Development of a combined activated carbon / microfiltration process for the treatment of industrial effluents

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EXECUTIVE SUMMARY

Background to the project

The applicability of microfiltration for the removal of colloidal and suspended solids from industrial effluent and wastewater is well documented. The performance of a microfilter may be substantially improved by *precoating*, i.e. a fouling layer of specific characteristics may be formed on the tube wall prior to the introduction of the feed stream. In general, precoating can significantly increase the permeate flux, while simultaneously increasing the permeate quality. Extensive studies have been performed with mineral precoats, e.g. limestone, kaolin, diatomaceous earth and waste ash, where there is not expected to be any significant physio-chemical interactions between the precoating material and the foulants in the feed stream. The question then arises as to whether the performance of WFMF could be significantly enhanced by utilising an *active* precoat, i.e. where there would be some form of physio-chemical attraction between the precoat material and the foulants.

Preliminary investigations into the aspect of *active* precoats were undertaken by the Water Technology Group, M L Sultan Technikon, in 2001. The performance of a WFMF with an active precoat (powdered activated carbon) was compared to that with an inactive precoat (kaolin), as well as that of an un-precoated tube. Investigations were performed on an effluent obtained from a textile dyehouse. The comparative performance is summarized in the table below:

	FEED	**PERMEATE**		
		Raw tube (no precoat)	**Kaolin precoat**	**PAC Precoat**
COD (mg/L)	1450	825 to 640	680 to 440	205 to 229
TURBIDITY (NTU)	> 999	179	8	< 1
Flux (LMH)		10 to 7	10	30

The above results clearly indicate that there is a major improvement in performance when an active precoat is used in terms of COD removal, permeate quality and permeate production rates. The combined PAC/WFMF system was tested on other untreated effluents, and similar

trends were indicated i.e. the PAC precoated system gave a significantly better permeate quality and significantly higher fluxes. It emerged that WFMF with an active precoat could be a very powerful pretreatment step for industrial effluents, giving a significant COD reduction and permeate of very low turbidity in a single step.

The overall objective of this project is to develop and demonstrate the combined PAC/WFMF system for the pretreatment of industrial effluents. This combined process will hereafter be referred to as the actived carbon microfilter (ACMF).

Objectives

The specific objectives of the project are:

(i) Process development of the activated carbon / microfiltration (ACMF) system up to semi-pilot scale

(ii) To evaluate and characterise the performance of the optimised ACMF process on three "priority" effluents

(iii) To evaluate economics of the ACMF process on these "priority" effluents and compare to alternative technologies

(iv) To demonstrate the ACMF process to potential users on a semi-pilot scale

Approach

Textile effluent from David Whiteheads, Tongaat, Durban, was the main effluent investigated in this project. Initial laboratory-scale investigations were performed on a textile effluent obtained from David Whiteheads. The main objectives of these trials were to quantify the performance of ACMF on this difficult effluent, and to determine the efficiency of PAC usage in the ACMF system. In the second stage of investigations, a semi-pilot rig was set up at the David Whiteheads plant, and operated directly off the main effluent sump. This was mainly to facilitate extended runs and to confirm the results obtained in the laboratory trials. The third part of the project involved laboratory-scale investigations into the effects of the main precoating variables on ACMF performance. Finally, laboratory-scale investigations were performed on three other effluents, viz. a brewery effluent, effluent from a paper processing plant and an effluent from a printing plant.

Initial laboratory scale investigations

ACMF performance

The effluent used was a combined effluent from the David Whiteheads plant. Typically, the feed had a COD of about 1200 to 1500 mg/L, a turbidity ranging from 300 NTU to > 999 NTU, and was black in colour.

All laboratory-scale trials were performed on a microfiltration unit having a single woven fibre tube of length 2,2 m and 25 mm diameter. This tube was precoated with a 5 g/L PAC suspension for about 30 minutes to 1 hour. Once a precoat was formed the flow of the PAC suspension was stopped, and the effluent was pumped through the microfilter. Note that during the filtration of the effluent, no fresh PAC entered the microfilter. Filtration occurred in a *constant concentration* mode, i.e. both the reject and permeate streams were returned to the feed tank, giving a relatively constant effluent feed concentration with time.

Typically, the permeate COD was around 100 mg/L for a feed COD of 1200 mg/L. The permeate turbidity was about 1 NTU for a feed turbidity exceeding 999 NTU. This effluent quality was maintained over the duration of the runs (about 12 hours). Permeate fluxes started off at about 50 LMH, and declined to around 35 LMH during the runs.

The above results indicated clearly that ACMF was capable of producing a very good quality of permeate, giving a very good COD removal and an excellent turbidity removal in a single step.

Efficiency of PAC usage

It was assumed that the excellent COD removal was due to adsorption of organic material onto the PAC. Hence, it was expected that when the PAC in the ACMF reaches its adsorption capacity and becomes saturated, the permeate COD will increase sharply. By identifying when this *breakthrough* happens in the ACMF system and comparing the COD removed to the theoretical adsorption capacity of the PAC, the efficiency of PAC usage in the ACMF may be determined.

The approach in determining the efficiency of PAC usage was as follows:

(i) adsorption experiments were performed on a filtration cell, from which the adsorption capacity of the PAC for the COD in that effluent was determined (mg COD/g PAC)

(ii) the mass of PAC in the precoat was experimentally measured (g PAC)

(iii) from (i) and (ii), the theoretical adsorption capacity of the PAC in the precoat was computed

(iv) from the feed COD, permeate COD and permeate flux profiles obtained from the ACMF runs, the actual removal of COD was determined

(v) the actual removal was then compared to the theoretical removal, and hence the efficiency of usage was computed

The unit adsorption capacity on the textile effluent was approximately 100 mg COD/g PAC. The mass of PAC in the precoat was approximately 53 g. This gives a theoretical adsorption capacity of 5 300 mg COD.

In the initial 12 hour filtration runs, no breakthrough of COD was observed. The COD removal over the run was computed as 56 500 mg. According to these calculations, the PAC would have saturated after about 1,5 hours of filtration, but there was no indication of any increase in permeate COD over the 12 hour run.

To investigate the above further, a 72 hour run was performed in a batch concentration mode. Once again, the theoretical removal capacity was 5 300 mg/L. Over the 72 hour run, the feed COD increased from 1200 mg/L to over 3500 mg/L. However, the permeate COD remained constant at about 200 mg/L. The actual removal of COD was computed as 238 000 mg, about 50 times the theoretical adsorption capacity.

The above results indicated clearly that the system performance was not being limited by adsorption onto the PAC. Conversely stated, the removal of COD was substantially higher than could be expected if PAC was used conventionally.

On-site trials at David Whiteheads

A microfiltration rig was set up at David Whiteheads and operated off their main effluent sump. Initially the rig consisted of 2 microfiltration tubes of length 2,2 m and 25 mm diameter.

Runs of up to 9 days were performed in a batch concentration mode. Note that in these extended runs the system was precoated only once (at the beginning of the run). Typically, the feed COD started off at around 1 700 mg/L and then increased to about 12 000 mg/L over the duration of the run. The permeate COD remained around 450 mg/L over the run. The feed turbidity started off at around 300 NTU and increased to > 999 NTU. The permeate turbidity generally remained below 5 NTU.

The number of microfiltration tubes was then increased to six and further trials were performed with filtration times of up to 9 days. Once again, feed CODs started off at about 1 200 mg/L and progressively increased to >8 000 mg/L. Feed turbidities started of at around 300 NTU and increased to >999 NTU. The permeate CODs were consistently around 400 mg/L for the entire duration of the run, while the permeate turbidities were generally below 10 NTU.

The theoretical adsorption capacity of the PAC is compared to the actual COD removal in the following table:

Run	**Duration (h)**	**Theoretical Adsorption Capacity**		**Actual Removal**	
		G COD	**mg COD/g PAC**	**g COD**	**mg COD/g PAC**
1	92	31,2	100	28000	89 745
2	198	31,2	100	18400	58 980
3	212	31,2	100	21730	69 650
4	204	31,2	100	38700	124 040

The above results indicate clearly that the ACMF can consistently give a very good COD and turbidity removal over extended periods. In the on-site runs, the ACMF gave a consistently low permeate COD and turbidity for runs of up to 9 days. Once again, the actual removal of

COD was orders of magnitude greater than the adsorption capacity of the PAC. Further, there was no sign of any COD breakthrough over 9 days of filtration.

The on-site trials demonstrated clearly that ACMF is a potentially powerful process for the treatment of difficult industrial effluents.

Effect of precoat variables on system performance

The effects of precoat concentration, precoat velocity, precoat pressure and precoat grade on ACMF performance were investigated in the laboratory rig, also on textile effluent. Precoat concentrations ranged from 0,5 g/L to 5 g/L. Precoat velocity and pressure combinations were 1 m/s : 1 bar; 1 m/s : 2 bar; 2 m/s : 1 bar and 2 m/s : 2 bar. The PAC grades investigated were an expensive laboratory grade (approximately R800/kg) and a less expensive industrial grade (approximately R200/kg)

From the investigations into precoat concentration, precoat velocity, precoat pressure and PAC grade, the following trends may be inferred:

(i) changing the precoat concentration, velocity or pressure does not seem to substantially change the COD or turbidity removal efficiency. This is consistent with the postulation that the major mechanism for removal of contaminants is NOT adsorption onto the PAC.

(ii) increasing the precoat velocity seemingly increases the permeate flux. Increasing the pressure may have a detrimental effect on the flux. The reasons for this are not known.

(iii) the performance was not dependant on the grade of PAC, with an expensive laboratory grade yielding similar results to a less expensive industrial grade.

The above results have significant implications for the economics of the ACMF process, since the cost of PAC is expected to be one of the major operating expenses. The results indicate that inexpensive low grades of PAC may be used, and that relatively low precoat concentrations may be equally effective.

Investigations into other effluents

The performance of ACMF on three other effluents was investigated on the laboratory rig, viz Dyefin (printing effluent), Mondi (paper effluent) and South African Breweries (brewing effluent). In all instances, the effluent used was the combined effluent from the final effluent sump (excluding domestic effluent).

The ACMF process was not very effective on Dyefin effluent, giving COD removals of less than 50%. This effluent should be a part of any further investigations into the fundamental separating mechanisms in ACMF.

The performance of ACMF on the Mondi effluent and the SAB effluent were very good, with COD removals of 82% to 90% being obtained. Further, the amount of COD removed was orders of magnitude greater than the adsorption capacity of the PAC, similar to the extensive results obtained on the textile effluent.

The above indicates clearly that the very good results obtained on the David Whiteheads effluent was not a "flash in the pan", and that the ACMF process does have a major potential as a pretreatment step for industrial effluents. The trials on these other effluents also confirm that there are some removal mechanism/mechanisms other than standard adsorption that are occurring in the ACMF process.

Conclusions

Summary of ACMF Performance

This study has shown that:

(i) the ACMF process gives a very significant removal of COD and an excellent removal of turbidity in a single step

(ii) this very good removal of COD and turbidity can be obtained for long filtration times (up to 9 days in this study) with a single precoat

(iii) the removal of COD is not limited by the adsorption capacity of the PAC. Seemingly other mechanisms are involved which enable the removal of COD that is orders of magnitude greater than the adsorption capacity of the PAC

As such, the ACFM process is a potentially very powerful effluent treatment/pretreatment step, yielding a product with an excellent turbidity and a substantially reduced COD in a single step. This could be competitive as a pretreatment step to downstream polishing processes, including reverse osmosis or nanofiltration.

Comparison with competitive processes

In essence, the performance of the ACMF is very similar to that of a *loose* ultrafilter. Thus, the major competitors to ACMF would be conventional treatment (i.e. coagulation/flocculation followed by sand filtration/clarification) and ultrafiltration.

In comparison to conventional treatment, ACMF would have the following advantages:

(i) no chemical addition to the effluent

(ii) very low effluent turbidity

(iii) reduced requirement for sludge disposal

(iv) possibility of reusing the

(v) relatively consistent product quality irrespective of changes in feed quality

(vi) single step process

(vii) modular

ACMF is expected to offer the following advantages over ultrafiltration processes:

(i) no chemical cleaning required

(ii) can handle very highly fouling effluents

(iii) robust system that is more suited to lower skills levels

Economic Evaluation

The initial project objectives included a comparative economic evaluation with other effluent treatment processes. Whilst the project has shown that ACMF does work, it has raised various other questions impacting directly on the economics of the process. These need to be answered before a fair economic assessment of ACMF may be performed.

Recommendations

Whilst this project has demonstrated that ACMF is a potentially very powerful effluent treatment/pretreatment process, it has raised various issues which need to be addressed for the effective exploitation of the process.

Fundamental Mechanisms

The main issue concerns the fundamental separation mechanisms that are occurring in ACMF. This study has shown that the removal of COD is orders of magnitude greater than the adsorption capacity of PAC, as determined from adsorption isotherms. This indicates that adsorption is not the limiting mechanism for the removal of COD. Possible alternative mechanisms include:

(i) the COD being removed is "suspended" COD, and hence the performance is that of a normal microfilter.

(ii) biological activity is developing in the precoat, enabling the subsequent removal of COD.

(iii) the colloidal material and adsorbed organics are somehow combining to create a secondary membrane that is mainly responsible for subsequent COD removal.

Hypothesis (i) is contradicted by the fact that using PAC as a precoat gives a substantially better removal than "chemically inactive" precoats such as kaolin and limestone. Clearly, adsorption onto the PAC is playing a part, although it is not the limiting mechanism. Concerning hypothesis (ii) it was shown that the PAC saturates after about 1,5 hours of filtration. It is unlikely that biological activity could develop that quickly and effect subsequent COD removal.

It is strongly recommended that the fundamental separation mechanisms be investigated, with the following objectives:

(i) to either prove or disprove that something unique is occurring in the ACMF system

(ii) to effect process improvements, which will result from a fundamental understanding of the separation mechanisms

Process aspects

Even without a fundamental understanding of the basis separation mechanisms, there are some process issues which could have a significant bearing on ACMF economics and should be investigated further.

(i) reuse of PAC – if adsorption is not the limiting mechanism, it implies that the precoating step will not require fresh PAC. This further implies that PAC could be recovered after a wash and reused for precoating. This would have a huge impact on the economics, since it would obviate the costs associated with purchasing and handling fresh PAC as well as the cost of disposing of spent PAC.

(ii) dead-end operation. The major running cost in the ACMF process is the pumping cost. In this study, all experiments were carried out in the cross-flow mode, consistent with general effluent membrane processes. However, the operation of ACMF in the dead-end mode should be investigated.

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AC	activated carbon
ACMF	active precoat microfilter
COD	chemical oxygen demand
LMH	litres/m^2.hour
PAC	powdered activated carbon
WFMF	woven fibre microfiltration

1 Introduction

1.1 Background to the project

1.1.1 Woven Fibre Microfiltration

The applicability of microfiltration for the removal of colloidal and suspended solids from raw water, industrial effluent and wastewater is well documented in membrane journals and textbooks. The woven fibre microfiltration (WFMF) system (Figure 1) is a relatively unique microfilter that is fabricated from flexible woven polyester [Pillay, 1991]. In this system, the pores in the tube wall are relatively large, and the tube wall is not the main separating layer. The fouling layer which forms on the tube wall acts as a *dynamic membrane*, enabling the removal of particles that may be orders of magnitude smaller than the tube wall. When the permeate flux drops to an unacceptably low value, the flexible tube is mechanically perturbed, e.g. by pulsing the feed pump. This destroys the dynamic membrane, which is then flushed out of the system. Amongst the advantages exhibited over other microfilters is that WFMF could be operated on highly fouling effluents without irreversible fouling of the tube wall.

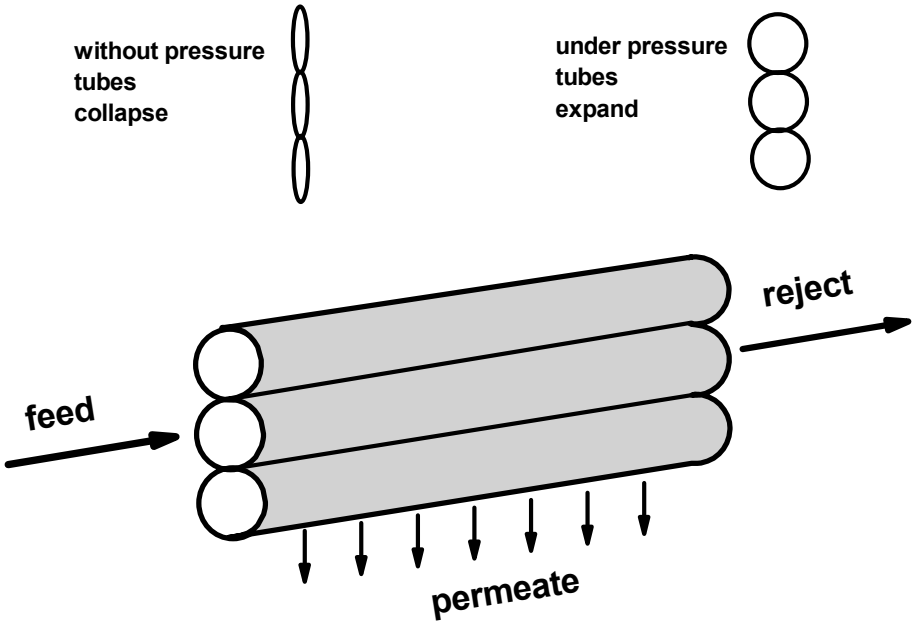

Figure 1: Woven fibre microfilter

The WFMF system also lends itself easily to precoating, i.e. a fouling layer of specific characteristics can be formed on the tube wall prior to the introduction of the feed stream. In

general, precoating can significantly increase the permeate flux obtained on a specific effluent, while simultaneously increasing the permeate quality [Pillay (1998), Pillay and Buckley (2001), Pillay (2001), Pillay and Buckley (2003)]. To date, studies on precoats have been limited to mineral precoats, e.g. limestone, kaolin, diatomaceous earth and waste ash, where there is not expected to be any significant physio-chemical interactions between the precoating material and the foulants in the feed stream.

1.1.2 Activated Carbon

Activated carbon (AC) is widely used in potable water treatment for the removal of trace levels of organics, and general polishing (taste, colour and odor removal) of treated wastewater. AC is available commercially in the powdered form (PAC) or a granular form (GAC), and is produced from a range of raw materials such as wood and coal.

PAC is generally used in batch or continuously stirred reactors and GAC in packed or fluidized bed reactors [Le Roux and Van der Walt (1991)]. The WRC Report indicates that PAC does show distinct advantages over GAC when used in particular applications. Some of these advantages are that PAC reaches adsorption equilibrium quicker; PAC can be incorporated into existing processes without major adaptations thus limiting additional costs; PAC can be applied intermittently in accordance with fluctuating treatment requirements; PAC has a lower cost per unit mass; PAC is well known for removing tastes and odors and PAC has a larger surface area per unit volume.

Several researchers make mention of using activated carbon in membrane biofilm reactors for the degradation of volatile organic carbons [Kolb and Wilderer (1998)], or adsorption of micropollutants onto fibrous activated carbon [Brasquet, Clorec, et al., (1996)]. The activated carbon is subsequently separated from the bulk stream using conventional filtration.

Numerous successes have been documented for hybrid water treatment processes that combine activated carbon with microfiltration or ultrafiltration. In Japan, [Suzuki, Watanabe et al. (1998)], soluble organics and manganese were removed using a hybrid MF hollow fiber membrane system. In a pilot plant, hollow fiber MF membranes are submerged in a tank. In another pre-mixing tank raw water was mixed with powdered activated carbon (PAC) and sludge circulated from the bottom of the MF membrane submerged tank. The mixed water was then fed into the membrane-submerged tank. The organics were adsorbed onto the PAC and the microorganisms in the sludge biologically oxidized the manganese and nitrates. The

MF membranes then removed the PAC and sludge. The removal efficiency was temperature dependent and at the optimal temperatures a removal efficiency of 100% was reported.

