RETENTION OF REACTIVE AZO DYE USING CHARGED ULTRAFILTRATION MEMBRANES

A Major Qualifying Project
submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the
Bachelor of Science Degree

Sponsoring Agency:
SHANGHAI JIAO TONG UNIVERSITY
School of Environmental Science and Engineering
Shanghai, China Project Center

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Date: March 1, 2013

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Abstract

Reactive azo dyes are present in textile effluents due to their stable nature and extensive use. The removal of reactive azo dyes is required before discharge due to negative environmental and health effects. Common methods of removal include biodegradation through bacteria or fungi, chemical precipitation, or filtration using membrane technologies. Enhanced ultrafiltration is an alternative membrane technology to retain charged pollutants with a membrane of the same charge. This study performed preliminary research focusing on the retention of negatively charged reactive azo dyes through the use of a negatively charged membrane. A low ionic strength solution promoted retention of the dye allowing colorless water to pass through for the application of further purification and reuse.

Key Words

Enhanced ultrafiltration, Textile effluent, Reactive azo dye

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Nomenclature and Units

Variable	Definition	Units
A	Surface Area of the Membrane	mm^2
AOX	Absorbable Organic Halogen	mg/L
BOD_5	Biochemical Oxygen Demand	mg/L
---	Degree Celsius	^oC
C_p	Average of the absorbance values at 520 nm for the permeate samples	---
C_f	Average of the absorbance at 520 nm for the stock solution and the solution in the stir cell after the sample collection	---
COD	Chemical Oxygen Demand	mg/L
---	Dalton or grams per mole	Da
---	Kilodalton or 1000 Daltons	kDa
J	Volumetric Flux	m/s
m_p	Mass of the permeate sample	g
---	millimole	mM
---	Cubic meter	m^3
ρ	Density of water	g/cm^3
S	Sieving Coefficient	---
Δt	Sample collection time	s
$\dot{v}$	Volumetric flowrate of the permeate	cm^3/s

1.0 Introduction

The textile industry traditionally uses a considerable amount of water during the washing process. With finite fresh water supplies, the textile industry strives to reduce water consumption throughout the whole production process. Around the globe increasing regulatory pressures are also being placed on water quality standards for textile effluents regarding the release of colorants into the environment. New technologies that allow for better dye fixation to the fiber as well as the removal of colorants from the textile process effluent streams are necessary to meet regulations for discharge.

Due to a large increase in production over the last ten years, China specifically is experiencing significant water pollution from poorly treated textile effluent streams. Since introduction in the mid 1950s, reactive azo dyes have become increasingly popular due to their stable nature and wide range of bright colors. Without proper removal or degradation however, reactive azo dyes can cause extensive pollution issues through bioaccumulation and increased turbidity in ground water systems. While toxicity studies are limited, some research has found that a few reactive azo dyes lead to bladder cancer.

Current treatment technologies include the creation of sludge which requires proper disposal or the use of biodegradation to break up potentially toxic dye compounds. Sludge can be created using either chemical precipitation or membrane filters. While these techniques are often effective, sludge containing reactive azo dyes is considered toxic and requires special disposal. Membrane filters do not require the addition of precipitant chemicals which would later need to be also removed, however due to the size of dye molecules nanofiltration is necessary leading to high operating costs as a result of low permeability and a high pressure systems. The alternative method includes biodegradation through the use of bacteria or fungi and can result in a colorless effluent. Biodegradation, along with destroying the structure of the dye, eliminates any possibility in dye reuse.

An additional membrane treatment technology has been recently studied in its application to charged pollutants, though it has never been used for textile effluent streams containing charged colorant molecules. Previous research indicates that negatively charged ultrafiltration can effectively retain negatively charged solutes that are smaller than the pore size of ultrafiltration membranes due to the electrostatic repulsion between the same charge property of the membrane and solute. This process leads to lower operating costs as a result of higher permeability in a low pressure system.

This study will lead to preliminary data on the ability for negatively charged ultrafiltration membranes to retain a negatively charged dye. Membranes with different spacer arm lengths were compared using a reactive azo dye, Reactive Red ED-2B. The goal is to explore the possibility of using charged ultrafiltration membranes for the separation of dye compounds from reusable water. As a result charged ultrafiltration membranes could be used to concentrate reusable dye in solution or could be coupled with biodegradation controlling the concentration of dye to optimize effluent decolorization.

2.0 Background

2.1 Textile Dyeing Industry

The Yangtze River basin, which currently encompasses 16 cities including Shanghai, provides drinking water for more than 25 million people. This area including the river is also a center for industrial activity contributing 40% of the nation's gross domestic product as well as 30 billion metric tons of wastewater annually. One main industry along the Yangtze River is the textile industry. Throughout China from 2000 to 2009 the textile industry has increased manufacturing volumes by 16% for manmade fibers and by 12% for cotton yarn [1]. Figure 1 compares the fiber production in both 2000 and 2009 for manmade fiber and cotton yarn. Based on this figure, production in China has increased greatly compared to other countries that produce fibers. Within the textile industry natural fibers such as cotton, silk, and wool comprise 39% of the total industry while synthetic fibers comprise nearly 61%. Textile industries consume large amounts of chemicals and clean water during the wet process for fabrics which includes dyeing, washing, printing, and fabric finishing. This process creates large quantities of wastewater containing toxic substances in which unknown amounts are dumped poorly treated.

Wastewater from textile factories is a significant source of environmental pollution. The German Association of Textile Finishers has estimated that the textile finishing industry in German consumes 65 x 10^6 m^3 of water where on average the water consumption is 146 m^3 per metric ton of fiber material. Of that, 89% is discharged as wastewater [2]. Table 1 shows the water consumption rate based on the type of fiber processed.

Table 1: Water consumption based on fabric material [2]

Textiles	**Consumption, m^3 per metric tons of fabric material**
Cotton fabric	80 – 240
Cotton woven goods	70 – 180
Woolen fabric	100 – 250
Polyacrylic fabric	10 – 70

In China alone, it is estimated that more than 1.6 x 10^9 m^3 of untreated dye-containing water is discharged annually into the environment [3]. With increasing development of the textile industry across Asia shown in Table 2, an increase in the amount of industrial effluent released into ground and surface water will persist.

Table 2: Regional distribution of textile processing, % [2]

Region	**1976**	**1992**
Western Europe	17	12
Eastern Europe	19	11
East Asia	35	44
North America	19	16
South America	6	6
Africa, West Asia	4	7

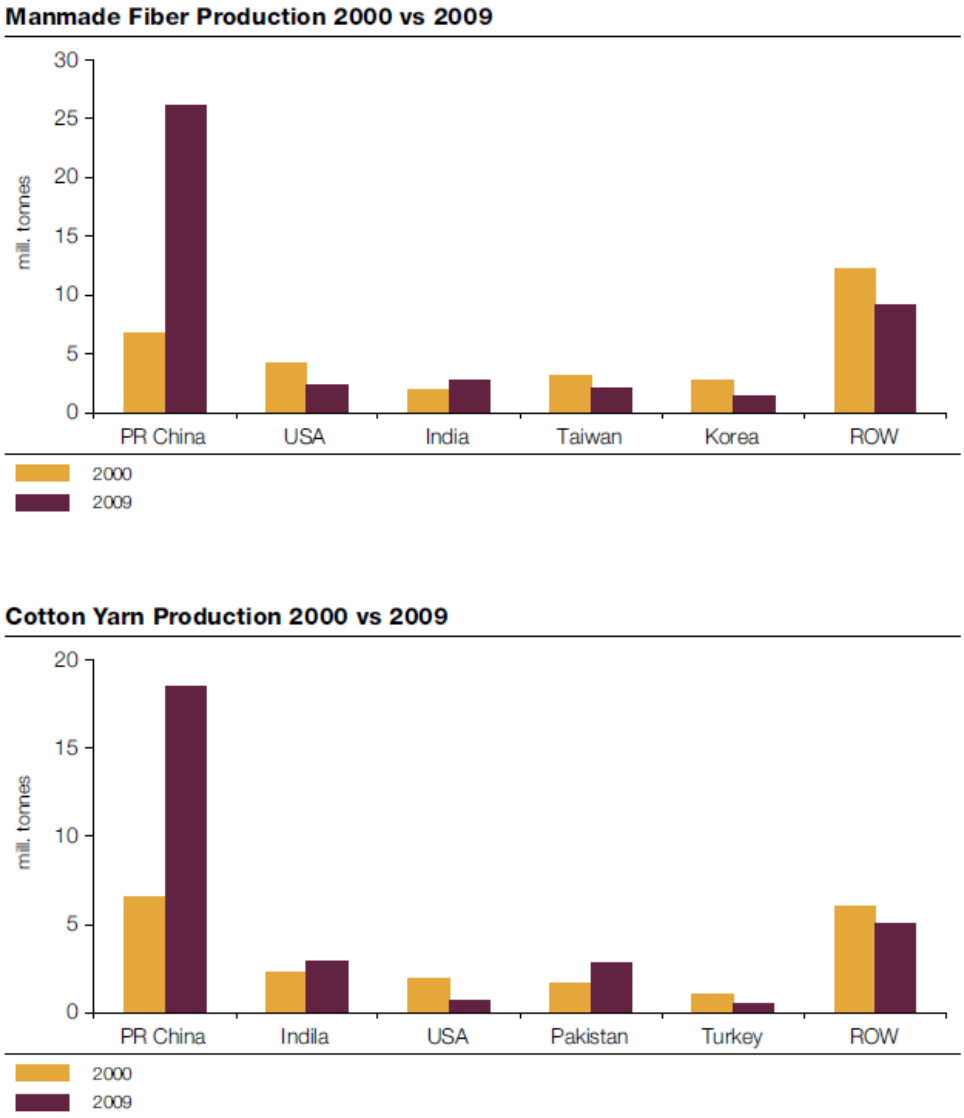

Figure 1: Fiber Production in 2000 and 2009 [1]

While there are many different types of dyes as well as many different types of textile fibers, they all require an aqueous wash at the end of the dyeing process [4]. This wash is used to remove any excess dye and dyeing chemical additives to help obtain the desired shade of color. This wash step however also often includes other chemicals such as surfactants and large amounts of water. As a result the composition of textile wastewater varies greatly based on the dye used, the textile fabric, and the other chemicals used. In general however untreated wastewater is alkaline, has a high conductivity, and has a poor biochemical oxygen demand to chemical oxygen demand (BOD_5 : COD) ratio leading to lower degradability [2] [5].

Cotton alone comprises about 37% of all textiles produced worldwide. The dyes most commonly used in the cotton process are direct, reactive, and azoic colorants. Direct dyes are water soluble

with an affinity for the fiber. Reactive dyes on the other hand directly react with the surface of the fabric. Azoic colorants are insoluble in water and rather than being applied to the fiber the azoic dye is produced within the fabric itself increasing the fixation of the dye. Table 3 shows the variability that exists within wastewater leaving a cotton finisher.

Table 3: Typical wastewater composition from a cotton finisher [2]

Parameter	Average	Minimum	Maximum
pH		8.5	10.3
Conductivity, mS/m	650	420	1400
Temperature, ^{o}C	27	25	38
COD, mg/L	650	420	1400
BOD5, mg/L	180	80	500
AOX, mg/L	0.8	0.5	1.2
Phosphate (P), mg/L	50	26	80
Sulfate, mg/L	810	750	1050
Ammonium (N), mg/L	0.7	0.6	1.0
Chloride, mg/L	800	400	1500
Hydrocarbons, mg/L	5	3	15

2.2 Methods of Dye Removal

Compounding both increased population and diminishing water resources, tighter standards for treating water that is released into the environment or reused immediately are becoming essential. Textile treatment plants process large amounts of water during the production of fibers in order to handle high concentrations of pollutants. Recent regulations however required not only lower pollution levels, but also lower water consumption making dilution no longer a reasonable solution [5]. Several different treatment methods exist to help decrease the level of contaminants in the wastewater effluent. The main methods either concentrate the dye into sludge or completely destroy the colored molecule into less toxic compounds. With increasing stringent regulations, speculations exist that biodegradation will be the preferred method in order to reduce the transfer of water pollution to solid waste management [5]. Due to being part of the wastewater, treatment methods must also consider high levels of dye and organic content, large electrolyte concentrations, and compounds that resist biodegradation [4].

2.2.1 Chemical Precipitation

Commonly precipitation is used to settle the contaminant into sludge, however in textile plants that utilize reactive azo dyes; this sludge is highly toxic and challenging to safely dispose. A study using aluminum chloride as the coagulant showed that at pH 6 the removal of the negatively charged dye was maximized. However when followed by adsorption using a coconut-based activated carbon (PAC), the overall dye removal increased producing less sludge [6]. A similar study that used activated carbon derived from coconut shells as the absorbent and aluminum chloride as the coagulant, obtained a non-toxic effluent with the dye removal efficiency of about 90% at the ideal dosage level, pH, temperature, and ionic strength [7].

Coagulation followed by flocculation and settling is a form of chemical precipitation in that the wastewater is treated by adjusting the pH and adding a coagulate chemical, often ferric or alum salts, to destabilize the dissolved particles in solution. The coagulate chemicals act as flocculating agents causing the dissolved particles to aggregate forming denser floccules formations that tend to precipitate out of solution. While coagulation-flocculation methods are effective in removing high concentrations of reactive azo dyes from the textile effluent, large amounts of coagulant chemicals are needed and as a by-product, large volumes of toxic sludge remain.

2.2.2 Biodegradation

Microorganisms have proven to metabolize dyes once the nitrogen double bond is broken forming amine compounds. The use of aerobic bacterium within industrial wastewater treatment plants is a method of reactive azo dye removal. Often this is done through the use of fixed bioreactors or suspended activated sludge reactors such as fluidized bed reactors [8]. One study has shown that using a single *Staphylococcus arlettae* strain under the combination of a microaerophilic stage and an aerobic stage can succeed in decolorization greater than 97% by breaking the azo bond forming non-toxic metabolites [9]. Ligninolytic fungi, a white-rot fungi, has also been extensively researched for its ability to degrade dye, however it is now understood that fungi have a long growth cycle and thrive best in a consistent environment. Due to the highly complex and variable composition of textile effluents, the overall degradation ability of the fungi is limited. Bacterial degradation on the other hand shows to be much quicker, which is important for large volumes of effluent, as well as less specified to specific dyes [9] [10]. While biodegradation is currently the preferred method, some experts are studying treatment methods that would allow for colorant dyes to be reused within the process.

2.2.3 Membrane Filtration

Membrane based filtration practices utilize semipermeable membranes to selectively remove undesired contaminates. The technique itself is chosen based on the pore size of the membrane and the size of the particle of interest. Membrane technology is preferred due to its simple process and reliable operation, low energy consumption, and the lack of an additional chemical reagent. Membrane separation is an effective and cost efficient technology providing the potential for material recovery and reuse.

Ultrafiltration membranes remove large molecular weight molecules from aqueous solutions. Often particles are on the order of 1 to 1000 kDa are removed through ultrafiltration membranes based on the membrane specification, while water and any other smaller particles pass through the membrane. Due to the size of most reactive azo dyes, ultrafiltration is not sufficient for providing sufficient water quality since ultrafiltration membranes allow most reactive azo dyes to pass through along with water molecules.

Nanofiltration is similar to ultrafiltration in that the objective is to selectively remove particles larger than the pore size allowing water to pass though the membrane. The typical pore size for nanofiltration membranes is one nanometer removing particles less than 1 kDa. Due to the particle size for most azo dyes, nanofiltration has traditionally been the chosen treatment process

in order to meet more stringent regulations [11]. While nanofiltration does obtain better removal through increased separation, it requires higher operating costs as a result of lowered permeability and high pressure. Due to solute adsorption, flux decline does occur over time with increasing rates at higher dye concentrations [11].

2.3 Reactive Dyes

Reactive dyes have become more widespread since their introduction of mid 1950s becoming the newest class of dyes for cellulose fibers due to their ease of application, brightness, and wide range of shades. Table 4 shows the estimated world consumption of synthetic dyes used in 1992. The use of reactive dyes makes up 20% of the total synthetic dyes used and more than 30% of the dye used for cellulose fibers currently.

Table 4: Estimated World Consumption of Synthetic Dyes in 1992 in 10^3 tons [2]

Indigo	12
Vat Dyes	26
Reactive Dyes	108
Direct Dyes	45
Naphtols	19
Sulfur Dyes	100
Cationic Dyes	21
Anionic Dyes	74
Disperse Dyes	102
Pigment Preparations	40
Total	547

Unfortunately reactive dyes also have significant disadvantages especially for the environment. When used in dyeing as a preferential dye for all types of cellulose-based clothing textiles, a considerable amount of electrolyte additive is necessary for solution stability. A stable solution is important for reducing defects such as uneven effects and spots. While this changes the ionic strength of the environment, reactive dyes are mainly applied under weakly acid or neutral conditions [2]. Reactive dyes are also the cause of several other contaminants in wastewaters, specifically an alkaline pH value, color residual, absorbable organic halogen (AOX) formation, and neutral salts. All reactive dyes that contain haloheterocyclic reactive groups also have the potential to create absorbable organic halogen compounds within the dye effluent. Finally, in the process of dye-fiber fixation alkali-induced dye hydrolysis is used resulting in about a 50% to 70% fixation efficiency depending on the type of dye and shade therefore resulting in 20% to 50% of the applied dye being discarded in the effluent which also contains the surfactants used within the process [12].

