Development and Evaluation of an Active Precoated Microfiltration System

Pravesh Bekraj Persadh

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Supervisors: Dr VL Pillay
Associate Director: Research
Department of Chemical Engineering
ML Sultan Technikon

Dr EP Jacobs
Chief Chemist: Institute of Polymer Science
University of Stellenbosch

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Declaration

I hereby declare that this dissertation is my own work, unless stated to the contrary in the text, and that it has not been submitted for a degree to any other institution.

PB Persadh

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Abstract

Whilst microfiltration (MF) has numerous uses and advantages over conventional separation processes it does have certain limitations. MF membrane process can effectively remove turbidity but cannot sufficiently remove low molecular organics. For a sufficient removal of such particles adaptations and modifications to the membrane has to be made or additional removal processes (e.g. nanofiltration or reverse osmosis) has to be added. This project makes an attempt at addressing the former issue. In MF, a membrane on a support performs the filtration. There are various types of materials used as supports e.g. ceramics, porous steel tubes, polymers etc. These materials are usually rigid or semi-rigid and thus offer the advantage of maintaining their shape thus enabling operation at high pressures. This project will concentrate exclusively on woven fibre microfiltration (WFMF). This is a tubular cloth-like filter, which becomes rigid when feed flows into it.

For a woven fiber microfilter to sufficiently prevent the low molecular pollutants from permeating the cloth, the actual pore size of the cloth needs to be altered. One such method of accomplishing this is the use of dynamic membranes or precoats. A dynamic membrane is a 'formed-in-place membrane'. These membranes have been in existence for some time now and have proved useful in treating, amongst others, industrial effluents. Dynamic membranes are formed either by colloidal and suspended matter settling at the woven fibre microfiltration (WFMF) tube wall or by using precoats. Precoats are added mineral substances that form a permeable layer at the WFMF tube wall. Precoats can either play an active role in the removal of contaminants i.e. by adsorption of contaminants into the precoat as in the use of powdered activated carbon (PAC) or they can play an inactive role whereby the precoat layer formed at the WFMF tube wall further limits, in terms of size of particles, the passage of particles through the filter.

Thus the objectives of this project were to:

1.1 Compare the performance of the WFMF system using an active precoat to that with no precoat.

1.2 Compare the performance of the WFMF system using an active precoat to that with an inactive precoat.

1.3 Compare the efficiency of the usage of PAC in the WFMF system to that where PAC is used in its conventional manner i.e. by mixing it into the effluent.

An experimental program was devised and implemented. The different processes considered were conventional usage of PAC (duplicated by mixing PAC into the effluent and then filtering this solution in a test-cell using a WFMF disc as the filtering medium) and continuous crossflow (CF) systems using WFMF. In continuous WFMF systems three systems were considered. These were a WFMF system (without precoat), a WFMF system precoated with Kaolin (non-active precoat) and a WFMF system precoated with PAC (active precoat). As such, in this report the systems will be referred to as WFMF system, Non-active WFMF system and Active WFMF respectively.

A raw effluent was identified as the test solution and sufficient volumes required per run were collected and homogenized. The performance criteria that were investigated were chemical oxygen demand (COD), turbidity and permeate flux.

Test-cell trials indicated that PAC could be further developed as the active precoat and Kaolin the non-active precoat. The precoat was operated at a concentration of 5g/l, precoating time of 1 hour and precoating volume of 40 l. All Runs (except Run 41) were performed in total recycle i.e. reject and permeate were returned to the feed tank. In Run 41 the permeate was removed from the system and fresh feed was added to the system as make-up.

The WFMF system without a precoat reduced the feed COD. Initially, the reduction was insignificant but became pronounced (>50%) after approximately 4 hours from start-up. Permeate turbidities were also monitored throughout the run. The permeate turbidity decreased, however still above generally acceptable levels (>1). Flux measurements for this system were comparatively low. A physical examination of permeates also revealed extensive colouration.

The WFMF system using kaolin as the precoat (inactive precoat) reduced the feed COD from start-up. The COD reduction in this system was greater than that obtained in the WFMF system with no precoat. The maximum COD reduction possible under these conditions was determined as 70 %. The system was able to reduce turbidity but the turbidities were still above 1. Over a five hour period the system displayed low fluxes (steady-state flux of ~8 LMH). There was still a bluish-black colour in the permeate.

The WFMF using PAC as the precoat (active precoat) reduced the COD by more than 85%. Approximately 60% of permeate turbidities were consistently below 1. Over a five hour period the fluxes were relatively high (steady-state flux of ~22 LMH). The permeate was clear.

In terms of the criteria used to evaluate the above systems, the actively precoated microfilter yielded more favourable results as compared to the other two systems.

Conventional usage of PAC was duplicated by intimately mixing the PAC with raw effluent. This was allowed to stand and then filtered in a test-cell. In this system the reductions in permeate COD was directly related to the amount of PAC added to the effluent, up to a point. The change in permeate COD rapidly increased (up to a certain mass of PAC the gradient of the graph was steep) and then gradually increased and levelled off as the amount of PAC added to the fixed volume of effluent increased. Measurements of turbidity revealed a small decrease as compared to the feed turbidity. The amount of COD removed per gram of PAC was calculated to be in the range of 70 – 105 mg/g PAC.

To compare the performance of the continuous WFMF system, using PAC as the active precoat, to the conventional usage of PAC longer run times were required using the Active WFMF system. It was anticipated that after a certain period of time, the PAC would become saturated and as such the permeate COD would start to increase. The conditions at which the PAC becomes saturated was determined. Theoretically, 4500 mg COD / g PAC could be removed and the PAC would become saturated after 1.2 hours of use. However, the results for this run showed that the COD of the permeate continuously averaged at 110 mg/l over the period (13 hours). Feed COD was 1156 mg/l, hence a COD reduction of 90% was achieved. The permeate turbidities settled in the 0.8 – 0.9 NTU region with steady-state fluxes of 35 LMH. Physical examination of the permeate also showed colour removal. A possible theory explaining the above could be the formation of a secondary separating layer. This secondary layer could have been formed by the adsorption of particles onto the PAC layer. These particles formed a 'tighter' layer on the PAC and thus also prevented the smaller polluting particles from eluting the system. It must be noted that it was not within the scope of this project to prove or disprove any mechanisms responsible for the separation characteristics achieved. However, a much longer run was performed to merely determine COD breakthrough, if any.

Using the Active WFMF system, a 72 hour run was performed whereby the permeate was continuously removed from the system and raw feed was introduced to the system as make-up for the removal of permeate. The WFMF tube was precoated with PAC, once only. Over the 72 hour period 160 l of raw effluent was pumped through the PAC precoated WFMF and 125 l of permeate was recovered. This represented a 78% recovery. During this time the feed COD increased from 1123 mg/l to 3390 mg/l. However, the permeate COD continuously averaged 260mg/l. This represented a COD reduction of >85% over 3 days with only one precoat cycle. For this system it was found that approximately 4500 mg COD could be removed per gram of PAC.

Using the same effluent in a test cell it was found that approximately 75 - 105 mg COD was removed per gram of PAC. This implies that the Active WFMF system is performing approximately 40 times better than conventional usage. During this time the average turbidity was below 0.6 NTU with more than 67% of the turbidity measurements falling below 0.55 NTU. Over the 72-hour period the fluxes ranged from 28 to 12 LMH.

Overall it was found that the Active WFMF system performed better than conventional usage of PAC, the WFMF system without precoat and the Non-active WFMF system in terms of the chosen performance criteria.

Summary

The findings from the experiments was summarized as follows:

a) PAC can be used as a suitable precoat on a WFMF tube.

b) The performance of the different systems considered was summarized as follows:

	WFMF	Kaolin / WFMF	PAC / WFMF
Feed COD (mg/l)	1200 - 1500		
Average Permeate COD	400 - 800	400 - 600	200 - 300
Feed Turbidity (NTU)	> 400		
Average Permeate Turb.	20 - 50	3 - 20	0.5 – 2
Flux (LMH)	5 - 12	10 - 20	25 - 40

c) The COD reduction for conventional usage of PAC was determined at 70 - 105 mg COD / g PAC. The PAC precoated WFMF removed 4500 mg COD / g PAC. For the duration of this experiment, one can therefore conclude that the PAC precoated WFMF is performing approximately 40 times better than the conventional usage of PAC.

D) When PAC is used in its conventional manner, it would become saturated after a period of time. For this investigation that time was determined at 1.2 hours. However the permeate produced for the duration of Run 41 (72 hours) was consistently of a good quality i.e. the COD and turbidity values did not increase after this time elapsed. This infers that a secondary mechanism besides PAC adsorption is also responsible for COD reduction.

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Nomenclature

A	Tube area	m^2
C_F	Fed concentration	g/l
C_{PR}	Precoat concentration	g/l
D	Tube diameter	m
J	Permeate flux	LMH
L	Tube length	m
P	Operating pressure	kPa
Q_F	Feed flowrate	m^3/s
Q_P	Permeate flowrate	m^3/s
R	Tube radius	m
T	Time	hrs
U_F	Feed inlet velocity	m
U_P	Permeate flow velocity	m
V_F	Volume of feed	l
V_P	Volume of permeate	l

Abbreviations

AC	Activated carbon
AC/MF	Activated carbon microfiltration
BMF	Batch microfiltration
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
CFMF	Crossflow microfiltration
ED	Electrodialysis
GAC	Granular activated carbon
LMH	Membrane permeate flux – litres per hour per square metre
MF	Microfiltration
MLST	ML Sultan Technikon
NOM	Natural organic matter
NRF	National Research Foundation
NTU	Nephelometric turbidity unit
PAC	Powdered activated carbon
PAC/B	Powdered activated carbon - Batch
PAC/M	Powdered activated carbon - Microfiltration
PAC/WFMF	Powdered activated carbon – Woven Fibre Microfiltration
Perm	Permeate
PVC	Polyvinyl chloride
RO	Reverse osmosis
TDS	Total suspended solids
THM	Tri-halo methane
TSS	Total suspended solids
UF	Ultrafiltration
WFMF	Woven fibre microfiltration
WRC	Water Research Commission

Chapter One

Introduction

Many industrial effluents are fairly complex, containing suspended and colloidal solids, dissolved organics and dissolved inorganic species. Industries experience major problems in the discharge of these effluents. Depending on the quality and quantity of the effluent, industrial effluent may be discharged to municipal works for treatment or treated on-site usually by a multi-stage process. This project concerns the development and evaluation of an active precoat microfiltration (ACMF) process that can remove all suspended and colloidal solids as well as reduce the organic content of an effluent in a single step.

Microfiltration (MF) processes have been used to treat industrial effluents. This technology offers regulatory compliance in a reliable and cost-effective fashion through physical removal of suspended and colloidal solids and reduced use of chemicals. A membrane on a support performs the filtration. There are various types of materials used as supports e.g. ceramics, porous steel tubes, polymers etc. These materials are usually rigid or semi-rigid and thus offer the advantage of maintaining their shape thus enabling operation at high pressures. This project will concentrate exclusively on woven fibre microfiltration (WFMF). This is a tubular cloth-like filter, which becomes rigid when feed flows through it.

In the treatment of industrial effluents, WFMF has been limited to removing suspended solids via a physical separation process. Whilst showing excellent removal of suspended and colloidal solids, WFMF shows little efficiency on natural organic matter (NOM), tastes, odors and color removal. Often current systems require some form of pretreatment by implementing a series of physico-chemical or biological unit-processes. This results in complex treatment trains that are expensive to build and operate [Lebeau (1998)]. A need therefore exists to further develop and modify WFMF.

One such method of improving the performance of WFMF is by using precoats. Precoats that have been in use so far are generally non-active mineral substances e.g. limestone, kaolin and bentonite. When these mineral substances are pumped into a WFMF tube, particles are deposited onto the tube forming a cake-like structure or precoat. Over a period of time a steady state cake thickness layer is achieved by a continuous deposition and shearing of particles from the cake surface. The cake-like structure or precoat forms a secondary separating layer on the tube wall and also acts as a filtration barrier thus improving the separation capability of the WFMF tube. The precoat also protects the MF from fouling by removing the fine particles. The close packing of the particles in the precoat layer enable the retention of particles that are often orders of magnitude smaller than the pores in the fabric tube wall.

[Teffry-Goatly *et al* (1987)] used a WFMF to treat a range of problematic waters. A calcium carbonate precoat was used. The precoated MF achieved water quality, which was comparable to the conventional method of water treatment. An increase in permeate quality and flux was also observed.

Due to continuous fines infiltration from the bulk feed to the cake layer, with time the permeate flow (flux) through the precoated MF tube continuously decreases. After a period of time the precoated MF tube needs to be washed of the precoat and precoated again for further use. In a typical treatment cycle one would then have precoating of the MF tube, followed by effluent treatment and then a wash cycle. With effluents that foul easily this treatment cycle is difficult to implement. Whilst, the use of inactive precoating substances have shown to be effective in improving the separation capability of a raw MF tube, over time the fouling of this precoat layer can become problematic. Consideration needs to be given to extending the capability and 'lifespan' of the precoat.

Activated carbon (AC) has been 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. Powdered activated carbon (PAC) is conventionally used by mixing it intimately with the wastewater. Organics adsorb onto the PAC, which is then removed by conventional filtration. A major drawback is that activated carbon has a finite adsorption capacity (saturation limit) and is relatively expensive. Hence its use in effluent treatment has been limited, since vast quantities would be required to remove the high organics loads in effluents. However, by using PAC as a precoat to form an active secondary separating layer could enhance the performance of the PAC and therefore improve the separation characteristics of the WFMF. Therefore, PAC will be used as the active precoat.

1.1 Project Objectives

1.1.1 Compare the performance of the WFMF system using an active precoat to that with no precoat.

1.1.2 Compare the performance of the WFMF system using an active precoat to that with an inactive precoat.

1.1.3 Compare the efficiency of the usage of PAC in the WFMF system to that where PAC is used in its conventional manner i.e. by mixing it into the effluent.

1.2 Approach and Thesis Organisation

Chapter one gives a brief introduction on CFMF, its usefulness as a tool in effluent treatment and highlights its limitations. It also introduces mineral precoats and the use of activated carbon (AC) in conventional treatment processes.

Chapter two provides a description of the WFMF process together with background information on dynamic membranes and precoating with in-active minerals. It also describes powdered activated carbon (PAC). The literature survey has been incorporated into this chapter.

In Chapter 3 the methodology is described. Herein, a sequence of steps is provided as to how the project developed. This chapter explains choice of precoats, test solutions, stability of precoats, performance criteria and performance characterization of the different systems.

Chapter 4 describes the experimental study. In this chapter the experimental apparatus, experiment types and experimental procedures are described. The different measurement techniques used to quantify the processes are also described.

Chapter 5 discusses the results.

Finally Chapter 6 summarizes the major findings.

Chapter Two

Theoretical Background

The potential of membrane separations in several industries has been realised and implemented for some time now. Large-scale commercial uses of membrane separations have displaced conventional separation processes. These membrane systems often prove to be both more cost effective and often yield some novel results. However for these systems to keep up with the ever improving and dynamically changing world of technology, membrane systems also have to be continually improved upon. One particular membrane separation process of interest to this project is microfiltration (MF) and more specifically woven fibre microfiltration (WFMF). WFMF describes the use of an interwoven fibrous network that forms a 'cloth-like' structure or filter. This cloth-like filter can either be used as a flat sheet or tubular filter. There are also two modes of operation viz. dead end and crossflow. In this project tubular WFMF was used in the crossflow mode.

2.1 Description of Crossflow Microfiltration (CFMF)

A membrane is an interphase between two bulk phases. A membrane process is the physical separation of two bulk phases by the membrane. In membrane separation processes the bulk phases are mixtures. One of the species in the mixture is allowed to be exchanged in preference to others. A membrane process thus allows selective and controlled transfer of one species from one bulk phase to another bulk phase separated by the membrane. In CFMF a suspension is pumped into a porous tube (Figure 2.1).

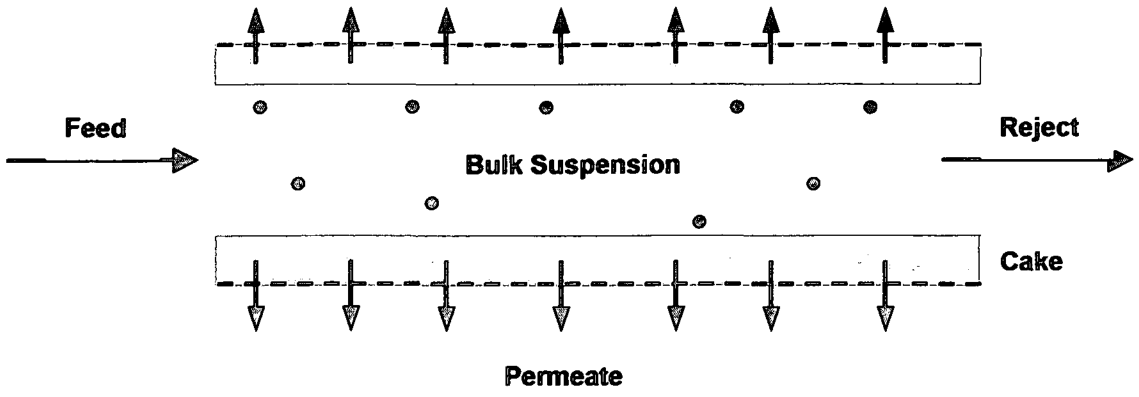


Figure 2.1 **Description of CFMF Process**

The pressure difference across the tube wall forces a clear liquid through the pores of the tube wall. This liquid is referred to as permeate. The flow of fluid normal to the wall convects particles to the wall where they accumulate to form a polarized layer. This layer is referred to as the cake. The cake continuously grows until it reaches a steady-state condition. With the continuous growth of the cake the resistance to flow of permeate through the wall increases thus reducing permeate flux continuously. Eventually, due to the tangential flow of the bulk suspension limiting the cake growth, permeate flux reaches a steady-state value that is relatively constant with time. At a much slower rate the flux will however continue to decline as time progresses.