In Saarland, Germany several plant construction companies and membrane manufacturers were involved in a pilot project with the objective of producing drinking water from surface waters using MF or UF as a part of the treatment works [Mavrov, et al. (1998)]. Once again in this system PAC was first added to the feed and the membrane was to be used to filter the PAC from the system. Results from the tests showed that suitable water quality (by German standards) could be produced. In both these cases each plant was fitted with powdered activated carbon feeders preceded by limestone filtration tanks. This could be viewed as additional expensive capital injection.

French researchers have gone on to couple PAC with UF. The process is flexible and adaptable to flowrates. The final water quality is constant and exceeds current water quality standards. Even though the system still uses chlorine, the combined effect with PAC adsorption has seen the concentration of disinfection by-products dramatically reduced [Anselme, Baudin, et al. (1999)].

Other papers have reported on the use of activated carbon membrane bio-film reactors [Kolb and Wilderer (2000)], biological PAC MF systems [Seo, Ohgaki and Suzuki (1998)], removal of humic substances using membranes and PAC [Odegaard et al. (2000)] etc.

In all of the above hybrid systems AC is mixed with the feed to act as an adsorbent, and then either UF or MF is used as the filtration step to separate the AC from the process stream.

1.1.3 Active and Inactive precoats

As noted in Section 1.1.1, previous studies on precoated WFMF systems have been limited to *inactive* precoats, e.g. limestone, kaolin, diatomaceous earth and waste ash, where there is not expected to be any significant physio-chemical interactions between the precoating material and the foulants in the feed stream. The question then arises as to whether the performance of WFMF could be significantly enhanced by utilising an *active* precoat, i.e. where there would be some form of physio-chemical attraction between the precoat material and the foulants. The obvious choice for an active precoat would be activated carbon, since its use in the removal of organics from waters has been widely established, and activated carbon is easily available.

There have been numerous reported studies on forming dynamic membranes in UF systems. De Wilde, et al. (1990, 1998, 1999) performed a series of studies in which dynamic UF membranes were formed on stainless steel porous tubes using zirconium hydroxide and fumed silica. These systems gave a very good removal of organics when tested on various industrial effluents.

However, there are no reported studies in the open literature concerning active precoats or active dynamic membranes in MF systems. Note that in all the studies reported in Section 1.1.2, the UF and MF was merely a filtration device to remove activated carbon from the process stream, and the activated carbon did not form an active precoat or dynamic membrane on the UF/MF.

This lack prompted the Water Technology Group at M L Sultan Technikon to investigate active precoats on WFMF systems. This work is summarized in Section 1.2, and was the major motivation for the current project (K5/1374).

1.2 Previous investigations into active precoats

Investigations into the aspect of active precoats were undertaken by the Water Technology Group, M L Sultan Technikon, in 2001. The results of that study are stated here for completeness. In the first part of that study, various precoat suspensions were investigated to find a suspension that would yield a stable precoat, i.e. where the precoat would not be leached or transported from the system through the permeate or the reject streams. Materials investigated included fumed silica, various polymeric gels, and powdered activated carbon (PAC). PAC was subsequently chosen as the most appropriate precoating material.

In the second stage of that study, the performance of a WFMF with an active precoat was compared to that with an inactive precoat. Investigations were performed on an effluent obtained from a textile dyehouse. In this, a deliberate attempt was made to obtain a highly fouling effluent that had not been pretreated. This effluent had a COD of about 1450 mg/L, a colour of about 500 (PtCo APHA), and a turbidity exceeding 999 NTU. Three comparative evaluations were performed:

(i) Firstly, a 25 mm uncoated WFMF was operated on the raw effluent, at a velocity of 2 m/s and a pressure of 1 bar.

(ii) Thereafter, the WFMF was precoated with a 5 g/L solution of an "inactive" precoat, i.e. kaolin, and then run on the effluent at the same velocity and pressure.

(iii) Finally, the WFMF was precoated with a 5 g/L solution of PAC, and then run on the effluent at the above velocity and pressure.

The performance obtained on the uncoated WFMF tube, WFMF with an inactive precoat and WFMF with an active precoat were then compared. The criteria chosen for comparison were permeate COD, permeate turbidity and permeate flux. The quality and production rates of the permeate obtained in the different operating modes are shown in Table 1:

Table 1: Comparison of performance obtained on a raw tube, with an inactive precoat and with an active precoat.

	FEED	**PERMEATE**		
		Raw tube (no precoat)	**Kaolin precoat**	**PAC Precoat**
COD* **(mg/L)**	1450	825 to 640	680 to 440	205 to 229
TURBIDITY (NTU)	> 999	179	8	< 1
Flux (LMH)		10 to 7	10	30

* *unfiltered COD*

The above results indicate clearly that there is a major improvement in performance when an active precoat is used, in terms of COD removal, permeate quality and permeate production rates. In the above instance, there was an 85% reduction in COD and a reduction in turbidity from > 999 NTU to < 1 NTU in a single step, and at permeate production rates that are regarded as economically viable. The combined PAC/WFMF system was tested on other untreated effluents, and similar trends were indicated i.e. the PAC precoated system gave a significantly better permeate quality and significantly higher fluxes.

It emerges that WFMF with an active precoat could be a very powerful pretreatment step for industrial effluents, giving a significant COD reduction and permeate of very low turbidity in a single step. The clarity of the permeate is expected to be significantly better than other

conventional pretreatment systems, e.g. sand filtration, coagulation and settling or DAF. This would have significant effects on the efficiency of downstream processes. The system would also have all the advantages of WFMF, i.e. being able to handle feeds of widely varying turbidities, robustness, and ease of cleaning.

1.3 Objectives of this study

The overall objective of this project is to develop and demonstrate the combined PAC/WFMF system for the pretreatment of industrial effluents. This combined process will hereafter be referred to as the actived carbon microfilter (ACMF). The specific objectives of the project are:

(v) Process development of the activated carbon / microfiltration (ACMF) system up to semi-pilot scale: - identify and investigate the important geometric and operating variables that determine process performance, and hence develop an optimal operating protocol for ACMF.

(vi) To evaluate and characterise the performance of the optimised ACMF process on three "priority" effluents

(vii) To evaluate economics of the ACMF process on these "priority" effluents and compare to alternative technologies

(viii) To demonstrate the ACMF process to potential users on a semi-pilot scale

The project was initiated in January 2002, and was completed in December 2004.

1.4 Approach

Textile effluent from David Whiteheads, Tongaat, Durban, was the main effluent investigated in this project, for three main reasons:

(i) It is a typical “difficult-to-treat” effluent, having a very high turbidity and a significant COD loading

(ii) Logistically, David Whiteheads was reasonably accessible to obtain effluent samples

(iii) A very good working relationship had been established with relevant staff at David Whiteheads, and an excellent co-operation was obtained from them.

In the first stage of the project, laboratory-scale investigations were performed on a textile effluent obtained from David Whiteheads in Tongaat, Durban. The main objective of these trials was to quantify the performance of ACMF on this difficult effluent, and to determine the efficiency of PAC usage in the ACMF system. This is reported in Section 2.

In the second stage of investigations, a pilot rig was set up at the David Whiteheads plant, and operated directly off the main effluent sump. This was mainly to facilitate extended runs and to confirm the results obtained in the laboratory trials, and is reported in Section 3.

The third part of the project involved laboratory-scale investigations into the effects of the main precoating variables on ACMF performance. This forms the topic of Section 4.

Finally, laboratory-scale investigations were performed on three other effluents, viz. a brewery effluent, effluent from a paper processing plant and an effluent from a printing plant. This is reported in Section 5.

2 Laboratory trials on textile effluent

2.1 Objectives

The main objective of these trials was to quantify the performance of ACMF on this difficult effluent, and to determine the efficiency of PAC usage in the ACMF system.

2.2 Experimental procedure

The laboratory experimental rig consisted of a 2,3 m long WFMF tube of diameter 25 mm, three tanks (precoat suspension, effluent feed and permeate) and a positive displacement pump controlled by a speed control. The details of the rig and operating procedure are presented in Appendix I.

Each experimental run consisted of three cycles:

(i) precoat cycle: - the precoat suspension was pumped through the MF tube, with the permeate and reject streams being returned to the precoat tank. Precoating took between 30 minutes and 1 hour.

(ii) filtration cycle: - at the end of the precoat cycle, the feed stream to the MF tube was changed over from precoat to effluent, ensuring that the tube was not de-

pressurised. The reject stream was redirected to the feed tank. The pressure and velocity was adjusted, and this defined the start of the filtration cycle. *Note that during the filtration cycle, only effluent entered the MF tube, and NO precoat entered the tube*.

(iii) cleaning cycle: - at the end of the filtration cycle, the tube was washed out by pumping water through it and pulsing the pump.

2.3 ACMF performance

Typical performance graphs in terms of COD removal, turbidity removal and permeate flux are shown in Figures 2 and 3. This experiment was performed in a *constant concentration* mode, i.e. the permeate and reject streams were both returned to the feed tank, giving a feed concentration that was relatively constant with time.

Note that all CODs reported in this project are *unfiltered* CODs.

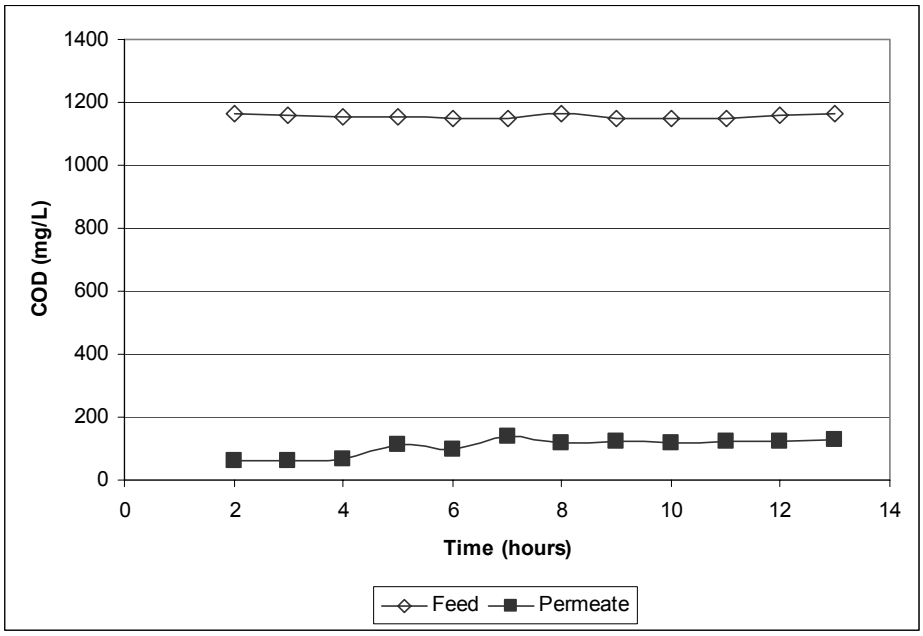

Figure 2: Typical COD profiles for the textile effluent

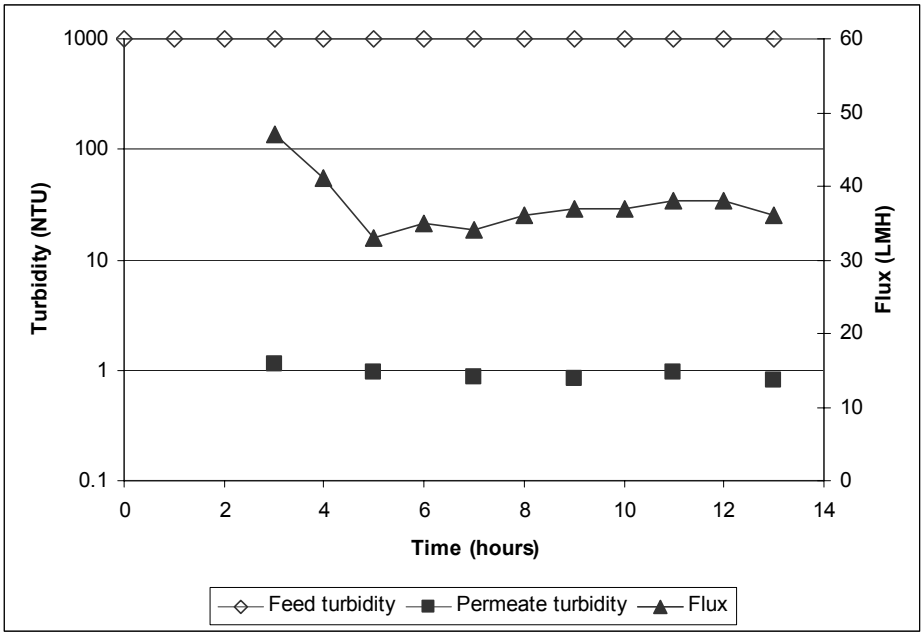

Figure 3: Typical turbidity and permeate flux profiles for the textile effluent

The feed COD starts off at around 1160 mg/L and remains close to this over the 12 hour run. The permeate COD starts off at about 70 mg/L, increases slightly and then remains substantially constant over the run. The feed turbidity starts off at a value > 999 NTU and remains at this high value, while the permeate turbidity is approximately 1 NTU and remains at this low value over the run. The permeate flux starts off at around 50 LMH and declines to around 38 LMH over the run.

The above result confirms the findings obtained in preliminary trials, i.e. that the ACMF system gives an excellent turbidity removal and a substantial COD removal in a single step. It also indicates that the quality of the product does not deteriorate with time, although the above run is not long enough to draw a conclusion on this.

2.4 Determination of efficiency of PAC usage in the ACMF system

The activated carbon has a finite COD adsorption capacity for a given effluent. This can be expressed in terms of mg COD removed per gram of PAC. In conventional use, PAC would be intimately mixed with the suspension to be treated and the suspension would then be filtered. The amount of COD removed by the PAC should equal the adsorption capacity of the PAC.

In the ACMF system, it is expected that COD would be removed until the adsorption capacity of the PAC is approached. At this point the COD of the permeate should increase rapidly and approach that of the feed (Figure 4). If this *breakthrough* point is identified, the actual removal of COD in ACMF can be quantified and compared to the theoretical adsorption capacity of the PAC. Hence, the *efficiency* of PAC usage in the ACMF system can be determined.

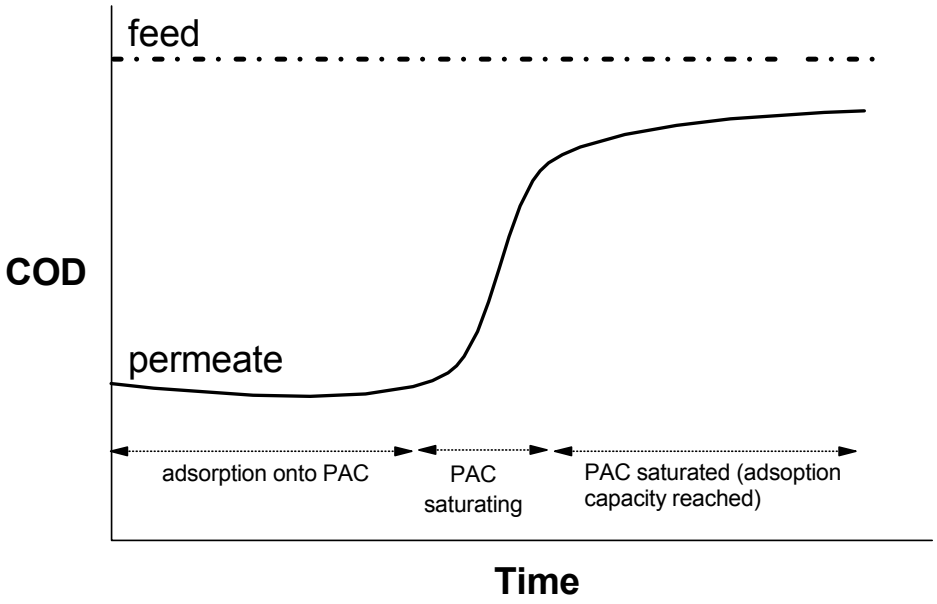

Figure 4: Expected COD profiles for an adsorption process

This section concerns the comparison of COD removal in the ACMF system with the COD removal when PAC is used conventionally.

2.4.1 Approach

The approach was as follows:

(i) The adsorption capacity of the PAC for the effluent used was determined from laboratory adsorption trials (mg COD/g PAC)

(ii) The mass of PAC in the precoated microfilter was calculated by mass balance.

(iii) From (i) and (ii), the theoretical maximum amount of COD that could be adsorbed was calculated

(iv) An experimental run was performed, where the ACMF system was run on the same effluent as in (i). From the measured feed and permeate COD profiles and

permeate fluxes, the amount of COD removed during the course of the experiment was calculated.

(v) The COD removal in (iv) was compared to (iii).

2.4.2 Determining the adsorption capacity of the PAC

The adsorption capacity was determined in a bomb filter, using WFMF cloth as the filter medium. The bomb filter and the experimental procedure are discussed in Appendix I.

Varying masses of PAC (from 0,1 g to 20 g PAC) were added to 1 L aliquots of raw effluent, and intimately mixed for over 1 hour. The mixtures were then filtered in the test-cell and measurements of both feed and permeate COD were recorded. These results are presented in Figures 5 and 6.

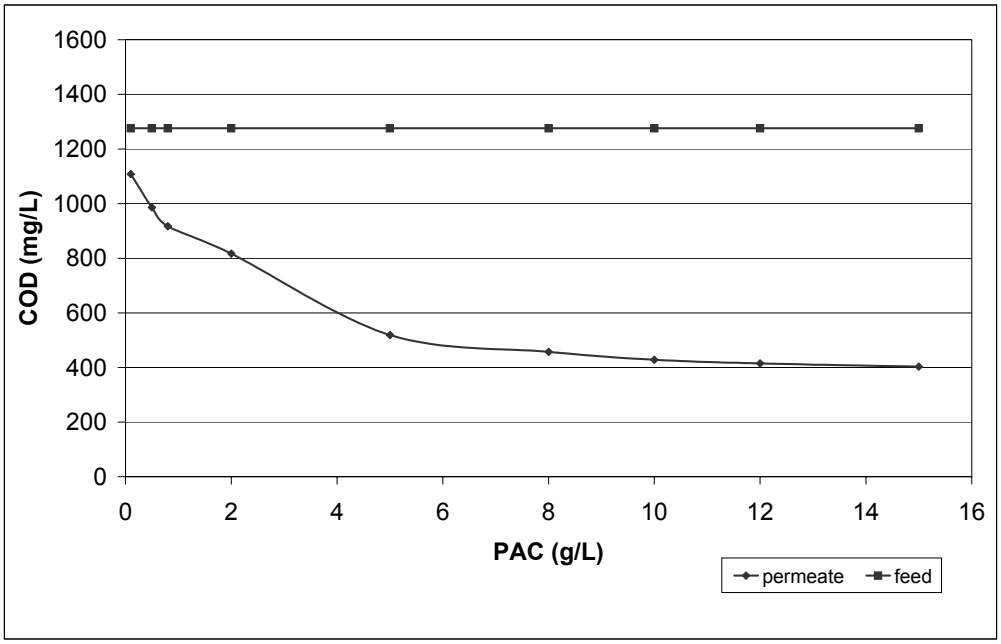

Figure 5: Feed and permeate COD vs mass of PAC added

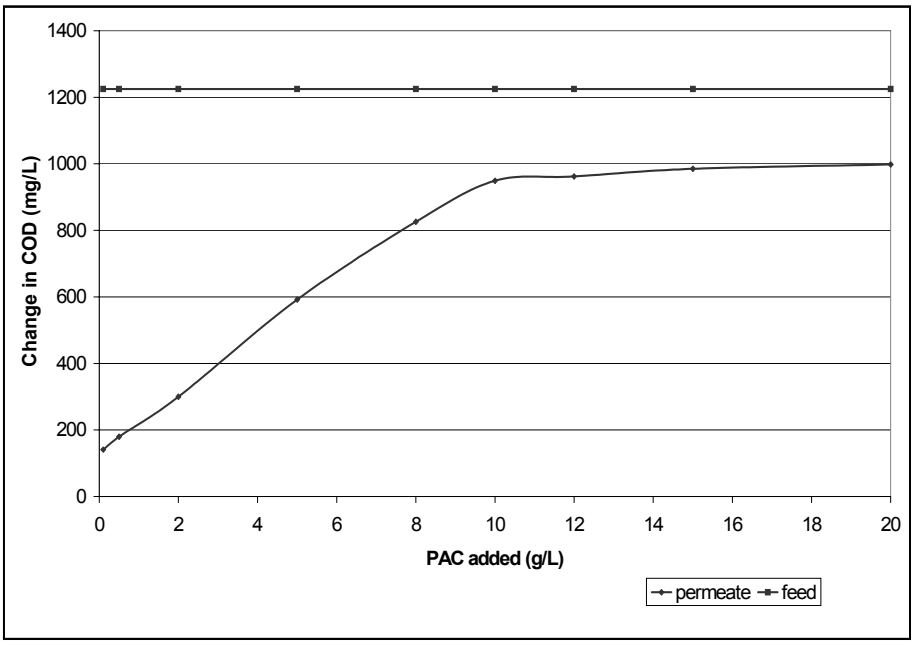

Figure 6: COD removed vs mass of PAC added

The permeate COD decreases with increasing PAC addition up to about 10 g/L of PAC, and thereafter becomes relatively independent of PAC addition. This *residual* COD, about 400 mg/L in Figure 5, indicates the COD component that cannot be adsorbed by PAC.