During dye fixation with reactive dyes, chemical reactions are used to covalently bond the dye to the fiber material. Since the chemical reactions proceed at a certain rate, this ultimately determines the fixation time. Reactive dyes have two possible mechanisms in bonding to cellulose either using addition or substitution. Figures 2 and 3 show an example of an addition and substitution mechanism [2]. A typical process for reactive dyes on cellulose fabrics is a semicontinuous process shown in Figure 4. The first part of the process cools the fabric (a) and

then the system measures the initial moisture content (b). The next step includes a high-speed cleaning (c) followed by the swimming rolls (d). The fabric is then dyed (e) and the color is measured (f, g). Depending on the mechanism and type of reactive dye, the colorfastness or the fabrics ability to maintain the color without running can be generalized. Reactive azo dyes however are difficult to generalize due to a wide range of derivatives leading to poor generalization.

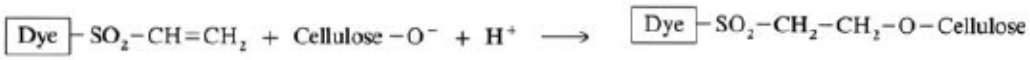

Figure 2: Addition Mechanism

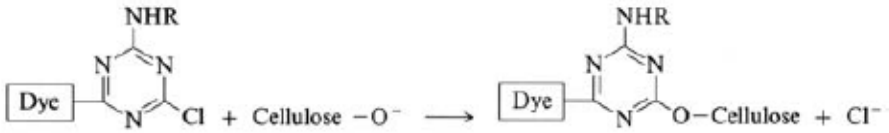

Figure 3: Substitution Mechanism

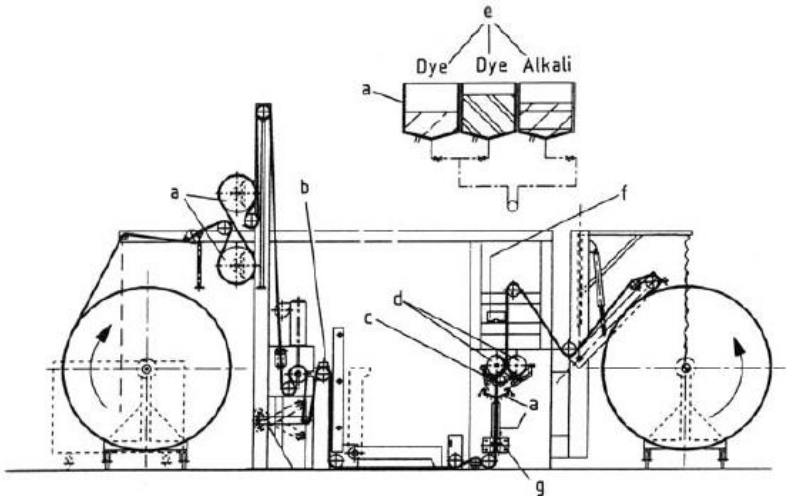

Figure 4: Cold pad-batch dyeing station [2]

Reactive dyes used on cotton fibers require extensive washes and high volumes of water after the fixation process to remove hydrolysed dye, unfixed dye, and other chemicals used in the process. Dye producers commonly suggest the use of certain wash processes which often include various chemicals while using dyes that fall within different ranges. As a result this washing process and the treatment of the resulting effluent contributes to about half the overall cost of the total dyeing process. For this reason, not only are various treatment methods studied, but also various washing techniques using water at different temperatures and for various lengths of time with the objective to save water usage as well as reduce the usage of chemicals used in the washing process [12]. The overall reactive dyeing process for cotton textile fiber uses and therefore creates a considerable amount of wastewater show in Table 5.

Table 5: Water use in a typical reactive dye process for cotton [4]

Process	Wastewater (L)	Temperature (^{o}C)
Wash/Bleaching	700	95
Overflow rinse	7300	10
Neutralise	700	30
Overflow rinse	7300	10
Dye	700	50
Overflow rinse	7300	10
Warm rinse	700	50
Neutralise	700	60
Overflow rinse	7300	10
Hot soap	700	95
Warm rinse	700	60
Overflow rinse	4300	10
Hot soap	700	95
Warm rinse	700	60
Overflow rinse	4300	10
Neutralise and soften	700	40
Total Wastewater	44800	

2.3.1 Reactive Azo Dyes

High levels of reactive azo dye compounds exist in the effluent discharge leaving consumer good production plants. Azo compounds are characterized by one or more azo bonds (-N=N-), which are responsible for their stable structure. Azo compounds are typically used in dye applications in textile, photography, and petroleum additives. As the largest used class of dye, azo dyes make up more than 50% of all synthetic dyes produces [8]. Azo dyes are aromatic, organic, hydrocarbon compounds that consist of two nitrogen atoms bonded by a double bond. These compounds are stable therefore favored for textile dyes due to their resistance to fading. With a poor dye-fiber fixation, 20 to 50% of the applied azo dye is discharged after the dyeing process, leading to a high concentration entering the treatment facility [12]. Due to such stable properties, azo dye compounds used as dyes often bioaccumulate within the environment as well as in sludge during the wastewater treatment process.

2.3.2 Hazards of Reactive Azo Dyes within Wastewater Effluent

Both the ecological and biological threats from azo dye concentrations are severe due to the ability for azo dyes to adjust protein configurations. Due to their ability to bind covalently to proteins, azo compounds are able to induce a reaction that biologically results in cancer development. Some azo dyes have been linked to human bladder cancer, specifically benzidine based azo-dyes, however little literature exists overall on the toxicity of reactive azo dyes [5] [8]. A ban throughout European nations exists on twenty-two azo dyes to protect human health from particular dyes that break down to form aromatic amines that will come in human contact [13]. Azo compounds easily bioaccumulate due to their stable structure within aquatic organisms. Along with bioaccumulation, azo dyes adversely affect the growth of fish due to lowering food

consumption and increasing overall stress experienced by the fish. Risk increases for human health based on consumption of seafood leading to other possible effects including mutations [8].

Azo dyes also pose a risk to aquatic plant life and agricultural land in the event that the irrigation water used is polluted. Plant growth and fertility can be effected significantly due to contaminated water supplies as well as poor soil qualities resulting from pollution. Plant growth can be measured by germination percent, seedling height, and seedling survival. Studies have shown that at higher concentrations specifically seedling height is greatly affected [8]. As a result of high dissolved solid concentrations, the chlorophyll contents can also be decreased effecting the overall growth with a lower photosynthesis rate. Similarly photosynthesis can be reduced in aquatic plant life due to the absorbance of light that enters the colored wastewater.

2.3.3 Reactive Red ED-2B (RR ED-2B)

In this study Reactive Red ED-2B (molecular weight 1027.17 Da) will be used as an example of one reactive azo dye. It is negative due to the lost of four sodium atoms when it dissolves in water. Each reactive azo dye however has a different charge depending on its structure and this study focused specifically on Reactive Red ED-2B. The structure of Reactive Red ED-2B is shown in Figure 5 and an example of a textile plant is shown in Figure 6.

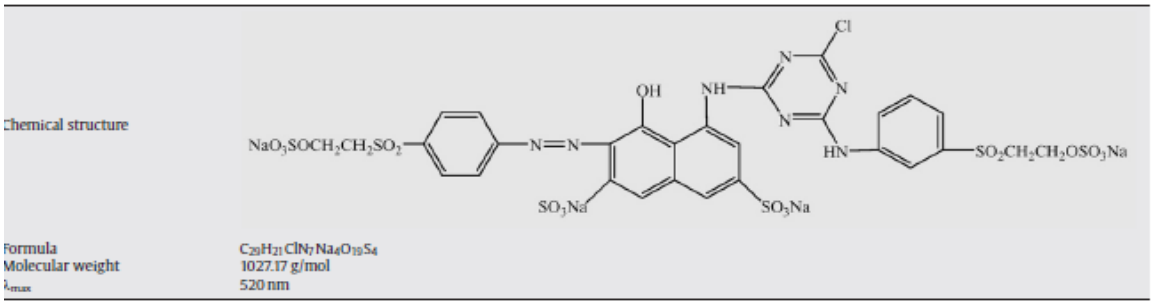

Figure 5: Chemical Structure of Reactive Red ED-2B


Figure 6: Cloth being produced in a Dyeing Facility [14]

2.4 Enhanced Ultrafiltration

In traditional membranes, selectivity and permeability exist as a trade off. When a membrane is modified to have a negative or positive charge however, increased separation can occur through electrostatic interaction increasing the retention rate of the pollutant. Due to the electrostatic repulsion, the solutes will have less deposition on the membrane resulting in the membrane fouling being greatly decreased [15].

Pollutant retention within membrane separation has been shown to not depend only on pore size however, but to be also affected by the electrostatic interactions between a negatively charged membrane and the negatively charged pollutant solute that is much smaller than the pore size [16] [17]. Now coined as enhanced ultrafiltration, the application of this membrane technology has the potential to be quite large throughout water quality [18]. Previously, the removal of natural organic matter in the form of humic acid was studied showing greater removal and lower fouling in the application of negatively charged ultrafiltration membranes. Also observed was the effect of different modifications on the overall removal including varying space arm length and charged groups [15] [19].

The retention ability of changed ultrafiltration membranes is affected by the condition of the solution such as pH and ionic strength as well as the charge property of the membrane and solutes. The retention ability can also be affected by the spacer arm length (Figure 7), the length counted in carbon atoms between the charged group and the surface of the membrane. A study on cytochrome c, a positively charged protein, and positively charged Ultracel 30 kDa membranes at pH 7 over a range of ionic strengths showed that greater retention was obtained using the membranes modified with a longer spacer arm and with solutions at lower ionic strengths [20]. This study will begin to analyze the use of enhanced ultrafiltration on reactive azo dyes as a new technology to be used in union with currently used methods of removal.

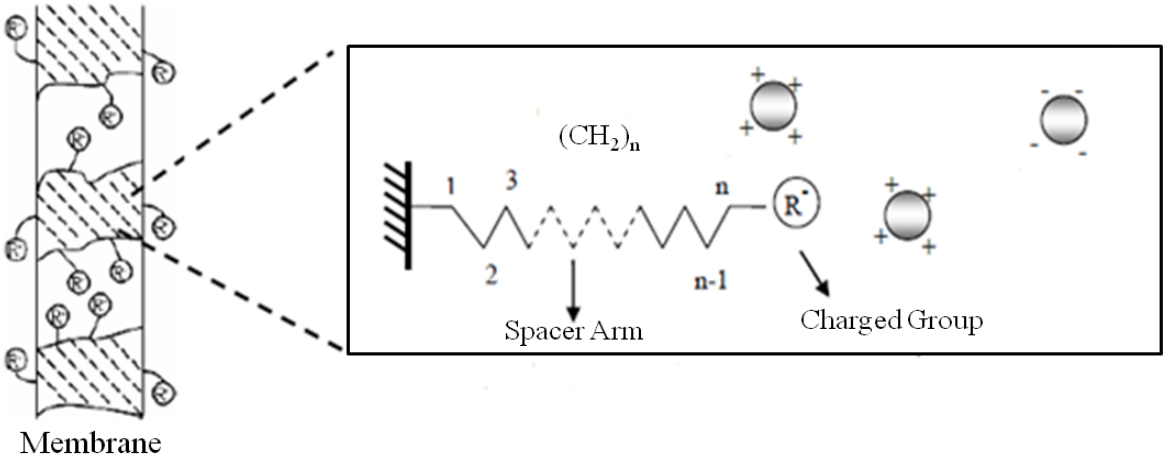

Figure 7: Schematic Diagram of the Spacer Arm

3.0 Methodology

Through understanding the negative impacts reactive azo dyes contribute to the environment and recognizing the importance of reduced water consumption for textile industries, the retention of dyes will be investigated.

3.1 Project Objectives

The main goal for the project was to investigate the retention ability of enhanced ultrafiltration membranes using a reactive azo dye, Reactive Red ED-2B. In order to begin this analysis, sieving coefficients have been obtained at various ionic strengths.

Under the direction of Professor Jiahui Shao, the primary objective of this project was to examine the sieving coefficients of Reactive Red ED-2B at transmembrane pressure drop of 3psi, 6psi, 9psi, 12psi and 15psi in the solutions of ionic strengths of 10mM, 50mM, 100mM and 500mM (pH=7.0) with neutral composite regenerated cellulose membranes, negatively-charged composite regenerated cellulose membranes with two different spacer arm lengths, and polyethersulfone membranes.

3.2 Theoretical

3.2.1 Membrane Analysis

Pure water membrane flux is calculated on a volumetric basis using the following equation:

$$J = \frac{\dot{v}}{A}$$

Where $\dot{v}$ is the volumetric flowrate of the permeate $\left[\frac{cm^3}{s}\right]$, A is the membrane surface area [490 mm^2], and J is the volumetric flux of permeate $\left[\frac{m}{s}\right]$. Volumetric flowrates were calculated using the mass of the collected sample and the density of water through the following equation:

$$\dot{v} = \frac{m_p}{\rho\, \Delta t}$$

Where m_p is the mass of the permeate sample [grams], ρ is the density of water $\left[1\,\frac{g}{cm^3}\right]$ assuming any variations in temperature and concentration of dye is negligible, and Δt is the sample collection time [seconds].

3.2.2 Sieving Coefficient Analysis

Reactive Red ED-2B sieving coefficient is calculated using the following equation:

$$S = \frac{C_p}{C_f}$$

Where S is the sieving coefficient, C_p is the average of the absorbance values at 520 nm for the permeate samples, and C_f is the average of the absorbance at 520 nm for the stock solution and the solution in the stir cell after the sample collection.

3.3 Reagents

Reactive Red ED-2B solutions were made from dye powder ordered from Li Chang Cheng, Yunfu, China and ultrapure water. The ionic strength of the solution was adjusted with hydrochloric acid, molecular weight 74.55, and Tris(hydroxymethyl)amionmethane, molecular weight of 121.14 Da, both supplied by Sinopharm Chemical Reagent Co., Ltd, Shanghai, China. Solutions used for modifying the membranes were created using 3-bromopropanesulfonate acid sodium salt and 6-chloro-1-hexanol supplied by Sigma. Acidic solutions used to adjust the pH were created with hydrochloric acid (HCl) supplied by Sinopharm Chemical Reagent Co., Ltd, Shanghai, China and basic solutions used to adjust the pH were created with sodium hydroxide (NaOH) supplied by Sigma.

3.4 Equipment

The ultrafiltration separation was conducted using an Amicon Corporation Model 8010 unit model. The unit had the maximum capacity to hold 10 mL and was made for polysulfone. The unit included an internal magnet stirrer. Figure 8 shows the separation unit assembled.

Figure 8: Millipore Corporation Model 8010 Stirred Cell

The two membranes used were polyethersulfone (Biomax^{TM}) membranes and composite regenerated cellulose (CRC) membranes both from Millipore Corporation. The membranes are listed with a normal molecular weight cut-off of 30kD. A UV-1800 Spectrophotometer was used for determining the absorbance of the Reactive Red ED-2B in solution.

3.5 Experimental

3.5.1 Membrane Preparation

Two composite regenerated cellulose membranes were modified changing the overall charge of the membrane from neutral to negative and the space arm of the charged group. Both membranes were placed in isopropyl alcohol (IPA) in a small glass bottle for at least an hour in order to clean the membrane of any chemicals within the membrane from the manufacturing process. The membranes were washed with ultrapure water and the flux was determined for both. The membrane modified with the space arm length of three was soaked in a 2 M/L solution of 3-bromopropanesulfonate acid/sodium hydroxide for over 48 hours. The membrane modified with the space arm length of nine was soaked in a 2 M/L solution of 6-chloro-1-hexanol/sodium hydroxide for 48 hours followed by the same soaking process for the negative charge modification of the membrane with the spacer arm length of three. Both membranes were stored in NaOH until use.

3.5.2 Solution Preparation

The 100 mg/L Reactive Red ED-2B solution was prepared new each day, therefore only 250ml was made of each ionic strength solution. In a small beaker the correct weight of potassium chloride (KCl), tris(hydroxymethyl)amionomethane (Tris), and Reactive Red ED-2B were be mixed in ultrapure water and added to a 250 ml flask for exact volume. The ionic strengths were in a 10:1 ratio of KCl:Tris at 0, 10, 50, 100, and 500. The pH was adjusted to 7.0 for all solutions using KCl and NaOH as pH adjustment chemicals to replicate natural water body conditions.

3.5.3 Ultrafiltration Experiment

In order to perform the ultrafiltration experiment the stir cell was assembled with the smooth side of the membrane facing up after washing it with ultrapure water. At each pressure the dead volume was flushed out from beneath the membrane and in the tube, collecting waste permeate in a beaker. Once the pressure had stabilized, a timer was started and three samples were collected each for 6 minutes changing the sample bottle at 6 minutes and 12 minutes. The pressure was turned off at 18 minutes, and the stir cell was emptied into a sampling bottle as the fourth sample for the given pressure. The stir cell was disassembled and all the parts were washed including the membrane with ultrapure water. The membrane was soaked in 0.1M NaOH as a washing agent. The ultrafiltration experiment was repeated for each pressure and ionic strength. Additional samples were collected from the bulk solution at the beginning and end of each experiment. The concentrations were later averaged and used as the feed concentration.

