspended biomass was relevant. The results obtained have led to increase the influent flow-rate to 25 l/h with a subsequent increase of the filtration velocity (CIS) to 1.6 m/h. The influent COD concentration was varied between 50 and 450 mg/l and the airflow rate was of 10 l/min. Several samples have been taken along the filter height. In particular, samples at 75 cm and at 5 cm from the bottom of the filter could be considered as the inlet and the outlet samples. In this phase a COD concentration profile along the height of the filter has been observed and the suspended biomass concentration was of 10–60 mg SSV/l with a relevant presence of attached biomass. As represented in Figure 1, influent COD concentrations greater than 300 mg/l resulted in the same removed COD amount.

Therefore the maximum removed COD along the filter height was about 160 mg/l. This could be due to the limited filter height or to the less amount of attached biomass in the filter bed. During the experimentation the COD removal efficiency varied between 30% and 70% and decreased with increasing organic load, as represented in Figure 2. These findings are supported by the results obtained by several authors (Hamoda, 1989; Odegaard *et al.*, 1994).

The organic load can be divided into three ranges: low load (COV = 0–5.7 kg/m^3 × d), medium load (COV = 5.7–11.4 kg/m^3 × d) and high load (COV = 11.4–17 kg/m^3 × d). To calculate the "specific removal efficiency" (SRE) the filter bed height has been divided into

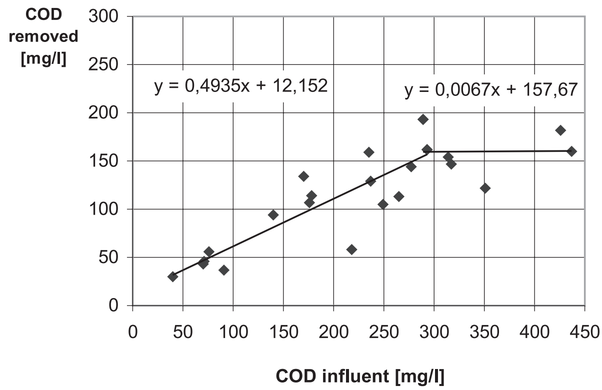

Figure 1 Influent COD versus removed COD of BAF with plastic media

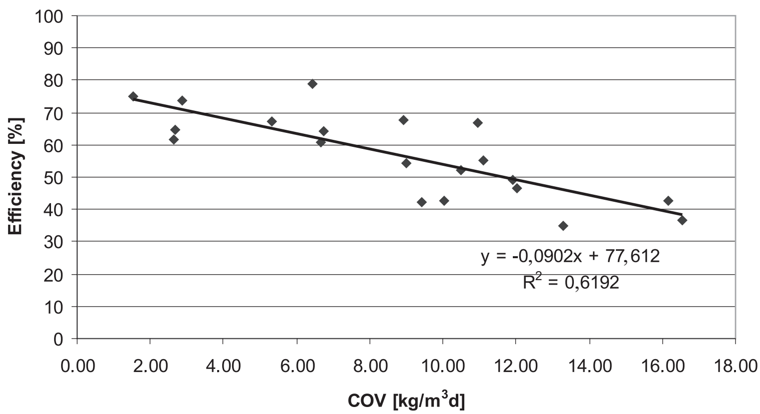

Figure 2 COD removal efficiency of BAF with plastic media

two consecutive parts of 40 cm and 30 cm from the bottom of the filter. The "specific removal efficiency" is the removal efficiency per unit of filter height, i.e. the amount of removed COD over the influent COD per unit of height (1/cm). Therefore the average specific removal efficiencies have been calculated for each load condition and for each part of the filter. Figure 3 shows these results.

The equation in Figure 3 could be used to determine the performance of the filter as a function of the organic load applied and to analyze the process. Writing the equation as the following:

$$SRE = -0.0005 \cdot COV_{\text{influent}} + 0.0133 \quad (1)$$

we can calculate for a step of 1 cm height the progressive amount of removed COD and simulate the removal profile in a filter bed that has the same characteristics as the pilot one (flow velocity and amount of biomass).

Mathematical model

The data obtained during the experiment were used for simulation with a numerical model (Viotti *et al.*, 2002). This model allows the calculation of the COD profile along the filter height and inside the biofilm thickness and simulates filter clogging due to the biomass growth. The model is based on double saturation Michaelis–Menten kinetics and considers the resistance to mass transport both within and outside the bioparticles. The model output is the result of the differential equation system that describes the filter performance. The equations are integrated using an implicit finite differences technique and, since equations are non-linear, calculation is carried out using an iterative method assigning to the terms causing non-linearity initial values updated at every iteration by previously calculated ones (Sbaffoni, 2000).