MF is distinguished from other membrane processes e.g. Ultrafiltration (UF) and Reverse Osmosis (RO) by the size of rejected species (Figure 2.2). In MF, discrete particles are retained as opposed to RO and UF where dissolved salts and macromolecules, respectively are retained.

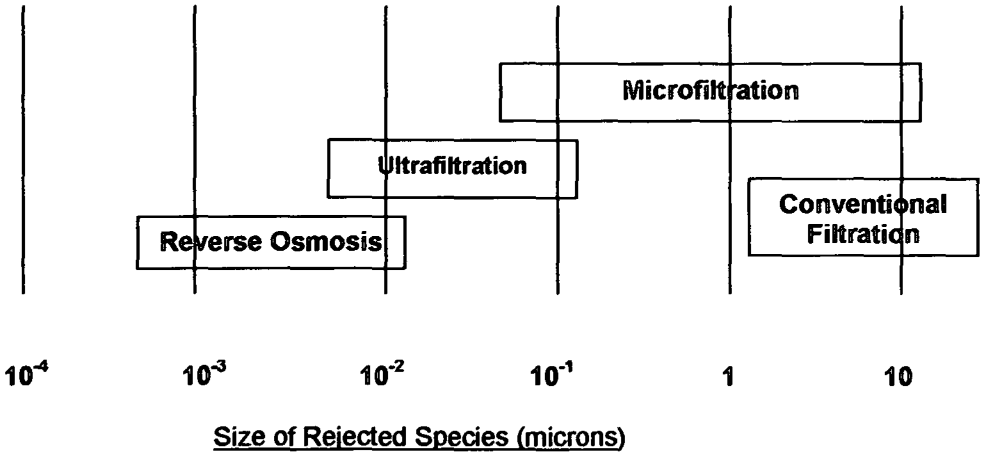


Figure 2.2 **Differentiation amongst Crossflow Processes**

There are a number of CFMF systems in use. Membrane processes have wide industrial applications covering many existing and emerging uses in the chemical, petrochemical, water treatment, pharmaceutical, food, beverage and dairy industries.

However WFMF does have limitations due particularly to the nature of the cloth and its pore sizes. This limitation does allow smaller, troublesome organic pollutants to permeate through the cloth. One such method of improving the retention capability of WFMF is by the use of precoats.

2.2 Precoats

In WFMF, a precoat is formed when particles from the bulk solution flowing through the MF tube deposit themselves onto the tube wall. As the feed suspension is pumped through the MF tube, particles from the bulk solution form successive layers on the tube, resulting in a cake-like structure, which is referred to as the precoat. A good precoat material should meet four basic requirements. Precoats should be inexpensive having a narrow particle size range and a variety of particle shapes. Under the various operating conditions experienced, precoats should also be chemically and mechanically stable. Once its maximum use has been exhausted, the precoat should be easy to dispose off.

2.2.1 Inactive Precoats

Previous use of precoats with WFMF, centered on mineral precoats e.g. limestone. This is a non-active precoat. A non-active precoat acts as an additional filter by forming a secondary layer on the tube wall. Pillay (1991) used particulate suspensions (e.g. limestone in water) and achieved promising results in terms of flux and rejection in that study. The precoat required should be relatively inert in water, resistant to abrasion and shear and inexpensive. Kaolin was therefore chosen as the non-active precoat.

2.2.2 Active Precoats

[De Wilde, *et al* (1998)] used fumed silica to develop gel-coated dynamic membranes. In attempting to duplicate this experiment fumed silica was added to water and filtered in a test cell using a WFMF disc as the filtering medium. It was postulated that the fumed silica would form a stable layer on the disc and thus behave as a precoat. The fumed silica did precoat the WFMF disc but it became immediately apparent that there would be difficulties using this material as a possible precoat. The precoated silica layer was quickly disturbed once the raw effluent was added to the system. This caused an uneven and sometimes even naked precoated disc. The second problem was that silica is soluble in water and traces of it was detected in the permeate. This is highly undesirable. On closer examination of the WFMF disc it was found that the silica particles tended to agglomerate and clusters of these particles were found unevenly distributed on the disc. It was also found that whenever any sodium hydroxide (in any concentration) came into contact with the silica, sodium silicates formed. This also was visible as an uneven spread or clusters of particles on the surface of the WFMF disc. It was decided to abandon this material.

Many organic materials found in water and wastewaters can be removed by adsorption. Activated carbon is preferentially used to remove taste and odour causing compounds as well as organic materials. AC is commercially available in powdered or granular (GAC) form and is produced from a range of raw materials such as wood and coal [Sontheimer, *et al*, 1998]. The production process involves the pyrolytic carbonization of the raw material during which the volatile components are released and the carbon realigns to form a pore structure that is developed during the activation process. The activation process selectively removes carbon resulting in an opening of the closed pores and an increasing in the size of micropores. Activation is either done chemically or physically depending on the raw material used. The most important feature is the resulting surface area of each particle that becomes available for adsorption and that most of the active surface is contained within the pores of the material. In the adsorption process there is a mass transfer of solute from a solvent on to the surface of a solid adsorbent. The driving force may be the lyophobic (i.e. solvent-rejecting) character of the solute or the affinity of the solute for the solid, or a combination of both. Thus, the substances that are removed from water and wastewaters by adsorption on to activated carbon are typically organic contaminants which may have a molecular structure comprised of both hydrophobic and hydrophilic parts [Sontheimer, *et al*, 1998].

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)]. Thereby the activated carbon is separated from the bulk stream using conventional filtration.

PAC is generally used in batch or continuously stirred reactors and GAC in packed or fluidized bed reactors [WRC Report No 244/1/91]. In selecting the appropriate form of activated carbon for a particular application various tests should be conducted e.g. activated carbon dosage, regeneration, developing adsorption isotherms for each specific activated carbon type in that particular application and cost of PAC vs. GAC etc. However the objective of this study was to verify whether PAC could form an active precoat and hence produce a better quality permeate as compared to no precoat or a non-active precoat. Hence the need to perform in depth studies as to the choice of an active precoat was not considered to be within the scope of this investigation. The literature did indicate that PAC does show distinct advantages over GAC when used in particular applications [WRC Report No 244/1/91]. Some of these advantages are that PAC reaches adsorption equilibrium quicker; PAC can be incorporated into existing processes (it is possible that the results of this investigation will be taken forward to yield alternative treatment 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.

PAC was therefore chosen as the active precoat. PAC was purchased from BHT Water Treatment as SUDCARB 3745.

2.3 Literature Survey

The methodology and applicability of woven fibre microfiltration for the removal of colloidal and suspended solids from wastewater or several types of industrial effluents are well documented. Groves, Buckley, *et al* (1985) have written on the use of WFMF as a separation technique for colloidal/suspended solids, thickening of weak sludge's, pretreatment prior to reverse osmosis (RO) and electrodialysis (ED), removal of organic compounds from certain industrial effluents and the filtration of suspended solids solutions with poor settling characteristics. In a recent study, [Mavrov, Chmiel, *et al* (1998)], the comparative performance of different MF membranes and UF membranes for the production of drinking water showed that even drinking water of high quality can be produced. These membranes produced drinking water that satisfied the German Standards for drinking water. With industry facing increasing problems in the discharge of its aqueous effluents and costs of its raw materials, the use of microfiltration and especially WFMF as less expensive alternative treatment options, becomes increasingly important.

Research has shown that to treat industrial effluents, the use of the relatively more expensive UF and HF separation techniques are more effective [Groves, Buckley (1980)]. Therefore from an industrial perspective the use of the WFMF separation process seems limited. As such it may be rewarding to adapt the WFMF separation process to have a wider range of uses. One such way is to find suitable materials that will coat the WFMF tube effectively reducing the size of the pores and hence trapping the 'smaller' pollutants. This has lead to the development of 'dynamic membranes'.

Dynamic membrane technology was pioneered by the Oak Ridge National Laboratory [Marcinkowsky, *et al* (1966); Johnson, *et al* (1972)]. Since then dynamic membrane technology has been extensively researched with particular reference to industrial effluent treatment. In fact, two major plants have been commissioned in the wool scouring and textile dyeing industries [Townsend, De Wilde, *et al* (1991)]. By definition dynamic membranes are formed-in-place membranes. Dynamic membranes are formed when chemical materials e.g. hydrous zirconium oxide, fumed silica, etc. form secondary layers on porous supports. These secondary layers improve the separation efficiency of the raw porous support. Dynamic membranes can also form when the suspended and colloidal material in an effluent forms a cake like structure in the primary membrane. This cake like structure effectively prevents larger molecules from permeating the primary membrane. Hence a secondary or dynamic membrane forms. The types of primary membranes or supports can vary from stainless steel porous tubes to ceramics and even cross flow MF (CFMF). Some of the minerals that can be used to form dynamic membranes are florspar, diatomite, zirconium, silicates and limestone [Holdich and Boston (1989)]. A cross flow filter which uses dynamic membranes formed from suspended solids has many potential advantages including inexpensive membrane regeneration, low trans-membrane pressure drop, pretreatment to remove solids is not critical and in the case of severe fouling the membrane can be cleaned by washing or 'pinch rolling' and a second dynamic membrane can be formed in situ. The deliberate design and use of dynamic membranes for cross flow microfiltration may find major applications in many phase separation processes.

A simple yet effective method of deliberately designing dynamic membranes involves the use of precoats with WFMF tubes. Mineral substances e.g. limestone in solution are pumped through a WFMF tube. The mineral particles in the solution are deposited onto the tube and form a cake like structure. The smaller particles of the suspension lodge themselves into the pores of the WFMF tube. The larger particles of the suspension then form successive layers until a steady state cake thickness is achieved. A continuous shearing and deposition of particle effect maintain the steady state cake thickness. Due to the presence of a wide size range of particles in most suspensions the structure of the cake continuously changes. These changes are primarily brought about by hydraulic compression of the cake, preferential deposition effect and fines infiltration effect [Pillay, (1991)]. 'Hydraulic compression occurs when fluid drag forces cause an irreversible collapse of the particulate structure, leading to a cake-decreased voidage. The preferential deposition effect concerns the deposition of smaller particles onto the cake, in preference to the larger size fractions. The fines infiltration effect concerns the progressive infiltration of very fine particles into the existing cake structure, until some saturation fines content is achieved.

The presence of this cake like structure substantially supports the separation capability of the WFMF tube. Effectively, the particles of the suspension have reduced the pore size of the WFMF tube thus preventing the particles in the effluent from permeating the tube. Numerous successes have been documented using a variation of this combination of precoat and WFMF. In Japan, [Suzuki, Watanabe *et al* (1998)], for example engineers have been able to remove soluble organics and manganese 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 is mixed with powdered activated carbon (PAC) and sludge circulated from the bottom of the MF membrane submerged tank. The mixed water is then fed into the membrane-submerged tank. The organics are adsorbed onto the PAC and the microorganisms in the sludge biologically oxidize the manganese and nitrates. The MF membranes then remove the PAC and sludge. The removal efficiency was temperature dependent and at the preferred temperatures removal efficiency was reported at 100%.

In Saarland, Germany several plant construction companies and membrane manufacturers were involved in a pilot phase 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.

The French have gone on to couple PAC with UF. The process is flexible and adaptable to flow rate. 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)]. The perspective for this system should be to continuously reduce chlorine usage and hence diminish total trihalo methane (TTHM) levels and to find alternatives for UF.

Other notable papers often report 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 [Hallvard Odegaard (2000)] etc. All of these systems use PAC first for adsorption and then either UF or MF (in most cases UF) as the filtration step. This investigation is aiming to develop a one step process whereby PAC will be used to precoat the WFMF tube and treatment will be effected in the ACMF system.

Chapter Three

Methodology

3.1 Test Solution

A test solution that met certain criteria was required. The required test solution needed a suitably high COD, high colour, high turbidity, suitable total solids count and a low sodium hydroxide concentration (sodium hydroxide negatively affects the performance of the chosen precoat and is generally used as a cleaning aid to remove particulate contaminants that tend to lodge themselves at the membrane wall). Certain practical aspects such as ease of transportation of large quantities of effluent and access to a plant (if necessary) also needed to be satisfied. A textile mill satisfying the above requirements supplied the test solution, which was the raw effluent produced by the plant.

Large quantities of effluent were collected and homogenised. The feed was obtained in batches of 200 l from the mill. It was retrieved from a common sampling point. This sampling point was at the effluent treatment section of the plant. The feed used in this investigation represents a combination of the effluents produced in different sections of the plant and was not subjected to any pretreatment before being used in this investigation.

The plant comprises of five different sections. These are the desizing, bleaching, mercerization, dyeing and printing sections. In the desizing section the cloth is treated with enzymes and wetting agents so as to remove sizing materials. Effluent produced here has a high biochemical oxygen demand (BOD), total dissolved solids (TDS) and suspended solids (SS). In the bleaching section large amounts of water is consumed. Caustic soda, soda ash etc. enter the effluent stream. Effluent produced here has a high BOD, TDS, cations, temperature, pH and SS. In the mercerisation section the cloth is treated with concentrated solutions of caustic soda. Effluent produced here has high alkalinity. In the dyeing section the cloth is treated with different colour recipes. Effluent produced here has a high COD, TDS and SS. Dyeing imparts dyes, solvents and sodium ions to bulk effluent. In the printing section the cloth is printed with different prints. Printing is followed by washing and soap operations. Effluent produced here has a high COD, TDS.

All of the above effluent streams combine into one bulk stream. The characteristics of this effluent stream therefore continuously change. In this report it was decided to characterise each batch of feed as and when received in terms of its COD. This is reported in each result table for each run.

3.1.1 Test Solution Preparation and Storage

The test solution was collected from the mill and stored in the engineering laboratory at the ML Sultan Technikon, under ambient conditions. At any one time eight twenty five litre containers would be taken to the mill and filled with effluent. At the laboratory, the effluent from the 25l containers were transferred into a two hundred litre sealed drum. The drum was then sealed and stored away from sunlight. This feed was then used up either the same day or within the following 2-3 days thus ensuring minimal change in its characteristics.

To perform an experiment, forty litres of feed was required. In order to obtain a representative sample the sealed drum was opened and continuously stirred for a 10 minutes. Thereafter 40 litres of effluent was drawn out, transferred to the feed tank and immediately used in the experiment. Cooling water flowing through a cooling coil in the feed tank maintained the temperature of the feed. This protocol was followed for all of the runs.

3.2 Choice of Precoats

Different (active and non-active) precoating materials were investigated. The investigation required one inactive and active precoat. A precoat was selected on the basis that it formed a stable uniform layer on the WFMF and the leachate was either negligible or none at all.

3.2.1 Inactive Precoat

[Pillay (1991)] used particulate suspensions (e.g. limestone in water) on a wastewater effluent and achieved promising results in terms of flux and rejection in that study. This investigation required a precoat that has several average particle size distributions, relatively inert in water, resistant to abrasion and shear and is inexpensive.

In a laboratory test cell unit, kaolin was used to precoat a WFMF disc at a specific pressure to determine whether the kaolin particles pass through the cloth. Little or no leachate was observed.

On closer examination of the WFMF disc, an evenly spread layer of particles was also observed. Kaolin was therefore chosen as the in-active precoat material.

3.2.2 Active Precoat

Activated carbon has been used in treatment processes due to its adsorptive properties. It has been used in e.g. the degradation of organic compounds [Kolb and Wilderer (1998)] or adsorption of micropollutants onto fibrous activated carbon in association with ultrafilters [Brasquet, Clorec, *et al*, (1996)]. Thereafter the AC was removed by some filtration step. As such it was decided to develop AC as a possible precoat.

In a laboratory test cell unit, AC was used to precoat a WFMF disc at a specific pressure to determine whether the AC particles pass through the cloth. Little or no leachate was observed. On closer examination of the WFMF disc, an evenly spread layer of particles was also observed. AC was therefore chosen as the active precoat material.

3.3 Performance Criteria

The performance of an actively precoated MF was to be compared to the performance of an inactively precoated MF as well as a MF without any precoat. This investigation also required the comparison of the adsorptive ability of an AC (active) precoated MF to that used in ideal conditions where AC is intimately mixed with the test solution and a measure of its adsorptive ability at saturation, is made. The following parameters were used to evaluate the performance of the different systems.

3.3.1 Chemical Oxygen Demand (COD)

COD is defined as the amount of oxygen in the form of oxidizing agent consumed in the oxidation of organic water components. The degree of oxidation depends upon the type of substance, pH values, temperature, reaction time and concentration of oxidizing agent as well as any types of added accelerators, if any. The COD was measured using a Hach Spectrophotometer that was regularly calibrated.

3.3.2 Turbidity

Turbidity is an expression of the optical properties of a sample that causes light rays to be scattered and adsorbed rather than transmitted in straight lines through the sample (ASTM D 1889-88A). Measurement of the turbidity is accomplished by passing a strong beam of light through the sample. Suspended matter reflects a portion of the light beam (proportional to the turbidity present), and a photoelectric detector receives reflected light. The light energy is then converted to an electrical signal and displayed on a meter. Turbidity is caused by the presence of suspended organic and inorganic material in water. Turbidity was measured using a Hach Spectrophotometer.