Figure 9: Equipment Setup

The ultrafiltration experiment was run with four different membranes. The polyethersulfone (PES) membrane was used unmodified but exists with a negative charge. The Composite Regenerated Cellulose membrane was used in its naturally neutral state. Two modified composite regenerated cellulose membranes were also used, one with a spacer arm of three and the other with a spacer arm of nine, both modified to hold a negative charge.

3.5.4 Analysis

The samples were weighed to calculate the flux. The absorbance was determined for each sample at 520nm using a UV spectrophotometer. The sieving coefficient could be calculated by dividing the average of the absorbance values for the samples by the average of the absorbance for the stock solution and the solution in the stir cell after the collection of the three samples.

4.0 Results and Discussion

Results at each ionic strength and set pressure for the unmodified CRC membrane are shown in Figure 10.

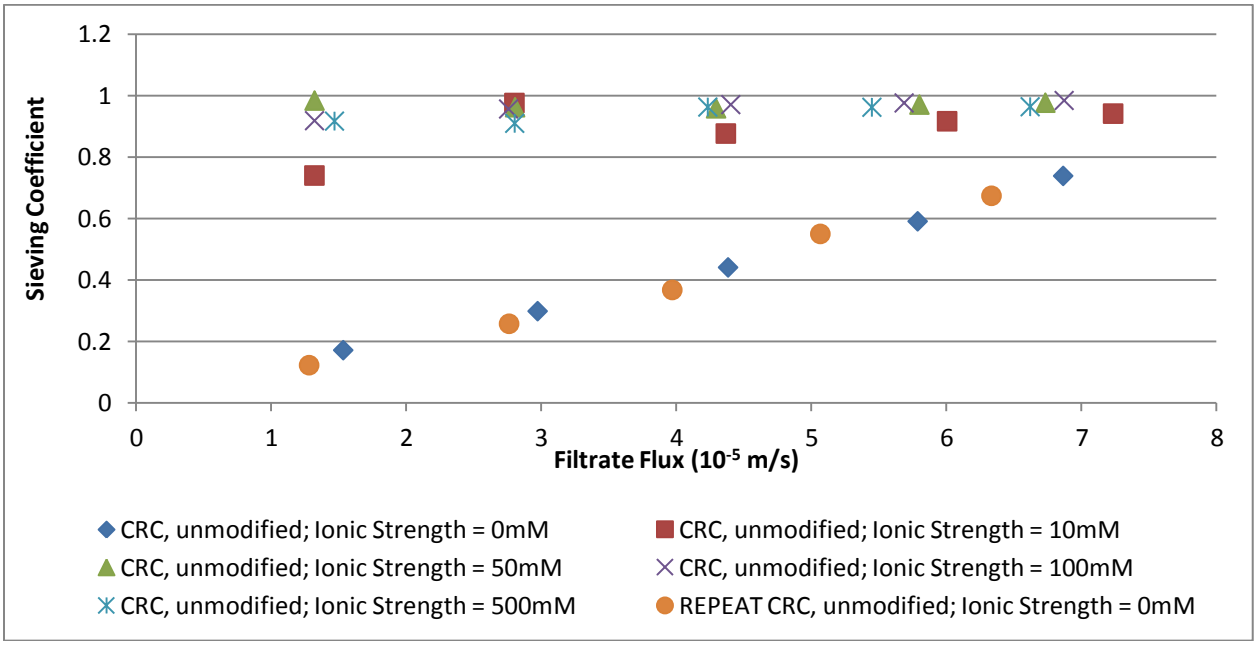

Figure 10: Unmodified CRC Membrane

Since this system consists of a 30 kDa neutral membrane and a 1 kDa negatively charged dye, the expected results were a sieving coefficient of one for all ionic strengths showing that the electrostatic repulsion effect was the dominant mechanism in retention and should not be present if the membrane and dye are not both negative. For the ionic strength of 0mM however, the retention was more than 80% in both the original run as well as in a repeated test therefore suggesting that there is an alternative mechanism aiding in retaining the dye.

To possibly help understand why the retention was high for the neutral membrane and negative azo dye, the same membrane was tested with a neutral compound, Vitamin B12, with the ionic strength 0mM and peak wavelength of 360.2 nm. As expected Figure 11 shows the sieving coefficient was equal to 1 since the compound has a molecular weight of 1350 Da and the membrane used had a 30 kDa cut off. Unfortunately, this does not help explain why there was high retention of the dye for the same membrane and ionic strength.

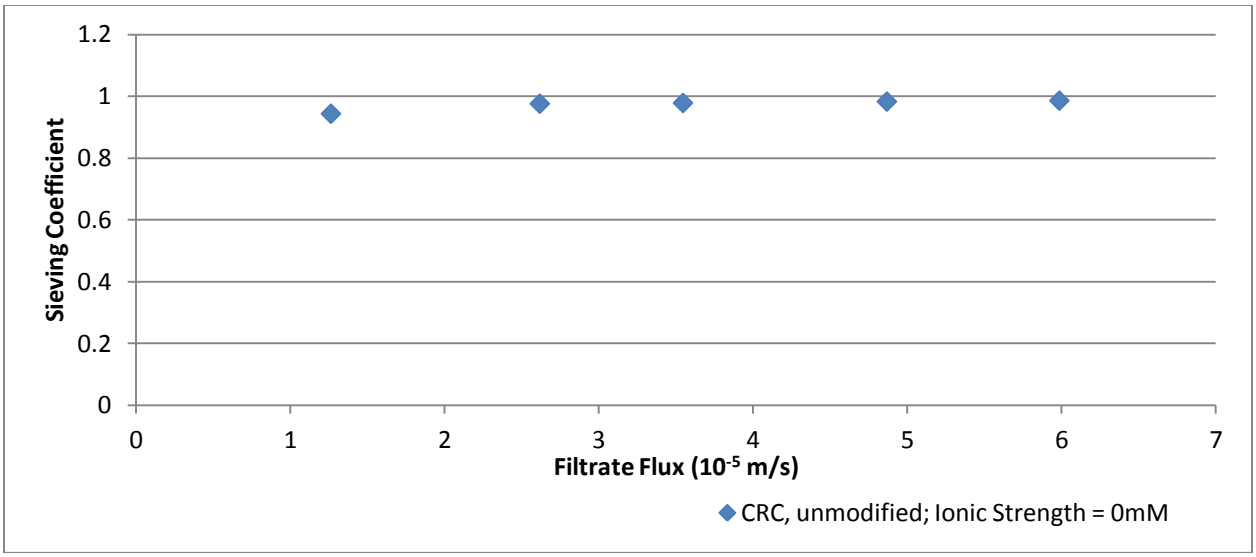

Figure 11: CRC, unmodified; Ionic Strength = 0mM for Vitamin B12

Results at each ionic strength and set pressure for the CRC membrane with the spacer arm length of 3 are shown in Figure 12. Here again the ionic strength of zero performs the most favorable.

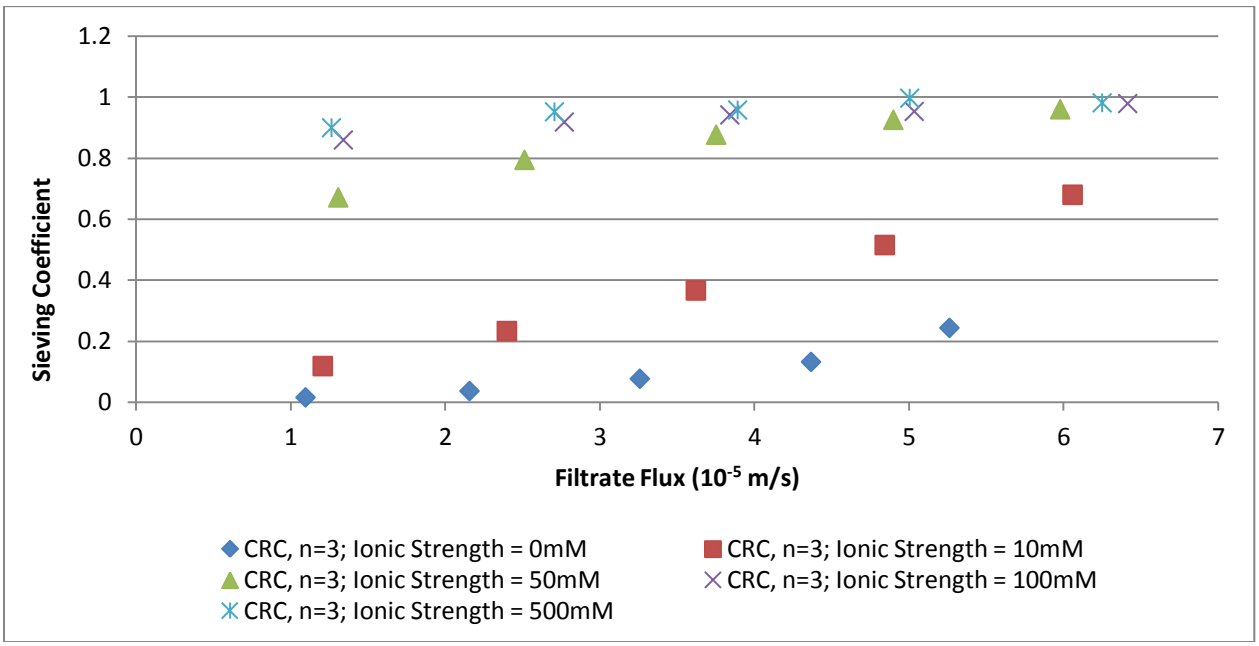

Figure 12: CRC n = 3 Membrane

Results at each ionic strength and set pressure for the CRC membrane with the spacer arm length of nine and the PES membrane are shown in Figure 13 and 14.

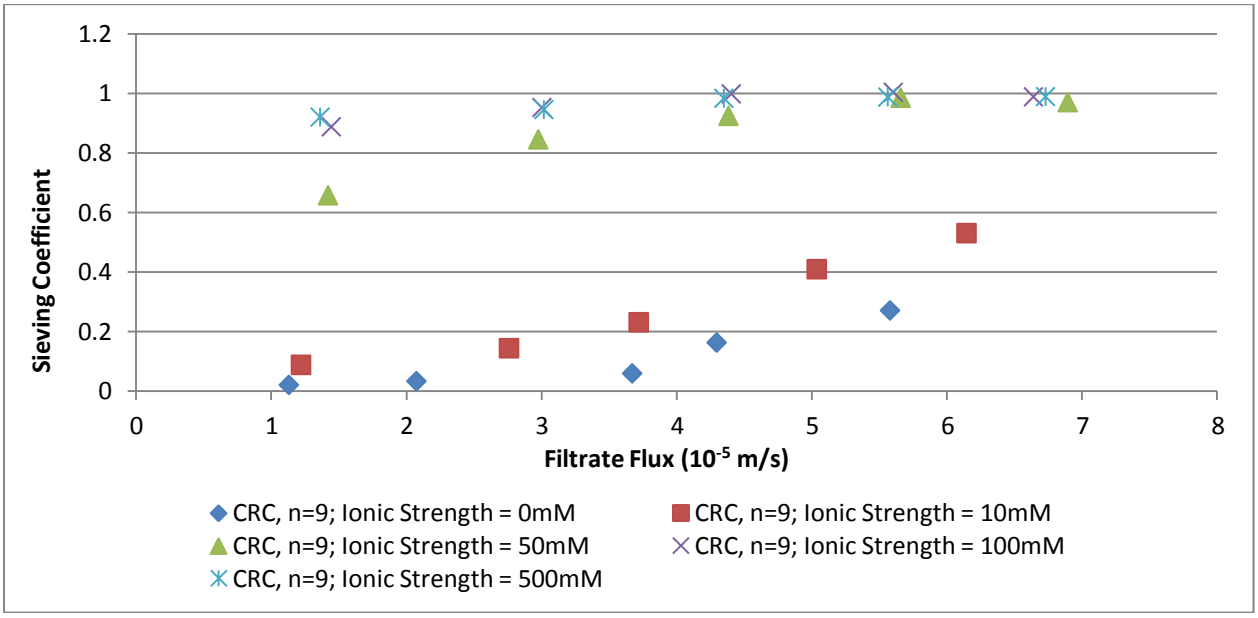

Figure 13: CRC n = 9 Membrane

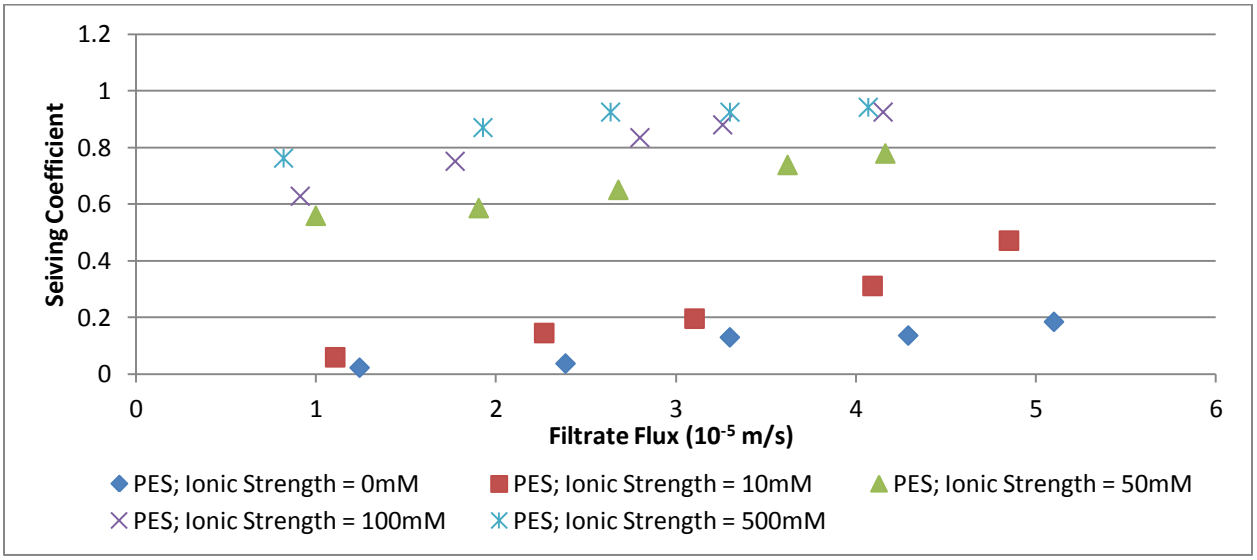

Figure 14: PES Membrane

With the horizontal axis as filtrate flux in Figure 15 and the different membranes plotted at the ionic strength of 0mM, at the lowest flux the retention of Reactive Red ED-2B is greater than 80% for the unmodified CRC membrane. This suggests that there are other mechanisms retaining the negatively charged reactive azo dye in addition to the electrostatic repulsion present when filtering with a negatively charged membrane.

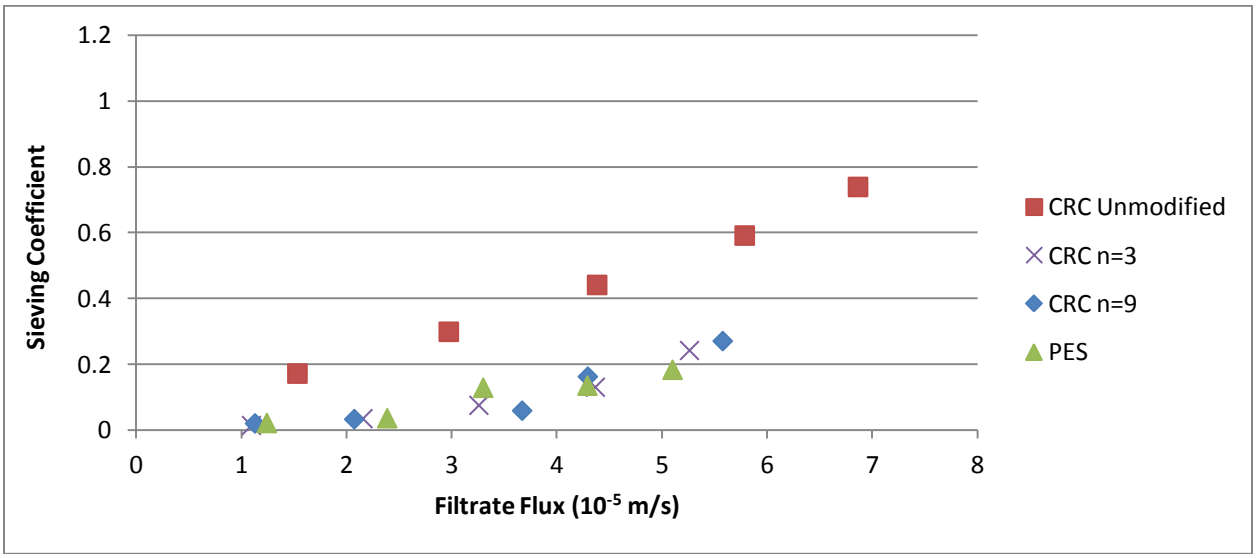

Figure 15: Ionic Strength 0mM

With the horizontal axis in Figure 16 ionic strength, it is clear that with increasing ionic strength the retention nears zero and almost all the dye passes through the membranes. Focusing on the ionic strength of 10, it can clearly be seen that the PES membrane is the most favorable in this process, followed by the modified CRC membrane with the spacer arm length of nine.