Correspondingly, the graph of change in COD versus PAC added shows a linear increase up to about 10g/L PAC, and thereafter becomes independent of PAC addition. The slope of the first linear part of the graph represents the amount of COD removed per gram of PAC, and is thus the adsorption capacity of the PAC for the COD in the particular effluent.

For the textile effluent tested, the adsorption capacity was found to be in the range of **70 mg to 105 mg COD removed per gram PAC**. This adsorption capacity is, of course, specific to the effluent tested.

2.4.3 Calculation of mass of PAC on WFMF Tube

A woven fibre tube of the same length used in effluent treatment runs was precoated with PAC, at the same precoating conditions used in effluent treatment runs. The PAC concentrations in the pipework (lines) and that left in the tank after precoating was determined by taking samples from the respective section and determining the solids content in them. The mass of PAC on the tube was then calculated as follows:

(Initial precoat volume)(PAC concentration) = $PAC_{TUBE} + PAC_{LINES} + PAC_{LEFT\ IN\ TANK}$

$(V_i)(PAC_i)$ = PAC_{TUBE} + $(V_{LINES})(PAC_{LINES})$ + $(V_F)(PAC_F)$

(40 L)(5 g/L) = PAC_{TUBE} + (6,55 L)(3,43 g/L) + (37,5 L)(3,33 g/L)

200 g = PAC_{TUBE} + 22,48 g + 124,99 g

PAC_{TUBE} = 200 - 147,5 g

= 52,5 g

The above determination was repeated four times, giving an average value of 53 g PAC in the precoat layer.

2.4.4 Theoretical adsorption capacity of ACMF system

The amount of PAC on the tube was found to be 52,5 g. Hence the theoretical amount of COD (calculated to the nearest one hundred) removed by the PAC precoated WFMF system should be **approximately 4000 mg to 5500 mg** COD [(52,5)(75 to 105)] mg/l).

2.4.5 Determination of actual COD removal in ACMF system

The cumulative COD removed in the ACMF system at any time *T* can be calculated from the COD and flux profiles as follows:

$$COD_{Adsorbed} = \int_0^T J(t)\, A\, [(COD_{Fi}(t) - COD_{Pi}(t)]\, dt$$

where J(t) = flux at time t

COD_{Fi} (t) = feed COD at time t

COD_{Pi} (t) = permeate COD at time t

A = filtration area (fixed)

For the laboratory WFMF system, the filtration area was 0,115 m^2.

The COD concentrations in the feed and permeate were determined hourly. It was assumed that the flux did not change significantly during that hour. Hence A and J were considered as constants. Therefore,

$$COD_{Adsorbed} = (J_i)\,(A) \int (COD_{Fi}\text{-}COD_{Pi})\,dt$$

Using the COD and flux profiles from Figure 2 and 3, the cumulative amount of COD removed with time can be calculated, and is shown in Figure 7. The total COD removed by the system over 12 hours was approximately 56 500 mg.

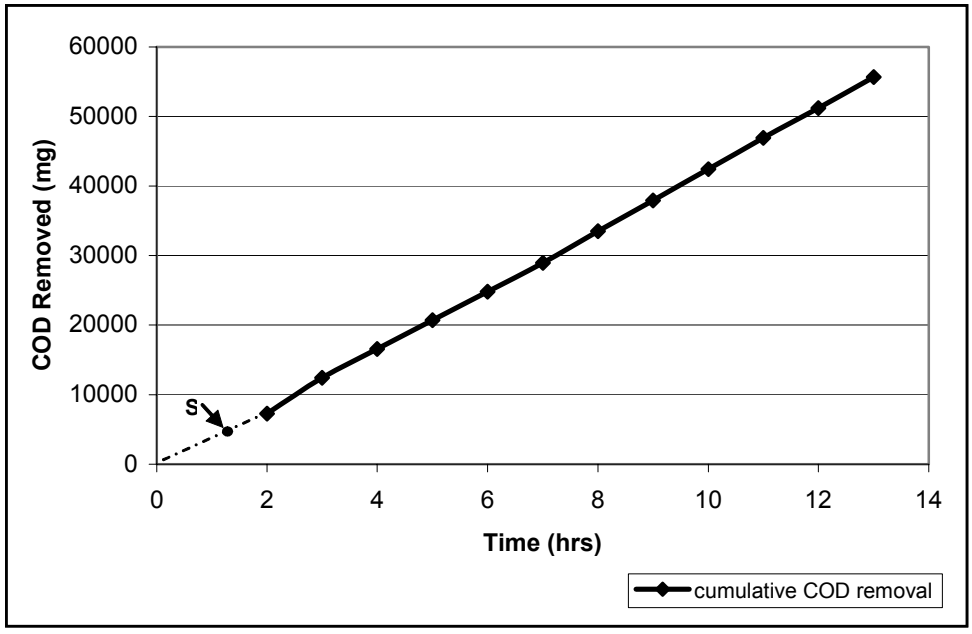

Figure 7 : Cumulative removal of COD in ACMF system

From Section 2.4.4, the theoretical adsorption capacity of the PAC on the WFMF tube was approximately 5500 mg COD (for the particular effluent). This is represented by point S on the above graph. According to Figure 7, the maximum adsorption was achieved after about 1,5 hours. However, the ACMF continued to remove COD for 11 hours after the theoretical adsorption capacity of the PAC was exceeded, as indicated in the permeate COD profile in Figure 2.

This result was unexpected and extremely puzzling, indicating that the ACMF system was removing more COD than was theoretically possible. One possible explanation was that some other mechanism of separation besides adsorption was at play. This would explain why COD removal continued after the PAC became saturated.

However, it was still expected that if the run were continued, there will eventually be a breakthrough of COD into the permeate. To test this, an extended run on the textile effluent was performed.

2.5 Extended laboratory run on textile effluent

An experimental run of 72 hours duration was carried out. This run was performed in a batch concentration mode i.e. the reject was returned to the feed tank, but the permeate was discarded. The feed tank was periodically topped up with fresh effluent to maintain a constant feed level (volume). Hence, the feed concentration progressively increased with time. The crossflow velocity was approximately 1 m/s, and the operating pressure was 1 bar.

The COD and flux profiles are shown in Figure 8.

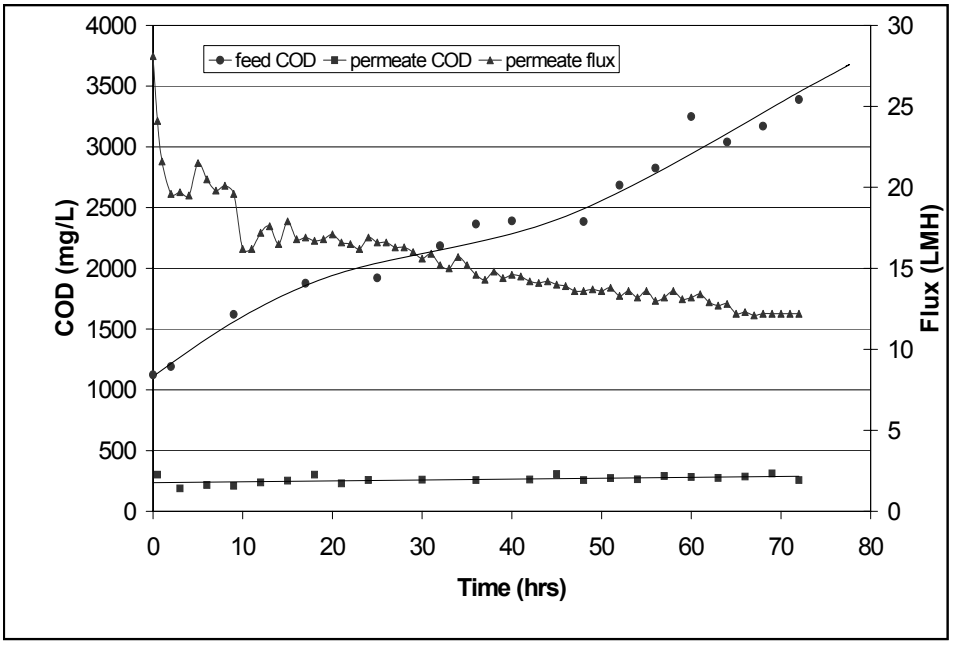

Figure 8 : COD, turbidity and flux profiles for 72 hour run

The cumulative COD removal for the above run is shown in Figure 9.

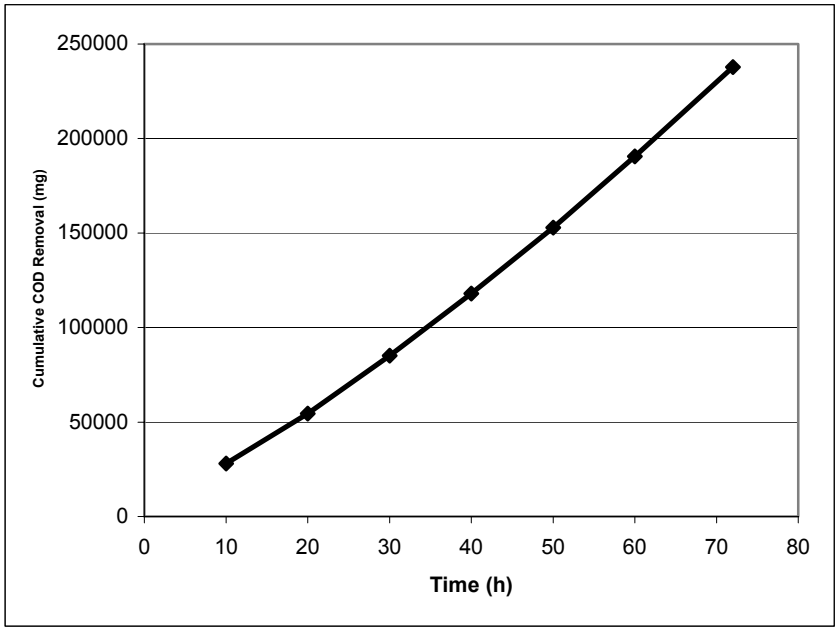

Figure 9 : Cumulative removal of COD in 72 hour run

The adsorption capacity of the PAC for the textile effluent under test was approximately 70 mg to 105 mg COD per g PAC. The mass of PAC in the precoat layer averaged 53 g. This indicates that the theoretical adsorption capacity of the ACMF system was approximately 5 500 mg COD.

In the 12 hour run, the calculated COD removal was 56 500 mg. In the 72 hour run, the calculated COD removal was approximately 238 000 mg. This indicates that in the 12 hour run, the PAC adsorption efficiency was approximately 1000%, and that in the 72 hour run 4300%. In both runs, the PAC should theoretically have reached its saturation capacity after about 1,5 hours. However, at the ends of the 12 and 72 hour runs, there was no indication of an increase in permeate COD.

The above results confirm that the removal of COD in the ACMF system is significantly greater than the removal when PAC is used conventionally (i.e. mixed with the effluent and filtered), lending credence to the postulation that that there is a second mechanism (beside PAC adsorption) occurring in the system that is also responsible for COD removal.

Further investigation of this unexpected result would require extended runs, greater than 72 hours. This posed a logistical problem with transport and storage of effluent. The project

team then decided to fast track the setting up of a pilot scale rig, so that trials could be performed on site at David Whiteheads.

3 Onsite trials at David Whiteheads

3.1 Initial trials

In the original project workplan, a pilot rig was to have been constructed during the third quarter of 2003, for field investigations at suitable industries. One of the problems encountered in the laboratory trials was the logistics of transporting effluent from the textile mill to Durban Institute of Technology. Further, the effluent could not be stored for a long period due to biological activity occurring. This limited the length of runs that could be performed in the laboratory. Accordingly, the project team decided to move the construction of the semi-pilot rig forward, and the rig was constructed and commissioned in the first quarter of 2003.

The pilot rig consists of a positive displacement pump with speed control, two feed tanks, and a permeate collection channel on a transportable frame. For the two runs reported here, the ACMF module consisted of two WFMF tubes of length 2,2 m, connected in parallel. The rig was situated next to the main effluent sump at David Whiteheads, Tongaat. Runs were performed in a fed batch concentration mode. The feed tank is initially charged with 120 L of raw effluent. During the filtration cycle, the permeate is discarded while the concentrate is returned to the feed tank. When the level in the feed tank drops by 20 L, it is topped up with raw effluent.

Two runs are reported here: Run 1 in Figure 10 (5 days) and Run 2 in Figure 11 (9 days).