3.3.3 Flux

The permeate flow (flux) was measured by recording the time taken to collect a fixed volume of sample. For all flux measurements, readings were often performed three times and the average recorded.

3.4 Data Processing

The results from the experiments was divided into two sections viz. measured variables and fixed variables. This information was then tabled and graphed. The results of the experimental program were reported in a specific format. This took the form of objective of the run, table of data and graphs.

3.5 Conclusions and Discussion

The results were discussed providing possible explanations for some of the findings. Finally, the findings were summarized and concluded.

Chapter 4

Experimental

4.1 The Laboratory Test-cell

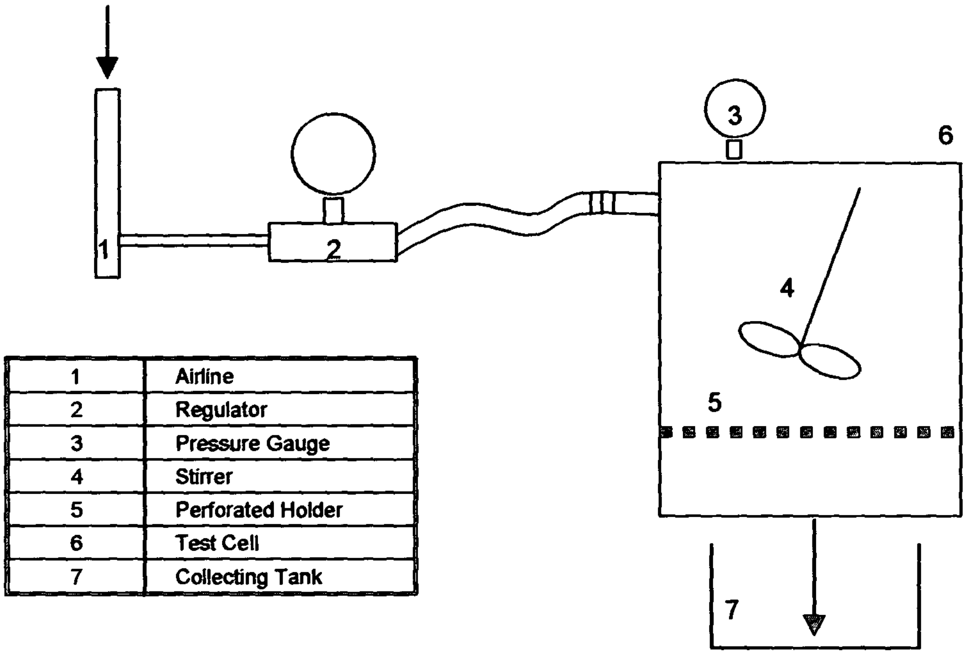
This test-cell was designed to represent the usage of activated carbon (AC) in its conventional manner i.e. intimate mixing of AC with the test solution to determine adsorptive efficiency of AC at saturation.

4.1.1 Apparatus

A schematic diagram of the test-cell is shown in Figure 4.1.

The test-ell 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 400ml 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 76mm. 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.



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

Figure 4.1 **Diagram of Test-cell**

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.

4.1.2 Experimental Procedure

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.

4.2 Crossflow Microfiltration Experimental System

4.2.1 Apparatus

A schematic diagram of the CFMF system is shown in Figure 4.2.

The CFMF 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 CFMF 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.

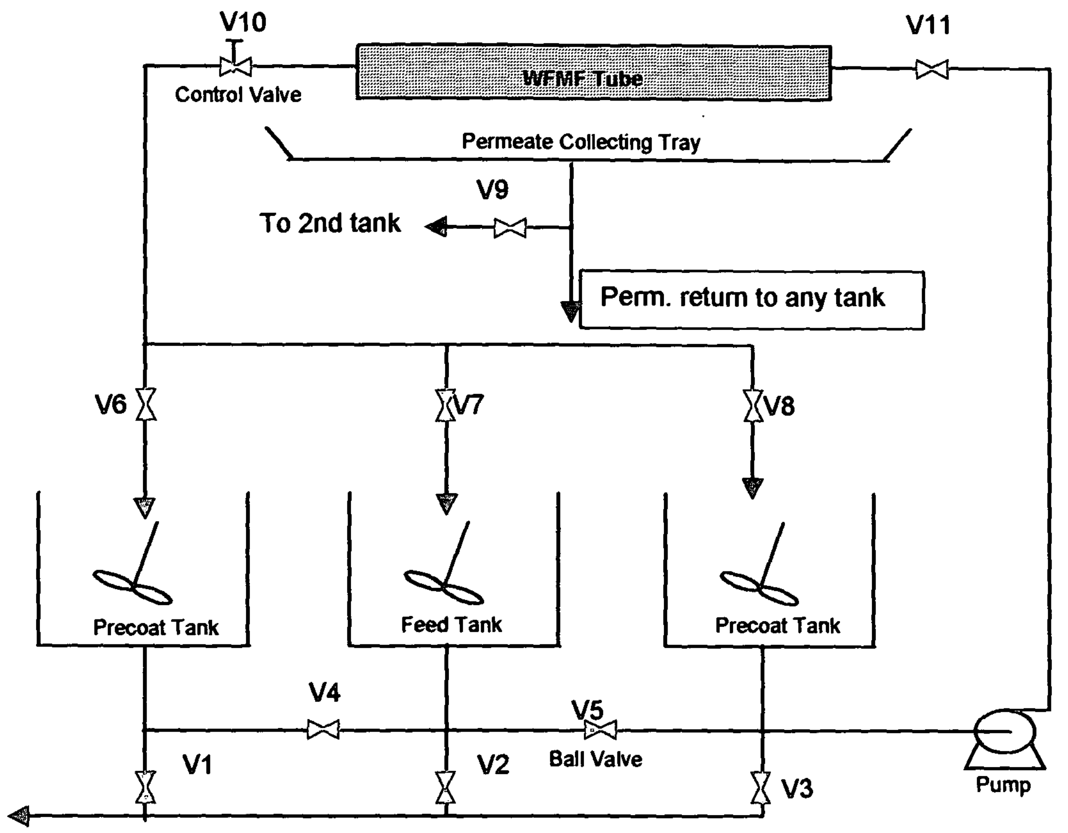


Figure 4.2 Schematic Diagram of the Continuous WFMF System

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 Galvanor. 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. In all of the experiments, except Run 41, the reject and permeate were both returned to the feed tank (closed recycle mode), so as to keep the feed concentration constant. The pressure in the tubes was adjusted using a Saunders diaphragm valve located downstream from the tube.

The tanks and pipe-work was made from PVC to prevent any contamination possibly arising from corrosion.

4.2.2 Instrumentation

a) Flowrate

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.

b) Pressure

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.

c) Temperature

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

d) Level

The CFMF system was continuously run in full recycle commencing with a feed input of 40 liters. The level was prevented from falling below a lower limit by a level controller, which would shut down the pump if and only if the tank level falls below this set point. However, this was prevented from occurring by a continuous physical presence during this run.

e) Concentration

In all the runs, except Run 41 the system was run in closed recycle. Hence the concentration of the effluent did not change considerably. The adsorption of various species onto the PAC will however affect the feed concentration. In order to prevent bringing about huge changes in concentration during Run 41, it was decided to top up the effluent tank only once ten litres of permeate was collected. This then represented a concentration change in the feed of ~ 25 %.

4.2.3 Experimental Procedure

The feed was prepared as outlined in section 3.1.1. The following procedure was observed for each of the cross-flow runs.

a) Cleaning Cycle

Each of the tanks were thoroughly washed and filled with tap water. The WFMF tube was connected to the rig (Figure 3.1). 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.

b) 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.

c) Operation of Experimental Rig when Treating Raw Effluent

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.

4.3 Measurement Techniques and Error Analysis

Measurements of flux, turbidity and COD were recorded. These measurements together with their uncertainties are summarized in Table 4.1

Table 4.1 Values and Uncertainties in Primary Measurements

	Value	Uncertainty	%Uncertainty
Equipment Variables			
Tube Radius (m)	0.0254	0.00025	0.98
Tube Length (m)	1.44	0.005	0.35
Operating Variables			
Pressure (kPa)	100	3	3
Flowrate (l/h)	1850	50	2.70
Measured Variables			
Volume of Permeate Collected (l)	1	0.01	1
Time to collect Permeate (s)	20 to 60	0.4	0.67 to 2

4.3.1 Flux

a) Measurement Procedure

The flux was monitored at different time intervals by measuring the time taken to obtain a specific volume. Flux measurements were generally made after the first half-hour of commencement of operation and thereafter every hour.

b) Calculation Procedure

The permeate flux was calculated as follows:

Permeate Flux

$$J\ (l/m^2h) = [\text{permeate flowrate}\ (l/s) / \text{area}\ (m^2)]\ [(s)/(h)]$$
$$= [(V_{perm})(3600) / (t_{perm})[(2)(3.14)(0.0126)(1.44)]$$
$$= [(0.03)(3600) / (t_{perm})[(2)(3.14)(0.0126)(1.44)]$$
$$= [(947.8) / (t_{perm})]$$

where, V_{perm} refers to permeate volume and t_{perm} refers to time taken to collect permeate.

4.3.2 Error Analysis

Let F (x) represent % uncertainty in the measured quantity x.

a) Uncertainty in Permeate Flux

$$F(J) = \max[F(\text{permeate flowrate}); F(\text{filtration area})]$$
$$= \max[F(V_{perm}); F(t_{perm}); F(R); F(L)]$$
$$= \max[1; 2; 0.98; 0.35]$$
$$= 2\ \%$$

b) Errors in Flux-Time Curves

There are two sources of errors inherent in the flux-time curves reported in Chapter 5.

1) Uncertainty in the flux value (Section 4.3.2.1)
2) Uncertainty in the time at which the flux is plotted. Assume that at time *t* after start-up a period t_{perm} was required for the permeate to fill the measuring cylinder. The flux so calculated has been plotted at time *t*, rather than the *mean* time of $t + (t_{perm} / 2)$. The uncertainty in the time is thus ~ $(t_{perm} / 2)$.

A typical flux-time curve, with an error envelope representing the uncertainty is presented in Figure 4.3. It is seen that the uncertainties are insignificant when compared to point values. For clarity, error envelopes have been excluded from subsequent presentations of flux-time curves.

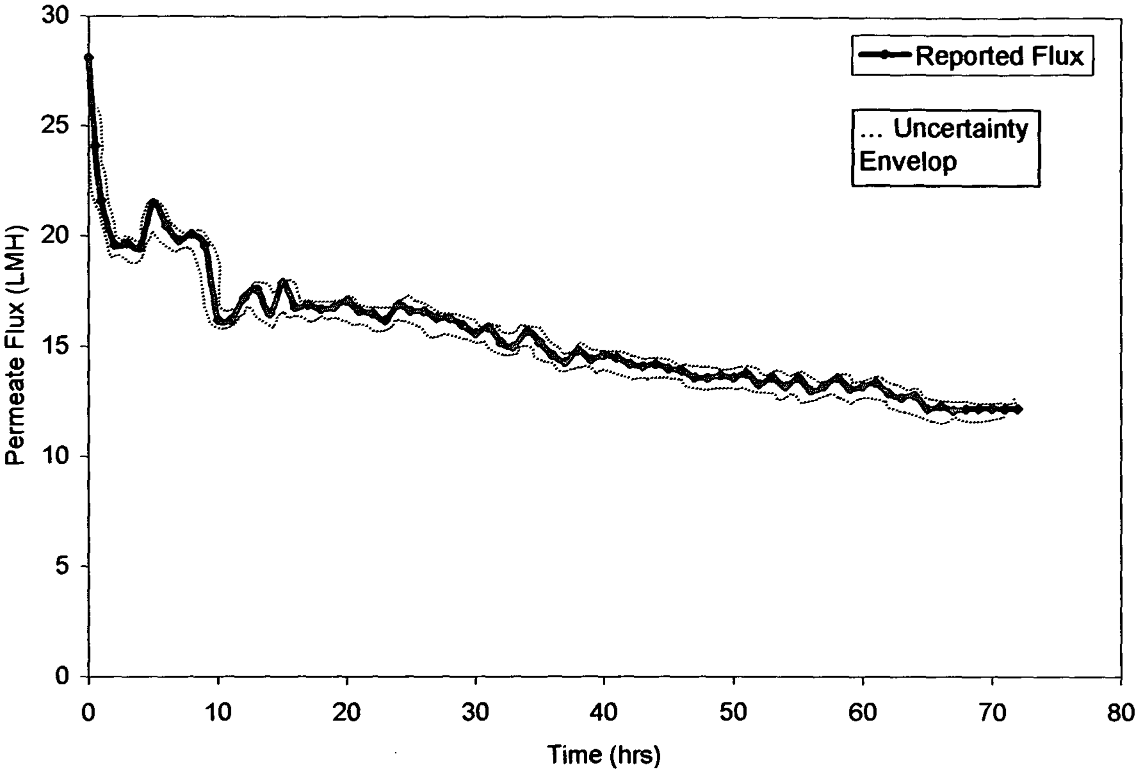


Figure 4.4 Typical Uncertainties in Measured Flux Values

c) Turbidity

A HACH Spectrophotometer 2100A was used to record turbidity in accordance with the ASTM Standard Test Methods. The meter was regularly calibrated against HACH secondary turbidity standards, which showed no difference to the primary Formazin standards. Turbidity measurements were generally made after thirty minutes of commencement of operation and thereafter every hour.

d) COD

A HACH Spectrophotometer 2100A was used to measure COD in accordance with the ASTM Standard Test Methods. The method employed was the open reflux method. Samples for COD measurements were generally taken after thirty minutes of commencement of operation and thereafter every hour. This required placing a sample into a reagent (derivative of potassium dichromate) and allowing this mixture to react for two hours. Thereafter the mixture is cooled to below 393K and placed into a spectrophotometer. The applicable program is entered into the instrument. The reagent vial is then placed into the instrument and the COD of the sample is then recorded. The volume of sample to be reacted with the reagent provided, depending on the sample COD, is either 2 ml or 0.2ml. When one is dealing with liters of permeate it is immediately apparent that the position in the container from which the original sample is taken represents the COD of that sample's surrounding area and not necessarily that of the whole sample even if the entire sample is thoroughly mixed. This was indeed the case when finding CODs for large volumes. In order to overcome this small volumes of COD samples were taken directly from the permeate outlet. In dealing with large batches of samples a common sampling point was used.

Chapter 5

Results and Discussion

5.1 Choice of Precoats

Suitable materials that would form precoats on a WFMF membrane had to be identified. These were then tested using the test cell and a microfiltration disc as the separation barrier.

5.1.1 In-active Precoat

[Pillay, (1991)] conducted successful investigations using particulate suspensions as non-active precoats. It was therefore decided to first confirm those results and then select the non-active precoat.

In a test-cell, different concentrations of kaolin in water were used to precoat a WFMF disc. Upon examination of the subsequent permeate there appeared to be little or no leachate of the kaolin particles. An even layer of the kaolin was also formed on the WFMF disc. This indicated that kaolin could be used as an in-active precoating material.

5.1.2 Active Precoat

Fumed silica was first used as a possible active precoat. Several difficulties with this precoating material were immediately apparent (Section 2.2.2). Hence the use of fumed silica as a possible active precoat was discarded.

PAC is used in treatment systems as a final polishing agent (e.g. removal of colour and odours). To determine whether PAC can form a stable precoat, different concentrations of PAC in water were used to precoat a WFMF disc in a test cell. Upon examination of the subsequent permeate there appeared to be little or no leachate of the PAC particles. An even layer of the PAC was also formed on the WFMF disc. This indicated that PAC could be used as an active precoating material.

5.2 Evaluation of PAC as an Active Precoat

The objective for these experiments was to determine whether PAC when used as an active precoat on a WFMF disc, will produce a permeate that is different to the feed. This improvement, if any, will be realized in lower permeate COD and turbidity values as compared to the feed values.

Different quantities of PAC (5g-20g) was added to a litre of effluent and mixed for a suitable time period in a mechanical shaker. Thereafter the mixture was filtered in the test-cell using a WFMF disc as the filtering medium. The permeate was collected and analyzed for COD. The COD results (Figure 5.1) indicated a significant difference (>70%) between the feed and permeate COD's. For the concentration of PAC used (5g-20g), the corresponding reduction in permeate COD was 73-80% (Run 25). Run 26 was performed under similar conditions to Run 25. Both runs showed similar COD reduction.