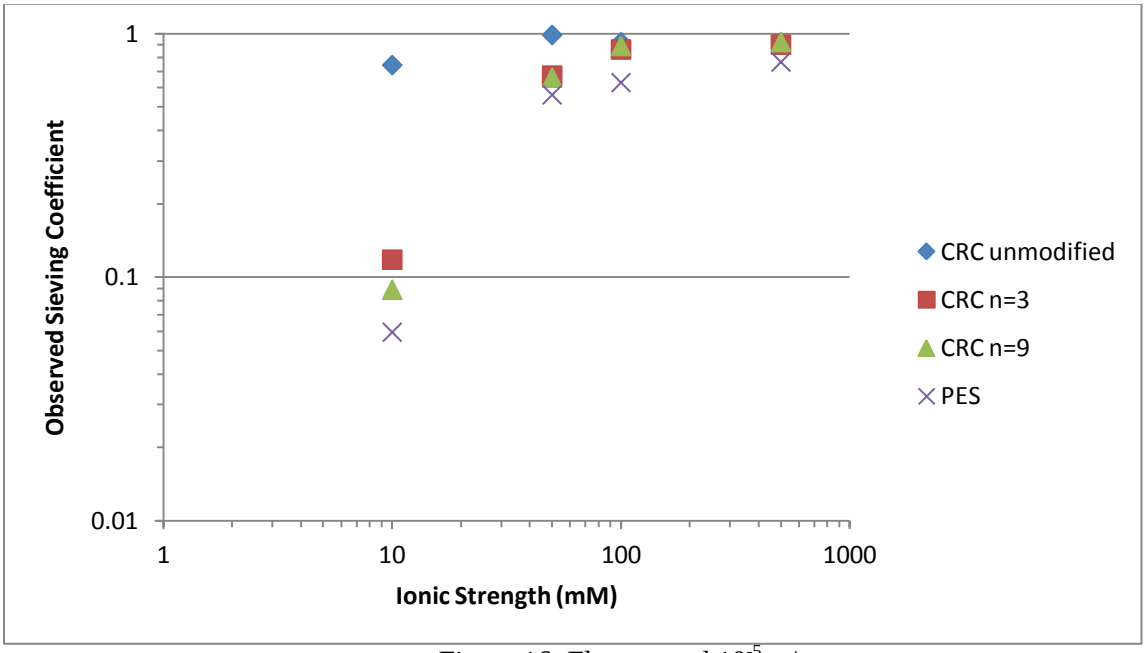

Figure 16: Flux around 10^{-5} m/s

5.0 Conclusion and Recommendations

In conclusion, based on the first set of graphs showing each membrane individually, the ionic strength of zero is ideal. This is understood to be true through theory in that the ionic strength is adjusted using potassium chloride. In water this compound dissociates creating negatively charged chloride ions. The negative ions repel from the negative membrane however also shielding the ability of the membrane to also repel or retain the negatively charged dye leading to less dye retained by the membrane. The second conclusion that can be drawn is that the polyethersulfone membrane is the most effective at retaining Reactive Red ED-2B dye.

As this project continues, it is recommended that more tests be done on the membranes including a test to determine the zeta potential, and the pore size and distribution. It is also recommended to perform a permeability and selectivity analysis on each membrane. Since these studies were only performed at pH 7, it would be interesting to test the effect of pH on the dye retention. Within textile effluent, many other chemicals used in the washing process are present possibly changing the overall pH, and therefore this enhanced membrane technology should be tested at different pH values. This study should also expand to multiple dyes as a more universal treatment would be more favorable.

One application for this research could be in the concentration of the dye for the use of degradation. While the reuse of dye is unlikely due to the other chemicals used and found in the effluent stream, the use of enhanced ultrafiltration membranes could be used in reducing the size of holding tanks. If water could pass through the holding tank for more specific treatment, the concentrated dye solution could undergo a bacterial degradation treatment that can take up to several days.

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Appendix

Appendix 1 – PES Membrane Data

PES; Ionic Strength = 0mM			PES; Ionic Strength = 10mM			PES; Ionic Strength = 50mM		
Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance
original solution		1.91	original solution		2.049	original solution		
0.02 MPa	1	0.058	0.02 MPa	1	0.012	0.02 MPa	1	1.201
	2	0.057		2	0.183		2	1.206
	3	0.055		3	0.221		3	1.288
	4	3.110		4	2.631		4	2.204
0.04 MPa	5	0.096	0.04 MPa	5	0.357	0.04 MPa	5	1.214
	6	0.103		6	0.369		6	1.401
	7	0.107		7	0.406		7	1.433
	8	3.740		8	3.160		8	2.303
0.06 MPa	9	1.784	0.06 MPa	9	0.473	0.06 MPa	9	1.440
	10	0.423		10	0.528		10	1.541
	11	0.234		11	0.616		11	1.604
	12	3.158		12	3.460		12	2.350
0.08 MPa	13	0.470	0.08 MPa	13	0.734	0.08 MPa	13	1.621
	14	0.318		14	0.880		14	1.684
	15	0.363		15	0.992		15	1.732
	16	3.730		16	3.536		16	2.274
0.10 MPa	17	0.448	0.10 MPa	17	1.129	0.10 MPa	17	1.707
	18	0.600		18	1.292		18	1.756
	19	0.677		19	1.350		19	1.792
	20	4.328		20	3.288		20	2.249

Sample Averages			Sample Averages			Sample Averages		
0.02 MPa	0.057		0.02 MPa	0.139		0.02 MPa	1.232	
0.04 MPa	0.105		0.04 MPa	0.377		0.04 MPa	1.349	
0.06 MPa	0.329		0.06 MPa	0.539		0.06 MPa	1.528	
0.08 MPa	0.384		0.08 MPa	0.869		0.08 MPa	1.679	
0.10 MPa	0.575		0.10 MPa	1.257		0.10 MPa	1.752	
Before and After Stir Cell			Before and After Stir Cell			Before and After Stir Cell		
0.02 MPa	2.510		0.02 MPa	2.340		0.02 MPa	2.204	
0.04 MPa	2.825		0.04 MPa	2.605		0.04 MPa	2.303	
0.06 MPa	2.534		0.06 MPa	2.755		0.06 MPa	2.350	
0.08 MPa	2.820		0.08 MPa	2.793		0.08 MPa	2.274	
0.10 MPa	3.119		0.10 MPa	2.669		0.10 MPa	2.249	
Sieving Coefficient			Sieving Coefficient			Sieving Coefficient		
0.02	0.022576361		0.02	0.05925926		0.02	0.55895923	
0.04	0.037168142		0.04	0.14487746		0.04	0.58602968	
0.06	0.129636938		0.06	0.1956798		0.06	0.65049301	
0.08	0.136052009		0.08	0.31107132		0.08	0.73834653	
0.1	0.18435396		0.1	0.47105115		0.1	0.77886468	

PES; Ionic Strength = 100mM			PES; Ionic Strength = 500mM		
Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance
original solution		1.953	original solution		1.822
0.02 MPa	1	0.912	0.02 MPa	1	0.568
	2	1.326		2	1.232
	3	1.457		3	1.480
	4	1.970		4	1.736
0.04 MPa	5	1.363	0.04 MPa	5	1.414
	6	1.541		6	1.637
	7	1.642		7	1.679
	8	2.082		8	1.802
0.06 MPa	9	1.569	0.06 MPa	9	1.63
	10	1.707		10	1.699
	11	1.774		11	1.722
	12	2.081		12	1.819
0.08 MPa	13	1.700	0.08 MPa	13	1.623
	14	1.787		14	
	15	1.815		15	1.74
	16	2.064		16	1.816
0.10 MPa	17	1.835	0.10 MPa	17	1.641
	18	1.822		18	1.729
	19	1.870		19	1.752
	20	2.031		20	1.804

Sample Averages			Sample Averages		
0.02 MPa	1.232		0.02 MPa	1.356	
0.04 MPa	1.515		0.04 MPa	1.577	
0.06 MPa	1.683		0.06 MPa	1.684	
0.08 MPa	1.767		0.08 MPa	1.682	
0.10 MPa	1.842		0.10 MPa	1.707	
Before and After Stir Cell			Before and After Stir Cell		
0.02 MPa	1.962		0.02 MPa	1.7790	
0.04 MPa	2.018		0.04 MPa	1.8120	
0.06 MPa	2.017		0.06 MPa	1.8205	
0.08 MPa	2.009		0.08 MPa	1.8190	
0.10 MPa	1.992		0.10 MPa	1.8130	
Sieving Coefficient			Sieving Coefficient		
0.02	0.62792081		0.02	0.76222597	
0.04	0.75109459		0.04	0.870125092	
0.06	0.83461418		0.06	0.924837499	
0.08	0.87992698		0.08	0.924409016	
0.1	0.92486613		0.1	0.941717227	

PES; Ionic Strength = 0mM						
	SN	Flask (g)	Flask + Sample (g)	Sample (mL)	Time (sec)	J_v(m/s)*10^-5
0.02 MPa	1	17.7167	20.0946	2.3779	360	1.34801587
	2	17.1676	19.3088	2.1412	360	1.21383220
	3	17.2866	19.3360	2.0494	360	1.16179138
0.04 MPa	5	18.0154	22.4241	4.4087	360	2.49926304
	6	17.8284	21.9620	4.1336	360	2.34331066
	7	17.4117	21.4949	4.0832	360	2.31473923
0.06 MPa	9	18.1683	22.4976	4.3293	360	2.45425170
	10	18.3743	25.0223	6.6480	360	3.76870748
	11	17.8511	24.3316	6.4805	360	3.67375283
0.08 MPa	13	17.9394	25.9533	8.0139	360	4.54302721
	14	17.8171	25.1802	7.3631	360	4.17409297
	15	17.4495	24.7751	7.3256	360	4.15283447
0.10 MPa	17	17.2794	26.1917	8.9123	360	5.05232426
	18	17.4911	26.7207	9.2296	360	5.23219955
	19	17.8041	26.6510	8.8469	360	5.01524943
Sample Averages						
0.02 MPa	1.24121315					
0.04 MPa	2.38577098					
0.06 MPa	3.29890401					
0.08 MPa	4.28998488					
0.10 MPa	5.09992441					

PES; Ionic Strength = 10mM						
	SN	Flask	Flask + Sample	Sample (mL)	Time (sec)	J_v(m/s)*10^-5
0.02 MPa	1	17.7193	19.7696	2.0503	360	1.16230159
	2	17.1699	19.0686	1.8987	360	1.07636054
	3	17.2899	19.1923	1.9024	360	1.07845805
0.04 MPa	5	18.0187	22.2558	4.2371	360	2.40198413
	6	17.8346	21.6629	3.8283	360	2.17023810
	7	17.4183	21.3507	3.9324	360	2.22925170
0.06 MPa	9	18.1692	23.7988	5.6296	360	3.19138322
	10	18.4796	23.8999	5.4203	360	3.07273243
	11	17.8570	23.2262	5.3692	360	3.04376417
0.08 MPa	13	17.9424	25.8441	7.9017	390	4.13485086
	14	17.8027	24.3905	6.5878	330	4.07408782
	15	17.4485	24.6226	7.1741	360	4.06695011
0.10 MPa	17	17.2783	26.2928	9.0145	360	5.11026077
	18	17.5089	25.7800	8.2711	360	4.68883220
	19	18.0293	26.4094	8.3801	360	4.75062358
Sample Averages						
0.02 MPa	1.10570673					
0.04 MPa	2.26715797					
0.06 MPa	3.10262661					
0.08 MPa	4.09196293					
0.10 MPa	4.84990552					

PES; Ionic Strength = 50mM						
	SN	Flask	Flask + Sample	Sample (mL)	Time (sec)	J_v(m/s)*10^-5
0.02 MPa	1	17.7157	19.2471	1.5314	360	0.86814059
	2	17.1664	19.2200	2.0536	390	1.07462062
	3	17.2857	19.1395	1.8538	360	1.05090703
0.04 MPa	5	18.0144	21.1212	3.1068	360	1.76122449
	6	17.8274	21.4667	3.6393	360	2.06309524
	7	17.4110	20.7385	3.3275	360	1.88633787
0.06 MPa	9	18.0168	23.0845	5.0677	360	2.87286848
	10	18.3733	23.0453	4.6720	360	2.64852608
	11	17.8502	22.2888	4.4386	360	2.51621315
0.08 MPa	13	17.9378	24.4633	6.5255	360	3.69926304
	14	17.8000	24.2733	6.4733	360	3.66967120
	15	17.4467	23.6032	6.1565	360	3.49007937
0.10 MPa	17	17.2771	24.8654	7.5883	360	4.30175737
	18	17.4893	24.7825	7.2932	360	4.13446712
	19	17.8021	24.9500	7.1479	360	4.05209751
Sample Averages						
0.02 MPa	0.99788941					
0.04 MPa	1.90355253					
0.06 MPa	2.67920257					
0.08 MPa	3.61967120					
0.10 MPa	4.16277400					

PES; Ionic Strength = 100mM						
	SN	Flask	Flask + Sample	Sample (mL)	Time (sec)	J_v(m/s)*10^-5
0.02 MPa	1	17.7137	19.1444	1.4307	360	0.81105442
	2	17.1652	18.9145	1.7493	360	0.99166667
	3	17.2839	18.9280	1.6441	360	0.93202948
0.04 MPa	5	18.0123	20.9940	2.9817	360	1.69030612
	6	17.8261	20.7620	2.9359	360	1.66434240
	7	17.4088	20.8710	3.4622	360	1.96269841
0.06 MPa	9	18.1650	22.6384	4.4734	360	2.53594104
	10	18.3718	23.7578	5.3860	420	2.61710398
	11	17.8493	22.6181	4.7688	300	3.24408163
0.08 MPa	13	17.9360	23.8153	5.8793	360	3.33293651
	14	17.7976	23.5361	5.7385	360	3.25311791
	15	17.4443	23.0725	5.6282	360	3.19058957
0.10 MPa	17	17.2748	24.8891	7.6143	360	4.31649660
	18	17.4869	24.8489	7.3620	360	4.17346939
	19	17.7999	24.7885	6.9886	360	3.96179138
Sample Averages						
0.02 MPa	0.91158352					
0.04 MPa	1.77244898					
0.06 MPa	2.79904222					
0.08 MPa	3.25888133					
0.10 MPa	4.15058579					

CRC, n=9; Ionic Strength = 500mM						
	SN	**Flask**	**Flask + Sample**	**Sample (mL)**	**Time (sec)**	**J_v(m/s)*10^-5**
0.02 MPa	1	18.1022	19.7059	1.6037	390	0.83919414
	2	18.3912	19.8157	1.4245	360	0.80753968
	3	18.2436	19.6724	1.4288	360	0.80997732
0.04 MPa	5	18.1094	21.6045	3.4951	390	1.82893773
	6	18.5068	21.9913	3.4845	360	1.97534014
	7	18.2421	21.7289	3.4868	360	1.97664399
0.06 MPa	9	17.5490	22.2493	4.7003	360	2.66456916
	10	18.4782	23.1253	4.6471	360	2.63441043
	11	17.1020	21.7055	4.6035	360	2.60969388
0.08 MPa	13	18.1084	24.1383	6.0299	360	3.41831066
	14			0.0000	360	0.00000000
	15	17.4936	23.1042	5.6106	360	3.18061224
0.10 MPa	17	18.3875	25.7612	7.3737	360	4.18010204
	18	17.9751	25.1929	7.2178	360	4.09172336
	19	18.0254	24.9618	6.9364	360	3.93219955
Sample Averages						
0.02 MPa	0.81890372					
0.04 MPa	1.92697395					
0.06 MPa	2.63622449					
0.08 MPa	3.29946145					
0.10 MPa	4.06800831					

Appendix 2 – Unmodified Membrane Data

CRC, unmodified; Ionic Strength = 0mM			CRC, unmodified; Ionic Strength = 10mM			CRC, unmodified; Ionic Strength = 50mM		
Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance
original solution		1.996	original solution		1.869	original solution		1.942
0.02 MPa	1	0.376	0.02 MPa	1	1.461	0.02 MPa	1	1.860
	2	0.416		2	1.395		2	1.884
	3	0.465		3	1.431		3	1.889
	4	2.855		4	1.989		4	1.871
0.04 MPa	5	0.673	0.04 MPa	5	1.742	0.04 MPa	5	1.887
	6	0.734		6	1.820		6	1.853
	7	0.860		7	1.823		7	1.859
	8	3.324		8	1.807		8	1.933
0.06 MPa	9	1.013	0.06 MPa	9	1.822	0.06 MPa	9	1.828
	10	1.131		10	1.616		10	1.867
	11	1.281		11	1.630		11	1.882
	12	3.170		12	1.982		12	1.933
0.08 MPa	13	1.296	0.08 MPa	13	1.719	0.08 MPa	13	1.854
	14	1.465		14	1.761		14	1.883
	15	1.613		15	1.797		15	1.895
	16	2.930		16	1.966		16	1.922
0.10 MPa	17	1.543	0.10 MPa	17	1.751	0.10 MPa	17	1.872
	18	1.752		18	1.806		18	1.892
	19	1.855		19	1.819		19	1.899
	20	2.646		20	1.935		20	1.919