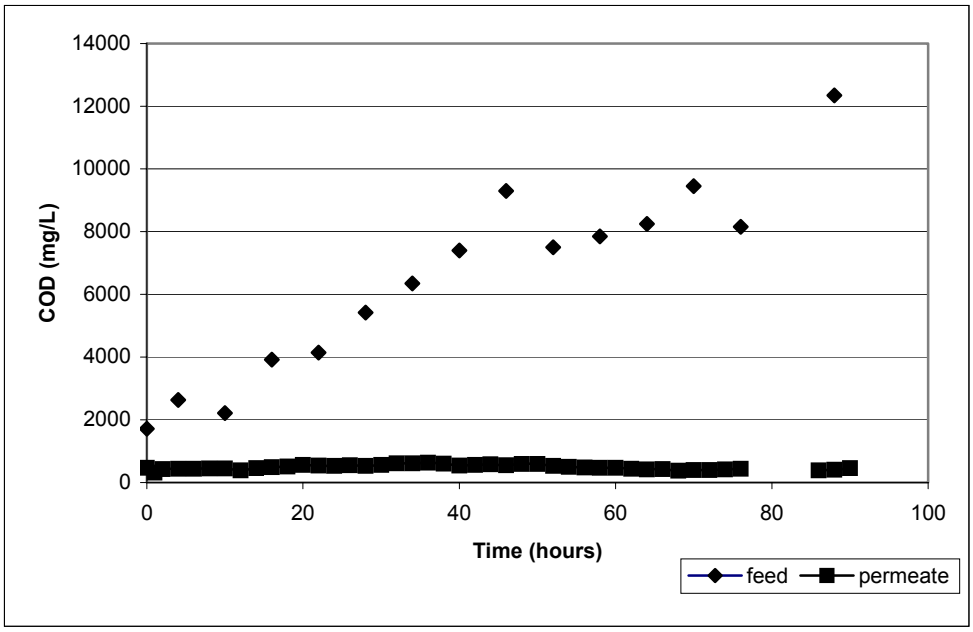

Figure 10 (a) : COD profiles for 5 day run at David Whiteheads

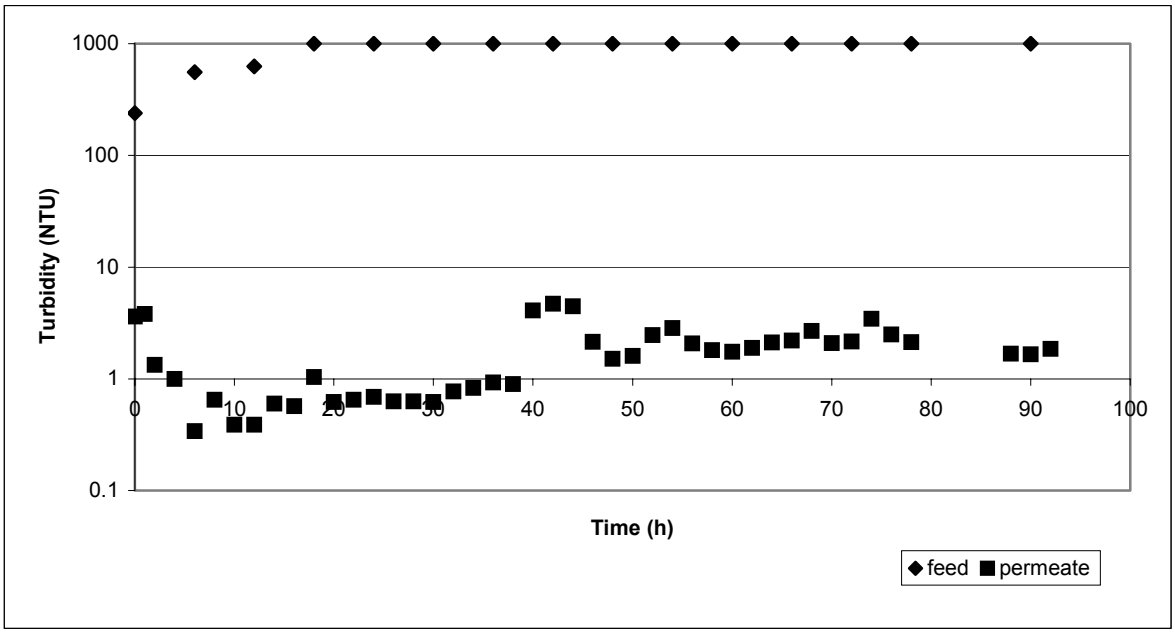

Figure 10 (b) : Turbidity profiles for 5 day run at David Whiteheads

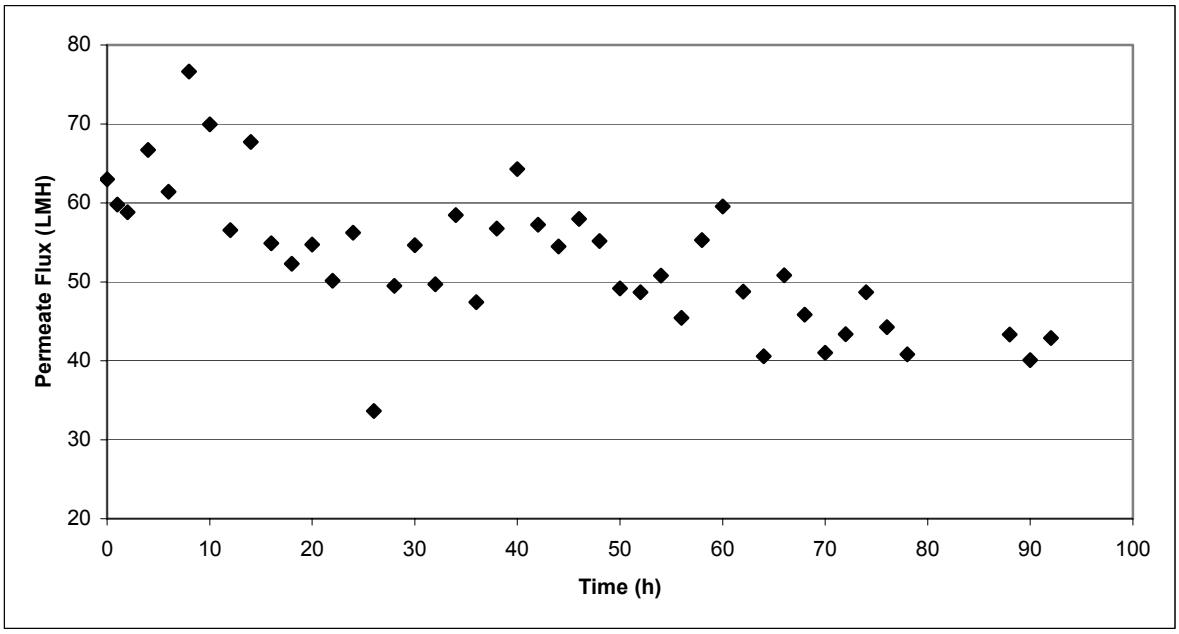

Figure 10(c)– Permeate flux profile for 5 day run at David Whiteheads

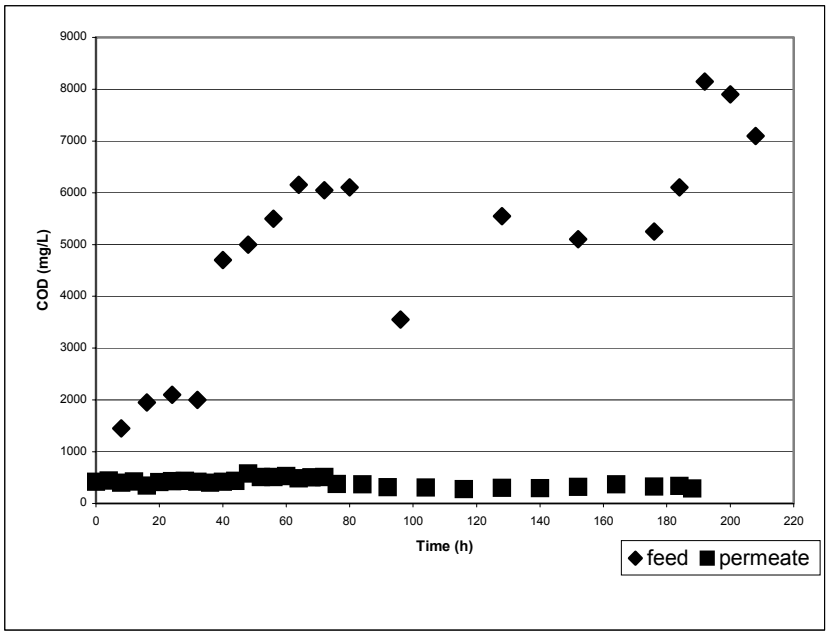

Figure 11(a)– COD profiles for 9 day run at David Whiteheads

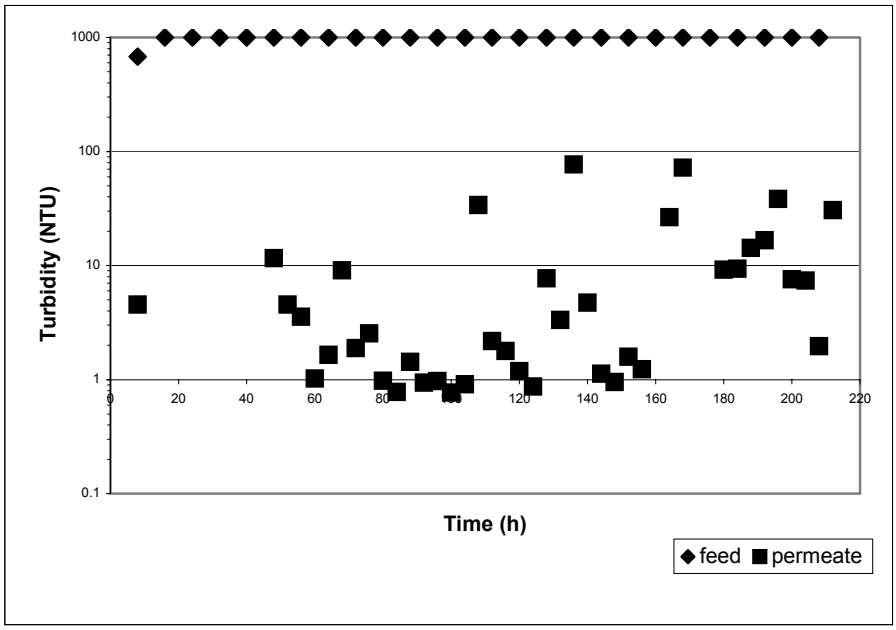

Figure 11(b)– Turbidity profile for 9 day run at David Whiteheads

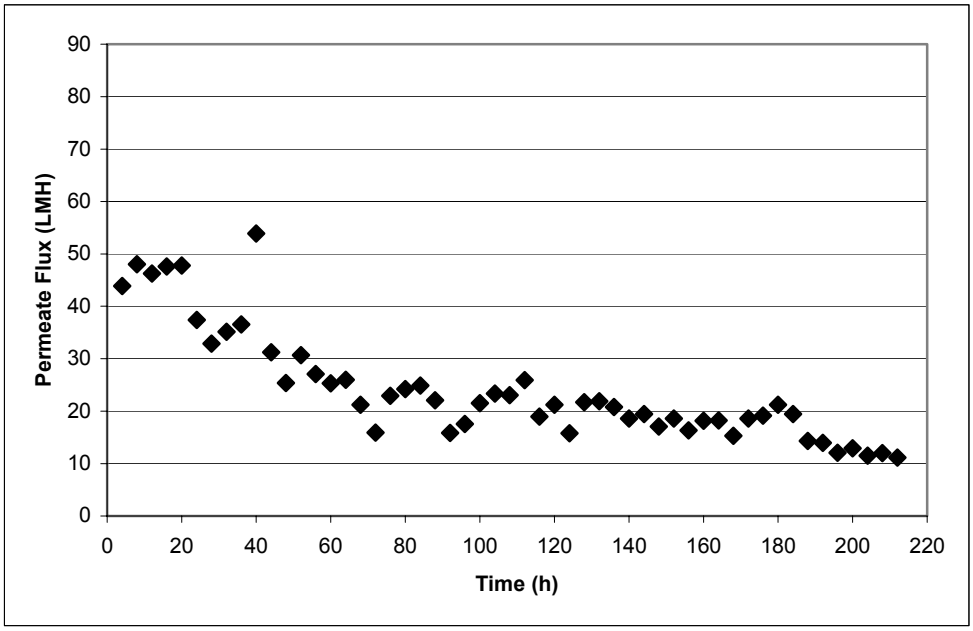

Figure 11(c) – Permeate flux profile for 9 day run at David Whiteheads

In Run 1 the filtration period was 92 hours. At this point a leak developed in the module, and the run was stopped. The initial feed COD was 1710 mg/L, and this increased to over 12000 mg/L due to the batch concentration. The initial permeate COD was 468 mg/L. This increased to about 609 mg/L after 2 days, and then decreased to about 450 mg/L. The feed

turbidity was initially 239 NTU, and increased to over 999 NTU within 2 days. The permeate turbidity ranged from 0,2 NTU to around 5 NTU. The permeate flux started off at around 60 LMH, and declined to 40 LMH after 90 hours.

The performance in Run 2 was significantly poorer. The turbidities were extremely high, and the fluxes correspondingly much lower than Run 1. It was observed that dust etc tended to collect in the (uncovered) permeate collection channel, since the rig was open to the elements. Whilst this could contribute to a higher turbidity, it does not explain the excessive turbidities and low fluxes. A further possibility is that the suspension underwent aerobic degradation due to biological activity. This could explain the "dip" in the feed COD, as well as the poor fluxes. However, the permeate COD remained at a low level throughout the run, with no signs of "saturation" of the system.

The above runs confirm that the ACMF process is capable of removing significantly more COD than the theoretical saturation capacity of the PAC. In Run 2, the system was operated for 9 days without any increase in permeate COD. However, it also emerged that there may be secondary processes, e.g. biological activity, which may be changing the nature of the suspension and hence affecting the performance of the system.

3.2 Further trials at David Whiteheads

Over the period October 2003 to July 2004, further trials were performed on David Whiteheads effluent, both on site and in the laboratory. The objectives of these further trials were as follows:

(i) operate with a larger filtration area – in the previous on site trials, two microfiltration tubes of length 2,2 m each were used. This gave a nominal permeate flowrate of about 10 L/h, which was not "visually impressive". A new module was constructed consisting of 6 x 2,2 m tubes arranged in a 2 x 3 arrangement, i.e. two parallel trains of three tubes each. This was regarded as the maximum filtration area that could be operated off the existing pump.

(ii) confirm turbidity removal efficiency – in the previous on site trials, permeate turbidities in the first run were consistently below 5 NTU, while the turbidities in the second run ranged from below 1 NTU to 100 NTU. The reasons for the wide discrepancy needed to be investigated.

(iii) confirm performance on different effluent batches – the project team had been informed that the quality of the effluent varied from batch to batch. Hence, the process performance needed to be proven over a wider range of effluent batches.

(iv) demonstrate the process to David Whiteheads management

(v) evaluate effect of effluent age on performance – here laboratory filtration trials were performed on "fresh" effluent and on effluent that was four weeks old.

As in previous runs, the tubes were precoated with a suspension of 5 g/L of PAC for 1 hour at a pressure of 2 bar and velocity of 2 m/s. Thereafter raw feed was filtered through the system at 2 m/s and 2 bar. The system operated in a batch concentration mode. The experimental rig was situated next to the main effluent sump at David Whiteheads, Tongaat. The feed tank was initially charged with 120 L of raw effluent. During the filtration cycle, the permeate was discarded while the concentrate was returned to the feed tank. When the level in the feed tank dropped by 20 L, it was topped up with raw effluent from the effluent sump.

3.2.1 COD removal and permeate flux

Four extended runs are reported in Figures 12 to 15 : Run 11 (3,8 days), Run 12 (8,25 days), Run 13 (8,8 days) and Run 14 (9 days).

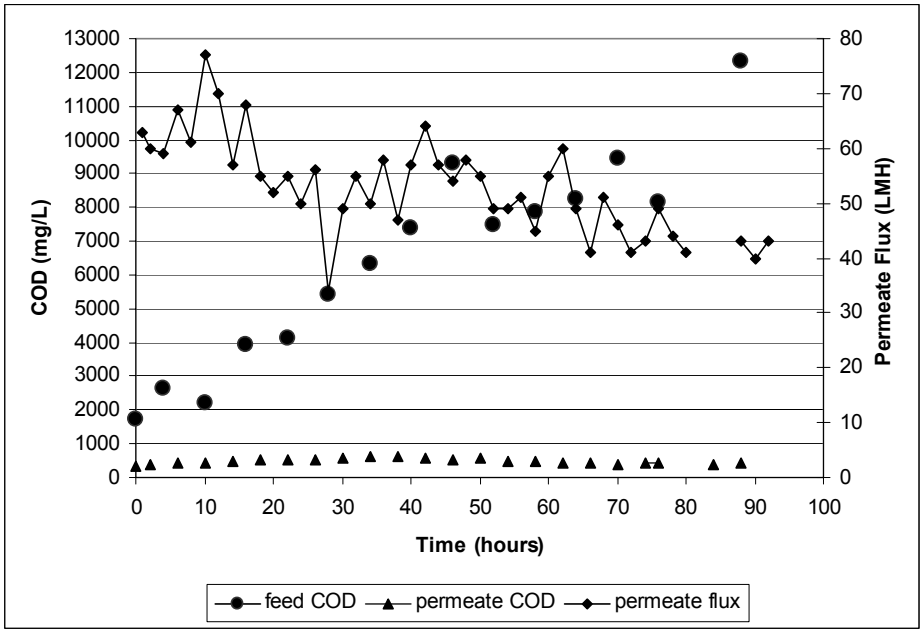

Figure 12 : Permeate fluxes and CODs for Run 11

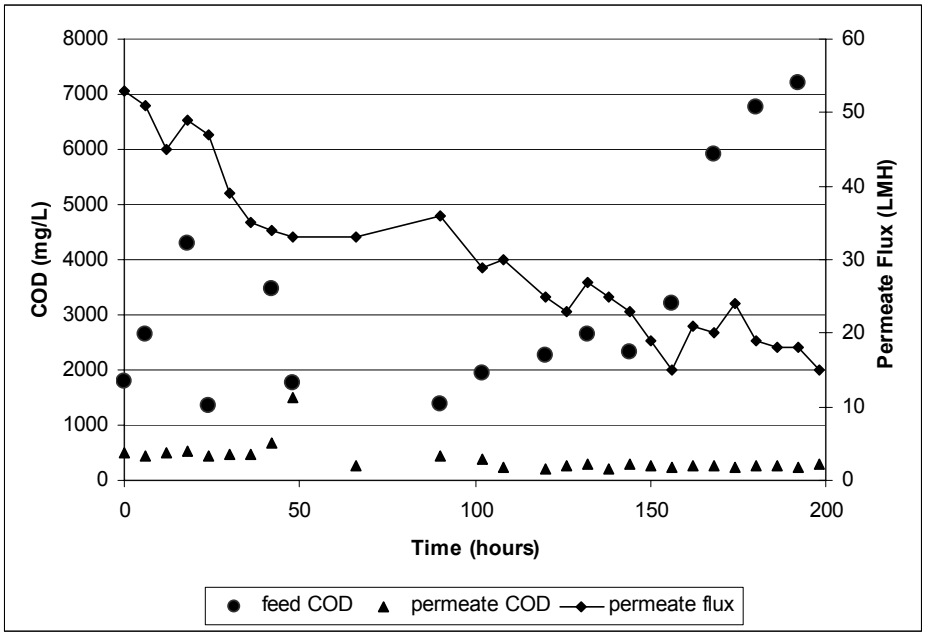

Figure 13 : Permeate Fluxes and CODs for Run 12

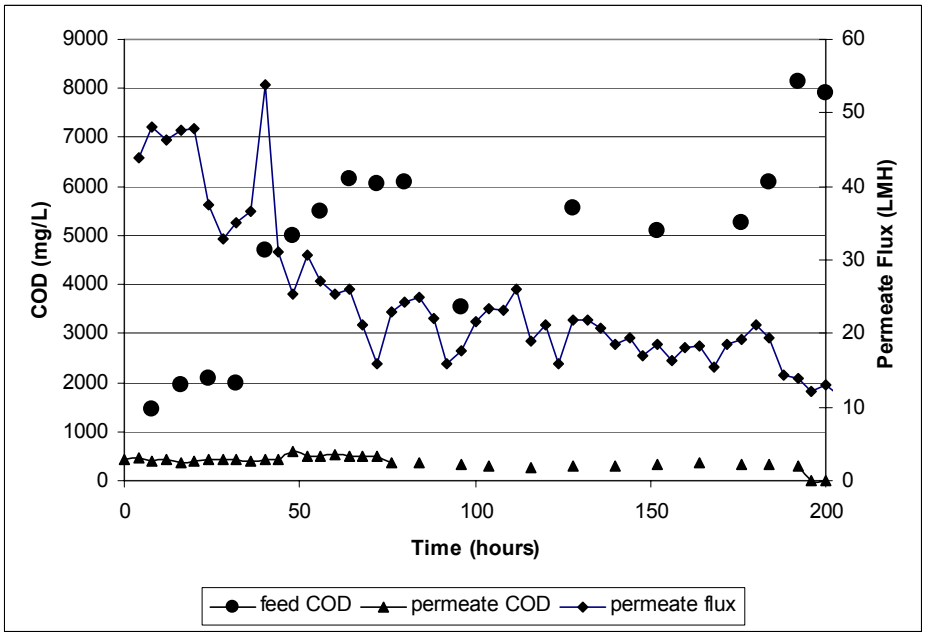

Figure 14 : Permeate Fluxes and CODs for Run 13

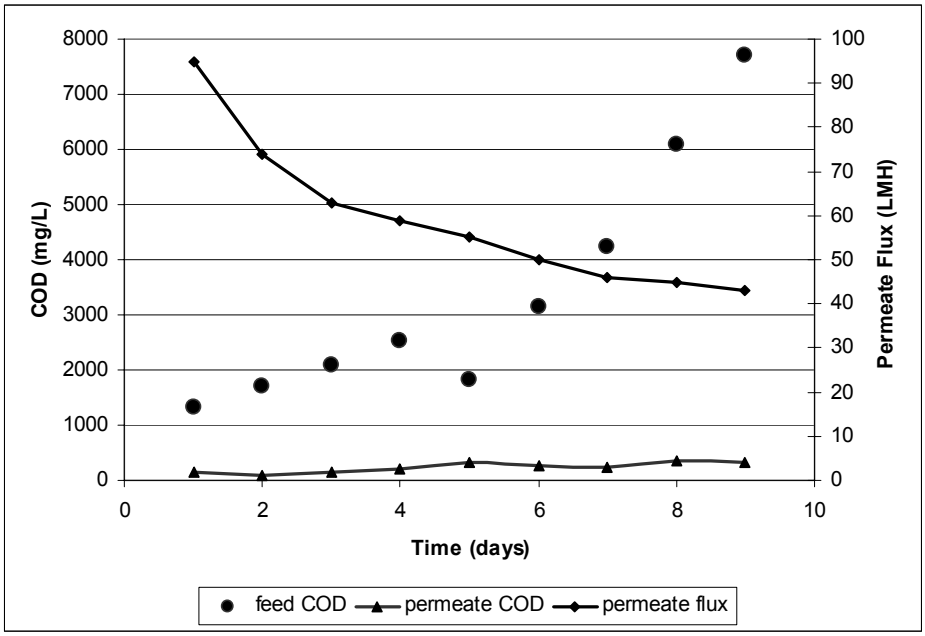

Figure 15 : Permeate Fluxes and CODs for Run 14

In Run 11, the feed COD starts off at around 1700 mg/L and increases to about 12 000 mg/L after about 90 hours. The permeate COD is initially around 400 mg/L. This increases to 600 mg/L and then decreases back to 400 mg/L over the run. In Run 12 the feed COD goes through peaks and troughs during the run. This is due to different qualities of effluent entering the effluent sump. The permeate COD starts off at around 450 mg/L, increases to 600 mg/L and then decreases to 300 mg/L. There is one data point indicating a permeate COD of 1500 mg/L, which is most probably an error. The CODs for Run 13 show similar trends to Run 2. Once again the permeate COD increases slightly during the run, and then decreases down to about 300 mg/L. In Run 14 samples were taken only once a day. The trends exhibited by the CODs are similar to the previous runs.

Consistent with previous extended trials, the permeate COD shows no sign of breakthrough, as would be expected when the PAC adsorption capacity is reached.

3.2.2 Turbidity removal

The turbidity profiles obtained in Runs 11 to 14 are presented in Figures 16 to 19.