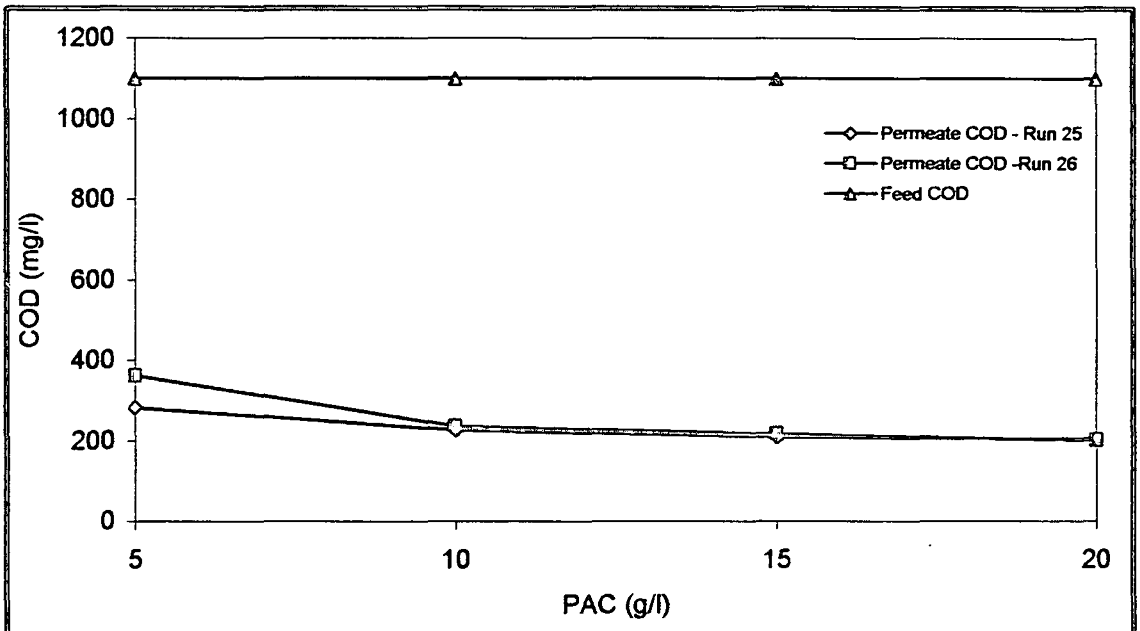


Figure 5.1 Comparison of Feed and Permeate COD vs PAC

Figure 5.1 shows that there are significant reductions in permeate COD as compared to the feed COD. Hence PAC does improve the performance of the system.

5.3 Quantifying the effect of the WFMF disc without precoat in terms of COD reduction

The WFMF disc does remove suspended and colloidal matter from the raw feed. This action will contribute to a certain reduction in the overall COD reduction. The significance of this contribution needs to be determined so as not to over-estimate the contribution of the role of PAC in COD reduction. Hence the objective for this section was to quantify the role of the WFMF disc without precoat in COD reduction.

In Run 27, the effluent was first filtered through a WFMF (without a PAC precoat) disc. COD determinations were made of both feed and permeate (Figure 5.2). It was found that the WFMF disc alone, removed roughly 17% of the feed COD. This was interpreted as COD contributed by the large colloidal particles in the feed.

To the permeate (this permeate used, effectively removes the reduction in COD brought about by the WFMF disc) from the above exercise, PAC (1-20g) was added to 1l aliquots. Again COD determinations were made of both feed (which was the permeate from the previous exercise) and permeate (Figure 5.2). It was found that the PAC brought about a further, significant reduction in COD (53-77%).

Run 28 was similar to Run 27. In this run, it was also found that the WFMF disc without a precoat was responsible for a small (5-17%) COD reduction. The reduction of COD when PAC was added was found to be in the range 26-84% (depending on the quantity of PAC added to each sample).

These experiments concluded that the cloth is responsible for some COD reduction (probably due to the quantity of suspended and colloidal material in the raw feed, hence the discrepancies in the COD reduction brought about by the disc alone). The contribution to COD reduction by the disc alone plays a minor role in overall COD reduction and hence future results does not attempt to differentiate between the two.

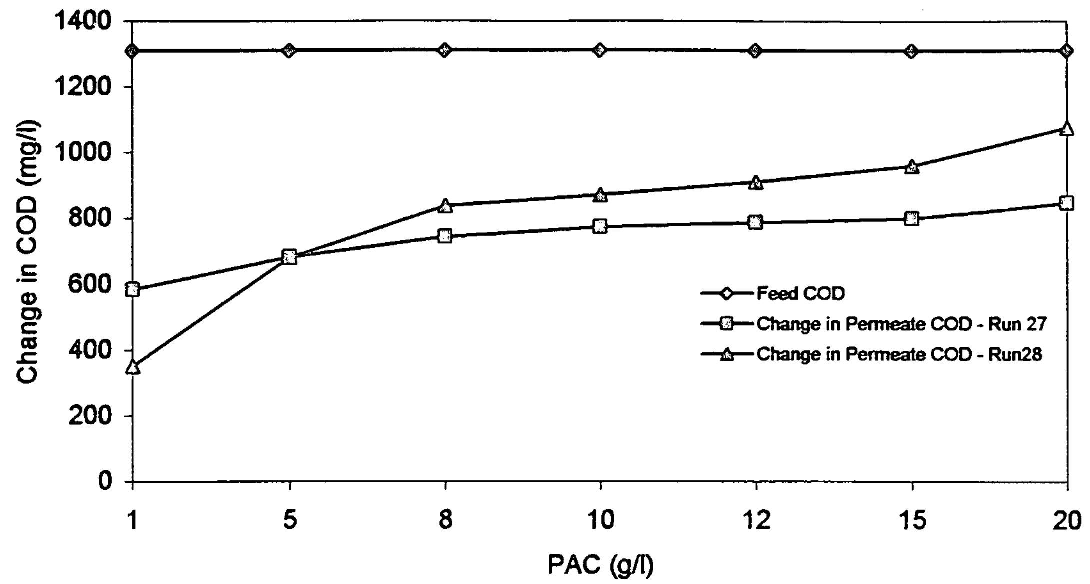


Figure 5.2 Change in Permeate COD compared to Feed COD vs PAC Added

From Figure 5.2, the difference in COD reduction from the 5g of PAC used to the 20 g of PAC used was slight. As such it was decided to use 5g PAC / l effluent in the continuous WFMF experiments.

5.4 Determining the Ratio COD removed per gram of PAC

The conventional usage of PAC describes its use as the intimate mixing of a quantity of PAC into a raw feed. The amount of PAC to be used in such methods is determined by the adsorptive ability of the PAC and the type of raw feed being used. Adsorption isotherms are developed for specific types of raw feed and this indicates the 'lifespan' of the PAC before it needs to be either regenerated (which is usually difficult) or dumped. The adsorption capacity is usually finite in these types of applications.

In this project the adsorptive capacity of the PAC was determined by the amount of COD removed per gram of PAC specific to the type of feed being used. To determine the quantity of PAC that will be required to suitably reduce the COD of a particular effluent, one needs to determine the amount of COD that could be removed per gram of PAC under specific experimental conditions. This ratio (COD removed: g PAC) could be used to differentiate between the different processes examined in this study.

Varying masses of PAC (from 0.1-20g PAC) were added to 1 L aliquots of raw feed (Runs 31 - 32). The mixtures were then filtered in the test-cell and measurements of both feed and permeate COD was recorded. These results are presented in Figures 5.3 - 5.4.

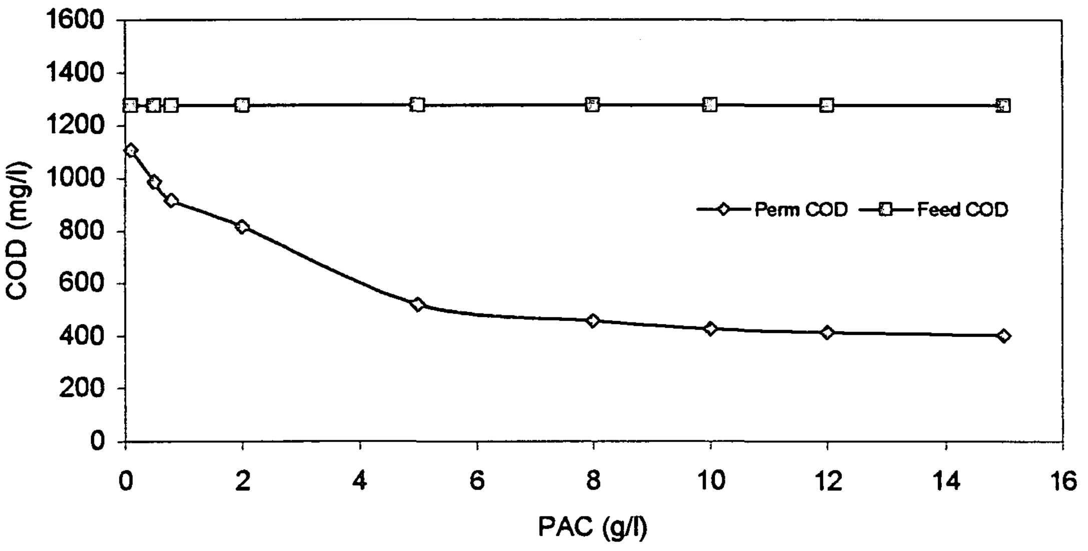


Figure 5.3 Comparison of Permeate and Feed COD vs PAC Added

The change in COD versus PAC added exhibits an initial rapid increase followed by an almost linear increase as more PAC was added. This was a common feature for the test-cell experiments (Runs 25–33). The slope of the graph represented the amount of COD removed per gram of PAC. This ratio was found to be in the range of 70 - 105 mg COD removed per gram PAC.

These experiments indicate that the PAC precoated WFMF does produce a better quality permeate than that which would be produced by using a WFMF without PAC. It was also found that for every gram of PAC mixed into the effluent a possible reduction of 70 – 105 mg COD is possible. This COD reduction represents the usage of PAC in it's conventional manner. These conclusions are specific to this effluent subject to these experimental conditions.

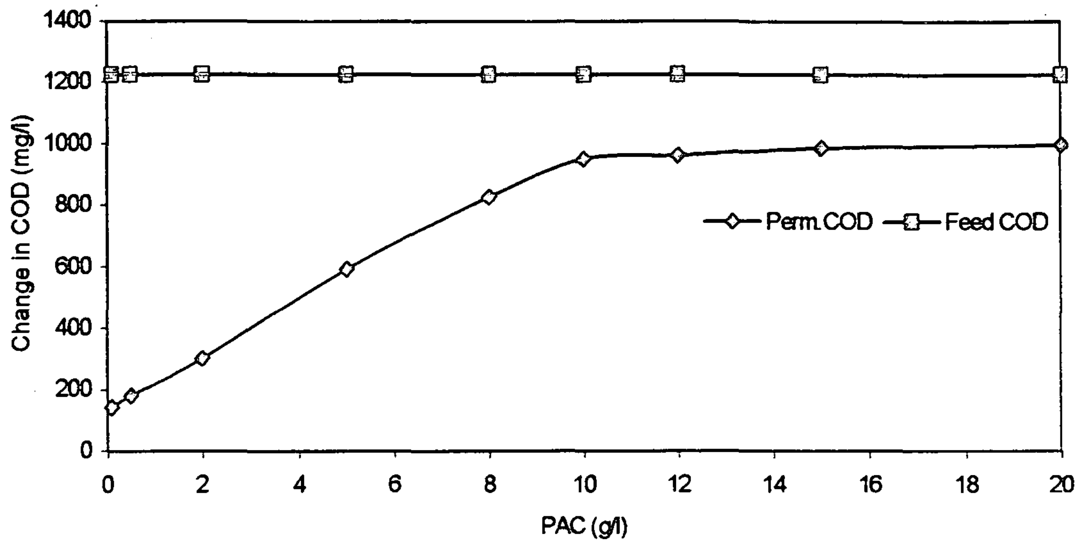


Figure 5.4 Comparison of Change in Permeate COD to Feed COD vs PAC Added

5.5 Evaluation of Precoats in Crossflow (CF) Mode

5.5.1 Experimental Approach

The objective for this set of experiments was to compare the performance of the WFMF tube without precoat to that which is precoated with an active precoat and to that which is precoated with an inactive precoat in CF mode. The active precoat was PAC. The in-active precoat was kaolin. The precoating concentration used was 5g precoat material per liter of raw effluent. The precoating time was 1 hour.

The WFMF tube was precoated either using PAC or kaolin. The raw effluent was not allowed to come into contact with the precoating material. Contact between the precoat and the effluent only occurred in the WFMF tube. Precoating was done in full recycle i.e. the reject and permeate were both returned to the precoating feed tank. Immediately after precoating, effluent was pumped into the tube thus preventing the precoat layer on the tube from collapsing. Samples of feed and permeate were collected and analysed for COD. COD samples were taken after the first half-hour and then every subsequent hour. Turbidity and flux measurements of the permeate samples were also measured. The experimental conditions for the different experiments were kept constant.

The experiment was divided into three parts viz.:

a) 40 liters of raw effluent was passed through a WFMF tube without precoat for 3 hours.

b) The same tube used in (a), was then thoroughly washed with tap water and precoated using 5g kaolin / L water for 1 hour (the non-active precoat). Immediately thereafter 40 liters of raw effluent was passed through the precoated WFMF tube for 3 hours.

c) The same tube used in (a) and (b), was again then thoroughly washed with tap water and precoated using 5g PAC / l water for 1 hour (the active precoat). Immediately thereafter 40 liters of raw effluent was passed through the pre-coated WFMF tube for 3 hours.

In each of these runs the operating conditions were kept constant. At suitable time intervals samples were collected and analyzed for COD and turbidity. The results are shown in Table 5.1.

5.5.2 Results

a) Comparison of the Different Systems

Table 5.1 Comparison of the Different Systems

Run Conditions:

Run Time	3 hours
Filtration Area	0.11 m^2
Filtration Pressure	1 bar
Temperature	293 K
Flow Velocity	1 m/s
Feed Volume	40 liters

Time (hrs)	COD (mg/l)					
	Feed			Permeate		
	No Precoat	Kaolin	PAC	No Precoat	Kaolin	PAC
0.5	1432	1413	1447	825	435	205
1				684	684	229
2	1523	1432	1452	542	524	240
3	1545	1447	1541	432	402	251

Figures 5.5 – 5.6 shows the performance of each of the different systems over a three-hour experimental period. These graphs compare the feed COD to that of the respective permeate COD's. In each of these runs, it is clear that the WFMF tube that is precoated with PAC is performing better (in terms of COD removed) than the WFMF system without a precoat and the WFMF tube that is precoated with Kaolin. The permeate for the PAC/WFMF continuous system exhibits much lower COD's.

It also shows a far lower turbidity than the other systems. The turbidity measured in the PAC/WFMF system averaged around 1 NTU from an initial feed of 482 NTU. That measured in the WFMF system and Kaolin/WFMF system were 30 and 3 NTU's respectively.

The steady state flux in the PAC/WFMF system was approximately 25 LMH and did not change much for the duration of the experiment. That measured in the WFMF system and Kaolin/WFMF system was 6 and 7 LMH respectively.

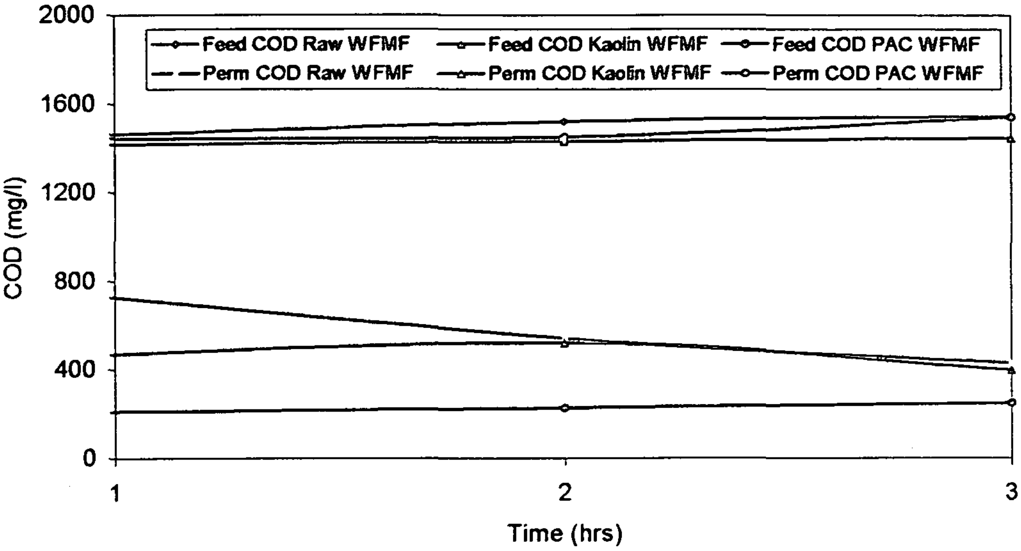


Figure 5.5 **Comparison of Feed and Perm COD vs Time**

From the above experiments it was concluded that the Active WFMF system continuously performed better than the Non-active WFMF system and the WFMF (without precoat) system. The Active WFMF also produced better fluxes and turbidities.

One of the contributing factors as to why the PAC/WFMF system was performing better than the other systems could possibly have been the order in which the different tests were performed even though the WFMF tube was thoroughly washed after each experiment. It was thought that there probably was some precoat material that was still lodged on the tube.

b) Order of Experiments

In Runs 38 - 39 it was decided to change this order around.

In Run 38 the order was effluent was passed through the WFMF system, then through the Active WFMF system, followed by the Non-active WFMF system, repeat WFMF, repeat Active, repeat Non active, and finally back to Non-active. In Run 39 the same exercise was performed. The order this time was WFMF, Non-active, Active, Active, WFMF and then Non-active.

Measurements of COD, turbidity and flux were made of both permeate and feed, where applicable. It was found that the Active WFMF system still performed better than the other systems.

In Run 38 the experimental approach was similar to that provided in 5.5.2 with the following adaptations:

d) 40 liters of raw effluent was passed through a WFMF tube for 4 hours.

e) The same tube used in (a), was then thoroughly washed with tap water and precoated using 5g PAC / l water for 1 hour (the active precoat). Immediately thereafter 40 liters of raw effluent was passed through the actively pre-coated WFMF tube for 4 hours.

f) The same tube used in (a) and (b), was again then thoroughly washed with tap water and precoated using 5g Kaolin / l water for 1 hour (the non-active precoat). Immediately thereafter 40 liters of raw effluent was passed through the precoated WFMF tube for 4 hours.

g) Repeat (a)

h) Repeat (b)

i) Repeat (a)

j) Repeat (c)

In each of these runs the operating conditions were kept constant. At suitable time intervals samples were collected and analyzed for COD and Turbidity. Measurements of Flux were also recorded. This then formed the basis of differentiating between the processes.