Sample Averages		Sample Averages		Sample Averages	
0.02 MPa	0.419	0.02 MPa	1.429	0.02 MPa	1.878
0.04 MPa	0.797	0.04 MPa	1.795	0.04 MPa	1.866
0.06 MPa	1.142	0.06 MPa	1.689	0.06 MPa	1.859
0.08 MPa	1.458	0.08 MPa	1.759	0.08 MPa	1.877
0.10 MPa	1.717	0.10 MPa	1.792	0.10 MPa	1.888
Before and After Stir Cell		Before and After Stir Cell		Before and After Stir Cell	
0.02 MPa	2.426	0.02 MPa	1.929	0.02 MPa	1.907
0.04 MPa	2.660	0.04 MPa	1.838	0.04 MPa	1.938
0.06 MPa	2.583	0.06 MPa	1.925	0.06 MPa	1.938
0.08 MPa	2.463	0.08 MPa	1.917	0.08 MPa	1.932
0.10 MPa	2.321	0.10 MPa	1.902	0.10 MPa	1.931

CRC, unmodified; Ionic Strength = 100mM			CRC, unmodified; Ionic Strength = 500mM			REPEAT CRC, unmodified; Ionic Strength = 0mM		
Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance
original solution		1.918	original solution		1.638	original solution		2.129
0.02 MPa	1	1.693	0.02 MPa	1	1.387	0.02 MPa	1	0.29
	2	1.756		2	1.512		2	0.33
	3	1.772		3	1.528		3	0.368
	4	1.868		4	1.578		4	3.186
0.04 MPa	5	1.807	0.04 MPa	5	1.326	0.04 MPa	5	0.643
	6	1.849		6	1.539		6	0.753
	7	1.857		7	1.56		7	0.797
	8	1.921		8	1.602		8	3.524
0.06 MPa	9	1.833	0.06 MPa	9	1.527	0.06 MPa	9	0.849
	10	1.869		10	1.576		10	1.063
	11	1.888		11	1.588		11	1.186
	12	1.918		12	1.608		12	3.474
0.08 MPa	13	1.850	0.08 MPa	13	1.514	0.08 MPa	13	1.292
	14	1.877		14	1.588		14	1.386
	15	1.898		15	1.598		15	1.515
	16	1.920		16	1.617		16	2.945
0.10 MPa	17	1.869	0.10 MPa	17	1.524	0.10 MPa	17	1.575
	18	1.888		18	1.58		18	1.716
	19	1.899		19	1.594		19	1.848
	20	1.910		20	1.609		20	2.947

Sample Averages	
0.02 MPa	1.740
0.04 MPa	1.838
0.06 MPa	1.863
0.08 MPa	1.875
0.10 MPa	1.885
Before and After Stir Cell	
0.02 MPa	1.893
0.04 MPa	1.920
0.06 MPa	1.918
0.08 MPa	1.919
0.10 MPa	1.914

Sieving Coefficient	
0.02	0.919352
0.04	0.95736737
0.06	0.97149809
0.08	0.97707139
0.1	0.98502264

Sample Averages	
0.02 MPa	1.476
0.04 MPa	1.475
0.06 MPa	1.564
0.08 MPa	1.567
0.10 MPa	1.566
Before and After Stir Cell	
0.02 MPa	1.6078
0.04 MPa	1.6198
0.06 MPa	1.6228
0.08 MPa	1.6273
0.10 MPa	1.6233

Sieving Coefficient	
0.02	0.9178459
0.04	0.9106344
0.06	0.9635906
0.08	0.9627695
0.1	0.9647312

Sample Averages	
0.02 MPa	0.329
0.04 MPa	0.731
0.06 MPa	1.033
0.08 MPa	1.398
0.10 MPa	1.713
Before and After Stir Cell	
0.02 MPa	2.6575
0.04 MPa	2.8265
0.06 MPa	2.8015
0.08 MPa	2.5370
0.10 MPa	2.5380

Sieving Coefficient	
0.02	0.123926
0.04	0.2586237
0.06	0.3686121
0.08	0.5509132
0.1	0.6749409

CRC, unmodified; Ionic Strength = 0mM						
	SN	Flask	Flask + Sample	Sample (mL)	Time (sec)	J_v(m/s)*10^-5
0.02 MPa	1	17.7139	20.5381	2.8242	360	1.60102041
	2	17.1644	19.8616	2.6972	360	1.52902494
	3	17.2840	19.8690	2.5850	360	1.46541950
0.04 MPa	5	18.0147	23.6020	5.5873	360	3.16740363
	6	17.8283	22.8366	5.0083	360	2.83917234
	7	17.4114	22.5404	5.1290	360	2.90759637
0.06 MPa	9	18.1677	26.1103	7.9426	360	4.50260771
	10	18.3746	25.9993	7.6247	360	4.32239229
	11	17.8506	25.4727	7.6221	360	4.32091837
0.08 MPa	13	17.9389	28.3644	10.4255	360	5.91014739
	14	17.8014	27.9658	10.1644	360	5.76213152
	15	17.4479	27.4771	10.0292	360	5.68548753
0.10 MPa	17	17.2781	29.7131	12.4350	360	7.04931973
	18	17.4914	29.1692	11.6778	360	6.62006803
	19	17.8034	30.0124	12.2090	360	6.92120181
Sample Averages						
0.02 MPa	1.53182162					
0.04 MPa	2.97139078					
0.06 MPa	4.38197279					
0.08 MPa	5.78592215					
0.10 MPa	6.86352986					

CRC, unmodified; Ionic Strength = 10mM						
	SN	Flask	Flask + Sample	Sample (mL)	Time (sec)	J_v(m/s)*10^-5
0.02 MPa	1	17.7185	19.7090	1.9905	360	1.12840136
	2	17.1698	19.3797	2.2099	360	1.25277778
	3	17.2900	20.0674	2.7774	360	1.57448980
0.04 MPa	5	18.0179	23.2300	5.2121	360	2.95470522
	6	17.8353	22.6342	4.7989	360	2.72046485
	7	17.4150	22.2195	4.8045	360	2.72363946
0.06 MPa	9	18.1696	25.9709	7.8013	360	4.42250567
	10	18.3806	26.3172	7.9366	360	4.49920635
	11	17.8548	25.2185	7.3637	360	4.17443311
0.08 MPa	13	17.9432	28.6750	10.7318	360	6.08378685
	14	17.8027	28.2119	10.4092	360	5.90090703
	15	17.4493	28.0818	10.6325	360	6.02749433
0.10 MPa	17	17.2799	30.0224	12.7425	360	7.22363946
	18	17.4920	30.2840	12.7920	360	7.25170068
	19	17.8048	30.5490	12.7442	360	7.22460317
Sample Averages						
0.02 MPa	1.31855631					
0.04 MPa	2.79960317					
0.06 MPa	4.36538171					
0.08 MPa	6.00406274					
0.10 MPa	7.23331444					

CRC, unmodified; Ionic Strength = 50mM						
	SN	**Flask**	**Flask + Sample**	**Sample (mL)**	**Time (sec)**	**J_v(m/s)*10^-5**
0.02 MPa	1	17.716	20.0082	2.2922	360	1.29943311
	2	17.1670	19.3536	2.1866	360	1.23956916
	3	17.2863	19.7899	2.5036	360	1.41927438
0.04 MPa	5	18.0149	22.8172	4.8023	360	2.72239229
	6	17.8282	22.5744	4.7462	360	2.69058957
	7	17.4112	22.7047	5.2935	360	3.00085034
0.06 MPa	9	18.1680	25.9293	7.7613	360	4.39982993
	10	18.3743	25.9835	7.6092	360	4.31360544
	11	17.8511	25.1997	7.3486	360	4.16587302
0.08 MPa	13	17.9391	28.4556	10.5165	360	5.96173469
	14	17.8012	28.1041	10.3029	360	5.84064626
	15	17.4484	27.3180	9.8696	360	5.59501134
0.10 MPa	17	17.2806	29.7315	12.4509	360	7.05833333
	18	17.4917	29.0696	11.5779	360	6.56343537
	19	17.8046	29.3997	11.5951	360	6.57318594
Sample Averages						
0.02 MPa	1.31942555					
0.04 MPa	2.80461073					
0.06 MPa	4.29310280					
0.08 MPa	5.79913076					
0.10 MPa	6.73165155					

CRC, unmodified; Ionic Strength = 100mM						
	SN	**Flask**	**Flask + Sample**	**Sample (mL)**	**Time (sec)**	**J_v(m/s)*10^-5**
0.02 MPa	1	18.1026	20.5495	2.4469	360	1.38713152
	2	18.3920	20.7090	2.3170	360	1.31349206
	3	18.2441	20.4609	2.2168	360	1.25668934
0.04 MPa	5	18.1108	23.0740	4.9632	360	2.81360544
	6	18.5073	23.3712	4.8639	360	2.75731293
	7	18.2433	23.0024	4.7591	360	2.69790249
0.06 MPa	9	17.5502	25.2819	7.7317	360	4.38304989
	10	18.4789	26.4481	7.9692	360	4.51768707
	11	17.1034	24.6967	7.5933	360	4.30459184
0.08 MPa	13	18.0187	28.2082	10.1895	360	5.77636054
	14	18.2001	28.1762	9.9761	360	5.65538549
	15	17.4944	27.4174	9.9230	360	5.62528345
0.10 MPa	17	18.3884	30.7244	12.3360	360	6.99319728
	18	17.9764	30.1668	12.1904	360	6.91065760
	19	18.0265	29.8608	11.8343	360	6.70878685
Sample Averages						
0.02 MPa	1.31910431					
0.04 MPa	2.75627362					
0.06 MPa	4.40177627					
0.08 MPa	5.68567649					
0.10 MPa	6.87088057					

CRC, unmodified; Ionic Strength = 500mM						
	SN	Flask	Flask + Sample	Sample (mL)	Time (sec)	J_v(m/s)*10^-5
0.02 MPa	1	17.7184	20.6776	2.9592	360	1.67755102
	2	17.1696	19.7589	2.5893	360	1.46785714
	3	17.2896	19.5052	2.2156	360	1.25600907
0.04 MPa	5	18.0167	23.0960	5.0793	360	2.87942177
	6	17.8443	22.7714	4.9271	360	2.79314059
	7	17.4142	22.2344	4.8202	360	2.73253968
0.06 MPa	9	18.1686	25.1629	6.9943	360	3.96502268
	10	18.3818	26.0768	7.6950	360	4.36224490
	11	17.8564	25.5606	7.7042	360	4.36746032
0.08 MPa	13	17.9412	27.9045	9.9633	360	5.64812925
	14	17.8015	27.4055	9.6040	360	5.44444444
	15	17.4481	28.2487	10.8006	420	5.24810496
0.10 MPa	17	17.2783	29.2460	11.9677	360	6.78441043
	18	17.4908	29.1080	11.6172	360	6.58571429
	19	17.8035	29.2461	11.4426	360	6.48673469
Sample Averages						
0.02 MPa	1.46713908					
0.04 MPa	2.80170068					
0.06 MPa	4.23157596					
0.08 MPa	5.44689288					
0.10 MPa	6.61895314					

REPEAT CRC, unmodified; Ionic Strength = 0mM						
	SN	Flask	Flask + Sample	Sample (mL)	Time (sec)	J_v(m/s)*10^-5
0.02 MPa	1	17.7146	20.0371	2.3225	360	1.31660998
	2	17.1649	19.3555	2.1906	360	1.24183673
	3	17.2847	19.5415	2.2568	360	1.27936508
0.04 MPa	5	18.0123	23.4254	5.4131	390	2.83260073
	6	17.8264	22.6837	4.8573	360	2.75357143
	7	17.4097	22.1627	4.7530	360	2.69444444
0.06 MPa	9	18.1657	25.2167	7.0510	360	3.99716553
	10	18.3719	25.3437	6.9718	360	3.95226757
	11	17.8481	24.8269	6.9788	360	3.95623583
0.08 MPa	13	17.9359	27.0308	9.0949	360	5.15583900
	14	17.7983	26.9100	9.1117	360	5.16536281
	15	17.4450	26.0438	8.5988	360	4.87460317
0.10 MPa	17	17.2753	28.5903	11.3150	360	6.41439909
	18	17.4879	28.6508	11.1629	360	6.32817460
	19	17.8004	28.8347	11.0343	360	6.25527211
Sample Averages						
0.02 MPa	1.27927060					
0.04 MPa	2.76020554					
0.06 MPa	3.96855631					
0.08 MPa	5.06526833					
0.10 MPa	6.33261527					

Appendix 3 – CRC n = 3 Membrane Data

CRC, n=3; Ionic Strength = 0mM			CRC, n=3; Ionic Strength = 10mM			CRC, n=3; Ionic Strength = 50mM		
Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance
original solution		1.994	original solution		2.044	original solution		1.942
0.02 MPa	1	0.030	0.02 MPa	1	0.277	0.02 MPa	1	1.292
	2	0.038		2	0.267		2	1.363
	3	0.036		3	0.303		3	1.421
	4	2.610		4	2.755		4	2.111
0.04 MPa	5	0.075	0.04 MPa	5	0.531	0.04 MPa	5	1.507
	6	0.102		6	0.594		6	1.635
	7	0.100		7	0.659		7	1.691
	8	3.156		8	3.074		8	2.119
0.06 MPa	9	0.183	0.06 MPa	9	0.847	0.06 MPa	9	1.697
	10	0.233		10	0.985		10	1.771
	11	0.254		11	1.090		11	1.835
	12	3.868		12	3.286		12	2.094
0.08 MPa	13	0.342	0.08 MPa	13	1.171	0.08 MPa	13	1.787
	14	0.379		14	1.338		14	1.838
	15	0.497		15	1.469		15	1.870
	16	4.188		16	3.112		16	2.020
0.10 MPa	17	0.673	0.10 MPa	17	1.510	0.10 MPa	17	1.863
	18	0.757		18	1.659		18	1.890
	19	0.819		19	1.747		19	1.904
	20	4.180		20	2.783		20	1.990

Sample Averages			Sample Averages			Sample Averages		
0.02 MPa	0.035		0.02 MPa	0.282		0.02 MPa	1.359	
0.04 MPa	0.092		0.04 MPa	0.595		0.04 MPa	1.611	
0.06 MPa	0.223		0.06 MPa	0.974		0.06 MPa	1.768	
0.08 MPa	0.406		0.08 MPa	1.326		0.08 MPa	1.832	
0.10 MPa	0.750		0.10 MPa	1.639		0.10 MPa	1.886	
Before and After Stir Cell			Before and After Stir Cell			Before and After Stir Cell		
0.02 MPa	2.302		0.02 MPa	2.399		0.02 MPa	2.026	
0.04 MPa	2.575		0.04 MPa	2.559		0.04 MPa	2.030	
0.06 MPa	2.931		0.06 MPa	2.665		0.06 MPa	2.018	
0.08 MPa	3.091		0.08 MPa	2.578		0.08 MPa	1.981	
0.10 MPa	3.087		0.10 MPa	2.413		0.10 MPa	1.966	
Sieving Coefficient			Sieving Coefficient			Sieving Coefficient		
0.02	0.01505937		0.02	0.1176757		0.02	0.6705326	
0.04	0.03585761		0.04	0.2324051		0.04	0.7934983	
0.06	0.07619697		0.06	0.3655127		0.06	0.8760583	
0.08	0.13134908		0.08	0.5144021		0.08	0.9247339	
0.1	0.24284634		0.1	0.679029		0.1	0.9592607	

CRC, n=3; Ionic Strength = 100mM			CRC, n=3; Ionic Strength = 500mM		
Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance
original solution		1.943	original solution		1.811
0.02 MPa	1	1.645	0.02 MPa	1	1.459
	2	1.690		2	1.665
	3	1.701		3	1.688
	4	1.967		4	1.759
0.04 MPa	5	1.753	0.04 MPa	5	1.654
	6	1.811		6	1.727
	7	1.844		7	1.749
	8	1.987		8	1.786
0.06 MPa	9	1.808	0.06 MPa	9	1.663
	10	1.844		10	1.741
	11	1.868		11	1.755
	12	1.969		12	1.784
0.08 MPa	13	1.839	0.08 MPa	13	1.751
	14	1.822		14	1.786
	15	1.899		15	1.789
	16	1.950		16	1.756
0.10 MPa	17	1.878	0.10 MPa	17	1.736
	18	1.902		18	1.771
	19	1.916		19	1.783
	20	1.940		20	1.787

Sample Averages			Sample Averages		
0.02 MPa	1.679		0.02 MPa	1.604	
0.04 MPa	1.803		0.04 MPa	1.710	
0.06 MPa	1.840		0.06 MPa	1.720	
0.08 MPa	1.853		0.08 MPa	1.775	
0.10 MPa	1.899		0.10 MPa	1.763	
Before and After Stir Cell			Before and After Stir Cell		
0.02 MPa	1.955		0.02 MPa	1.78475	
0.04 MPa	1.965		0.04 MPa	1.79825	
0.06 MPa	1.956		0.06 MPa	1.79725	
0.08 MPa	1.947		0.08 MPa	1.78325	
0.10 MPa	1.942		0.10 MPa	1.79875	
Sieving Coefficient			Sieving Coefficient		
0.02	0.858653		0.02	0.8987253	
0.04	0.9173876		0.04	0.9509245	
0.06	0.9406953		0.06	0.9568322	
0.08	0.9521363		0.08	0.9955605	
0.1	0.977938		0.1	0.9803104	