Fitting the data obtained from the sample points at different filter height, and using typical values of kinetic and biological parameters (COD consumption rate, biomass density of the biofilm), an indirect measure of the active biofilm thickness can be obtained. The linear relationship between COD removed and the active biofilm thickness is represented in Figure 4. The maximum active biofilm thickness was about 425 μm.

BAF with Arlita media

The filter with Arlita media was fed with an influent concentration between 50–200 mg/l COD. After a start up period of some days the influent flow-rate was increased from 5 l/h to 25 l/h, in order to reach steady state conditions. Under such conditions a COD concentration profile along the height of the filter has been observed and the suspended biomass

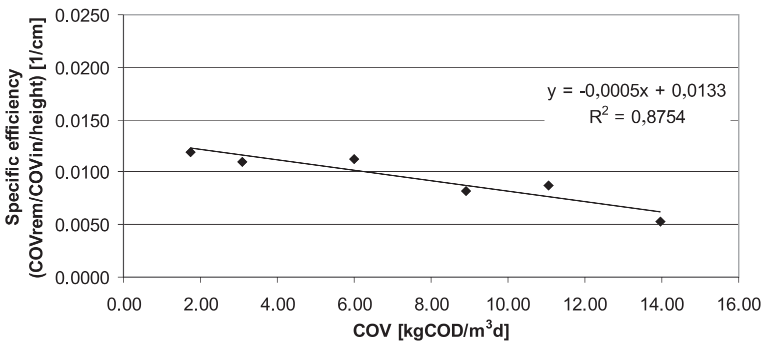

Figure 3 Specific removal efficiencies of BAF with plastic media

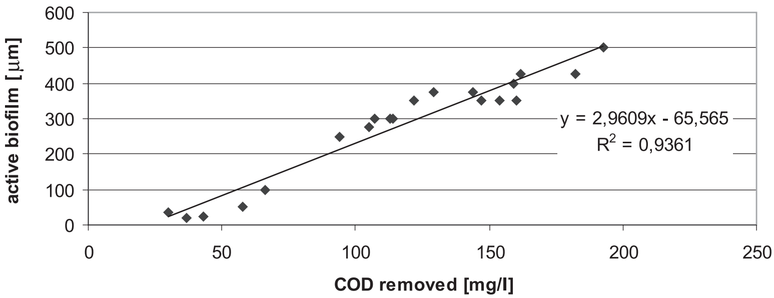

Figure 4 Active biofilm thickness versus removed COD of BAF with plastic media

concentration was of 30 mg SSV/l with a relevant presence of attached biomass. As can be seen in Figure 5, increasing influent COD concentrations corresponded to increasing removed COD concentrations along the filter height and the filter had not yet reached the plateau phase, as in the case of BAF with plastic media.

During experimentation the COD removal efficiency varied between 55% and 75%, with a mean value of 67%, and decreased with increasing organic load, as represented in Figure 6.

As described in Figure 7, the average specific removal efficiency calculated for the two parts of the filter height (40 cm and 30 cm), was different from the average specific removal efficiency of the BAF with plastic media, decreasing more rapidly with the increase of the organic load.