The results of this determination are in tabled in Appendix 1. Below follows a graphical representation of the results.

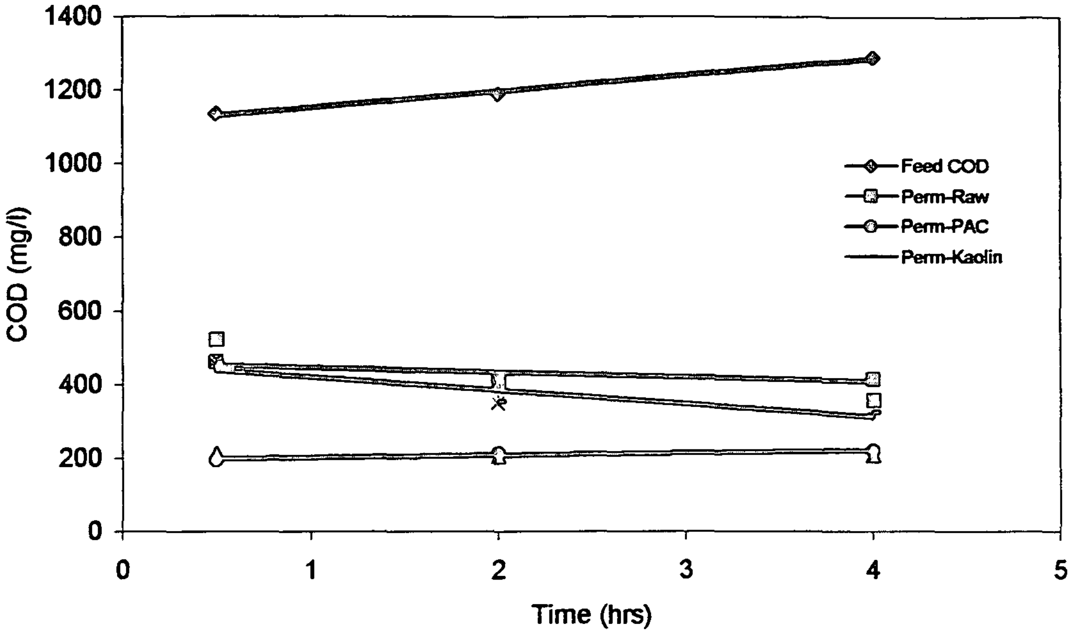


Fig 5.6 Comparison of the Different WFMF Systems

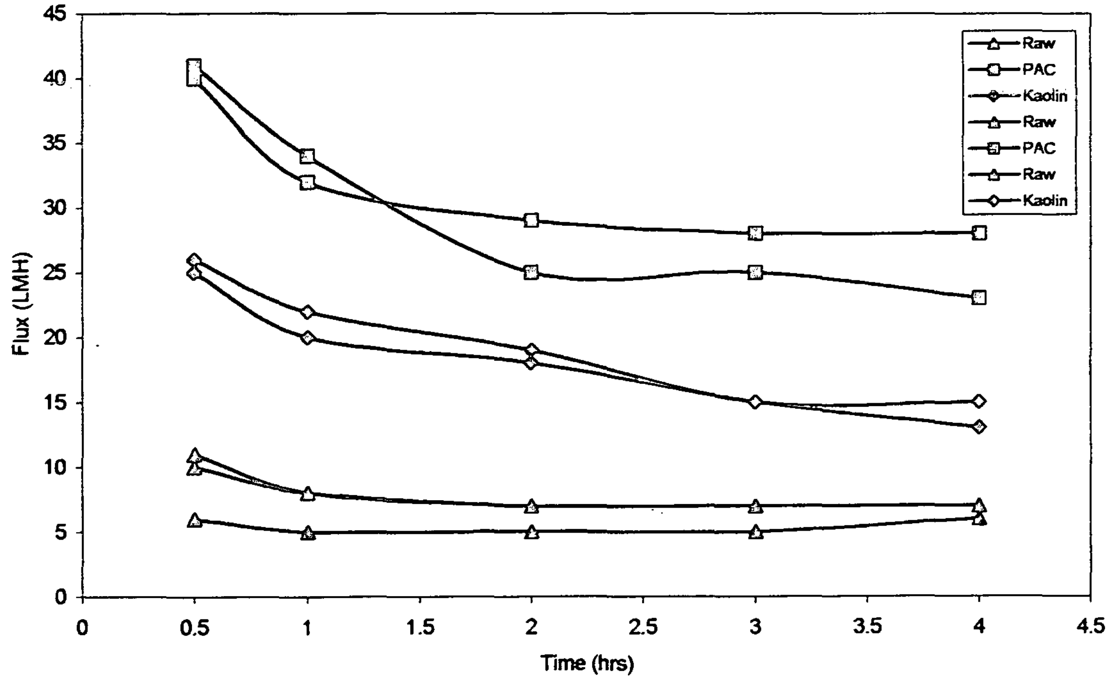


Fig 5.7 Comparison of Different Systems - Flux vs. Time

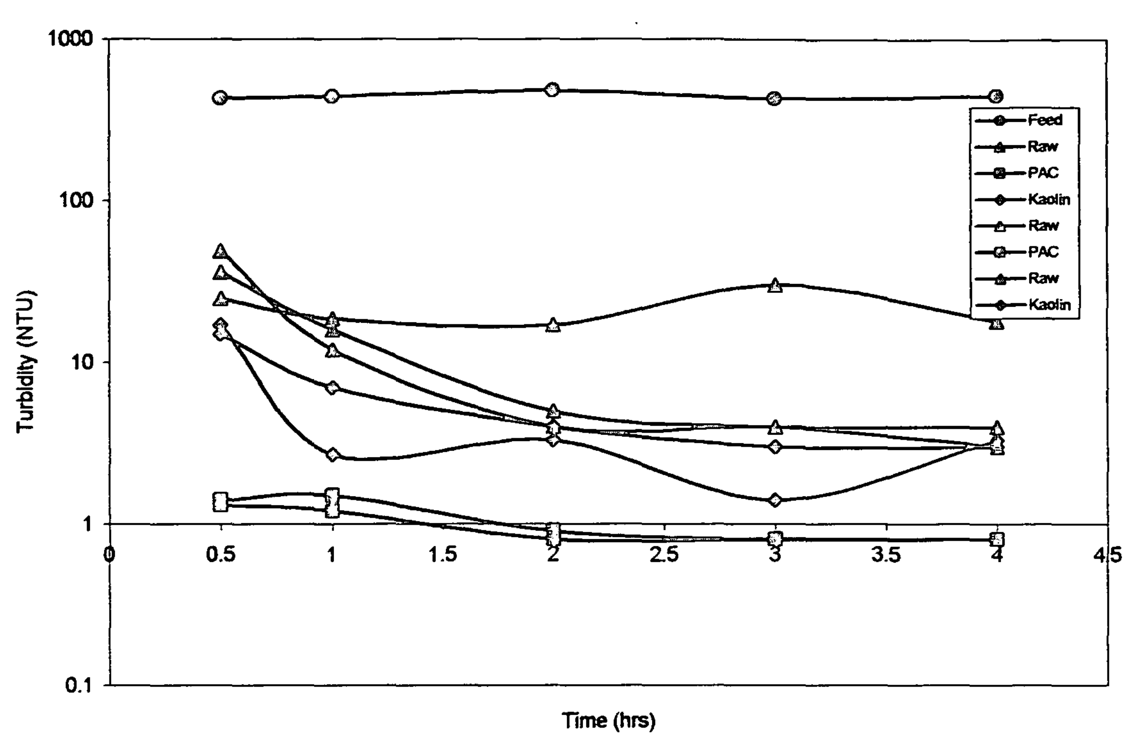


Fig 5.8 Comparison of the Different Systems - Turbidity vs. Time

Figures 5.7 – 5.9 represents a comparison of the different systems. The parameters compared were COD, Flux and Turbidity. The WFMF system clearly produces a permeate quality (in terms of COD and Turbidity) that is better to the WFMF without a precoat and the WFMF system precoated with an inactive precoat. This experiment also showed that the flux produced in the actively precoated system is higher than that in the other two systems investigated.

A similar run (Run 39) was performed with the following adaptations:

a) 40 liters of raw effluent was passed through a raw WFMF tube for 4 hours.

b) The same tube used in (a) was then thoroughly washed with tap water and pre-coated using 5g Kaolin / l water for 1 hour (the active pre-coat). Immediately thereafter 40 liters of raw effluent was passed through the pre-coated WFMF tube for 4 hours.

c) The same tube used in (a), was then thoroughly washed with tap water and pre-coated using 5g PAC / l water for 1 hour (the active pre-coat). Immediately thereafter 40 liters of raw effluent was passed through the pre-coated WFMF tube for 4 hours.

d) repeat c
e) repeat a
f) repeat b

The results of this determination are tabled in Appendix 1. Below follows a graphical representation of the results.

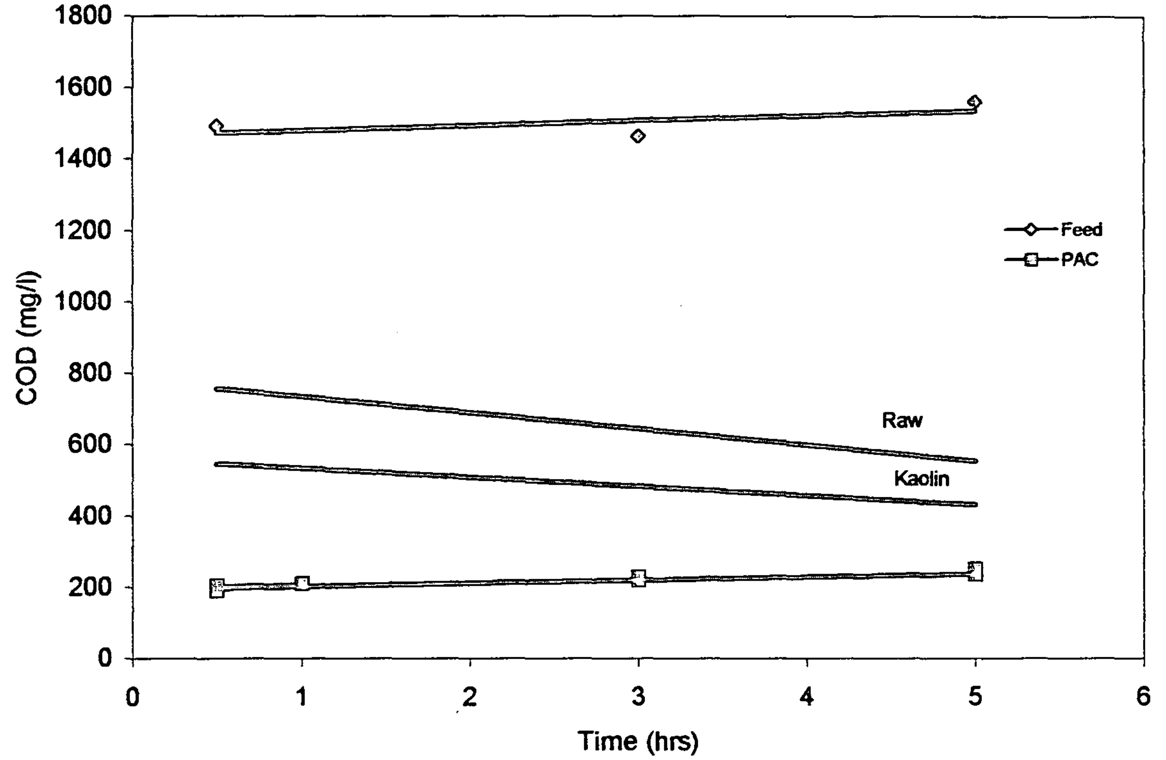


Fig 5.9 Comparison of the Different Systems - COD vs Time

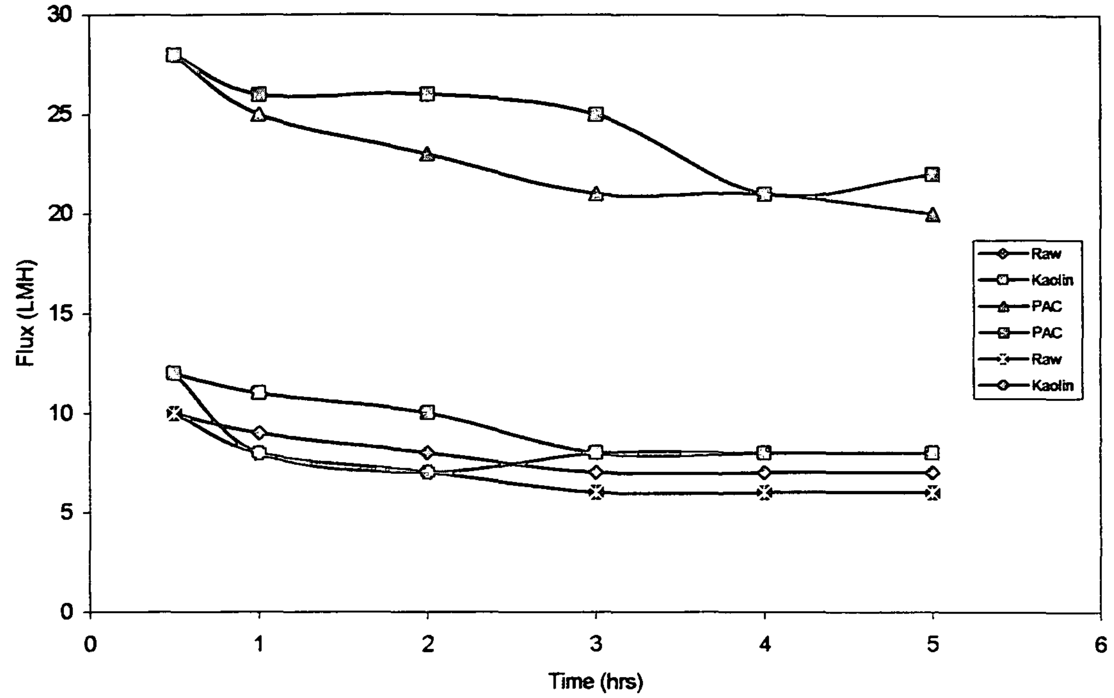


Figure 5.10 Comparison of the Different Systems - Flux vs. Time

Figures 5.9 – 5.10 represents a comparison of the different systems. Similarly to Run 38, the WFMF system produces a permeate quality (in terms of COD) that is superior to the WFMF without a precoat and the WFMF system precoated with an inactive precoat. This experiment also showed that the flux produced in the actively precoated system is higher than that in the other two systems investigated.

The above experiments indicate that the WFMF system precoated with PAC performed better in terms of COD, turbidity and flux than the raw WFMF and the inactively precoated WFMF. Visibly, the permeate produced from an actively precoated MF was also of a clearer quality.

5.6 Evaluation of the Efficiency of PAC Usage

In terms of COD removal, the objective for these experiments were to compare the efficiency of conventional PAC usage to PAC usage in the PAC / WFMF precoated system.

5.6.1. Determining Theoretical removal of COD for Conventional Usage of PAC

The COD removed when PAC was used in it's conventional manner was previously determined (Section 5.4). In this determination, it was found that the amount of COD removed per gram of PAC was in the range of 75-105mg (i.e. 75-105 mg COD/g PAC).

5.6.2 Determining Theoretical COD Removal for PAC / WFMF System

To determine the COD removed in the PAC / WFMF precoated system, the WFMF tube was first precoated with PAC. Thereafter raw effluent was processed by this system. To quantify this system the actual amount of PAC on the tube was also required.

a) Calculation of quantity (g) of PAC on WFMF Tube

$$\text{(Initial volume)(Initial PAC)} = PAC_{TUBE} + PAC_{LINES} + PAC_{LEFT\ IN\ TANK} \qquad \ldots\text{(a)}$$

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

$$(40\ l)(5\ g/l) = PAC_{TUBE} + (6.55\ l)(3.4333\ g/l) + (37.5\ l)(3.3333\ g/l)$$

$$200\ g = PAC_{TUBE} + 22.48\ g + 124.99\ g$$

$$PAC_{TUBE} = 200 - 147.5\ g$$
$$= 52.5\ g$$

The PAC in the 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 amount of PAC on the tube was found to be 52.5g. Hence the theoretical amount of COD (calculated to the nearest one hundred) removed by the PAC precoated WFMF system should be approximately 4000-5500mg COD [(52.5)(75 – 105)] mg/l).

Theoretically, therefore, the PAC precoat on the WFMF should become saturated (Point A on Figure 5.11) as time of PAC usage progresses, which should relate to the theoretical amount of COD removal. At this point a typical graph of COD removed versus Time should show the permeate COD increasing due to the saturation of the PAC precoat (Figure 5.12).