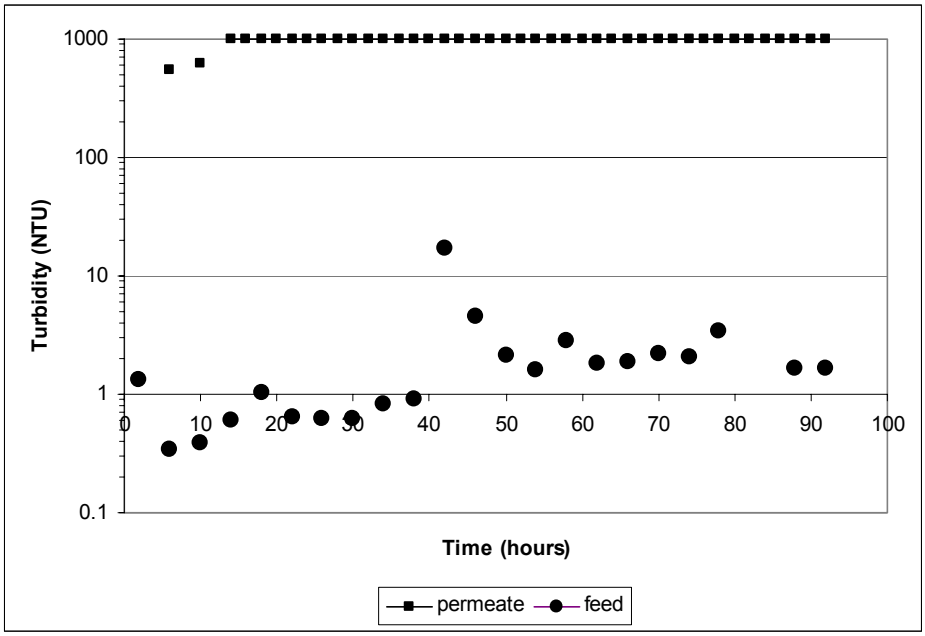

Figure 16 : Turbidity profiles for Run 11

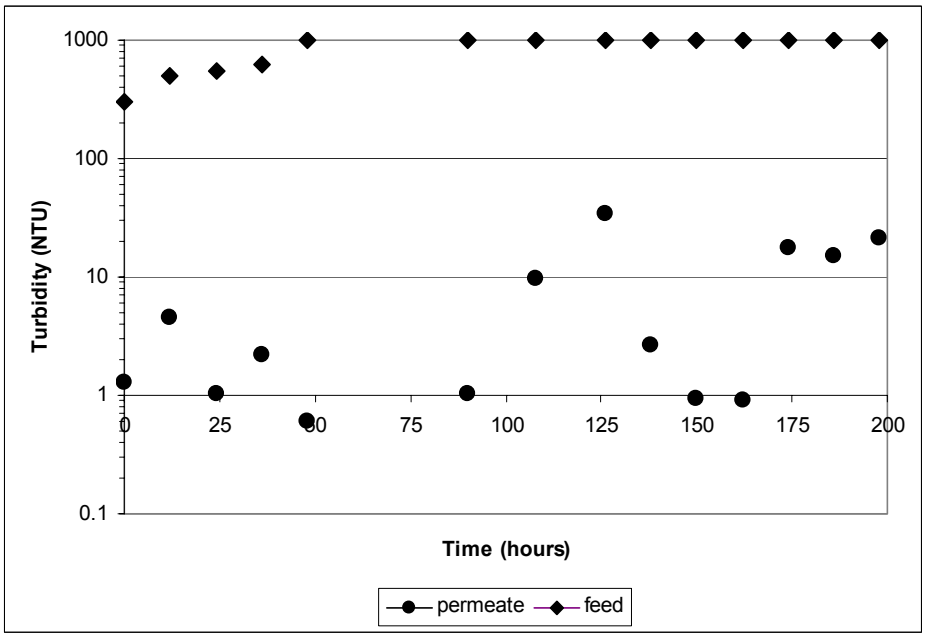

Figure 17 : Turbidity profiles for Run 12

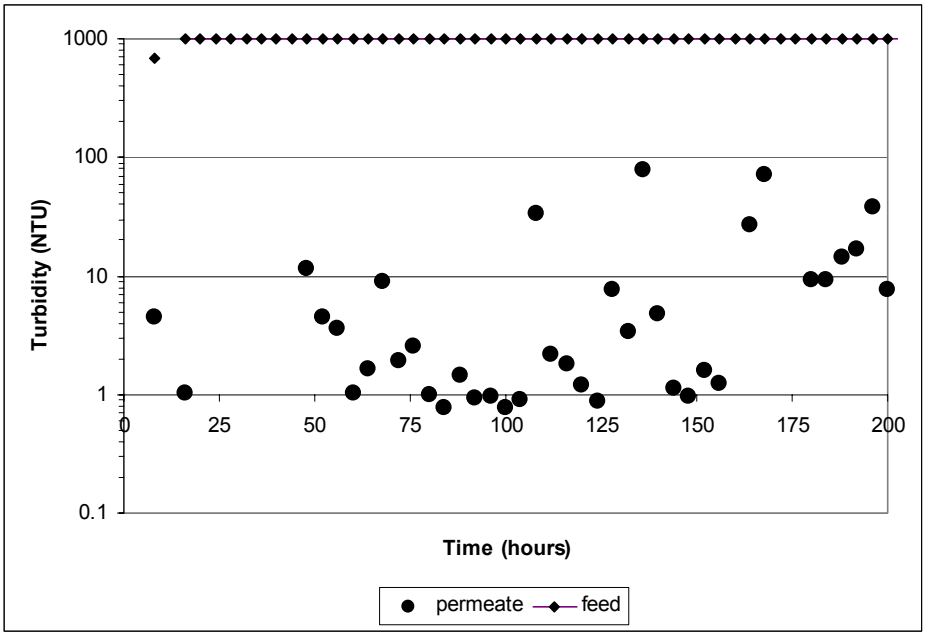

Figure 18 : Turbidity profiles for Run 13

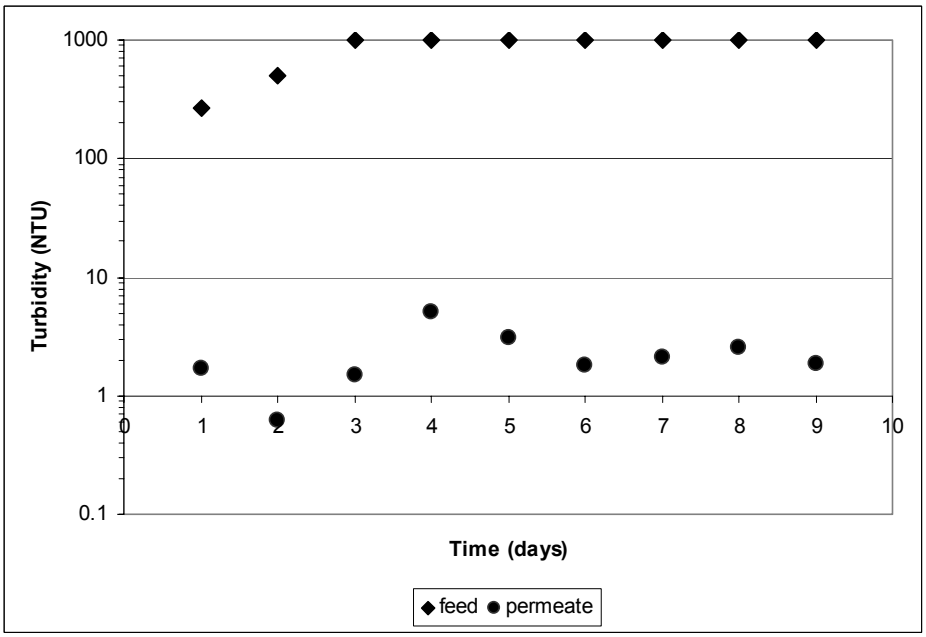

Figure 19 : Turbidity profiles for Run 14

In all the runs, the feed turbidity starts off at around 200 to 300 NTU, and then increases to > 999 NTU within 1 to 2 days. In Run 11 the permeate turbidities are between 0,3 NTU and 5 NTU, with one data point at 11 NTU. In Run 12 the permeate turbidities are generally between 0,8 NTU and 12 NTU. In Run 13 the permeate turbidities change drastically over the run, and range from 0,8 NTU to 80 NTU. This was perplexing, since the permeate CODs

for Run 13 were consistently low, and did not mimic the great variation exhibited by the permeate turbidity. If the great variation in turbidity was caused by contaminants breaking through the microfilter, it would be expected that the COD would have increased as well.

Investigations into this discrepancy did not yield any definite conclusion. A possible explanation was that the David Whiteheads operators who were taking the samples did not exercise due caution when taking the samples and transporting them back to the laboratory for analysis. Contamination of the samples by dust etc would have affected the turbidity reading, but not the COD reading.

To obviate this possibility, all samples for Run 14 were taken and analysed by DIT project staff. Hence, only one sample was taken per day. In Run 14 the permeate turbidities were consistently between 2 NTU and 7 NTU, without the huge variation observed in Run 13.

3.2.3 COD Removal Efficiency

From previous laboratory isotherm trials the saturation capacity of the PAC for David Whiteheads effluent was approximately 100 mg COD/g PAC (range 70 mg/L to 105 mg/L). The mass of PAC on a single tube precoated with a 5 g/L suspension was determined as 52 g. Hence, the theoretical removal capacity of six tubes is:

Theoretical COD removal = 6 tubes x 52 g PAC/tube x 100 mg COD/g PAC

= 31 200 mg COD

Using the previous approach to calculate the actual COD removed in each run yields the following (Table 2)

Table 2 : Comparison of theoretical and actual COD removal

Run	Duration (h)	Theoretical Adsorption Capacity		Actual Removal	
		g COD	mg COD/g PAC	g COD	mg COD/g PAC
1	92	31,2	100	28000	89 745
2	198	31,2	100	18400	58 980
3	212	31,2	100	21730	69 650
4	204	31,2	100	38700	124 040

As in previous runs, the actual COD removed is significantly greater than the theoretical adsorption capacity of the PAC. This further confirms that in the ACMF system there are other removal mechanisms than adsorption, but these have not been determined as yet.

3.2.4 Effect of Age of Effluent on performance

The objective of this investigations was to determine whether effluent age played any major role in system performance. The investigation was performed on a laboratory microfilter. The first run (R1) was performed on effluent that was 1 day old. The second run (R2) was performed on effluent that was 4 weeks old. In both instances the microfilter was precoated with a 5 g/L suspension at 2 m/s and 2 bar, and the filtration was performed at 2 m/s and 2 bar. The feed and product turbidities and CODs and the permeate fluxes obtained are shown in Figure 20, 21 and 22.

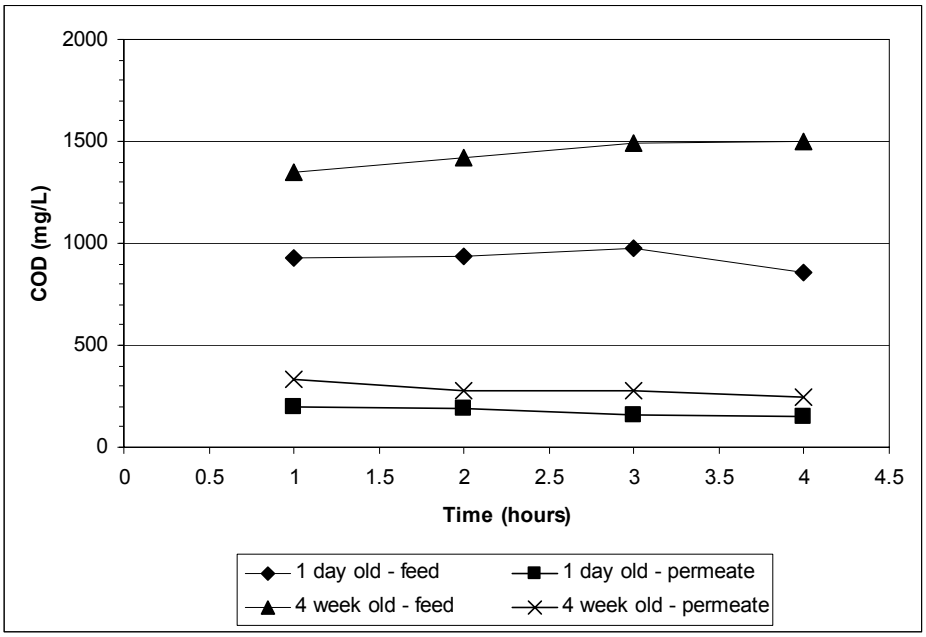

Figure 20 : Effect of effluent age on COD removal

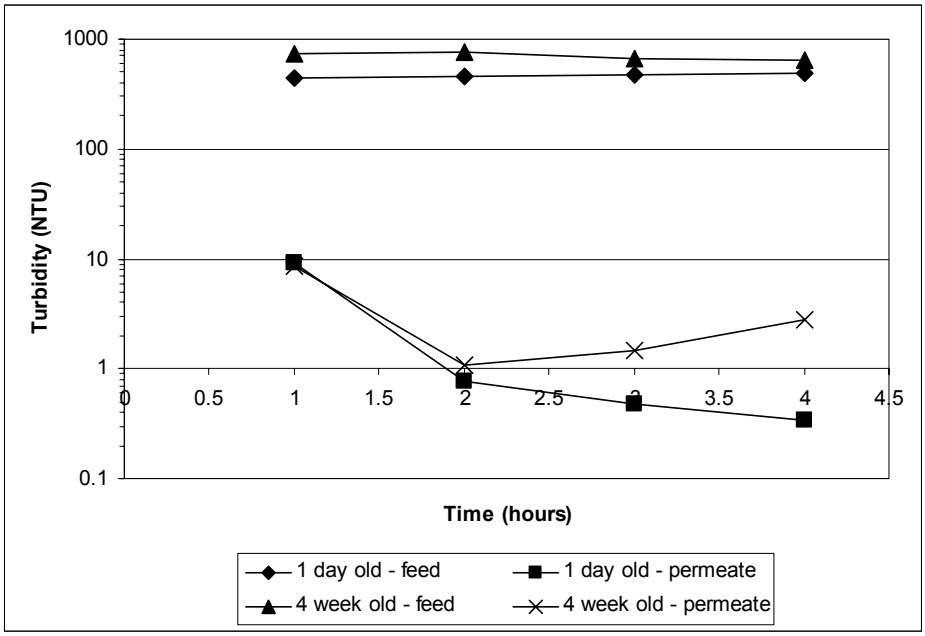

Figure 21 : Effect of effluent age on turbidity removal

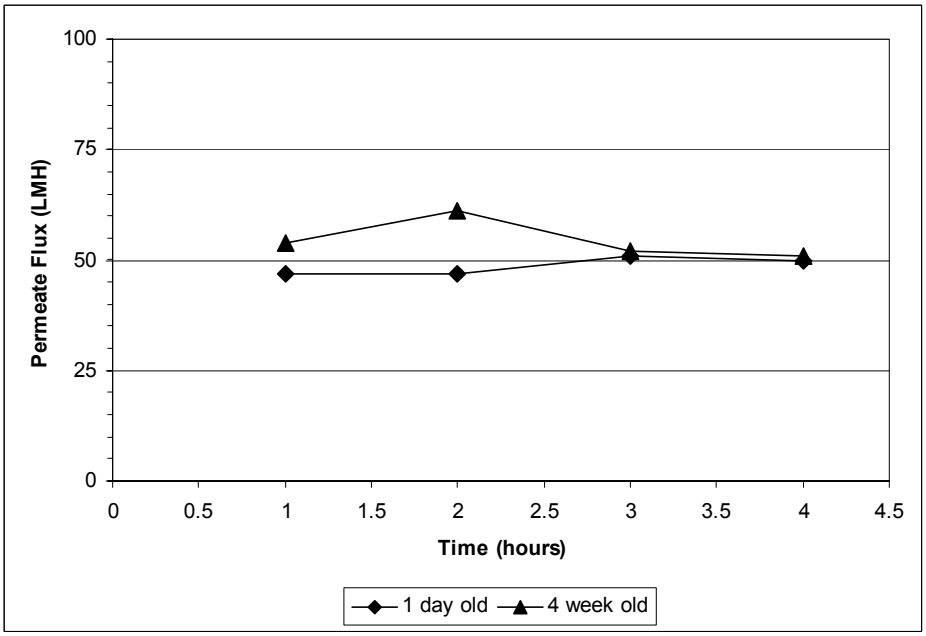

Figure 22 : Effect of effluent age on permeate fluxes

The feed turbidity and COD for the 4 week old effluent are significantly higher than that of the 1 day old effluent. The permeate turbidities are very similar (the reason for the high initial turbidities are not known). The product COD for the 4 week old effluent is slightly

higher than that of the 1 day old effluent, but does not increase in proportion to the feed COD. The permeate fluxes for both runs are similar.

The above demonstrates that the performance of the ACMF on David Whiteheads effluent is not adversely affected by effluent age.

4 Effect of precoating variables on ACMF performance

4.1 Introduction

The precoating variables for the system include precoating velocity, precoating pressure, precoating time and precoat concentration. In this section the effects of precoat concentration, precoat velocity and pressure, and grade of PAC on ACMF performance is investigated.

4.2 Effect of Precoat concentration

The variable that is likely to have the most significant effect on the economics of the ACMF process is the precoat concentration. If a high precoat concentration is required for good separation, it implies that a larger mass of PAC would be required for each run, and *vice versa*. Accordingly, to improve the economics of the process, it is desirable to operate at the lowest precoat concentration that would yield a good separation efficiency.

The effect of precoat concentration was evaluated in the laboratory rig, on a single woven fibre tube of length 2,2 m. David Whiteheads textile effluent was used in all investigations. The precoat suspension was recirculated through the tube for approximately 1 hour, at a velocity of 1 m/s and a pressure of 1 bar. Thereafter the feed was switched to the textile effluent, taking care not to depressurise the tube and destroy the precoat. Filtration then occurred at 2 m/s and 2 bar. Precoat concentrations of 0,5 g/L, 1 g/L, 3 g/L and 5 g/L were investigated, in random order.

The COD removals, turbidity rejection and fluxes are shown in Figures 23, 24 and 25 respectively.