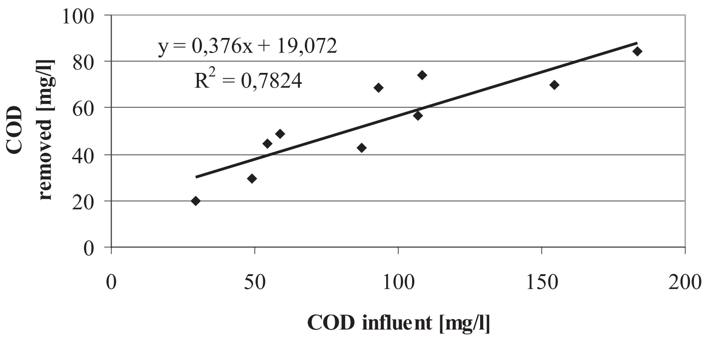

Figure 5 Influent COD versus removed COD of BAF with Arlita media

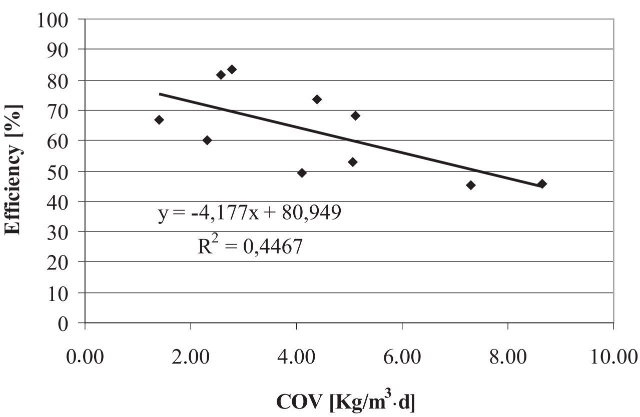

Figure 6 COD removal efficiency of BAF with Arlita media

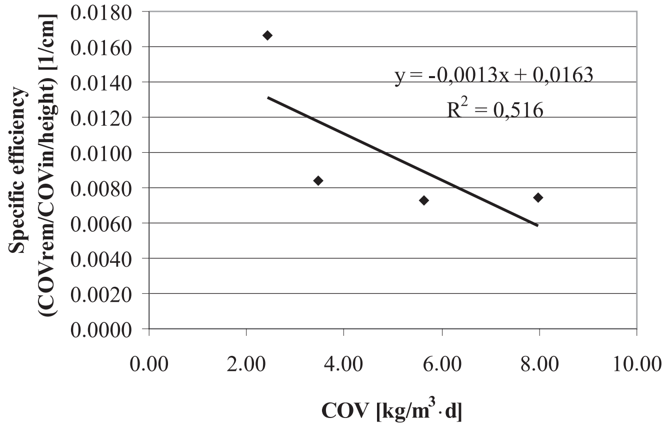

Figure 7 Average specific removal efficiency of BAF with Arlita media

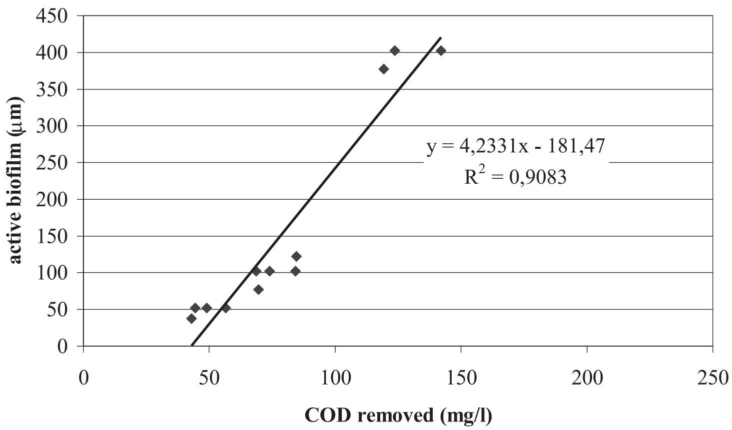

Figure 8 Active biofilm thickness versus removed COD of BAF with Arlita media

Mathematical model

The data obtained during the experiments were used for the simulation with the numerical model. Also in this case it was possible to determine the active biofilm thickness and to obtain a linear relationship between COD removed and the active biofilm thickness as shown in Figure 8. The maximum active biofilm thickness was about 400 μm.

Conclusions

From the experiments with the BAF filled with the plastic media, it has been found that:

1. the COD removal efficiency varied between 30% and 70% and decreased with increasing organic load. The maximum removed COD along the filter height was about 160 mg/l at influent COD concentrations greater than 300 mg/l;
2. once having calculated the specific removal efficiency from Eq. (1) it is possible to obtain the optimal filter height, as a function of the organic load applied, to meet the COD effluent standards;
3. the maximum active biofilm thickness obtained by the numerical model was about 425 μm.

From the experiments with the BAF filled with the Arlita media, it has been found that:

1. the COD removal efficiency varied between 55% and 75%, with a mean value of 67%, and decreased with increasing organic load;

2. the specific removal efficiency decreased more rapidly with the increase of the organic load than the specific removal efficiency of the BAF with plastic media;
3. the maximum active biofilm thickness obtained by the numerical model was about 400 μm.

In conclusion, both materials seem to give optimal performance in terms of removal of organic matter and suspended solids and allow us to achieve the more strict limits on final effluent.

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