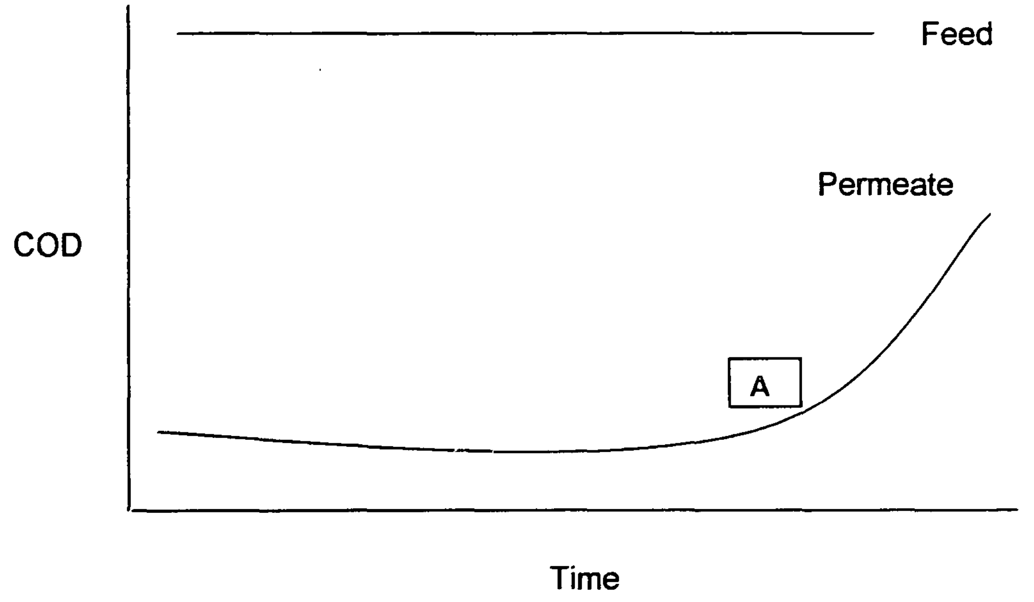


Figure 5.11 Typical COD vs. Time Profile showing saturation

To determine whether this does occur, a similar experiment (to Run 39) was performed, but for a longer time period (Run 40). The results are shown in Table 5.2.

Table 5.2 Run 40 - PAC WFMF

Run Conditions:	
Pre-coat Conc.	5g / l water
Pre-coat Time	1 hour
Pre-coat Volume	40 liters
Run Time	13 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	COD (mg/l)			Turbidity (NTU)		Flux
(hrs)	Feed	Perm	Change	Feed	Perm	LMH
0	PRECOAT CYCLE					
1						
2	1163	64				
3	1160	60			1.12	57
4	1153	68	1085			41
5	1153	115			0.96	33
6	1147	96	1051			35
7	1150	137			0.88	34
8	1162	118	1044			36
9	1151	125			0.85	37
10	1147	119	1028			37
11	1150	124			0.95	38
12	1160	121				38
13	1165	127	1038		0.82	36

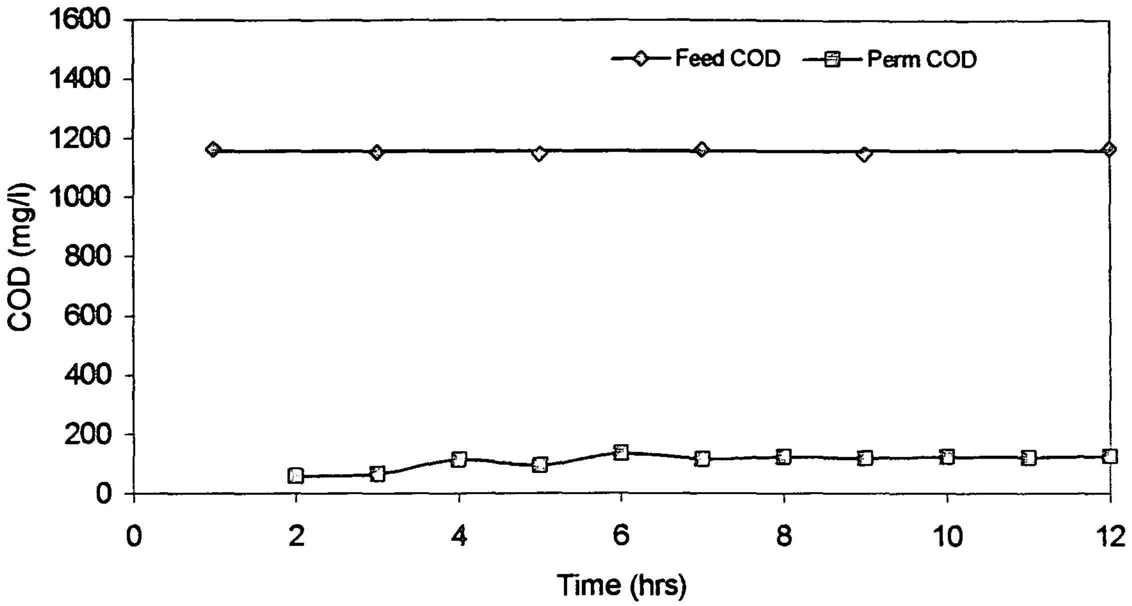


Figure 5.12 Comparison of Feed and Perm COD vs Time

b) Determination of PAC Saturation Point

The time at which PAC should theoretically become saturated was determined as follows.

$$COD_{Adsorbed} = (J_i)(A)(COD_{Fi} - COD_{Pi})\,\Delta t$$

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

J_i - flux (LMH)
A – area (m^2)
COD_{Fi} – feed COD
COD_{Pi} – perm. COD

The area available for filtration is fixed (0.115 m^2). The COD adsorbed was determined for every hour. It was assumed that the flux did not change significantly during that hour. Hence A and J were considered as constants.

Therefore,

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

Figure 5.12 (Run 40) represents the feed and permeate COD as a function of time. The area between the two graphs represents the total amount of COD adsorbed. For this run, the initial flux reading was ignored and the average flux used since from the results table it can be concluded that the flux from the third hour of operation to the thirteenth hour falls within a close range.

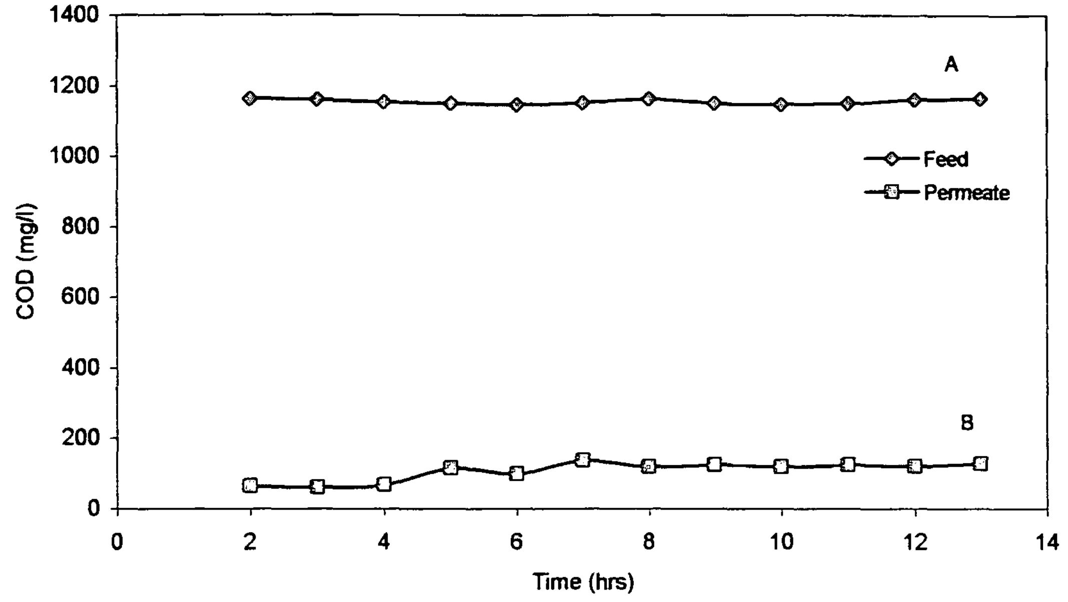


Figure 5.13 Run 40 - Feed and Permeate COD vs Time

From Figure 5.13,

Area under curve = $\int_{0}^{t} [A(t) - B(t)]dt$ ...1

$= \int_{2}^{13} [0.021t + 1154.7] - \int_{2}^{13} [6.021t + 67.03t]$

$= \left(\left[\frac{0.021}{2} t^2 + 1154.7t \right] \right)_2^{13} - \left(\frac{6.021}{2} t^2 + 67.03t \right)_2^{13}$

= 12 942 (mg/l) hr

[Flux (average)][COD removed] = [12 942 (mg/l) hr][4.4 l/hr]

= 56 557 mg COD

Theoretical COD removal = (52.5 g PAC)(105 mg COD / g PAC) using max. COD removal for conventional PAC usage

= 5513 mg COD

To determine how long (in hours) it would take for the PAC to become saturated, the following procedure was followed.

Firstly the COD adsorbed was determined for each hour using equation 1.

Table 5.3 Cumulative COD Removal					
Time	**COD_F**	**COD_P**	**$COD_{Adsorbed}$**	**Flux**	**(Flux)(COD_{Ad})**
(hrs)	**(mg/l)**	**(mg/l)**	**(mg/l)**	**l/hr**	**mg COD**
2	1163	64	1099	6.6	7253
3	1160	60	1100	4.7	5170
4	1153	68	1085	3.8	4123
5	1153	115	1038	4.0	4152
6	1147	96	1051	3.9	4099
7	1150	137	1013	4.1	4153
8	1162	118	1054	4.3	4532
9	1151	125	1026	4.3	4412
10	1147	119	1028	4.4	4523
11	1150	124	1026	4.4	4514
12	1160	121	1039	4.1	4260
13	1165	127	1038	4.3	4463
				Σ	55654

Table 5.4 shows the cumulative COD removed after each hour.

Table 5.4 Cumulative COD Removal	
Time	**Accumulative COD removal**
(hrs)	**(mg COD)**
2	7253
3	12423
4	16546
5	20698
6	24797
7	28950
8	33482
9	37894
10	42417
11	46931
12	51191
13	55654

Secondly using the data in Table 5.4, a graph of cumulated COD removal versus time was constructed.

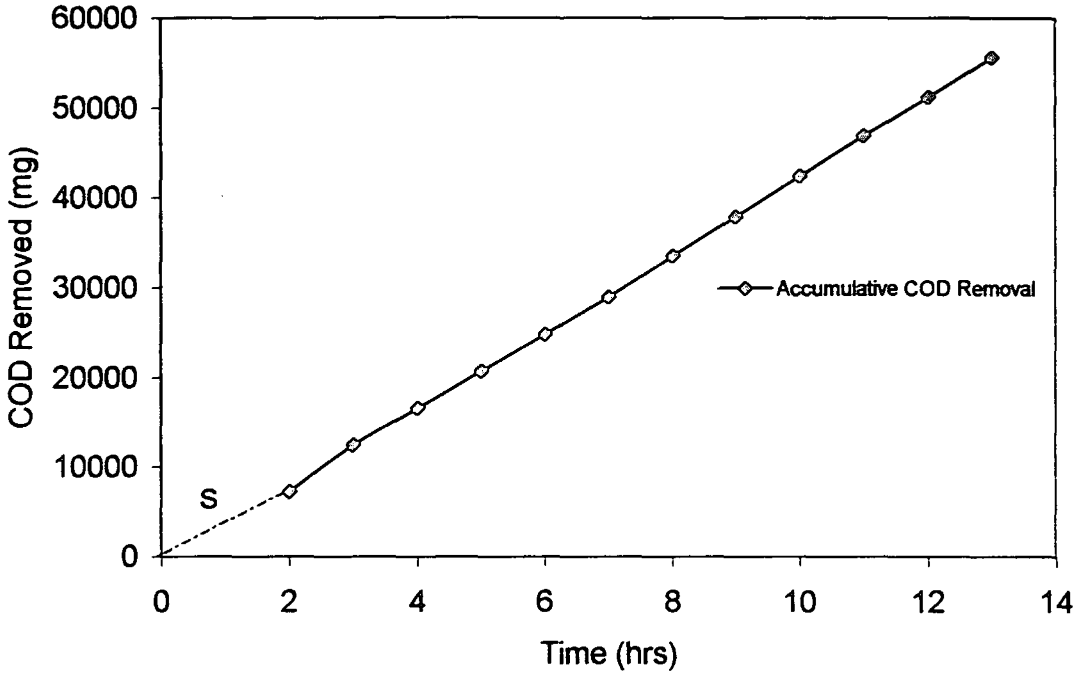


Fig 5.14 **Accumulative COD Removal vs. Time**

The theoretical saturation point (calculated as 5513 mg) is shown as point S on Figure 5.15. By extrapolating the graph the theoretical time for saturation was determined. Thus the time for PAC saturation was determined as approximately 1.2 hours. This implies that the permeate COD should therefore start to increase after 1.2 hours in use in the PAC/WFMF system. However for the duration of this run the system continued removing COD (Figure 5.14) and for the total time (13 hours) approximately 55 000 mg COD was removed. It must therefore be concluded that there is a second mechanism (beside PAC adsorption) occurring in the system that is also responsible for COD removal. At this point, it was realized that it is not within the scope of this investigation to examine the mechanisms responsible. However, a much longer run was performed to determine whether there will be a breakthrough in the COD i.e. the permeate COD will start to increase.

c) Determining COD Breakthrough - Run 41

Initially it was thought that the reduction in COD was mainly due to the adsorptive ability of the PAC and therefore once the adsorptive properties of the PAC became exhausted then the COD of the permeate will correspondingly start to increase. This does not appear to be the case. A possible explanation of this occurrence could be the formation of a secondary layer on the WFMF tube, which acts as a further barrier to the pollutants in the raw effluent. This secondary layer could be formed by the adsorption of particles onto the PAC. The effect of this dynamic layer is the formation of a tight secondary barrier, which also prevents the movement of smaller pollutants through the precoated tube, and hence the stable COD levels. However at some point related to the duration of the experiment there should be a breakthrough in the COD measurements i.e. the permeate COD would start to increase.

To determine this COD breakthrough, it was decided to conduct an experiment whereby a WFMF tube would be precoated once only using 5g PAC per litre of effluent and then raw effluent was processed by the system for 72 hours. All operating conditions were kept constant. The permeate produced was removed from the system and new effluent was introduced to the Active WFMF system (as make-up for the removal of permeate). To prevent drastic changes in the feed quality it was decided to only add new effluent once 10 L of permeate was collected. This translates into a 25% change in feed characteristics. This was allowed to continue for 72 hours. Permeate and feed quality was continuously monitored over this period for COD, flux and turbidity. During this 72 hour period 160 L of raw effluent was processed in the Active WFMF system. 125 L of permeate was recovered representing a 78% water recovery. The result for this determination is represented in Figure 5.16.

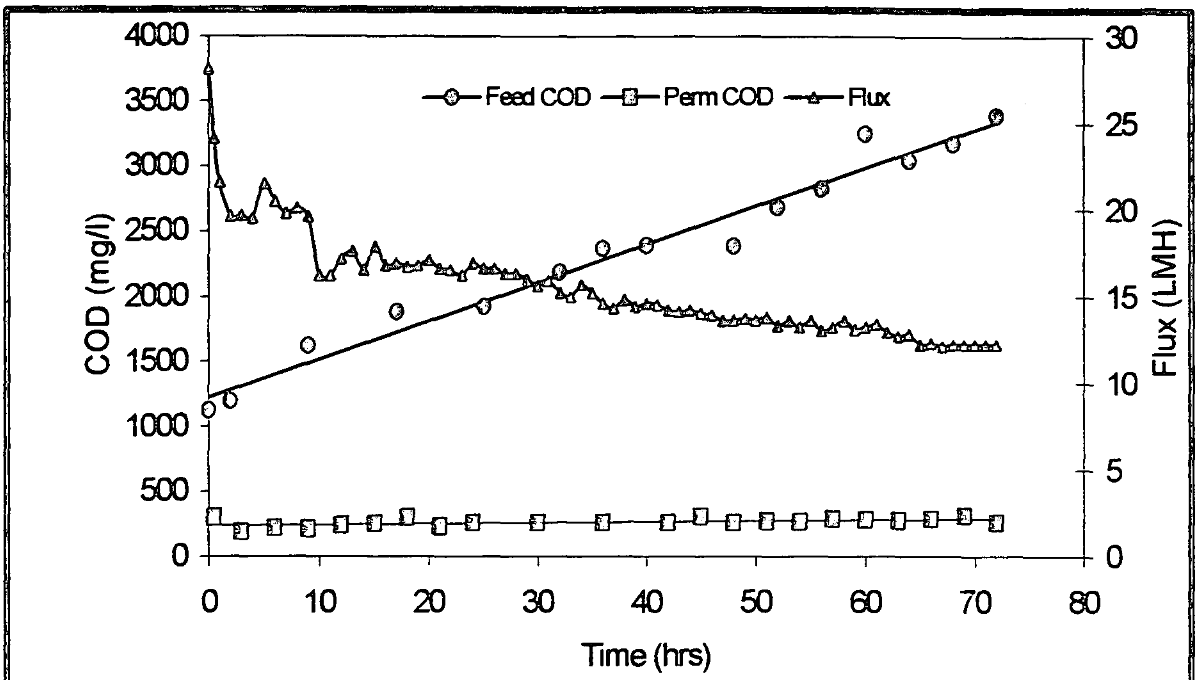


Figure 5.15 Comparison of Feed, Perm COD and Flux vs. Time

The cumulative COD removed was determined (as in Section 5.6.2.2).