CRC, n=3; Ionic Strength = 0mM						
	SN	Flask	Flask + Sample	Sample (mL)	Time (sec)	J_v(m/s) *10^-5
0.02 MPa	1	17.7144	19.7612	2.0468	360	1.16031746
	2	17.1644	19.1651	2.0007	390	1.04693878
	3	17.2836	19.1818	1.8982	360	1.07607710
0.04 MPa	5	18.0123	21.9052	3.8929	360	2.20685941
	6	17.8256	21.5817	3.7561	360	2.12930839
	7	17.4087	21.1653	3.7566	360	2.12959184
0.06 MPa	9	18.1652	23.8094	5.6442	360	3.19965986
	10	18.3714	24.1944	5.8230	360	3.30102041
	11	17.8481	23.6199	5.7718	360	3.27199546
0.08 MPa	13	17.9358	25.7701	7.8343	360	4.44121315
	14	17.7979	25.1090	7.3111	360	4.14461451
	15	17.4445	25.4002	7.9557	360	4.51003401
0.10 MPa	17	17.2760	26.7112	9.4352	360	5.34875283
	18	17.4870	26.6874	9.2004	360	5.21564626
	19	17.8005	27.0048	9.2043	360	5.21785714
Sample Averages						
0.02 MPa	1.09444444					
0.04 MPa	2.15525321					
0.06 MPa	3.25755858					
0.08 MPa	4.36528723					
0.10 MPa	5.26075208					

CRC, n=3; Ionic Strength = 10mM						
	SN	Flask	Flask + Sample	Sample (mL)	Time (sec)	J_v(m/s) *10^-5
0.02 MPa	1	18.1027	20.3602	2.2575	360	1.27976190
	2	18.3924	20.8868	2.4944	360	1.41405896
	3	17.4461	19.0759	1.6298	360	0.92392290
0.04 MPa	5	18.1099	22.2280	4.1181	360	2.33452381
	6	18.5205	22.7730	4.2525	360	2.41071429
	7	18.2427	22.5580	4.3153	360	2.44631519
0.06 MPa	9	17.5493	23.7668	6.2175	360	3.52465986
	10	18.4788	24.8346	6.3558	360	3.60306122
	11	17.1030	23.6880	6.5850	360	3.73299320
0.08 MPa	13	18.0186	26.6049	8.5863	360	4.86751701
	14	18.1999	26.7508	8.5509	360	4.84744898
	15	17.4945	25.9826	8.4881	360	4.81184807
0.10 MPa	17	18.3883	29.0994	10.7111	360	6.07205215
	18	17.9765	28.7091	10.7326	360	6.08424036
	19	18.0265	28.6399	10.6134	360	6.01666667
Sample Averages						
0.02 MPa	1.20591459					
0.04 MPa	2.39718443					
0.06 MPa	3.62023810					
0.08 MPa	4.84227135					
0.10 MPa	6.05765306					

CRC, n=3; Ionic Strength = 50mM						
	SN	Flask	Flask + Sample	Sample (mL)	Time (sec)	J_v(m/s) *10^-5
0.02 MPa	1	17.7157	19.9800	2.2643	360	1.28361678
	2	17.1674	19.2855	2.1181	360	1.20073696
	3	17.2863	19.8152	2.5289	360	1.43361678
0.04 MPa	5	18.015	22.0695	4.0549	360	2.29869615
	6	17.828	22.3130	4.4852	360	2.54263039
	7	17.412	22.1611	4.7495	360	2.69246032
0.06 MPa	9	18.167	24.4328	6.2656	360	3.55192744
	10	18.374	25.1384	6.7645	360	3.83475057
	11	17.852	24.6741	6.8226	360	3.86768707
0.08 MPa	13	17.938	26.5690	8.6310	360	4.89285714
	14	17.800	26.4899	8.6898	360	4.92619048
	15	17.447	26.0443	8.5977	360	4.87397959
0.10 MPa	17	17.277	27.9810	10.7037	360	6.06785714
	18	17.490	27.9911	10.5015	360	5.95323129
	19	17.803	28.2300	10.4275	360	5.91128118
Sample Averages						
0.02 MPa	1.30599017					
0.04 MPa	2.51126228					
0.06 MPa	3.75145503					
0.08 MPa	4.89767574					
0.10 MPa	5.97745654					

CRC, n=3; Ionic Strength = 100mM						
	SN	Flask	Flask + Sample	Sample (mL)	Time (sec)	J_v(m/s) *10^-5
0.02 MPa	1	18.1041	20.3699	2.2658	360	1.28446712
	2	18.3927	20.8249	2.4322	360	1.37879819
	3	17.4457	19.8346	2.3889	360	1.35425170
0.04 MPa	5	18.1099	22.9897	4.8798	360	2.76632653
	6	18.5223	23.1694	4.6471	360	2.63441043
	7	18.2436	23.3705	5.1269	360	2.90640590
0.06 MPa	9	17.5490	24.4954	6.9464	360	3.93786848
	10	18.4803	25.2729	6.7926	360	3.85068027
	11	17.1033	23.6827	6.5794	360	3.72981859
0.08 MPa	13	18.0186	26.7929	8.7743	360	4.97409297
	14	18.1997	27.2634	9.0637	360	5.13815193
	15	17.4946	26.2917	8.7971	360	4.98701814
0.10 MPa	17	18.3876	29.9072	11.5196	360	6.53038549
	18	17.9758	29.2197	11.2439	360	6.37409297
	19	18.0264	29.2064	11.1800	360	6.33786848
Sample Averages						
0.02 MPa	1.33917234					
0.04 MPa	2.76904762					
0.06 MPa	3.83945578					
0.08 MPa	5.03308768					
0.10 MPa	6.41411565					

CRC, n=3 Ionic Strength = 500mM						
	SN	**Flask**	**Flask + Sample**	**Sample (mL)**	**Time (sec)**	**J_v(m/s)*10^-5**
0.02 MPa	1	17.7153	20.1015	2.3862	360	1.35272109
	2	17.1660	19.4648	2.2988	360	1.30317460
	3	17.2854	19.2819	1.9965	360	1.13180272
0.04 MPa	5	18.0142	22.7028	4.6886	360	2.65793651
	6	17.8277	22.7404	4.9127	360	2.78497732
	7	17.4111	22.1250	4.7139	360	2.67227891
0.06 MPa	9	18.1672	25.1944	7.0272	360	3.98367347
	10	18.3731	25.2550	6.8819	360	3.90130385
	11	17.8503	24.5282	6.6779	360	3.78565760
0.08 MPa	13	17.9379	27.1538	9.2159	360	5.22443311
	14	17.8004	26.3498	8.5494	360	4.84659864
	15	17.4474	26.1612	8.7138	360	4.93979592
0.10 MPa	17	17.2774	28.5692	11.2918	360	6.40124717
	18	17.8025	28.6561	10.8536	360	6.15283447
	19	17.4896	28.4127	10.9231	360	6.19223356
Sample Averages						
0.02 MPa	1.26256614					
0.04 MPa	2.70506425					
0.06 MPa	3.89021164					
0.08 MPa	5.00360922					
0.10 MPa	6.24877173					

Appendix 4 – CRC n = 9 Membrane Data

CRC, n=9; Ionic Strength = 0mM			CRC, n=9; Ionic Strength = 10mM			CRC, n=9; Ionic Strength = 50mM		
Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance
original solution		1.936	original solution		2.043	original solution		1.957
0.02 MPa	1	0.158	0.02 MPa	1	0.214	0.02 MPa	1	1.786
	2	0.008		2	0.209		2	1.817
	3	0.005		3	0.214		3	1.825
	4	3.412		4	2.752		4	1.765
0.04 MPa	5	1.757	0.04 MPa	5	0.359	0.04 MPa	5	1.712
	6	0.136		6	0.441		6	1.785
	7	0.051		7	0.521		7	1.824
	8	3.590		8	4.052		8	2.237
0.06 MPa	9	0.375	0.06 MPa	9	0.575	0.06 MPa	9	1.798
	10	0.136		10	0.691		10	1.838
	11	0.195		11	0.777		11	1.871
	12	5.914		12	3.840		12	2.014
0.08 MPa	13	1.943	0.08 MPa	13	1.021	0.08 MPa	13	1.891
	14	1.948		14	1.233		14	1.895
	15	1.952		15	1.389		15	1.895
	16	1.989		16	3.884		16	1.886
0.10 MPa	17	0.727	0.10 MPa	17	1.345	0.10 MPa	17	1.884
	18	0.933		18	1.517		18	1.876
	19	1.080		19	1.642		19	1.873
	20	4.796		20	3.614		20	1.912

Sample Averages		Sample Averages		Sample Averages	
0.02 MPa	0.057	0.02 MPa	0.212	0.02 MPa	1.809
0.04 MPa	0.094	0.04 MPa	0.440	0.04 MPa	1.774
0.06 MPa	0.235	0.06 MPa	0.681	0.06 MPa	1.836
0.08 MPa	1.948	0.08 MPa	1.214	0.08 MPa	1.894
0.10 MPa	0.913	0.10 MPa	1.501	0.10 MPa	1.878
Before and After Stir Cell		Before and After Stir Cell		Before and After Stir Cell	
0.02 MPa	2.674	0.02 MPa	2.398	0.02 MPa	1.861
0.04 MPa	2.763	0.04 MPa	3.048	0.04 MPa	2.097
0.06 MPa	3.925	0.06 MPa	2.942	0.06 MPa	1.986
0.08 MPa	1.963	0.08 MPa	2.964	0.08 MPa	1.922
0.10 MPa	3.366	0.10 MPa	2.829	0.10 MPa	1.935
Sieving Coefficient		Sieving Coefficient		Sieving Coefficient	
0.02	0.0213164	0.02	0.0885645	0.02	0.9722371
0.04	0.03384	0.04	0.14449	0.04	0.8458115
0.06	0.0599575	0.06	0.2315145	0.06	0.9245362
0.08	0.9924416	0.08	0.4097632	0.08	0.9855148
0.1	0.2713409	0.1	0.5307878	0.1	0.9706212

CRC, n=9; Ionic Strength = 100mM			CRC, n=9; Ionic Strength = 500mM		
Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance
original solution		2.1055	original solution		1.883
0.02 MPa	1	1.851	0.02 MPa	1	1.579
	2	1.888		2	1.781
	3	1.916		3	1.800
	4	2.141		4	1.855
0.04 MPa	5	2.009	0.04 MPa	5	1.656
	6	2.023		6	1.818
	7	2.042		7	1.838
	8	2.146		8	1.863
0.06 MPa	9	2.088	0.06 MPa	9	1.833
	10	2.090		10	1.845
	11	2.095		11	1.849
	12	2.084		12	1.864
0.08 MPa	13	2.093	0.08 MPa	13	1.843
	14	2.098		14	1.856
	15	2.101		15	1.866
	16	2.074		16	1.874
0.10 MPa	17	2.070	0.10 MPa	17	1.838
	18	2.082		18	1.862
	19	2.088		19	1.869
	20	2.103		20	1.871

Sample Averages			Sample Averages		
0.02 MPa	1.885		0.02 MPa	1.720	
0.04 MPa	2.025		0.04 MPa	1.771	
0.06 MPa	2.091		0.06 MPa	1.842	
0.08 MPa	2.097		0.08 MPa	1.855	
0.10 MPa	2.080		0.10 MPa	1.856	
Before and After Stir Cell			Before and After Stir Cell		
0.02 MPa	2.123		0.02 MPa	1.8688	
0.04 MPa	2.126		0.04 MPa	1.8728	
0.06 MPa	2.095		0.06 MPa	1.8733	
0.08 MPa	2.090		0.08 MPa	1.8783	
0.10 MPa	2.104		0.10 MPa	1.8768	
Sieving Coefficient			Sieving Coefficient		
0.02	0.8877899		0.02	0.92040134	
0.04	0.9524482		0.04	0.94549014	
0.06	0.9982098		0.06	0.98349571	
0.08	1.0036288		0.08	0.98762146	
0.1	0.9884757		0.1	0.98912126	

Repeated Data					
CRC, n=9; Ionic Strength = 0mM			CRC, n=9; Ionic Strength = 50mM		
Pressure	Sample #	Absorbance	Pressure	Sample #	Absorbance
original solution		2.123	original solution		1.982
0.08 MPa	1	0.561	0.02 MPa	1	1.367
	2	0.534		2	1.448
	3	0.565		3	1.522
	4	4.650		4	2.412
Sample Average			Sample Average		
0.08 MPa	0.553		0.02 MPa	1.446	
Before and After Stir Cell			Before and After Stir Cell		
0.08 MPa	3.386		0.02 MPa	2.197	
Sieving Coefficient			Sieving Coefficient		
0.08	0.1634059		0.02	0.6580185	

CRC, n=9; Ionic Strength = 0mM						
	SN	**Flask**	**Flask + Sample**	**Sample (mL)**	**Time (sec)**	**J_v(m/s) *10^-5**
0.02 MPa	1	18.1024	20.4691	2.3667	480	1.00625000
	2	18.3918	21.4136	3.0218	480	1.28477891
	3	17.4468	20.0198	2.5730	480	1.09396259
0.04 MPa	5	18.1098	20.2604	2.1506	360	1.21916100
	6	18.5170	22.9769	4.4599	360	2.52828798
	7	18.2426	22.5982	4.3556	360	2.46916100
0.06 MPa	9	17.5494	24.0816	6.5322	360	3.70306122
	10	18.4803	24.9715	6.4912	360	3.67981859
	11	17.1038	23.4965	6.3927	360	3.62397959
0.08 MPa	13	18.0192	23.4919	5.4727	360	3.10243764
	14	18.2020	23.7416	5.5396	360	3.14036281
	15	17.4962	23.0792	5.5830	360	3.16496599
0.10 MPa	17	18.3907	28.5086	10.1179	360	5.73577098
	18	17.9783	27.8215	9.8432	360	5.58004535
	19	18.0283	27.5803	9.5520	360	5.41496599
Sample Averages						
0.02 MPa	1.12833050					
0.04 MPa	2.07220333					
0.06 MPa	3.66895314					
0.08 MPa	3.13592215					
0.10 MPa	5.57692744					

CRC, n=9; Ionic Strength = 10mM						
	SN	**Flask**	**Flask + Sample**	**Sample (mL)**	**Time (sec)**	**J_v(m/s) *10^-5**
0.02 MPa	1	17.7196	20.0351	2.3155	360	1.31264172
	2	17.1701	19.3371	2.1670	360	1.22845805
	3	17.2900	19.2545	1.9645	360	1.11366213
0.04 MPa	5	18.0185	22.9318	4.9133	360	2.78531746
	6	17.8329	22.9409	5.1080	360	2.89569161
	7	17.4143	21.9855	4.5712	360	2.59138322
0.06 MPa	9	18.1712	24.9444	6.7732	360	3.83968254
	10	18.3778	24.9053	6.5275	360	3.70039683
	11	17.8542	24.2250	6.3708	360	3.61156463
0.08 MPa	13	17.9422	27.0588	9.1166	360	5.16814059
	14	17.8052	26.5946	8.7894	360	4.98265306
	15	17.4530	26.1909	8.7379	360	4.95345805
0.10 MPa	17	17.2831	28.4825	11.1994	360	6.34886621
	18	17.4945	28.2988	10.8043	360	6.12488662
	19	17.8076	28.3122	10.5046	360	5.95498866
Sample Averages						
0.02 MPa	1.21825397					
0.04 MPa	2.75746410					
0.06 MPa	3.71721466					
0.08 MPa	5.03475057					
0.10 MPa	6.14291383					

CRC, n=9; Ionic Strength = 50mM						
	SN	**Flask**	**Flask + Sample**	**Sample (mL)**	**Time (sec)**	**J_v(m/s) *10^-5**
0.02 MPa	1	18.114	20.8147	2.7007	360	1.53100907
	2	18.3996	21.0568	2.6572	360	1.50634921
	3	17.4460	20.0562	2.6102	360	1.47970522
0.04 MPa	5	18.1206	23.4891	5.3685	360	3.04336735
	6	18.5362	23.6987	5.1625	360	2.92658730
	7	18.2601	23.4690	5.2089	360	2.95289116
0.06 MPa	9	17.5522	25.3634	7.8112	360	4.42811791
	10	18.5590	26.3025	7.7435	360	4.38973923
	11	17.1133	24.7456	7.6323	360	4.32670068
0.08 MPa	13	18.0217	28.0929	10.0712	360	5.70929705
	14	18.2099	28.2101	10.0002	360	5.66904762
	15	17.5179	27.3780	9.8601	360	5.58962585
0.10 MPa	17	17.1992	29.7483	12.5491	360	7.11400227
	18	17.7379	30.1822	12.4443	360	7.05459184
	19	18.5850	30.0631	11.4781	360	6.50685941
Sample Averages						
0.02 MPa	1.50568783					
0.04 MPa	2.97428193					
0.06 MPa	4.38151927					
0.08 MPa	5.65599017					
0.10 MPa	6.89181784					