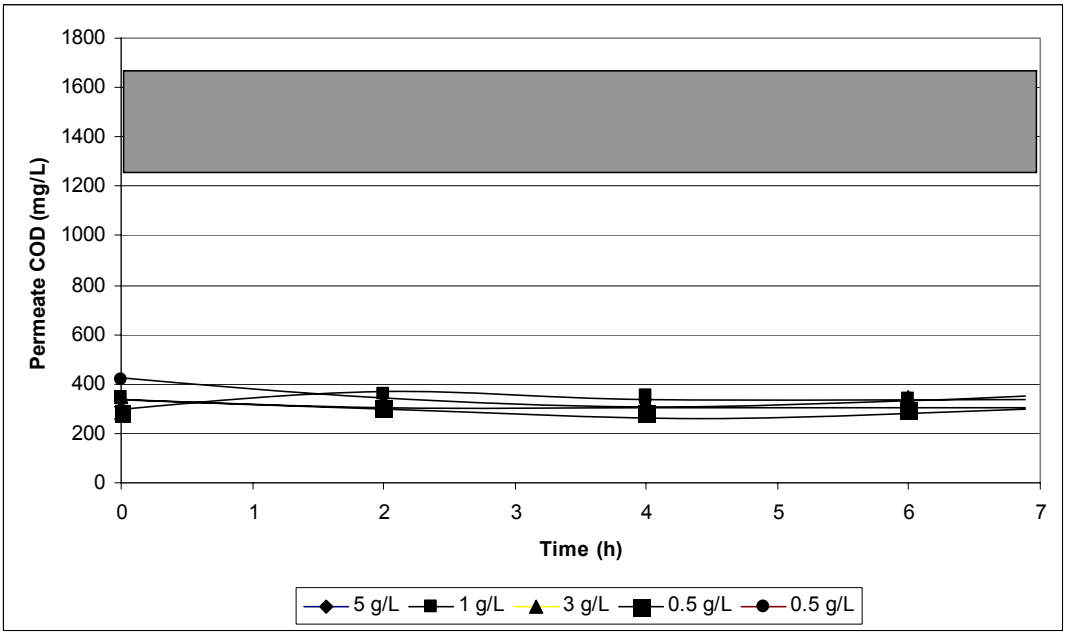

Figure 23: Effect of precoat concentration on permeate COD (Feed CODs range from 1300 to 1700 mg/L)

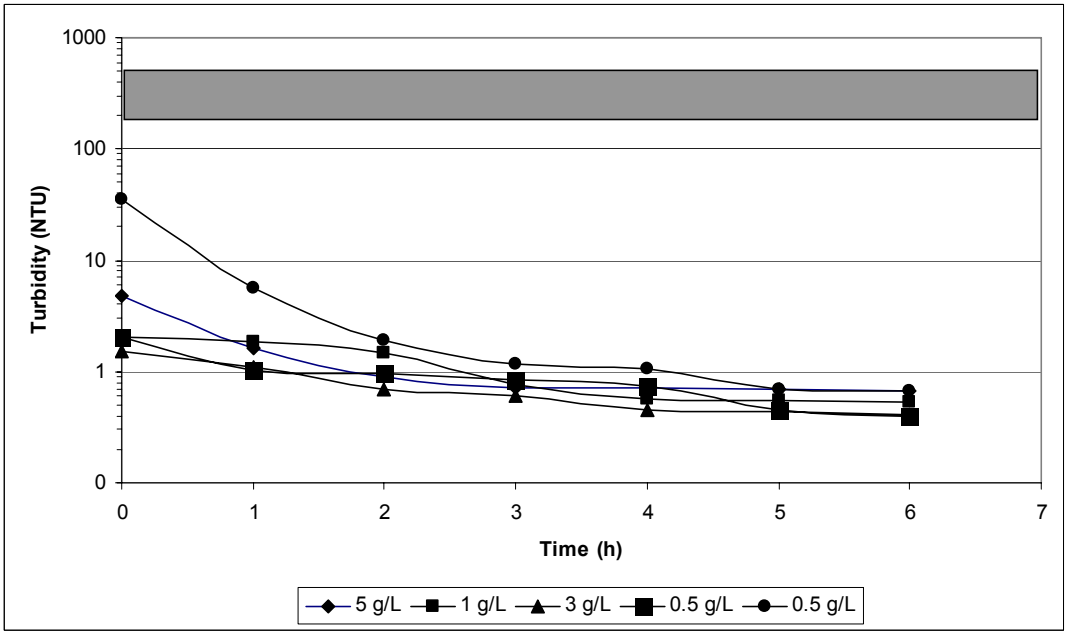

Figure 24: Effect of precoat concentration on permeate turbidity (Feed turbidities range from 200 NTU to 700 NTU)

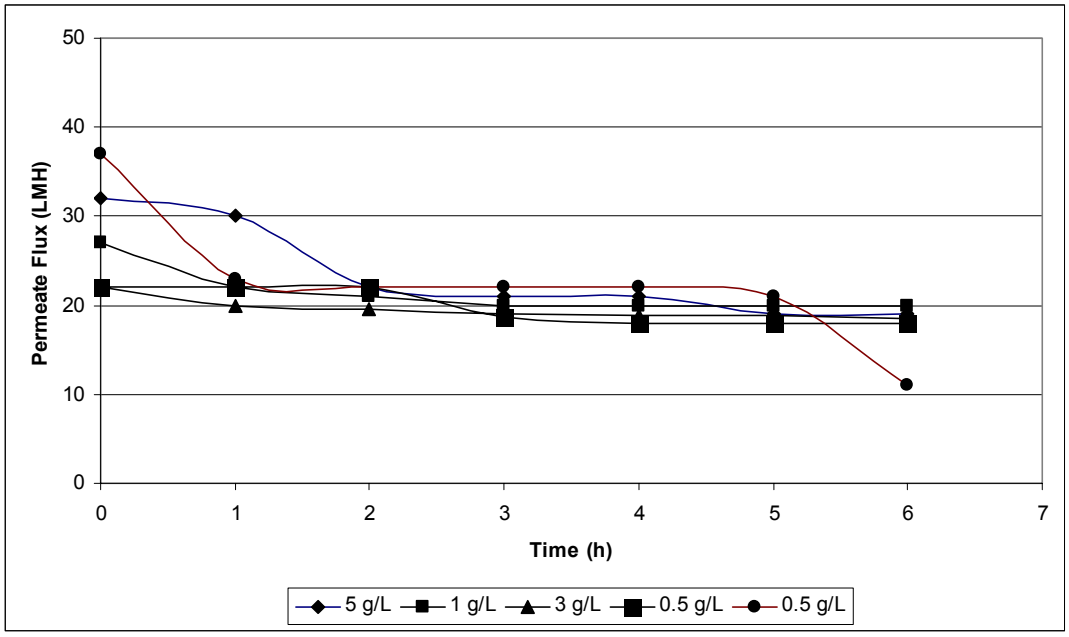

Figure 25: Effect of precoat concentration on permeate fluxes

Over the range 0,5 g/L to 5 g/L, the precoat concentration did not have any significant effect on the permeate COD. In general, there was a 66% to 76% reduction in COD. Similarly, reducing the precoat concentration from 5 g/L to 0,5 g/L had no significant effect on the permeate turbidity or the permeate flux.

All investigations into the ACMF process reported in Sections 2 and 3 were conducted at a precoat concentration of 5 g/L. The above results indicate that there is no decrease in performance when the precoat concentration is reduced to a tenth of this value. This has significant implications for PAC usage, and hence the economics, of the ACMF process.

These results also confirm that the system performance is not being limited by the adsorption capacity of the PAC. A lower precoat concentration results in the formation of a thinner precoat, i.e. a lower mass of PAC on the tube. Figure 23 indicates that the COD removal is *independent* of the mass of PAC in the precoat.

It is not known whether *breakthrough* could occur at very low precoat concentrations. This could not be investigated due to the closure of David Whiteheads, as discussed in Section 5.

4.3 Precoat velocity and pressure

The effect of precoat velocity and pressure on performance was investigated by precoating the tube at different combinations of velocity and pressure, and evaluating COD removal, turbidity removal and fluxes, on David Whiteheads textile effluent. The conditions investigated are given in Table 3 below, and the results are shown in Figures 26, 27 and 28. For all runs the precoat concentration was 5 g/L, and the filtration occurred at 2 m/s and 2 bar.

Table 3 : Pressure and velocity combinations investigated

Run	Precoat Velocity (m/s)	Precoat Pressure (bar)
1	1	1
2	2	1
3	2	2

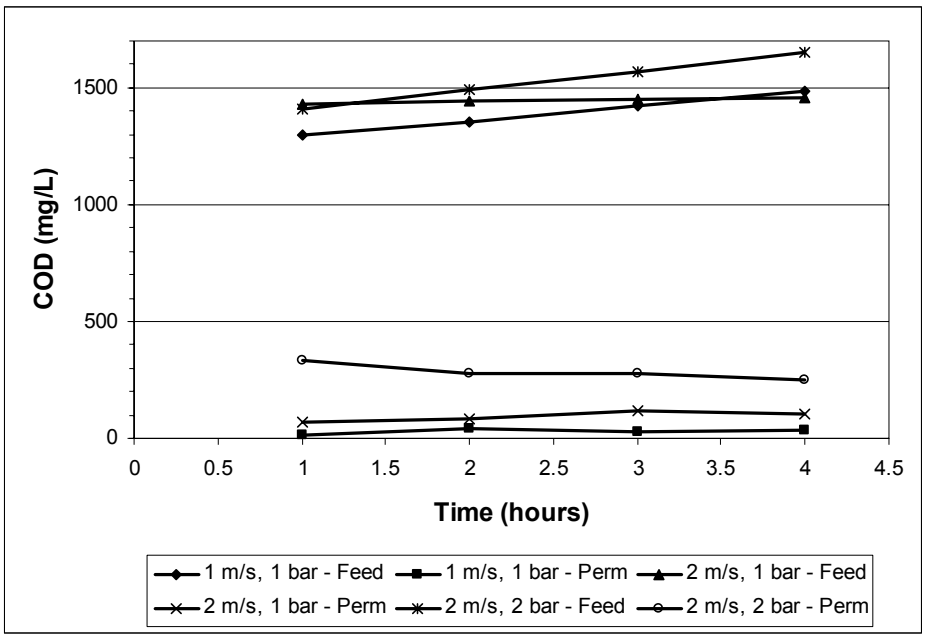

Figure 26 : Effect of precoat velocity and pressure on COD removal

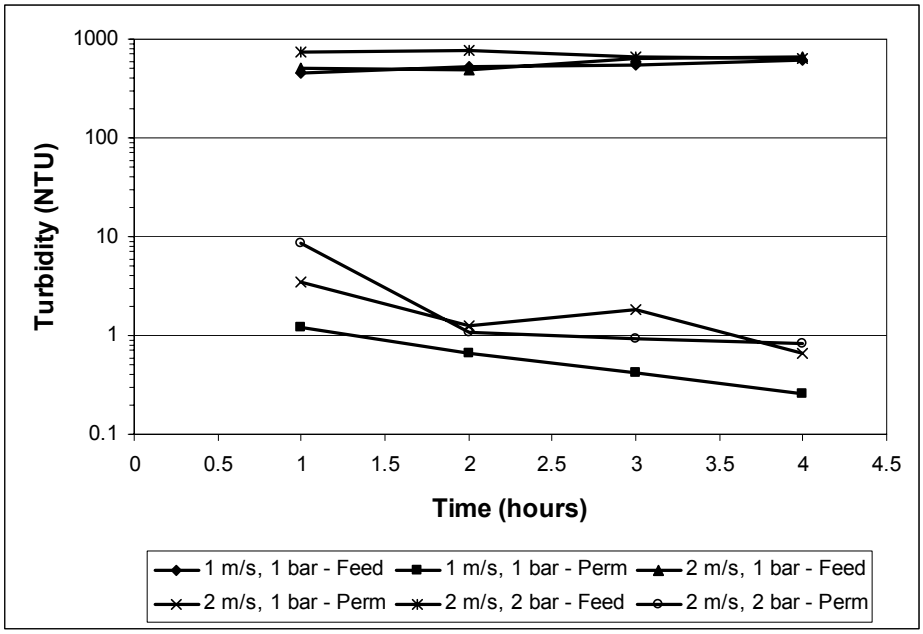

Figure 27 : Effect of precoat velocity and pressure on turbidity removal

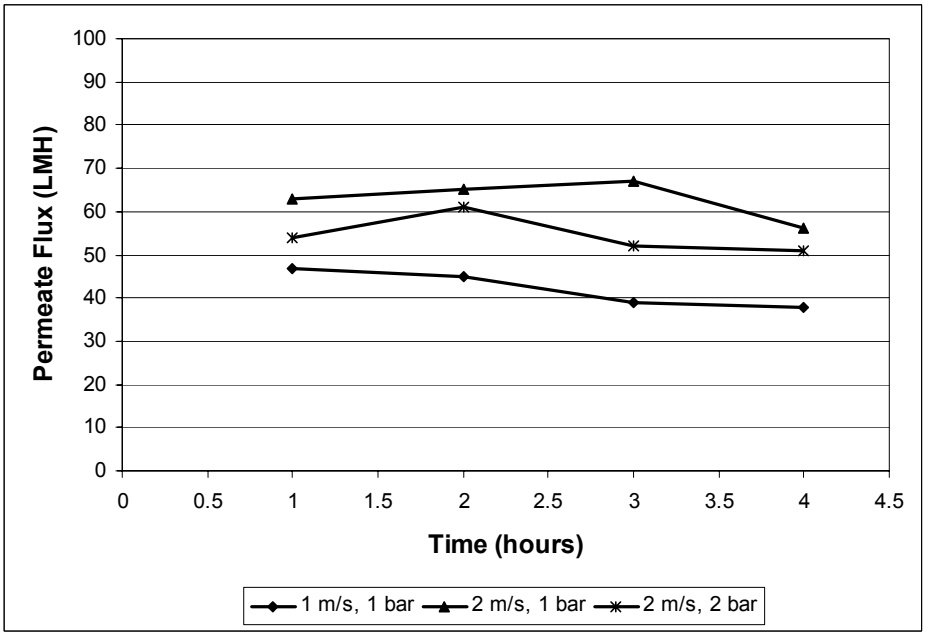

Figure 28 : Effect of precoat velocity and pressure on permeate flux

The permeate CODs obtained at 1 m/s : 1 bar and at 2 m/s : 1 bar are fairly similar. The CODs obtained at 2 m/s : 2 bar are definitely higher. However, the feed COD for the 2 m/s : 2 bar run are also higher than that of the other runs. Hence, it is difficult to conclude that there is any significant effect of velocity or pressure on COD removal.

Once again, this result points to the probability that the system is not controlled by adsorption. A higher precoat velocity results in the formation of a thinner precoat, i.e. smaller mass of PAC on the tube. Figure 26 implies that the COD removal is NOT related to the mass of PAC on the tube.

The feed turbidities for all 3 runs are substantially the same. The permeate turbidity for the 2 m/s: 2 bar run starts off higher than the other operating conditions, but then becomes substantially the same as the other operating conditions.

The permeate flux increases as the velocity increases. However the flux *decreases* as the pressure is increased from 1 bar to 2 bar, at a velocity of 2 m/s. The reasons for this are not known.

4.4 Grade of PAC

The objective here was to test whether the grade of PAC used had any effect on the performance of the ACMF system. An attempt was made to obtain a range of different PAC grades. However the only grades that could be easily obtained locally were a *laboratory grade* that retails for about R 800 /kg and an *industrial grade* that retails for about R 200/kg. The physical characteristics are given in Table 4 and the adsorption capacities, determined as in Section 2.4.2, is shown in Figure 29

Table 4 : Characteristics of PAC grades tested

	Type 1 (Sudcarb 3765)	**Type 2 (Norit Ca1)**
Ash Content	15% max	2% max
Moisture	8% max	11% max
Particle Size	>90% exits 45 mic. screen	>85% exits 45 mic. screen
Appearance	Fine black powder	Fine black powder
Iodine Adsorption	600 mg / g min	
Methylene Blue Adsorption		25 g / 100 g

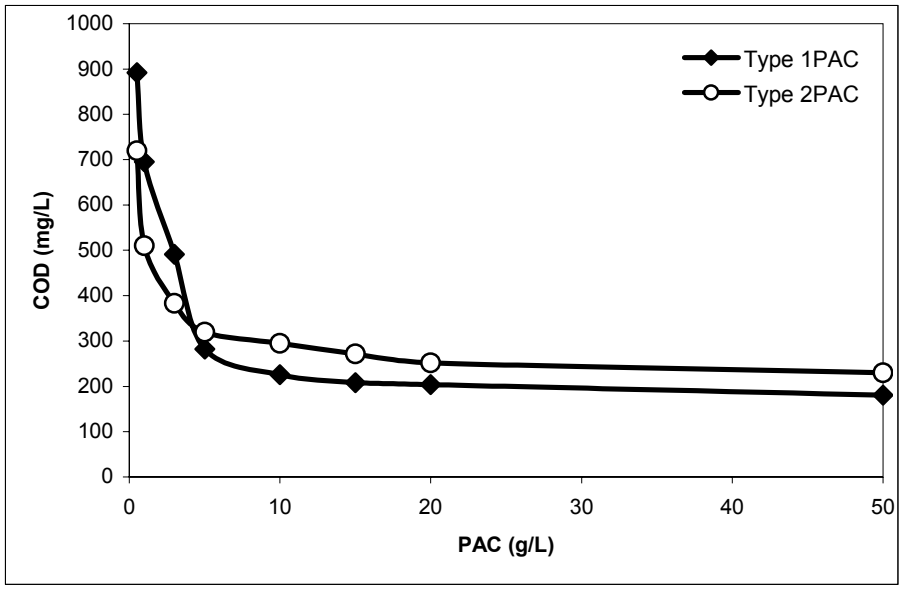

Figure 29 : Product COD vs PAC added for 2 Different Types of PAC

The more expensive grade was expected to show a higher removal of COD than the cheaper grade. However, Figure 29 indicates that this was not so. Similar trends in terms of product COD were observed, indicating that there was only a marginal difference in the adsorption capacities of the different grades. The ACMF performance of the different PAC types is shown in Figure 30. These investigations were performed on David Whiteheads textile effluent.

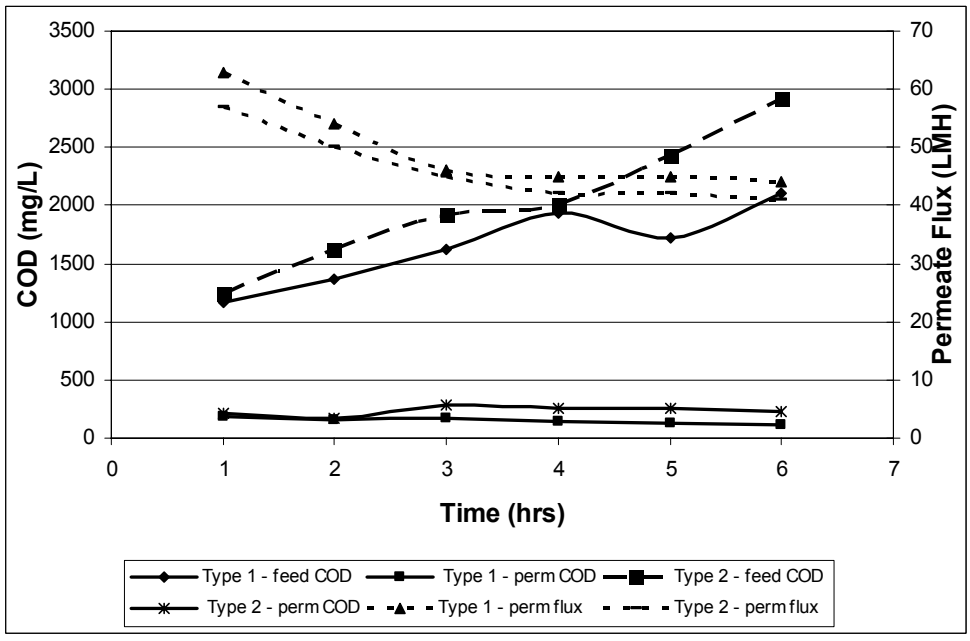

Figure 30: CODs and permeate fluxes for different PAC grades

The permeate flux stabilises after three hours, with Type 1 PAC giving a marginally higher value than Type 2. The feed COD continuously increases, as expected of a batch concentration, whilst the permeate COD remains at its low value. Both Types 1 and 2 display a similar performance in terms of COD removal.

The above results indicate that other less expensive forms of PAC could be used in the ACMF process, without any degradation in performance.

4.5 Summary

From the investigations into precoat concentration, precoat velocity, precoat pressure and PAC grade, the following trends may be inferred:

(i) changing the precoat concentration, velocity or pressure does not seem to substantially change the COD or turbidity removal efficiency. This is consistent with the postulation that the major mechanism for removal of contaminants is NOT adsorption onto the PAC.

(ii) increasing the precoat velocity seemingly increases the permeate flux. Increasing the pressure may have a detrimental effect on the flux. The reasons for this are not known.

(iii) the performance was not dependant on the grade of PAC, with an expensive laboratory grade yielding similar results to a less expensive industrial grade.

5 Closure of the Project at David Whiteheads

The majority of investigations in this project were performed on the textile effluent from David Whiteheads. In the early stages of this project, discussions were held with middle management at David Whiteheads concerning the possible outcomes of the project. They indicated strong support for the project, and also indicated that they may pursue the project further if the results were promising. Hence, it was anticipated that David Whiteheads would probably be interested in the further development and exploitation of ACMF if the results were promising.

However, in 2004 David Whiteheads went through a rationalization, and the factory was put onto “short time”. Continuous operation of the plant was halted, and operation was limited to

only half the week in some instances. It was decided that this would probably not be the ideal time to broach the issue of new effluent technologies with their management. Accordingly, while excellent results were obtained at David Whiteheads, it was felt that it would be appropriate to delay discussions with their Management concerning further development of ACMF.

Unfortunately, the David Whiteheads plant at Tongaat was subsequently shut down permanently towards the end of 2004. This was a significant blow to the project. It had been hoped that David Whiteheads could have been the first site for the further development and implementation of ACMF, in view of the vast body of excellent results obtained there. Further, a large database had already been obtained on David Whiteheads effluent. Whilst numerous other sources of test effluent exist, baseline experimental data would have to be obtained from scratch.

Fortunately, by this stage, the project team had obtained sufficient data to be able to fulfil the major part of the project objectives. However, it meant that no further comparative investigations could be performed on this textile effluent.