Table 5.5 COD Removal

Time	COD in Feed (1)	COD in Permeate. (2)	COD Remove(1-2)	COD Removed	Cumulative COD Removal
hrs	mg.hr/l	mg.hr/l	mg.hr/l	mg	mg
10	13 690	2 392	11 298	28 111	28 111
20	16 631	2465	14 166	26 444	54 555
30	19 572	2539	17 034	30 654	85 209
40	22 514	2612	19 902	32 773	117 982
50	25 456	2686	22 770	34 916	152 898
60	28 397	2759	25 638	37 678	190 576
72	37 959	3408	34 552	47 319	237 894

The theoretical saturation point (determine previously) was equivalent to a COD removal of 5500 mg and PAC usage of 1.2 hours. In this run, 237 894 mg COD was removed and the PAC was used for 72 hours without a COD breakthrough occurring (It must be pointed out that at this point samples of raw feed was exhausted and therefore the run was stopped).

The following observations were also made during the run. The feed COD increased (from 1123 to 3390 mg/l). The permeate COD averaged 260 mg/l even though the feed COD continuously increased. The turbidity readings were below 1, with more than 70% of them falling below 0.6. The fluxes dropped from 28 to 12 LMH over the time period. The feed colour was bluish black. The permeate was clear.

5.7 Summary

The findings from the experiments can be summarized as follows:

a) PAC can be used as a suitable precoat on a WFMF tube.

b) The performance of the different systems considered can be summarized as follows:

	WFMF	Kaolin / WFMF	PAC / WFMF
Feed COD (mg/l)	1200 - 1500		
Average Permeate COD	400 - 800	400 - 600	200 - 300
Feed Turbidity (NTU)	> 400		
Average Permeate Turb.	20 - 50	3 - 20	0.5 – 2
Flux (LMH)	5 - 12	10 - 20	25 - 40

c) The COD reduction for conventional usage of PAC was determined at 70 - 105 mg COD / g PAC. The PAC precoated WFMF removed 4500 mg COD / g PAC. For the duration of this experiment, one can therefore conclude that the PAC precoated WFMF is performing approximately 40 times better than the conventional usage of PAC.

d) When PAC is used in its conventional manner, it would become saturated after a period of time. In this investigation, that time was determined at 1.2 hours. However in using PAC as a precoat for a WFMF, this method of use has shown that the time of usage can be extended.

Chapter 6

Conclusion and Recommendations

The objective of this study was to develop and evaluate an active precoat that would improve crossflow wovenfibre microfiltration. A comprehensive experimental program was devised and implemented. The different processes considered were test-cell systems (representing the conventional usage of PAC) and continuous CF systems using WFMF. In continuous WFMF systems three systems were considered. These were a WFMF system (without precoat), a WFMF system precoated with Kaolin (non-active precoat) and a WFMF system precoated with PAC (active precoat). The parameters that were investigated to evaluate the processes were COD, turbidity and flux. A raw effluent that was provided by a textile mill was used as the test solution.

Kaolin was chosen as the inactive precoat. PAC was chosen as the active precoat. A test-cell was used to duplicate PAC usage in its conventional manner.

In the test-cell (conventional) system, the reductions in permeate COD was directly related to the amount of PAC added to the effluent up to a point. The change in permeate COD rapidly increased (up to a certain mass of PAC the gradient of the graph was steep) thereafter increasing gradually and finally levelling off as the amount of PAC added to the fixed volume of effluent increased. Measurements of turbidity revealed a small decrease as compared to the feed turbidity. It was virtually impossible to measure flux [permeate either exited the test cell immediately (as was the case for samples with high masses of PAC in them) or literally hours (as was the case for samples with low masses of PAC in them)]. The amount of COD removed per gram of PAC was calculated to be in the range of 70 – 105 mg.

From the test-cell experiments it was decided to use a precoat concentration of 5g PAC/l effluent. For the continuous systems precoating was done at the beginning of the run. Precoating was done consistently at 5g/l effluent, precoating volume of 40 l and precoating time of 1 hour. All of the Runs (except Run 41) were performed in total recycle i.e. reject and permeate were returned to the feed tank. In Run 41 the permeate was removed from the system and fresh feed was added to the system.

In the continuous WFMF system the WFMF tube without precoat was capable of reducing the feed COD. However the reduction was insignificant at first and only became pronounced (>50%) after approximately 4 hours from start-up. The permeate turbidity decreased, however it was still way above generally acceptable levels. Flux measurements were poor in this system. A physical examination of the permeate also revealed extensive colouration.

The continuous Non-active WFMF system also was able to reduce the feed COD. However it displayed a marginal improvement over the WFMF (without precoat) system. The maximum COD reduction possible under these conditions was determined as 70 %. The system was able to reduce turbidity but the turbidities were still above 1. Over a five-hour period the system displayed poor fluxes (steady-state flux of ~8 LMH). There was still a bluish-black colour in the permeate.

The continuous Active WFMF system reduced the COD by more than 85%. Turbidities achieved were less than 0.8 NTU. Over a five-hour period the system displayed steady-state fluxes of ~22 LMH). The permeate was clear and free of any traces of odor. Longer runs were perfomed (13 hours) using this system. Over the duration of the run the average feed COD was 1156 mg/l and a permeate with an average COD of 110 mg/l was produced. This represented a COD reduction of 90%. The permeate turbidities settled in the 0.8 NTU region with steady-state fluxes of 35 LMH.

Using the continuous Active WFMF system, a 72 hour run was perfomed whereby the permeate was continuously removed from the system and new, raw feed was introduced to the system. The WFMF tube was precoated with PAC once only at the start of the run. Over the 72 hour period 160 l of raw effluent was pumped through the PAC precoated WFMF and 125 l of permeate was recovered. This represented a 78% recovery. During this time the feed COD increased from 1123 mg/l to 3390 mg/l. However, the permeate COD continuously averaged 260mg/l. This represented a COD reduction of >85% over 3 days with only one precoat cycle. During this time the average turbidity was below 0.55 NTU with more than 67% of the turbidity measurements falling below 0.55 NTU. Over the 72-hour period the fluxes ranged from 28 to 12 LMH. For this system it was found that approximately 4500 mg COD could be removed per gram of PAC. Using the same effluent in a test cell it was found that approximately 75 - 105 mg COD was removed per gram of PAC. Hence the continuous system perfomed more favourably.

Recommendations

1. The system should be tested against a range of feeds.
2. The effect of changing operating variables (velocity, pressure, precoating time, precoating concentration) should be investigated.
3. Other sources of active carbonaceous precoats e.g. boiler ash, coconut shells etc. should be investigated as substitutes for PAC.
4. Longer run times are needed to ascertain COD breakthrough.
5. Cleaning strategies need to be developed.
6. PAC disposal/regeneration techniques are required
7. Investigations into the actual mechanism of COD reduction should be investigated.

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Appendix 1

A1.1 Properties and Calculation of PAC on WFMF Tube

Typical Properties

Appearance - fine black powder
Iodine number - 600mg/g min
Bulk density - 450g/l
Moisture - 8% max
Ash content - 15% max
Particle size - >90% passes a 45 micrometer screen (ASTM # 325)

Calculation of quantity (g) of PAC on WFMF Tube

$$\begin{aligned}
\text{(Initial volume)(Initial PAC)} &= \text{PAC}_{\text{TUBE}} + \text{PAC}_{\text{LINES}} + \text{PAC}_{\text{LEFT IN TANK}} \\
(V_i)(\text{PAC}_i) &= \text{PAC}_{\text{TUBE}} + (V_{\text{LINES}})(\text{PAC}_{\text{LINES}}) + (V_F)(\text{PAC}_F) \\
(40\ \text{l})(5\ \text{g/l}) &= \text{PAC}_{\text{TUBE}} + (6.55\ \text{l})(3.4333\ \text{g/l}) + (37.5\ \text{l})(3.3333\ \text{g/l}) \\
200\ \text{g} &= \text{PAC}_{\text{TUBE}} + 22.48\ \text{g} + 124.99\ \text{g} \\
\text{PAC}_{\text{TUBE}} &= 200 - 147.5\ \text{g} \\
&= 52.5\ \text{g}
\end{aligned}$$

Appendix 2

Results

Run 25

Objective

To identify a suitable substance that will form a stable pre-coat on a WFMF.

Experimental

PAC was chosen as the substance to be used to form a pre-coat for the WFMF tubes. Firstly it was necessary to determine whether PAC forms a stable layer on the WFMF flat sheet. In the test-cell varying concentrations of PAC per liter of industrial effluent were made up and allowed to stand for a period of 2 hours in a mechanical shaker. At the end of this cycle the resulting solutions were then filtered in the test cell, which has a WFMF disc as the filtering medium, at a fixed pressure. Permeates were then collected and COD analyses performed.

Results:

Table A2.1 COD Measurements – Run25

Run Conditions:		
	Mixing Time	2 hours
	Filtration Pressure	1 bar
	Temperature	293 K
	Feed COD	1068 mg/l
	Volume	1 liter

Concentration g PAC / l Effluent	COD mg/l
5	282
8	249
10	226
12	218
15	208
20	204

Run 26

Objective

This run was similar to Run 25 and performed to ascertain repeatability.

Experimental

As for Run 25.

Results

Table A2.2 COD Measurements - Run 26

Run Conditions:

Mixing Time	2 hours
Filtration Pressure	1 bar
Temperature	293 K
Feed COD	1117 mg/l
Volume	1 liter

Concentration g PAC / l Effluent	**COD mg/l**
5	361
10	236
15	217
20	201

Run 27

Objective

To determine the effect of the raw WFMF disc on the changes in COD, using an industrial effluent as the feed.

Experimental

Runs 25/26 show that the combined PAC/WFMF system is having an effect on the COD of the resulting permeates. In order to determine whether the filtering medium (the WFMF disc), the PAC or both in combination is responsible for this COD reduction the following experiment was conducted. The raw effluent was first filtered in the test cell using the WFMF disc as the separating medium. The resulting permeate was separated into one liter aliquots. To each one PAC was added with concentrations ranging from 1g to 20g per liter permeate. Measurements of the feed and resulting permeates COD's were then made. The conditions of the experiments were maintained constant.

Results

Table A2.3 COD Measurements - Run 27

Run Conditions:

Mixing Time	2 hours
Filtration Pressure	1 bar
Temperature	293 K
Feed COD	1309 mg/l
Permeate COD	1086 mg/l
Volume	1 liter

Concentration g PAC / l Effluent	**Permeate COD mg/l**	**Change in COD mg/l**
1	502	584
5	403	683
8	341	745
10	312	774
12	299	787
15	287	799
20	240	846

Run 28

Objective

This run was similar to Run 27 and performed to ascertain repeatability.

Experimental

The same procedure as in Run 27 was applied in Run 28.

Results

Table A2.4 COD Measurements - Run 28

Run Conditions:

Mixing Time	2 hours
Filtration Pressure	1 bar
Temperature	293 K
Feed COD	1309 mg/l
Permeate COD	1286 mg/l
Volume	1 liter

Concentration **g PAC / l Effluent**	**COD** **mg/l**	**Change in COD** **mg/l**
1	936	350
5	604	682
8	447	839
10	414	872
12	375	911
15	326	960
20	212	1074

Run 29

Objective

To compare the changes in permeate COD's for a test-cell system using different quantities of PAC per liter effluent.

Experimental

Runs 27/28 show that the WFMF separating disc is removing some COD from the feed effluent. Since this COD removal represents approximately 10 - 20 % raw feed COD, it was decided that future test-cell runs would follow the same experimental procedure as applied in Run 25 (i.e. PAC will be mixed directly with the unfiltered raw effluent).

Run 25 was thus repeated so that the amount of COD removed per gram of PAC can be determined for the test-cell system. As before all other experimental conditions were maintained constant.

Results

Table A2.5 COD Measurements - Run 29

Run Conditions:

Mixing Time	2 hours
Filtration Pressure	1 bar
Temperature	293 K
Feed COD	1309 mg/l
Volume	1 liter

Concentration g PAC / l Effluent	COD mg/l	Change in COD mg/l
1	499	810
5	429	880
8	341	968
10	312	997
12	293	1016
15	287	1022
20	254	1055

Run 31

Objective

To determine the amount of COD removed per gram of PAC for this effluent at these experimental conditions for a test-cell system.

Experimental

Runs 25-29 show that there is a reduction in COD when PAC is used in its conventional manner. In order to compare this usage of PAC to other systems, e.g. a continuous system, one needs to determine how much of COD per gram PAC is being removed in each of the different processes. By comparing these ratios (i.e. COD removed: g PAC) one can then see differences in each of the processes and all factors considered, one could then infer which is a more efficient process for particular applications. The same experimental procedure as applied in Run 25 was followed. As before all other experimental conditions were maintained constant.

Results

Table A2.6 COD Measurements - Run 31

Run Conditions:

Mixing Time	2 hours
Filtration Pressure	1 bar
Temperature	293 K
Feed COD	1276 mg/l
Volume	1 liter

Concentration **g PAC / l Effluent**	**COD** **mg/l**	**Change in COD** **mg/l**
0.1	1108	168
0.5	986	290
0.8	917	359
2	817	459
5	519	757
8	457	819
10	428	848
12	415	861
15	403	873

Run 32

Objective

To determine the amount of COD removed per gram of PAC for this effluent at these experimental conditions in a test-cell.

Experimental

As per Run 25.

Results

Table A2.7 COD Measurements - Run 32		
Run Conditions:		
Mixing Time		2 hours
Filtration Pressure		1 bar
Temperature		293 K
Feed COD		1225
Volume		1 liter
Concentration	**COD**	**Change in COD**
g PAC / l Effluent	**mg/l**	**mg/l**
0.1	1084	141
0.5	1045	180
2	925	300
5	633	592
8	399	826
10	276	949
12	263	962
15	240	985
20	227	998

Run 33

Objective

To determine the amount of COD removed per gram of PAC for this effluent at these experimental conditions in a test-cell.

Experimental

As per Run 25.

Results

Table A2.8 COD Measurements - Run 33

Run Conditions:		
Mixing Time	2 hours	
Filtration Pressure	1 bar	
Temperature	293 K	
Feed COD	1123	
Volume	1 liter	
Concentration	**COD**	**Change in COD**
g PAC / l Effluent	**mg/l**	**mg/l**
0.1	1023	100
0.4	906	217
0.7	810	313
1.0	695	428
3.0	491	632
5.0	399	724

Run 35

Objective

To determine the performance of a combined PAC/WFMF system run in the continuous cross flow mode versus the performance of PAC in a test-cell (representing conventional usage of PAC).

Experimental

In order to compare the test-cell system to other systems, e.g. a continuous system, one needs to determine how much of COD per gram PAC is being removed in each of the different processes. This experiment was performed to determine differences between the test-cell system and the PAC/WFMF continuous system. The same experimental procedure as applied in Run 25 was followed for the test-cell determinations. In the PAC/WFMF continuous system, it was first necessary to determine whether any significant changes in terms of COD and fluxes could be attained. To determine this a feed solution, a real industrial effluent, was passed through a pre-coated WFMF. As a first attempt, 480g PAC was added to forty liters of water, translating to 12g PAC / liter water. This solution was then circulated through the WFMF tube for a fixed time period and at fixed experimental conditions. Once the pre-coating cycle was completed, effluent was then immediately pumped through the pre-coated WFMF tube thereby ensuring that the pre-coat cake does not collapse. This treatment cycle was allowed to proceed for a suitable time period.

Results

Table A2.9 COD Measurements - Run 35 Test-cell

Run Conditions:

Mixing Time	2 hours
Filtration Pressure	1 bar
Temperature	293 K
Feed COD	1068 mg/l
Volume	1 liter

Concentration g PAC / Effluent	**COD mg/l**	**Change in COD mg/l**
5	282	786
8	249	819
10	226	842
12	218	850
15	208	860
20	204	864

Table A3.10 COD Measurements - Run 35 - Continuous

Run Conditions:

Pre-coat Conc.	12g PAC / l H_2O
Pre-coat Time	1 hour
Pre-coat Volume	40 l
Run Time	4 hours
Filtration Area	$0.11m^2$
Filtration Pressure	1 bar
Temperature	293 K
Feed COD	1068 mg/l
Feed Volume	40 liters

Time hours	**COD mg/l**	**Change in COD mg/l**	**Flux LMH**
1	**Pre-coat Cycle Time**		
2	116	952	53
3	142	926	50
4	101	967	35
5	87	981	32

Run 36

Objective

To determine the performance of a combined PAC/WFMF system run in the continuous cross flow mode versus the test-cell.

Experimental

A similar run (as per Run 35) was performed for purposes of repeatability.

Results

Table A2.11 COD Measurements - Run 36 Test-cell

Run Conditions:

Mixing Time	2 hours
Filtration Pressure	1 bar
Temperature	293 K
Feed COD	1177 mg/l
Volume	1 liter

Concentration	**COD**	**Change in COD**
g PAC / Effluent	**mg/l**	**mg/l**
5	361	816
10	236	941
15	217	960

Table A2.12 COD Measurements - Run 36 - Continuous	
Run Conditions:	
Pre-coat Conc.	12g PAC / l H_2O
Pre-coat Time	1 hour
Pre-coat Volume	40 l
Run Time	4 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Feed COD	1177 mg/l
Feed Volume	40 liters

Time hours	COD mg/l	Change in COD mg/l	Flux LMH
1	Pre-coat Cycle Time		
2	120	1057	38
3	145	1032	32
4	105	1072	32
5	95	1082	35

Run 37

Objective

To determine the performance of other WFMF systems, as compared to a PAC/WFMF system, run in the continuous cross flow mode as applied to a real industrial effluent.