CRC, n=9; Ionic Strength = 100mM						
	SN	**Flask**	**Flask + Sample**	**Sample (mL)**	**Time (sec)**	**J_v(m/s) *10^-5**
0.02 MPa	1	17.7144	20.3895	2.6751	360	1.51649660
	2	17.1652	19.7164	2.5512	360	1.44625850
	3	17.2846	19.6916	2.4070	360	1.36451247
0.04 MPa	5	18.0132	23.3400	5.3268	360	3.01972789
	6	17.8267	23.2497	5.4230	360	3.07426304
	7	17.4095	22.5405	5.1310	360	2.90873016
0.06 MPa	9	18.1656	26.0995	7.9339	360	4.49767574
	10	18.3728	26.1538	7.7810	360	4.41099773
	11	17.8486	25.4309	7.5823	360	4.29835601
0.08 MPa	13	17.9367	28.0769	10.1402	360	5.74841270
	14	17.7993	27.6070	9.8077	360	5.55992063
	15	17.4460	27.1403	9.6943	360	5.49563492
0.10 MPa	17	17.2775	29.4546	12.1771	360	6.90311791
	18	17.4888	29.2031	11.7143	360	6.64075964
	19	17.8017	29.0397	11.2380	360	6.37074830
Sample Averages						
0.02 MPa	1.44242252					
0.04 MPa	3.00090703					
0.06 MPa	4.40234316					
0.08 MPa	5.60132275					
0.10 MPa	6.63820862					

CRC, n=9; Ionic Strength = 500mM						
	SN	**Flask**	**Flask + Sample**	**Sample (mL)**	**Time (sec)**	**J_v(m/s)*10^-5**
0.02 MPa	1	17.7135	20.1293	2.4158	360	1.36950113
	2	17.1658	19.6365	2.4707	360	1.40062358
	3	17.2846	19.5923	2.3077	360	1.30821995
0.04 MPa	5	18.0125	23.6279	5.6154	360	3.18333333
	6	17.8268	22.8280	5.0012	360	2.83514739
	7	17.4092	22.7485	5.3393	360	3.02681406
0.06 MPa	9	18.1646	25.7477	7.5831	360	4.29880952
	10	18.3722	26.3700	7.9978	360	4.53390023
	11	17.8487	25.2736	7.4249	360	4.20912698
0.08 MPa	13	17.9357	27.9082	9.9725	360	5.65334467
	14	17.7989	27.6251	9.8262	360	5.57040816
	15	17.4454	27.0729	9.6275	360	5.45776644
0.10 MPa	17	17.2763	29.4700	12.1937	360	6.91252834
	18	17.4882	29.3444	11.8562	360	6.72120181
	19	17.8008	29.3558	11.5550	360	6.55045351
Sample Averages						
0.02 MPa	1.35944822					
0.04 MPa	3.01509826					
0.06 MPa	4.34727891					
0.08 MPa	5.56050642					
0.10 MPa	6.72806122					

Repeated Data						
CRC, n=9; Ionic Strength = 0mM						
	SN	**Flask**	**Flask + Sample**	**Sample (mL)**	**Time (sec)**	**J_v(m/s)*10^-5**
0.08 MPa	1	17.1603	25.1036	7.9433	360	4.50300454
	2	17.2804	24.8311	7.5507	360	4.28044218
	3	17.3493	24.5792	7.2299	360	4.09858277
Sample Averages						
0.08 MPa	4.29400983					

CRC, n=9; Ionic Strength = 50mM						
	SN	**Flask**	**Flask + Sample**	**Sample (mL)**	**Time (sec)**	**J_v(m/s)*10^-5**
0.02 MPa	1	18.3717	20.7805	2.4088	360	1.36553288
	2	17.8482	20.4944	2.6462	360	1.50011338
	3	17.8411	20.2910	2.4499	360	1.38883220
Sample Averages						
0.02 MPa	1.41815949					

Appendix 5 – Vitamin B_{12} Data

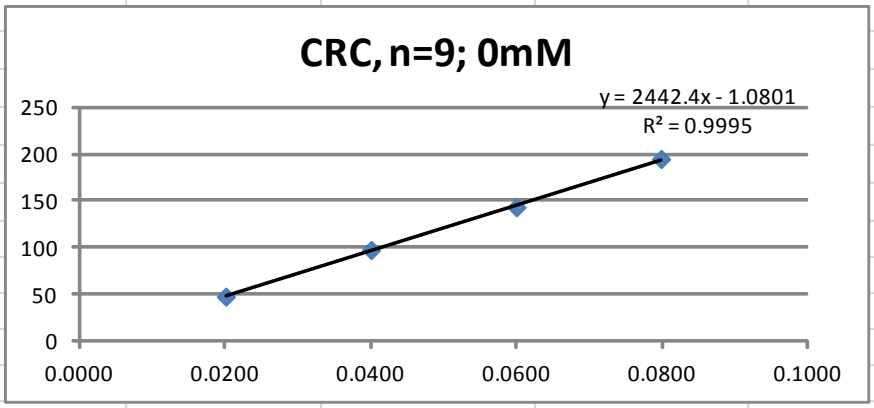
CRC, unmodified; Ionic Strength = 0mM		
Pressure	Sample #	Absorbance
original solution		1.883
0.02 MPa	1	1.710
	2	1.787
	3	1.791
	4	1.852
0.04 MPa	5	1.810
	6	1.831
	7	1.841
	8	1.878
0.06 MPa	9	1.821
	10	1.843
	11	1.857
	12	1.878
0.08 MPa	13	1.831
	14	1.851
	15	1.865
	16	1.878
0.10 MPa	17	1.834
	18	1.859
	19	1.867
	20	1.876

Sample Averages		
0.02 MPa	1.763	
0.04 MPa	1.836	
0.06 MPa	1.840	
0.08 MPa	1.849	
0.10 MPa	1.853	
Before and After Stir Cell		
0.02 MPa	1.868	
0.04 MPa	1.881	
0.06 MPa	1.881	
0.08 MPa	1.881	
0.10 MPa	1.880	
Sieving Coefficient		
0.02	0.943864346	
0.04	0.976336081	
0.06	0.978640433	
0.08	0.983249136	
0.1	0.986077858	

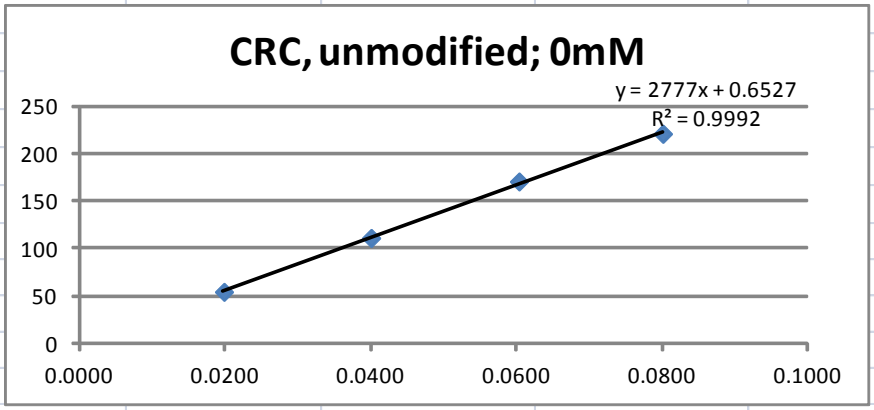
PES; Ionic Strength = 0mM						
	SN	**Flask (g)**	**Flask + Sample (g)**	**Sample (mL)**	**Time (sec)**	**J_v(m/s)*10^-5**
0.02 MPa	1	17.7157	19.9903	2.2746	360	1.28945578
	2	17.1657	19.4892	2.3235	360	1.31717687
	3	17.2852	19.3631	2.0779	360	1.17794785
0.04 MPa	5	18.0137	23.1014	5.0877	360	2.88418367
	6	17.8269	22.2334	4.4065	360	2.49801587
	7	17.4104	21.7595	4.3491	360	2.46547619
0.06 MPa	9	18.1676	24.4065	6.2389	360	3.53679138
	10	18.3726	24.5565	6.1839	360	3.50561224
	11	17.8497	24.1849	6.3352	360	3.59138322
0.08 MPa	13	17.9377	26.6158	8.6781	360	4.91955782
	14	17.8012	26.3587	8.5575	360	4.85119048
	15	17.4463	25.9636	8.5173	360	4.82840136
0.10 MPa	17	17.2767	28.0054	10.7287	360	6.08202948
	18	17.4890	27.6438	10.1548	360	5.75668934
	19	17.8015	28.5902	10.7887	360	6.11604308
Sample Averages						
0.02 MPa	1.26152683					
0.04 MPa	2.61589191					
0.06 MPa	3.54459562					
0.08 MPa	4.86638322					
0.10 MPa	5.98492063					

Appendix 6 – Lp Data

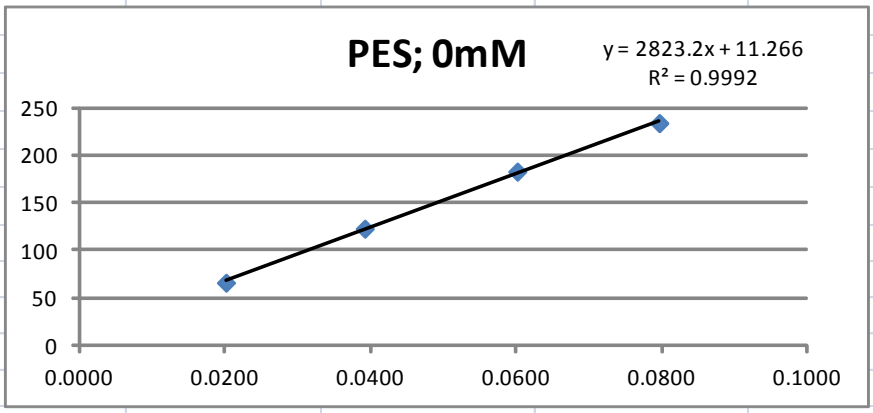
	CRC, n=9; 0mM				
P (MPa)		0.0201	0.0400	0.0600	0.0798
weight (g)	17.4809	18.2625	19.0604	20.2305	21.8217
time (sec)		120	60	60	60
Jv (LMH)		47.8531	97.7020	143.2776	194.8408



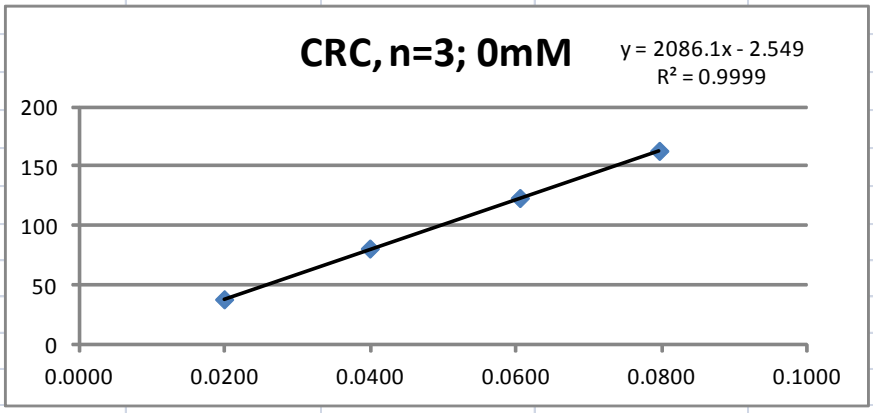
	CRC, unmodified; 0mM				
P (MPa)		0.0198	0.0400	0.0603	0.0801
weight (g)	17.4787	17.9341	18.8905	20.2165	22.0224
time (sec)		61	63	57	60
Jv (LMH)		54.8491	111.5335	170.9130	221.1306



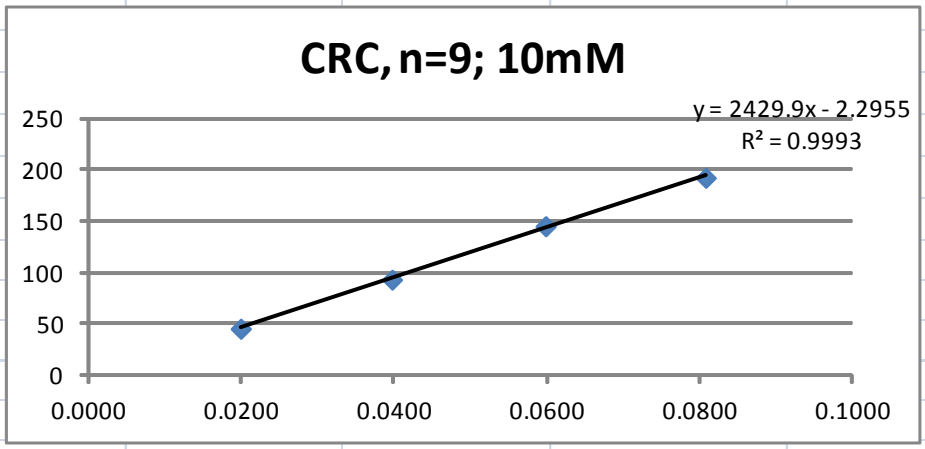
	PES; 0mM				
P (MPa)		0.0201	0.0392	0.0601	0.0796
weight (g)	17.3875	17.9565	19.0295	20.5250	22.4685
time (sec)		63	64	60	61
Jv (LMH)		66.3557	123.1760	183.1224	234.0783



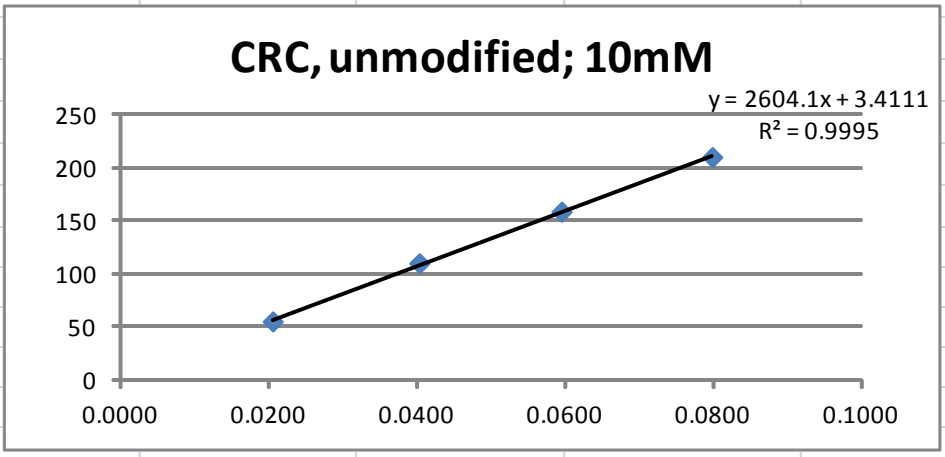
	CRC, n=3; 0mM				
P (MPa)		0.0199	0.0399	0.0605	0.0796
weight (g)	17.1695	17.5204	18.1939	19.0353	20.07978
time (sec)		67	61	50	47
Jv (LMH)		38.4782	81.1174	123.6343	163.2709



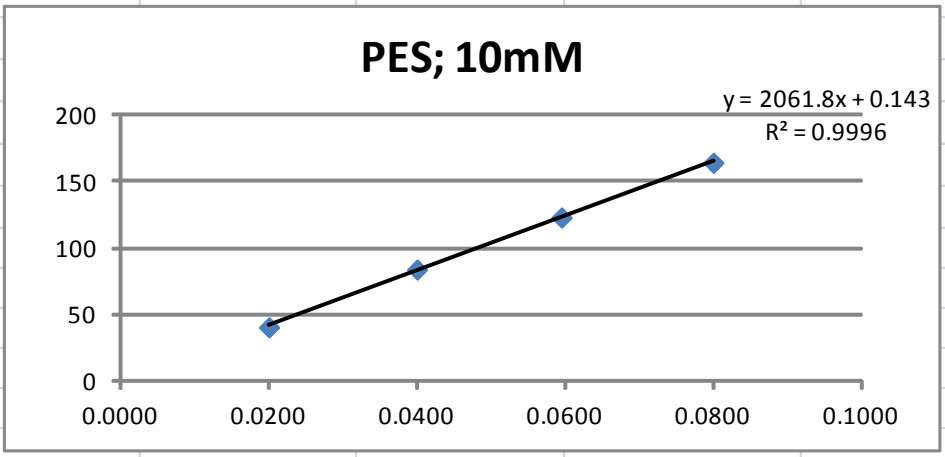
	CRC, n=9; 10mM				
P (MPa)		0.0199	0.0397	0.0598	0.0808
weight (g)	36.8658	37.6128	38.3758	39.5634	41.1362
time (sec)		120	60	60	60
Jv (LMH)		45.7347	93.4286	145.4204	192.5878



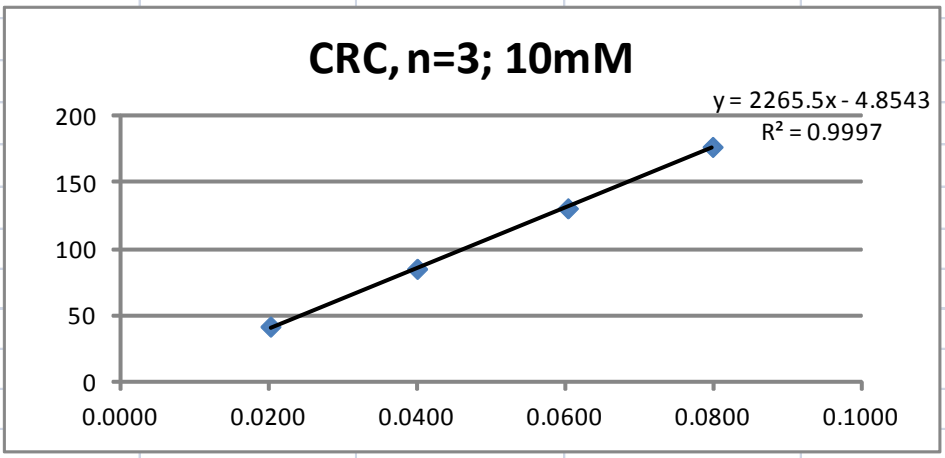
	CRC, unmodified; 10mM				
P (MPa)		0.0205	0.0403	0.0595	0.0799
weight (g)	17.4810	17.9784	18.8485	20.1246	21.9858
time (sec)		66	58	59	65
Jv (LMH)		55.3692	110.2167	158.9056	210.3711