6 Trials on other effluents

Effluents from three other sources were investigated, viz. Dyefin, Mondi and South African Breweries (SAB). In all instances, a combined effluent was used, i.e. combined factory effluent excluding sewage. The main characteristics of each effluent are summarized in Table 5.

Table 5 : Characteristics of effluents investigated

Effluent Type	**Parameter**			
	Unfiltered COD (mg/l)	SS (mg/l)	pH	Turbidity (NTU)
David Whiteheads	1200-1600	1-40	10-12	300-500
Mondi	2000-8000	1-50	9-11	400-800
SAB	2500-8000	1-80	5-7	500-900
Dyefin	7000-11000	1-100	7-10	300-600

Note that the above are grab samples of the effluents, and hence the actual values obtained in investigations (especially turbidities) may vary from the above.

6.1 Dyefin

ACMF performance on Dyefin effluent is shown in Figures 31. The microfilter was precoated with a 5g/L PAC suspension at 2 m/s and 2 bar for 45 mins. Thereafter raw effluent was filtered at 2 m/s and 2 bar under full recycle.

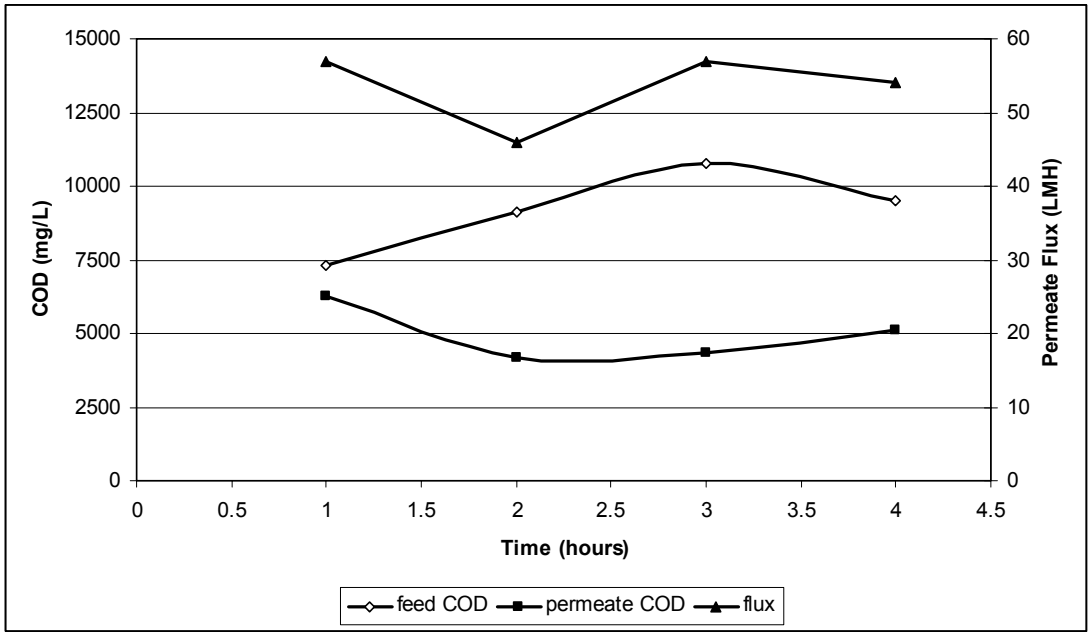

Figure 31: CODs and permeate flux obtained on Dyefin effluent

The COD removal was extremely poor, with very high permeate COD being obtained. The reasons for the very poor COD removal are not known, and would obviously relate to the basis separation mechanisms in ACMF. This was beyond the scope of this project.

The project team decided that no further investigations would be performed on this effluent.. However, when investigations are performed into the basic separation mechanisms in ACMF, Dyefin effluent should be investigated as an effluent that gives a poor performance.

6.2 Mondi Effluent

The WFM was precoated with a 5g/L PAC suspension at 2 m/s and 2 bar for 45 mins. Thereafter raw effluent was processed at 2 m/s and 2 bar under full recycle. The feed turbidity was recorded as >999 NTU. The feed and product CODs and the permeate flux are shown in Figure 32.

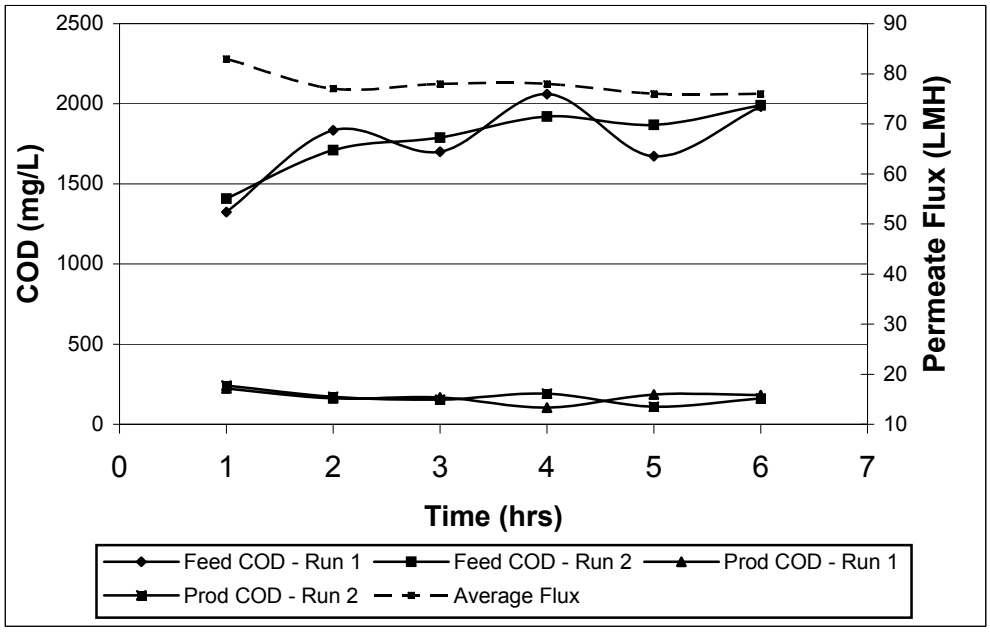

Figure 32: CODs and Permeate Fluxes for Mondi effluent

Similarly to the results obtained on David Whiteheads effluent, there is a very good removal of COD, ranging from 83% to 92%, and the permeate COD remains low over the total run.

Using the procedure from Section 2.4, the theoretical adsorption capacity for the Mondi effluent was determined. Thereafter, the actual COD removal over the run was computed from Figure 32, and compared to the theoretical adsorption capacity.

The residual CODs as a function of mass of PAC added are shown in Figure 33. After approximately 10 g PAC is added the product COD levels off indicating that the maximum adsorption has occurred. The slope of the graph represents the adsorption capacity of PAC for this particular effluent. Thus the amount of COD that can be removed using PAC in this manner falls within the range **32 to 48 mg COD per gram of PAC**.

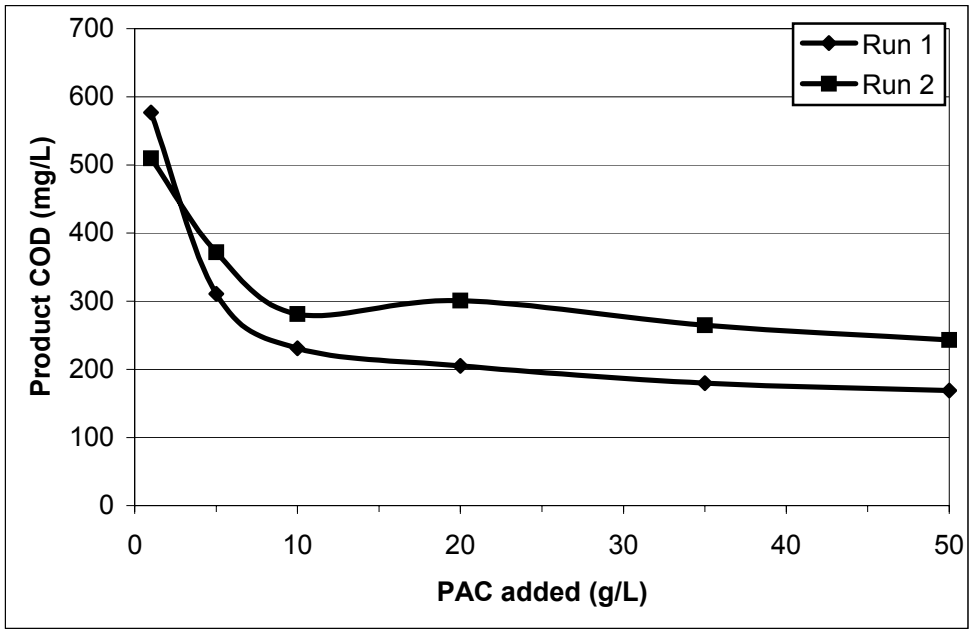

Figure 33: Product COD versus PAC added for Mondi effluent

The theoretical removal capacity is 1700 to 2500 mg COD. The actual removal of COD in the ACMF system is 76 358 mg COD. The COD removed in the isotherm trials is 32 to 48 mg COD / g PAC. The COD removed in the ACMF is 1450 mg COD / g PAC.

Similar to the David Whiteheads effluent, the COD removal for the Mondi effluent is substantially greater than the theoretical adsorption capacity of the PAC.

6.3 SAB Effluent

The WFM was precoated with 5g/L PAC at 2 m/s and 2 bar for 45 mins. Thereafter raw effluent was filtered at 2 m/s and 2 bar in full recycle. The feed and product CODs and the permeate fluxes are shown in Figure 34.

Similar to the David Whiteheads and the Mondi effluents, there is a very good removal of COD, ranging from 82% to 88%.

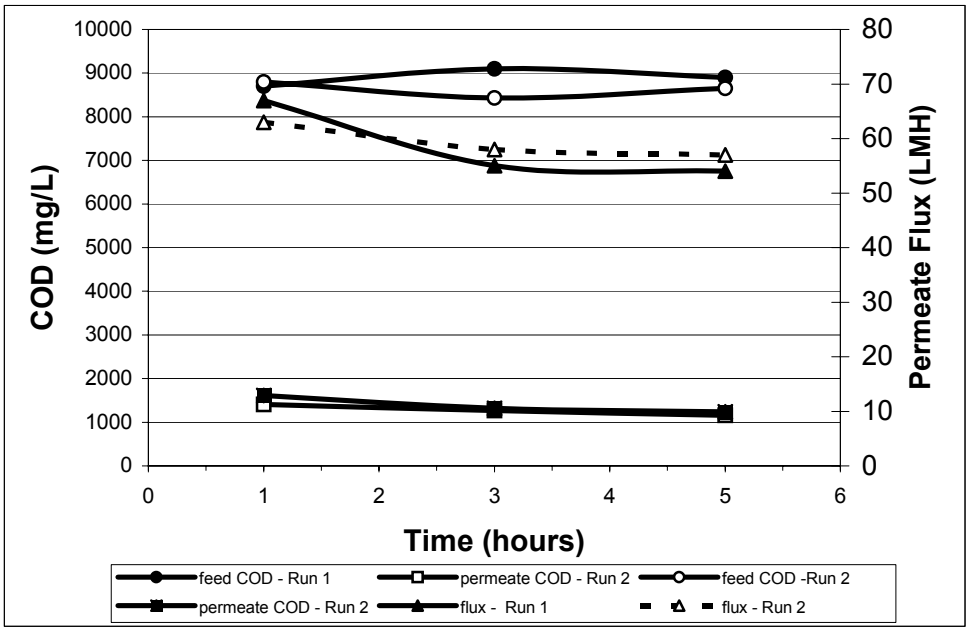

Figure 34: CODs and permeate fluxes on SAB effluent

Using the procedure from Section 2.4, the theoretical adsorption capacity for the Mondi effluent was determined. Thereafter, the actual COD removal over the run was computed from Figure 31, and compared to the theoretical adsorption capacity.

The residual COD as a function of mass of PAC added is shown in Figure 35.

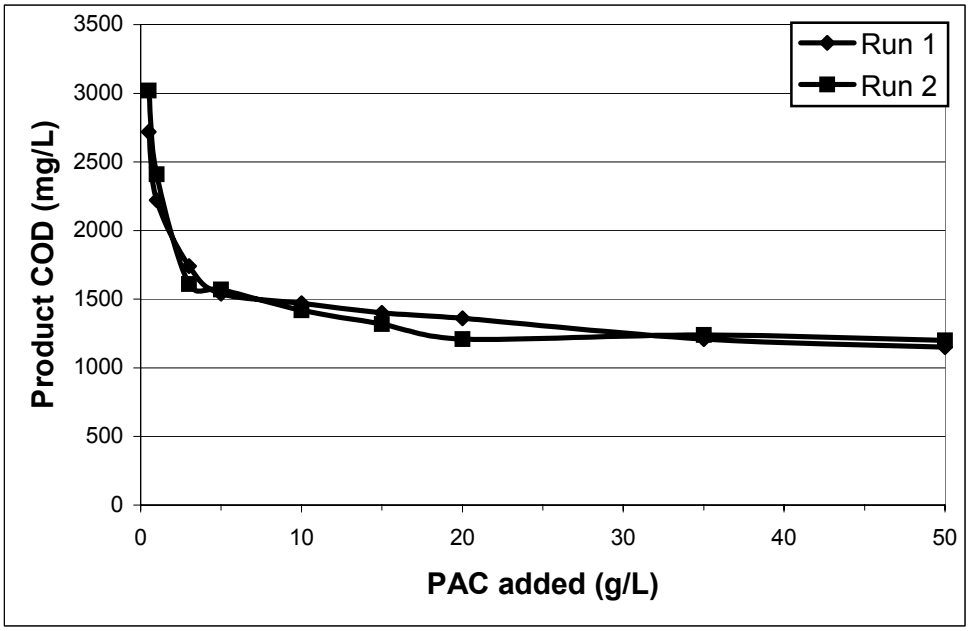

Figure 35: Product COD vs PAC Added on SAB effluent

The slope of the graph represents amount of removable COD. This is equivalent to 83 mg COD / g PAC.

The actual COD removed, calculated from Figure 34, is 236 033 mg COD. The theoretical removal of COD was calculated as 4316 mg COD.

6.4 Summary

The ACMF process is clearly not very effective on Dyefin effluent, giving COD removals of less than 50%. This effluent should be a part of any further investigations into the fundamental separating mechanisms in ACMF.

The performance of ACMF on the Mondi effluent and the SAB effluent were very good, with COD removals of 82% to 90% being obtained. Further, the amount of COD removed was orders of magnitude greater than the adsorption capacity of the PAC.

The above indicates clearly that the very good results obtained on the David Whiteheads effluent was not a "once off" result, and that the ACMF process does have a major potential as a pretreatment step for industrial effluents. The trials on these other effluents also confirm that there are some removal mechanism/mechanisms other than standard adsorption that are occurring in the ACMF process.

7 Comparative evaluation of the ACMF process

7.1 Summary of ACMF Performance

Effluents from four industries were investigated, viz. David Whiteheads, Mondi, S A Breweries and Dyefin. The ACMF performance on the selected effluents is summarized in the table below:

Effluent Source	COD (mg/L)		Turbidity (NTU)	
	Feed	**Permeate**	**Feed**	**Permeate**
David Whiteheads	1200 to 12500	250 to 400	> 999	0,3 to 2
Mondi	1400 to 2000	110 to 240	760	4 to 6
SAB	8400 to 8800	1200 to 1600		
Dyefin	7300 to 10000	4200 to 6300	390 to 620	0,3 to 1

The feed turbidities ranged from about 400 NTU to greater than 999 NTU. The permeate turbidities were generally below 1 NTU, except for the Mondi effluent where the permeate turbidity was below 5 NTU. The COD removal for David Whiteheads, Mondi and SAB are all greater than 85%, and approach 95% in some instances. However, the COD removal for the Dyefin effluent was fairly poor, and was below 50%.

This study has shown that:

(i) the ACMF process can give a very significant removal of COD and an excellent removal of turbidity, depending on the effluents

(ii) the removal of COD is not limited by the adsorption capacity of the PAC. Seemingly other mechanisms are involved which enable the removal of COD that is orders of magnitude greater than the adsorption capacity of the PAC

As such, the ACFM process is a potentially very powerful effluent treatment/pretreatment step, yielding a product with an excellent turbidity and a substantially reduced COD in a single step. This could be ideal as a pretreatment step to downstream polishing processes, including reverse osmosis or nanofiltration.

7.2 Comparative evaluation

The initial project objectives included a comparative economic evaluation with other effluent treatment processes. Whilst the project has shown that ACMF does work, it has raised various other questions impact directly on the economics of the process. These need to be answered before a fair economic assessment of ACMF may be performed. Two issues in particular are:

(i) If adsorption is not the controlling removal mechanism, does it imply that the WFMF may be precoated with *spent* PAC ? If so, this would have an enormous impact on the economics, since it would obviate the cost of new PAC, the cost of handling thereof, and the cost of discarding spent PAC.

(ii) Can the system be operated in dead-end or in dead-end with a periodic purge. This would have a significant impact on the pumping requirements and energy costs of the process.

However, it is still possible to conceptually compare ACMF with alternative effluent treatment processes. In essence, the performance of the ACMF is very similar to that of a *loose* ultrafilter. Thus, the major competitors to ACMF would be conventional treatment (i.e. coagulation/flocculation followed by sand filtration/clarification) and ultrafiltration.

7.2.1 Advantages over conventional chemical treatment methods

In comparison to conventional treatment, ACMF could have the following advantages:

(i) no chemical addition to the effluent – the only "chemical" used in the ACMF process is PAC. This makes the ACMF considerably more environmentally friendly than conventional treatment.

(ii) very low effluent turbidity – the final turbidity in ACMF is consistently low and independent of changes in the feed quality. This is not the case in conventional treatment.

(iii) reduced requirement for sludge disposal – the ACMF produces a concentrate and a product stream. Conventional processes produce a product stream, a backwash stream and a chemical sludge.

(iv) possibility of reusing the concentrate – the concentrate in ACMF is not contaminated with chemicals. Hence there should be a probability of easy disposal or reuse.

(v) relatively consistent product quality irrespective of changes in feed quality – this study has shown that the product turbidity and COD do not increase as the feed concentration increases.

(vi) single step process – ACMF is a single step process that produces a product similar to, or superior to, the product from multi-stage conventional processes

(vii) modular – similar to all membrane processes, the capacity of an ACMF system could be increased progressively, as demand increases.

7.2.2 Advantages over ultrafiltration

ACMF is expected to offer the following advantages over ultrafiltration processes:

(i) no chemical cleaning required – past, extensive, experience using WFMF tubes has shown that the WFMF system never requires a chemical clean. This is mainly because the WFMF system does not have pores as in rigid MF and UF systems. Most fouling on WFMF can be removed by alternatively pressurizing and depressurizing the tube. In the worst case scenario, allowing the WFMF tube to dry out causes residual fouling material to fall off.

(ii) can handle very highly fouling effluents – because of this resistance to irreversible fouling, the WFMF system can handle excessively high turbidities that would normally require frequent chemical cleaning in most UF systems.

(iii) robust system – if the tubes dry out they are not impaired, whereas most UF systems would be destroyed by drying. Hence, WFMF systems are more resistant to operator failure or poor operation. If a WFMF system ends up becoming totally blocked, it can be mechanically cleaned, unlike most UF systems. A final point is that a WFMF system can be easily repaired if the tubes become punctured, which is not possible in most UF systems.

8 Conclusions

This project concerned the evaluation and further development of the ACMF process, which results from precoating a woven fibre microfilter with activated carbon. The conclusions of this study are presented under four headings:

(i) ACMF performance in terms of COD and turbidity removal

(ii) removal mechanisms in ACMF

(iii) effects of precoating variables on ACMF performance

(iv) scale-up from laboratory to pilot scales

8.1 COD and turbidity removal

This study showed that the ACMF process is capable of giving an excellent turbidity removal and a very good COD removal in one step, depending on the effluent being treated. For the effluents from David Whiteheads, Mondi and SA Breweries, the turbidity removal was > 99,9%, while the COD removal ranged from 85% to 95%.