Experimental

In this experiment the PAC/WFMF SYSTEM was compared to that of three other systems viz.:

a) Using a non-active pre-coat to coat a WFMF tube and then pass a real effluent through it.
b) Using a WFMF tube alone and pass a real effluent through it.
c) Test-cell determinations.
d) Using an active precoat to coat a WFMF tube and then pass a real effluent through it.

The practical components of this exercise were divided into four parts viz.:

a) 40 liters of raw effluent was passed through a raw WFMF tube for 3 hours
b) The same tube used in (a), was then thoroughly washed with tap water and pre-coated using 5g kaolin / l water for 1 hour (the non-active pre-coat). Immediately thereafter 40 liters of raw effluent was passed through the pre-coated WFMF tube for 3 hours.
c) The same procedure used for a test-cell (as per Run 25) was performed.
d) The same tube used in (a) and (b), was again then thoroughly washed with tap water and pre-coated using 5g PAC / l water for 1 hour (the active pre-coat). Immediately thereafter 40 liters of raw effluent was passed through the pre-coated WFMF tube for 3 hours.

In each of these runs the operating conditions were kept constant. At suitable time intervals samples were collected and analyzed for COD, Turbidity and Color.

Results:

Table A2.13 Run 37 – Test-cell	
Run Conditions:	
Mixing Time	2 hours
Filtration Pressure	1 bar
Temperature	293 K
Feed COD	1427 mg/l
Volume	1 liter
Concentration	5g PAC / l Effluent

COD	Change in COD	Color (PtCo APHA)		Turbidity
mg/l	mg/l	Feed	Perm	Perm
456	971	480	300	179

Table A2.14 Run 37 - Raw WFMF	
Run Conditions:	
Run Time	3 hours
Filtration Area	$0.11m^2$
Filtration Pressure	1 bar
Temperature	293 K
Flow Velocity	1 m/s
Feed Volume	40 liters

Time	COD (mg/l)			Color (PtCo APHA)		Turbidity
hours	Feed	Perm	Change	Feed	Perm	NTU
0.5	1432	825	607			
1		684				
2	1523	542	981			
3	1545	432	1113	472	408	179

Table A2.15 Run 37 - Kaolin WFMF

Run Conditions:

Pre-coat Conc.	5g / l water
Pre-coat Time	1 hour
Pre-coat Volume	40 liters
Run Time	3 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Flow Velocity	1 m/s
Feed Volume	40 liters

Time	COD (mg/l)			Color (PtCo APHA)		Turbidity
hours	Feed	Perm	Change	Feed	Perm	NTU
0.5	1413	435	978			
1		684				
2	1432	524	908			
3	1447	402	1045	510	411	4.5

Table A2.16 Run 37 - PAC/WFMF SYSTEM

Run Conditions:

Pre-coat Conc.	5g / l water
Pre-coat Time	1 hour
Pre-coat Volume	40 liters
Run Time	3 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Flow Velocity	1 m/s
Feed Volume	40 liters

Time	COD (mg/l)			Color (PtCo APHA)		Turbidity
hours	Feed	Perm	Change	Feed	Perm	NTU
0.5	1447	205	1242			
1						
2	1452	229	1223			
3	1541	251	1290	502	370	1.9

Run 38

Objective

To determine the permeate quality, by measuring it's COD, when a change in the order with which the WFMF tube is pre-coated and comparing these different systems to a PAC/WFMF SYSTEM.

Experimental

Run 37 shows that the PAC/WFMF SYSTEM performs more favourably than the other systems tested in terms of the measured parameters. However one may still point out that the 'COD reduction properties' of the other systems e.g. the Kaolin from the Kaolin/WFMF system may still be residing in the WFMF tube and subsequently aiding the PAC/WFMF system in reducing the COD, and the other measured variables. In order to show that the PAC/WFMF system is performing more favourably than the other systems the following set of experiments were performed.

The experimental procedure is similar to that of Run 37 with the following adaptations:

e) 40 liters of raw effluent was passed through a raw WFMF tube for 4 hours.

f) The same tube used in (a), was then thoroughly washed with tap water and pre-coated using 5g PAC / l water for 1 hour (the active pre-coat). Immediately thereafter 40 liters of raw effluent was passed through the pre-coated WFMF tube for 4 hours.

g) The same tube used in (a) and (b), was again then thoroughly washed with tap water and pre-coated using 5g Kaolin / l water for 1 hour (the active pre-coat). Immediately thereafter 40 liters of raw effluent was passed through the pre-coated WFMF tube for 4 hours.

h) Repeat (a)

i) Repeat (b)

j) Repeat (a)

k) Repeat (c)

In each of these runs the operating conditions were kept constant. At suitable time intervals samples were collected and analyzed for COD and Turbidity. Measurements of Flux were also recorded. This then formed the basis of differentiating between the processes.

Results:

Table A2.17 Run 38 - Raw WFMF

Run Conditions:

Run Time	4 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	COD (mg/l)			Turbidity (NTU)		Flux
hours	Feed	Perm	Change	Feed	Perm	LMH
0.5	1150	460	690	430	24.9	6
1					18.6	5
2		418			17.1	5
3					30.4	5
4	1178	419	759		18.1	6

Table A2.18 Run 38 - PAC WFMF

Run Conditions:

Pre-coat Conc.	5g / l water
Pre-coat Time	1 hour
Pre-coat Volume	40 liters
Run Time	4 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	**COD (mg/l)**			**Turbidity (NTU)**		**Flux**
hours	**Feed**	**Perm**	**Change**	**Feed**	**Perm**	**LMH**
0.5	1220	212	1008	482	1.41	41
1					1.45	34
2		203			0.85	25
3					0.82	25
4	1290	207	1083		0.75	23

Table A2.19 Run 38 – Kaolin WFMF SYSTEM

Run Conditions:

Pre-coat Conc.	5g / l water
Pre-coat Time	1 hour
Pre-coat Volume	40 liters
Run Time	4 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	**COD (mg/l)**			**Turbidity (NTU)**		**Flux**
Hours	**Feed**	**Perm**	**Change**	**Feed**	**Perm**	**LMH**
0.5	1135	459	676	558	17.2	25
1					2.68	20
2		351			3.34	18
3					1.35	15
4	1084	337	747		3.34	13

Table A2.20 Run 38 - Raw WFMF	
Run Conditions:	
Run Time	4 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	**COD (mg/l)**			**Turbidity (NTU)**		**Flux**
hours	**Feed**	**Perm**	**Change**	**Feed**	**Perm**	**LMH**
0.5	1105	523	582	415	49.3	11
1					12.3	8
2		404			4.3	7
3					3.5	7
4	1069	357	712		3.1	7

Table A2.21 Run 38 - PAC WFMF

Run Conditions:

Pre-coat Conc.	5g / l water
Pre-coat Time	1 hour
Pre-coat Volume	40 liters
Run Time	4 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	COD (mg/l)			Turbidity (NTU)		Flux
hours	Feed	Perm	Change	Feed	Perm	LMH
0.5	1170	195	975	451	1.31	40
1					1.23	32
2		212			0.82	29
3					0.75	28
4	1024	219	805		0.81	28

Table A2.22 Run 38 - Raw WFMF

Run Conditions:

Run Time	4 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	COD (mg/l)			Turbidity (NTU)		Flux
hours	Feed	Perm	Change	Feed	Perm	LMH
0.5	1192	457	735	432	35.7	10
1					15.5	8
2		382			5.2	7
3					3.9	7
4	1107	320	787		3.5	7

Table A2.23 Run 38 – Kaolin WFMF SYSTEM

Run Conditions:

Pre-coat Conc.	5g / l water
Pre-coat Time	1 hour
Pre-coat Volume	40 liters
Run Time	4 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	COD (mg/l)			Turbidity (NTU)		Flux
Hours	Feed	Perm	Change	Feed	Perm	LMH
0.5	1187	457	730	470	15.2	26
1					7.2	22
2		352			4.3	19
3					3.4	15
4	1037	325	712		3.1	15

Run 39

Objective

To determine the permeate quality, by measuring it's COD, when a change in the order with which the WFMF tube is pre-coated and comparing these different systems to a PAC/WFMF SYSTEM.

Experimental

This run was similar to that of Run 38.

The experimental procedure is similar to that of Run 37 with the following adaptations:

a) 40 liters of raw effluent was passed through a raw WFMF tube for 4 hours.
b) The same tube used in (a) was then thoroughly washed with tap water and pre-coated using 5g Kaolin / l water for 1 hour (the active pre-coat). Immediately thereafter 40 liters of raw effluent was passed through the pre-coated WFMF tube for 4 hours.
c) The same tube used in (a), was then thoroughly washed with tap water and pre-coated using 5g PAC / l water for 1 hour (the active pre-coat). Immediately thereafter 40 liters of raw effluent was passed through the pre-coated WFMF tube for 4 hours.

The above experiments were done in duplicate. In the second set the order was changed to c, then a and finally b. In each of these runs the operating conditions were kept constant. At suitable time intervals samples were collected and analyzed for COD and Turbidity. Measurements of Flux were also recorded. This then formed the basis of differentiating between the processes.

Results:

Table A2.24 Run 39 - Raw WFMF						
Run Conditions:						
	Run Time					5 hours
	Filtration Area					$0.11m^2$
	Filtration Pressure					1 bar
	Temperature					293 K
	Inlet Flow Velocity					1 m/s
	Feed Volume					40 liters
Time	**COD (mg/l)**			**Turbidity (NTU)**		**Flux**
Hours	**Feed**	**Perm**	**Change**	**Feed**	**Perm**	**LMH**
0.5	1492	825	667			10
1		684				9
2						8
3	1463	542	779			7
4						7
5	1560	432	1128		3.1	7

Table A2.25 Run 39 – Kaolin WFMF SYSTEM						
Run Conditions:						
	Pre-coat Conc.					5g / l water
	Pre-coat Time					1 hour
	Pre-coat Volume					40 liters
	Run Time					5 hours
	Filtration Area					$0.11m^2$
	Filtration Pressure					1 bar
	Temperature					293 K
	Inlet Flow Velocity					1 m/s
	Feed Volume					40 liters
Time	**COD (mg/l)**			**Turbidity (NTU)**		**Flux**
Hours	**Feed**	**Perm**	**Change**	**Feed**	**Perm**	**LMH**
0.5	1413	435	978			12
1		684				11
2						10
3	1432	524	908			8
4						8
5	1447	402	1045		4.54	8

Table A2.26 Run 39 - PAC WFMF

Run Conditions:

Pre-coat Conc.	5g / l water
Pre-coat Time	1 hour
Pre-coat Volume	40 liters
Run Time	5 hours
Filtration Area	$0.11m^2$
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	**COD (mg/l)**			**Turbidity (NTU)**		**Flux**
Hours	**Feed**	**Perm**	**Change**	**Feed**	**Perm**	**LMH**
0.5	1447	205	1242			28
1		211				25
2						23
3	1452	229	1223			21
4						21
5	1541	251	1290		0.75	20

Table A2.27 Run 39 - PAC WFMF

Run Conditions:

Pre-coat Conc.	5g / l water
Pre-coat Time	1 hour
Pre-coat Volume	40 liters
Run Time	5 hours
Filtration Area	$0.11m^2$
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	**COD (mg/l)**			**Turbidity (NTU)**		**Flux**
Hours	**Feed**	**Perm**	**Change**	**Feed**	**Perm**	**LMH**
0.5	1457	190	1267			28
1						26
2		211				26
3	1452	219	1233			25
4						21
5	1521	237	1284		0.82	22

Table A2.28 Run 39 - Raw WFMF

Run Conditions:

Run Time	5 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	COD (mg/l)			Turbidity (NTU)		Flux
Hours	Feed	Perm	Change	Feed	Perm	LMH
0.5	1447	797	650			10
1						8
2		700				7
3	1523	623	900			6
4						6
5	1535	570	965		3.92	6

Table A2.29 Run 39 – Kaolin WFMF SYSTEM

Run Conditions:

Pre-coat Conc.	5g / l water
Pre-coat Time	1 hour
Pre-coat Volume	40 liters
Run Time	5 hours
Filtration Area	0.11m^2
Filtration Pressure	1 bar
Temperature	293 K
Inlet Flow Velocity	1 m/s
Feed Volume	40 liters

Time	COD (mg/l)			Turbidity (NTU)		Flux
Hours	Feed	Perm	Change	Feed	Perm	LMH
0.5	1427	505	922			12
1		577				8
2						7
3	1432	492	940			8
4						8
5	1501	422	1079		3.24	8

Run 40

Objective

To determine whether a once only pre-coat would consistently yield permeate of a suitable quality over a lengthy time period.

Experimental

The previous experiments (Run's 35-39), were performed to ascertain whether any changes in permeate quality is brought about by the different systems (therefore the runs were performed for only a short period of time). In this run, it was decided to pre-coat the WFMF tube once only at the beginning of the run and thereafter pass raw effluent through this system for a suitable, lengthy time period. The experimental procedure is similar to that of Run 37.

As before the operating conditions were kept constant. At suitable time intervals samples were collected and analyzed for COD. Measurements of Flux were also recorded.

Results:

Table A2.30 Run 40 - PAC WFMF						
Run Conditions:						
Pre-coat Conc.					5g / l water	
Pre-coat Time					1 hour	
Pre-coat Volume					40 liters	
Run Time					13 hours	
Filtration Area					$0.11m^2$	
Filtration Pressure					1 bar	
Temperature					293 K	
Inlet Flow Velocity					1 m/s	
Feed Volume					40 liters	
Time	**COD (mg/l)**			**Turbidity (NTU)**		**Flux**
hours	**Feed**	**Perm**	**Change**	**Feed**	**Perm**	**LMH**
0	PRECOAT CYCLE					
1						

2	1163					
3		60			1.12	57
4	1153	68	1085			41
5		115			0.96	33
6	1147	96	1051			35
7		137			0.88	34
8	1162	118	1044			36
9		125			0.85	37
10	1147	119	1028			37
11		124			0.95	38
12		121				38
13	1165	127	1038		0.82	36

Run 41

Objective

To determine whether a once only pre-coat would consistently yield permeate of a suitable quality over a chosen time period. To determine the change in COD per gram PAC and to compare this value to that for a test-cell.

Experimental

In the previous experiments (Run's 35-39), the pre-coated WFMF tubes were tasked with treating the raw effluent for a chosen short period of time, which was 3 – 5 hours. These runs were also conducted in total recycle i.e. permeate and reject were returned to the feed tank. In this run, it was decided to pre-coat the WFMF tube once only at the beginning of the run and thereafter pass raw effluent through this system for a lengthy time period, viz. 72 hours or such time that a 75-80% permeate recovery is achieved. The experimental procedure was similar to that of Run 37 with the only difference being in Run 41 is that permeate was removed from the system and only the reject was sent back to the feed tank.

As before the operating conditions were kept constant. At suitable time intervals samples were collected and analyzed for COD and Turbidity. Measurements of Flux were also recorded.

Results:

Table A2.31 Run 41 - Continuous Results		
Run Conditions:		
	Pre-coat Concentration	5g PAC / l water
	Pre-coat Volume	40 liters
	Pre-coat Time	1 hour
	Run Time	72 hours
	Filtration Pressure	1 bar
	Filtration Area	0.11 m^2
	Temperature	293 K
	Feed Volume	160 liters
	Permeate Volume	125 liters

Time	COD		Turbidity		Flux
	Feed	Perm.	Feed	Perm.	Perm.
hrs	mg/l	mg/l	NTU	NTU	LMH
0	1123		304	0.69	28.1
0.5		301			24.1
1				0.5	21.6
2	1192				19.6
3		188		0.42	19.7
4					19.5
5			620	0.52	21.5
6		216			20.5
7				0.43	19.8
8					20.1
9	1621	210		0.38	19.6
10					16.2
11				0.75	16.2
12		238			17.2
13				0.79	17.6
14					16.5
15		252		0.67	17.9
16					16.8
17	1877			0.76	16.9
18		301			16.7
19				0.61	16.8
20					17.1
21		230		0.43	16.6
22					16.5
23				0.42	16.2
24		258			16.9
25	1921			0.32	16.6
26					16.6
27				0.51	16.3
28					16.3
29				0.44	16
30		260			15.6
31				0.48	15.9
32	2185				15.2
33				0.47	15
34					15.7
35				0.39	15.2
36	2365	257			14.6
37				0.44	14.3
38					14.8
39				0.42	14.4
40	2390				14.6
41				0.36	14.5
42		261			14.2

43				0.35	14.1
44					14.2
45		306		0.48	14
46					13.9
47				0.37	13.6
48	2385	257			13.6
49				0.35	13.7
50					13.6
51		273		0.63	13.8
52	2685				13.3
53				0.43	13.6
54		263			13.2
55				0.43	13.6
56	2825				13
57		290		0.45	13.2
58					13.6
59				0.43	13.1
60	3250	282			13.2
61				0.48	13.4
62					12.9
63		274		0.66	12.7
64	3040				12.8
65				0.56	12.2
66		286			12.3
67				0.66	12.1
68	3170				12.2
69		311		0.57	12.2
70					12.2
71					12.2
72	3390	256		0.41	12.2

Table A2.32 Run 41 – Test-cell

Run Conditions:

Mixing Time	2 hours
Filtration Pressure	1 bar
Temperature	293 K
Feed COD	1123 mg/l
Feed Volume	1 liter

Concentration **g PAC / l Effluent**	**Permeate COD** **mg/l**	**Change in COD** **mg/l**
0.1	1023	100
0.4	906	217
0.7	810	313
1	695	428
3	491	632
5	399	724