However, a poor COD removal (< 50%) was obtained on Dyefin effluent. The reason for this discrepancy is not known, and could not be established in this study. This would have to form a part of the future development of ACMF.

For the effluents where a good performance was obtained, the permeate COD and turbidity are not adversely affected by filtration time and they can maintain their initial low values for filtration periods extending to days.

8.2 Removal mechanisms in ACMF

This study indicated that adsorption onto PAC is most probably *not* the main mechanism of COD removal in the ACMF process.

In all experiments conducted in this study, there wereas no degradation of permeate quality (COD) with increasing filtration times, as would be expected of an adsorption process. In fed-batch pilot scale experiments performed on the textile effluent, the permeate COD remained at approximately 400 mg/L for up to 9 days, while the feed COD increased from

1200 mg/L to over 12000 mg/L. The permeate turbidity also remained at its initial low level irrespective of the filtration run time.

The COD adsorption capacity of the PAC for each effluent was determined, and compared to the actual COD removal. Theoretically, the PAC in the ACMF system should have reached its adsorption capacity after 1,5 hours, hereafter the permeate COD would have been expected to increase up to the feed value. However, in all the runs performed, including the pilot scale runs that lasted up to 9 days, the permeate COD remained at its low initial value for the entire duration of the filtration. On comparing the actual COD removal to the theoretical capacity of the PAC, it was determined that the actual COD removal was orders of magnitude greater than the adsorption capacity of the PAC.

All the above indicate that there is some other separation mechanism(s) that is occurring in ACMF, which results in the unexpectedly high COD removal. This mechanism(s) could not be identified in this study.

8.3 Effect of precoat variables on system performance

From the investigations into precoat concentration, precoat velocity, precoat pressure and grade of PAC, the following trends were inferred:

(iv) changing the precoat concentration, velocity or pressure does not seem to substantially change the COD or turbidity removal efficiency. This is consistent with the postulation that the major mechanism for removal of contaminants is NOT adsorption onto the PAC.

(v) increasing the precoat velocity seemingly increases the permeate flux. Increasing the pressure may have a detrimental effect on the flux. The reasons for this are not known.

(vi) the performance was not dependant on the grade of PAC, with an expensive laboratory grade yielding similar results to a less expensive industrial grade.

The above results have significant implications for the economics of the ACMF process, since the cost of PAC is expected to be one of the major operating expenses. The results indicate that inexpensive low grades of PAC may be used, and that relatively low precoat concentrations may be equally effective.

8.4 Scale-up

The COD and turbidity removal obtained on a pilot scale rig was consistent with that obtained on a laboratory scale rig, indicating that there were no unexpected process complications introduced by scale-up. This indicates that performance data obtained on the laboratory scale could be applied to larger scales with a reasonable degree of confidence.

8.5 Overall assessment of ACMF

This study has shown that the ACMF process is a potentially very powerful one-step process for the pretreatment of industrial effluents:

(i) there is a very good COD removal and an excellent turbidity removal, which is not dependant on filtration time

(ii) the efficiency of PAC usage is seemingly substantially greater than when PAC is used in a conventional manner

(iii) there were no complications associated with scale-up

(iv) the ACMF process could have various process and economic advantages over conventional chemical treatment methods and ultrafiltration

9 Recommendations

Whilst this project has demonstrated that ACMF is a potentially very powerful effluent treatment/pretreatment process, it has raised various issues which need to be addressed for the effective exploitation of the process.

Fundamental Mechanisms

The main issue concerns the fundamental separation mechanisms that are occurring in ACMF. This study has shown that the removal of COD is orders of magnitude greater than the adsorption capacity of PAC, as determined from adsorption isotherms. This indicates that adsorption is not the limiting mechanism for the removal of COD. Possible alternative mechanisms include:

(iv) the COD being removed is "suspended" COD, and hence the performance is that of a normal microfilter.

(v) biological activity is developing in the precoat, enabling the subsequent removal of COD.

(vi) the colloidal material and adsorbed organics are somehow combining to create a secondary membrane that is mainly responsible for subsequent COD removal.

Hypothesis (i) is contradicted by the finding that using PAC as a precoat gives a substantially better removal than "chemically inactive" precoats such as kaolin and limestone. Clearly, adsorption onto the PAC is playing a part, although it is not the limiting mechanism. Concerning hypothesis (ii) it was shown that the PAC saturates after about 1,5 hours of filtration. It is unlikely that biological activity could develop that quickly and effect subsequent COD removal.

It is strongly recommended that the fundamental separation mechanisms be investigated, with the following objectives:

(iii) to either prove or disprove that something unique is occurring in ACMF

(iv) to effect process improvements, which will result from a fundamental understanding of the separation mechanisms

Possible approaches to identifying the controlling mechanisms should include the following:

(i) perform a size fractionation on the feed and permeate to identify the sizes of the species that are being removed in ACMF. This will assist in clarifying whether the separation mechanism is primarily a size exclusion effect or an adsorption effect

(ii) identify more effluents that give a poor performance in ACMF, similar to the Dyefin effluent. Comparison of effluents which give a good performance to those that don't yield clues on the separation mechanism(s)

Process aspects

There are some process issues which could have a significant bearing on ACMF economics and should be investigated further.

(iii) *reuse of PAC* – if adsorption is not the limiting mechanism, it implies that the precoating step will not require fresh PAC. This further implies that PAC could be recovered after a wash and reused for precoating. This would have a huge impact on the economics, since it would obviate the costs associated with purchasing and handling fresh PAC as well as the cost of disposing of spent PAC.

(iv) *dead-end operation* - the major running cost in the ACMF process is the pumping cost. In this study, all experiments were carried out in the cross-flow mode, consistent with general effluent membrane processes. However, the operation of ACMF in the dead-end mode should be investigated.

Even if there is no fundamental understanding of the basis mechanisms in ACMF, investigation of the above process aspects would enable ACMF to be implemented and evaluated, while the fundamental mechanisms are being investigated.

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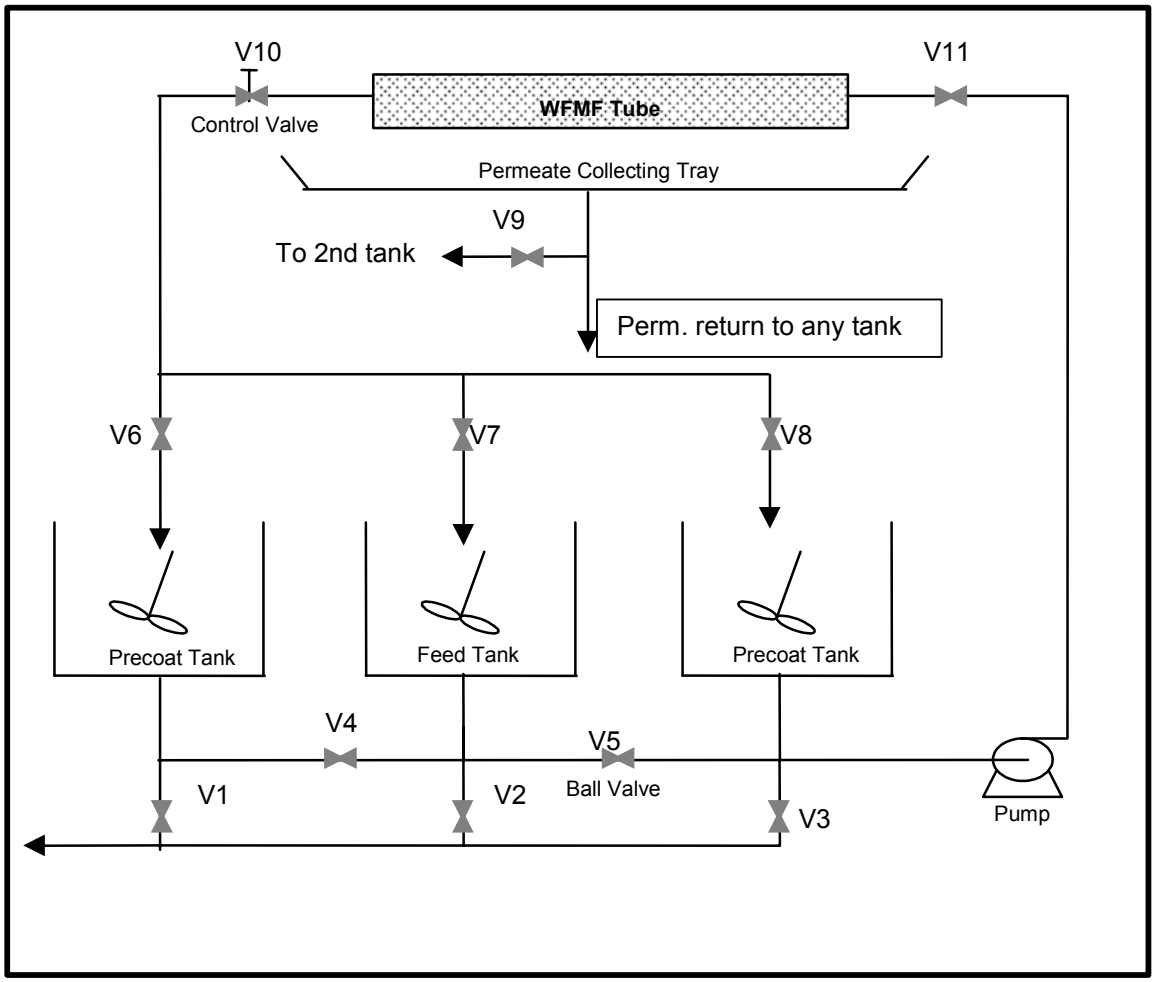
APPENDIX I – Experimental Apparatus

Laboratory ACMF rig

A schematic diagram of the ACMF system is shown below:



The ACMF system comprises three fifty liter tanks inter-connected to each other by schedule nine PVC 25 mm diameter piping. The tanks are all connected to a single suction point. The tanks can be independently used by opening/closing the respective actuator valves. The tanks also have a common discharge pipe with each tank having its own control ball valve for discharging. Each tank is fitted with a mixer. During the experimental work each of the three tanks was used to play a specific role. The first tank was used as a PAC pre-coating tank, the middle tank was used as the feed tank and the third tank was used as the Kaolin pre-coating tank. The feed tank is fitted with a cooling coil through which tap water passes through. This cooling coil proved to be effective in preventing large temperature fluctuations in the system due to the stirrer and pump.

Raw effluent or the pre-coat suspension was pumped into the WFMF tube by a Mono C-range positive displacement pump driven by a 7,5 kW motor. The speed of the motor and hence the pumping rate was controlled by a speed controller. Before any experimentation commenced the pump was calibrated. The pump was fitted with a pressure controller designed to cut off the pump once the high-pressure level was breached. A level controller was also engaged to cut off the pump once the lower level in the feed tank was breached.

The pump discharged feed into a 25 mm diameter WFMF tube. This WFMF tube was made by cutting a section of a larger piece of WFMF curtain manufactured by Gelvanor. The sides of the tube were sealed with a double stitch and to this a layer of glue (Genkem VAW 595) was applied. This proved to be effective in preventing the tubes from leaking. The ends of the tube were connected to PVC piping using a resin. This then made it possible to join the WFMF tubes to the already existing network of PVC pipes without any problems such as leaks or significant losses of pressure.

Permeate from the tube drained into a plastic permeate gutter. Permeate was either returned to the feed tank or removed from the system. This was made possible by a PVC pipe extending from the permeate tray discharge to the feed tanks. Ball valves on this line allowed for the permeate to be returned to the feed tank or collect it in a separate vessel. This permeate line could be positioned to empty into any one of the three tanks. The reject from the WFMF tubes was returned to the feed tank. During the experimentation the permeate gutter was always properly washed to prevent contamination of the permeate. The tanks and pipe-work was made from PVC to prevent any contamination possibly arising from corrosion.

The speed of the motor and hence the pumping rate was controlled by a speed controller. This then determined the inlet velocity. The system was also calibrated regularly. This was done by selecting a random frequency on the speed controller and measuring the flow delivered at this frequency. This was then compared to the original pump curves and the necessary adjustments were made.

Pressure tappings were placed at the entrance to and exit of the WFMF tube. These tappings were connected to a three way valve and then to a pressure gauge. By adjusting the valve position the pressure before, after or across the tube could be read. The pressure was read to the nearest 1 kPa.

The temperature in the feed tank was maintained at 20 – 25 ^{0}C. This was regularly checked using a mercury thermometer.

Experimental Procedure

Cleaning Cycle

Each of the tanks were thoroughly washed and filled with tap water. The WFMF tube was connected to the rig. All the valves, besides V1, V2 and V3, were fully open. The pump was started and the potentiometer was set to the required flowrate (the washing flowrate). The control valve (V10) was fully open to ensure a minimal pressure in the system. A squeeze and release action was performed on the tube to release the adhering particles. The tubes were cleaned in this manner. Permeate and reject was returned to the tanks. This process was continued until the permeate from the tubes was visibly free of any particulate matter.

The experiments were completed in two parts. This was made up of a precoating cycle followed by the filtration of the raw effluent through the precoated system.

The Precoat Cycle

The method of precoating was the same for each precoat with the only difference being the type of precoat. Hence the following method applied to both the active and non-active precoats. For both the different precoats a predetermined mass of precoat was chosen and added to a fixed volume of water and thoroughly stirred. For each new run a new batch of precoat was made up.

As before the entire system was thoroughly cleaned. The back pressure valve was left fully open. Ball valves V5, V10 and V11 were fully open. The flowrate was then set to the desired value by adjusting the speed of the pump. The desired flowrate was achieved within seconds of start-up. Diaphragm valve V10 was then adjusted to obtain the desired precoating pressure. Ball valve, V6 was opened to allow permeate to flow back into the precoating tank. Precoating was allowed to proceed for one hour. One hour was found to be an adequate time for a stable cake to form as indicated by the permeate flux reaching a steady state value. Once the precoating cycle was completed, the flow to the WFMF tube was immediately switched over to the raw effluent feed tank by opening and closing the necessary valves. This was critical to prevent the cake in the tube from collapsing.

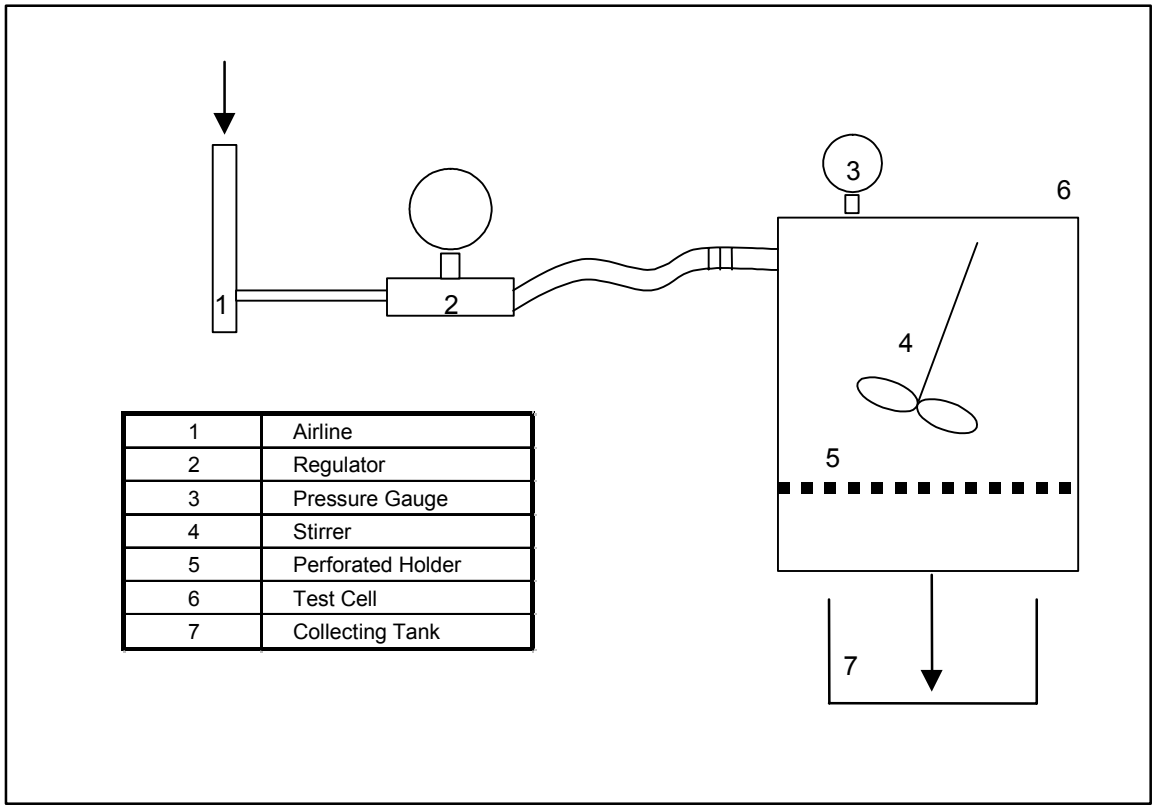
Filtration cycle

As mentioned before the raw effluent was transferred to the feed tank and thoroughly stirred. Once the precoating cycle was completed, V5 and V6 were closed and simultaneously V2 and V7 were opened. The permeate line was also positioned to empty into the feed tank. This thus ensured that the permeate and reject streams both emptied into the feed tank. If required the back pressure was adjusted to the desired operating condition, the temperature was carefully monitored and the system was allowed to run for the prescribed time interval.

At the completion of the run the cleaning procedure was again applied and the rig was made ready for the next set of experiments. This process of cleaning, precoating and raw effluent treatment through the system was repeated for the various runs.

Dead-end test Cell

A schematic diagram of the test-cell is shown below:



1	Airline
2	Regulator
3	Pressure Gauge
4	Stirrer
5	Perforated Holder
6	Test Cell
7	Collecting Tank

The test-cell comprises of a cylindrical stainless steel vessel of volume 400 ml. The vessel is made up of two portions locked together by two bolts. The upper portion has a volume of 400 ml and houses the feed solution. The upper portion is fitted with a magnetic stirrer. The bottom portion is merely a steel base within which is a porous plastic disc of diameter 76 mm. When the base of the vessel is separated from the main cylinder by opening the two bolts, this allows one to place any type of filter onto the porous plastic disc. An O-ring is used to keep the filtering discs in place and this ring also acts as a sealant when large pressures are applied to the contents of the vessel. In these experiments the filtering discs were cut from the cloth used to make the WFMF tube. The side of the bottom portion of the vessel has an outlet. A rubber hose is connected to this outlet. This facilitates in the collection of permeate. The vessel is rendered leak-proof when the bolts are fastened.

The upper portion of the vessel has two openings drilled into it. The first opening is used to introduce a fixed amount of feed into the vessel. When this is done, that opening is rendered

airtight by fastening a bolt into it. The second opening allows for the connection of an airline to it. Compressed air can then be used to force the feed in the system through the filtering medium.

The pressure in that airline is regulated using a standard gas cylinder regulator. The first opening can also be rendered airtight by screwing into the opening a pressure gauge. This then enables the reading of the pressure within the vessel.

The feed was prepared as in section 3.1.1. For the test-cell experiments the volume of feed used was 0.4 litres. In the test-cell experiments varying masses of PAC was added to the effluent. As each experiment dictated, the time allowed for mixing (ranged from 0 – 120 minutes) the PAC with the raw effluent varied. The mixing of the two components occurred in a mechanical shaker. Once the allocated time for mixing elapsed the mixture was immediately poured into the vessel. The pressure gauge was fastened to the feed opening. The airline was connected to the vessel and the desired air pressure obtained by adjusting the regulator. Once the contents of the test-cell was pressurized, permeate was collected. Permeate was collected and immediately analyzed for COD and turbidity.

Once all of the feed eluted the vessel the air supply was cut off and the vessel was cleaned and prepared for the next set of experiments.