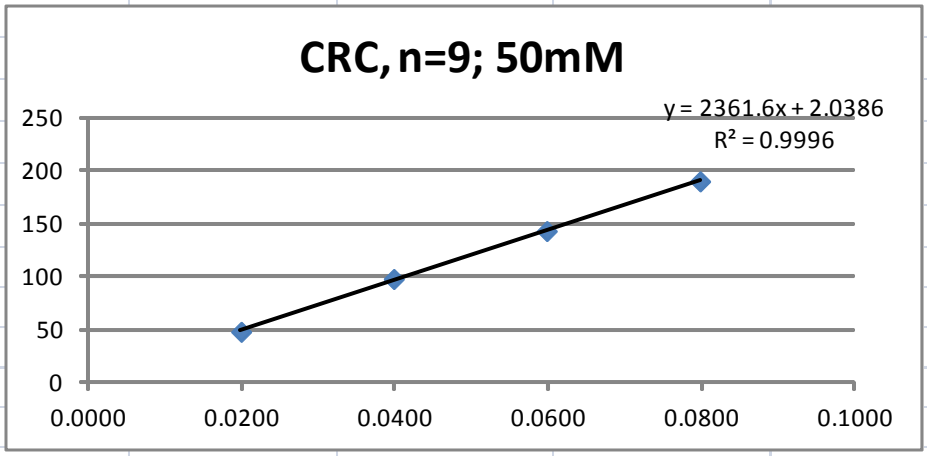
	PES; 10mM				
P (MPa)		0.0200	0.0400	0.0595	0.0800
weight (g)	17.3326	17.6735	18.3702	19.3928	20.7580
time (sec)		62	61	61	61
Jv (LMH)		40.3963	83.9117	123.1636	164.4269



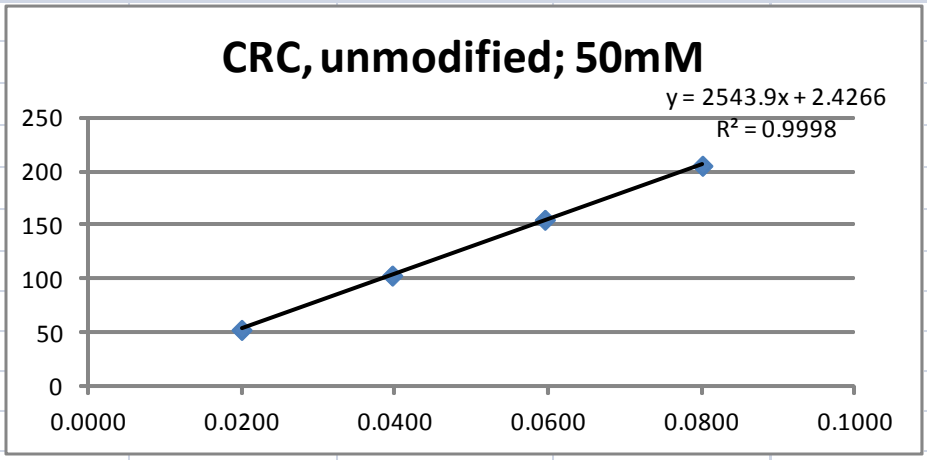
	CRC, n=3; 10mM				
P (MPa)		0.0202	0.0400	0.0604	0.0799
weight (g)	17.2253	17.5769	18.2955	19.435	20.9052
time (sec)		62	62	64	61
Jv (LMH)		41.6643	85.1534	130.8099	177.0733



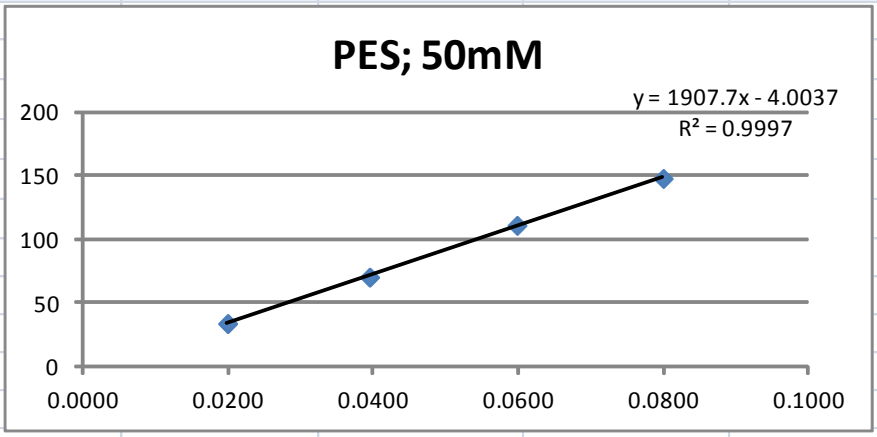
	CRC, n=9; 50mM				
P (MPa)		0.0200	0.0399	0.0598	0.0798
weight (g)	17.4912	18.2757	19.0752	20.2440	21.7957
time (sec)		120	60	60	60
Jv (LMH)		48.0306	97.8980	143.1184	190.0041



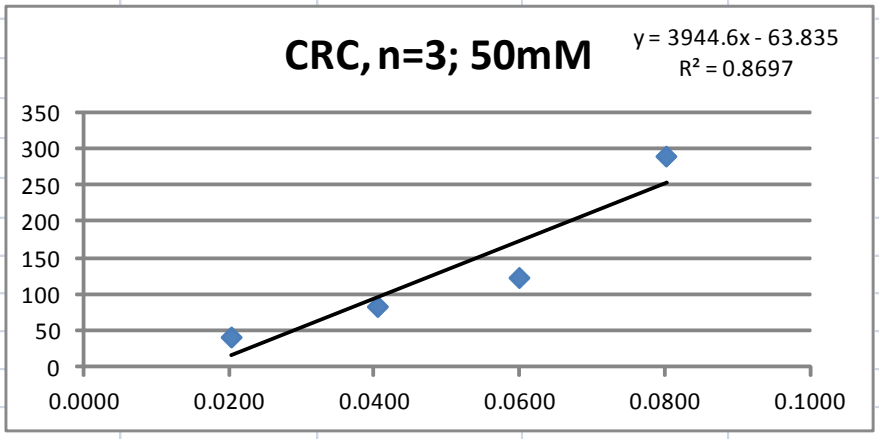
	CRC, unmodified; 50mM				
P (MPa)		0.0200	0.0397	0.0596	0.0801
weight (g)	18.0509	18.5115	19.3552	20.1576	21.8349
time (sec)		64	60	38	60
Jv (LMH)		52.8750	103.3102	155.1364	205.3837



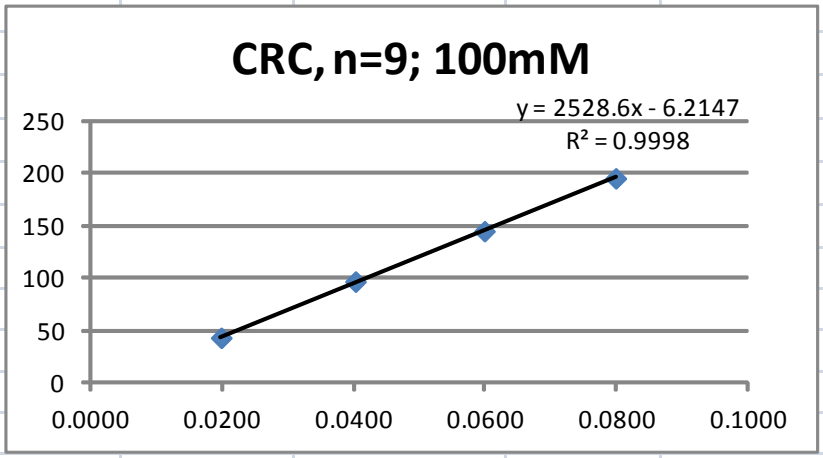
	PES; 50mM				
P (MPa)		0.0200	0.0395	0.0598	0.0800
weight (g)	17.3750	17.6682	18.2638	19.1720	20.4009
time (sec)		63	62	60	61
Jv (LMH)		34.1924	70.5780	111.2082	148.0107



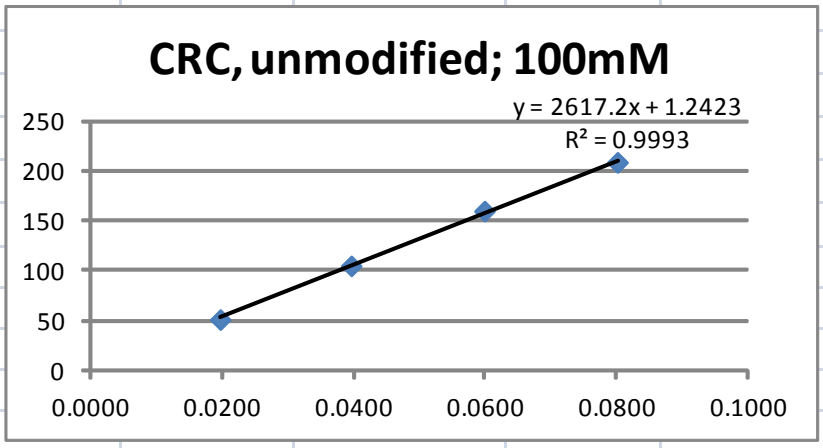
	CRC, n=3; 50mM				
P (MPa)		0.0203	0.0405	0.0600	0.0802
weight (g)	17.4755	17.8353	18.5039	19.4915	21.8565
time (sec)		64	59	59	60
Jv (LMH)		41.3036	83.2570	122.9803	289.5918



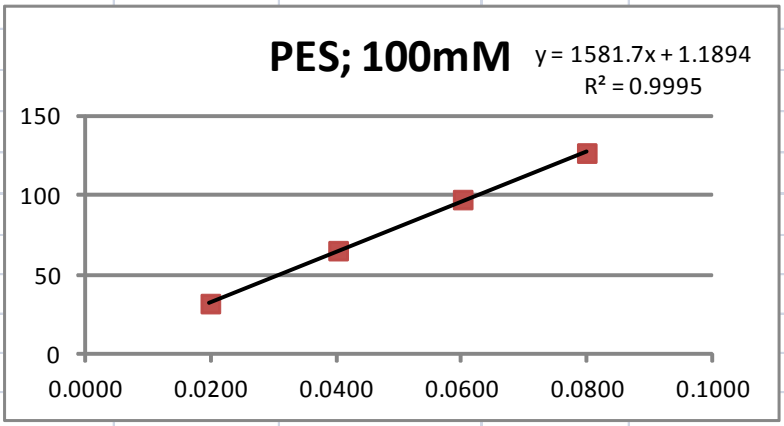
	CRC, n=9; 100mM				
P (MPa)		0.0199	0.0403	0.0599	0.0798
weight (g)	17.3801	18.0860	18.8766	20.0603	21.6550
time (sec)		120	60	60	60
Jv (LMH)		43.2184	96.8082	144.9429	195.2694



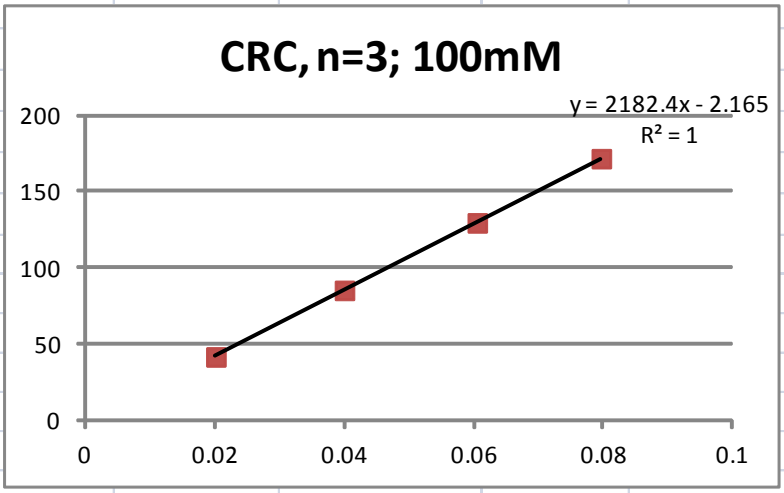
	CRC, unmodified; 100mM				
P (MPa)		0.0197	0.0396	0.0599	0.0801
weight (g)	17.3802	17.7882	18.6343	19.9213	21.6566
time (sec)		58	59	59	61
Jv (LMH)		51.6819	105.3601	160.2629	209.0023



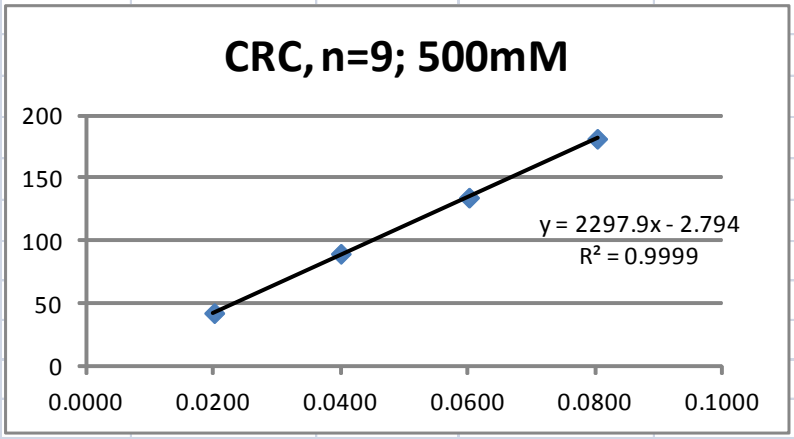
	PES; 100mM				
P (MPa)		0.0199	0.0403	0.0601	0.0799
weight (g)	17.3782	17.6745	18.2254	19.0339	20.0505
time (sec)		68	62	61	59
Jv (LMH)		32.0132	65.2811	97.3770	126.5915



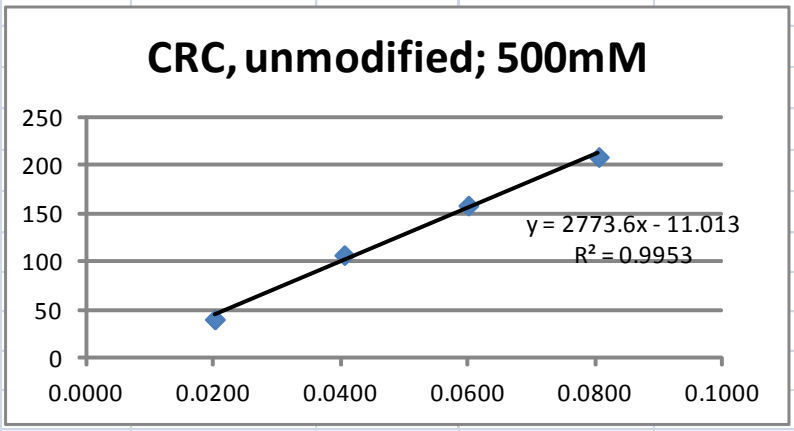
	CRC, n=3; 100mM				
P (MPa)		0.02015	0.04	0.0605	0.07965
weight (g)	18.0502	18.4025	19.1225	20.2168	21.6894
time (sec)		62	62	62	63
Jv (LMH)		41.7472	85.3193	129.6735	171.7318



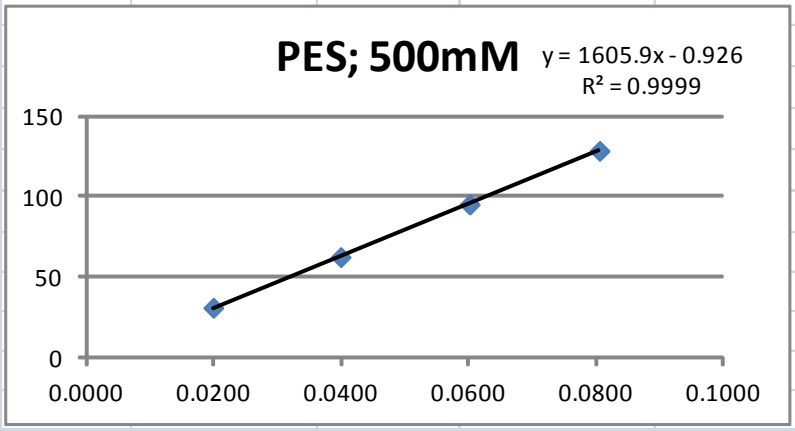
	CRC, n=9; 500mM				
P (MPa)		0.0201	0.0400	0.0601	0.0803
weight (g)	17.3771	18.1106	18.8581	19.9955	21.5282
time (sec)		126	61	62	62
Jv (LMH)		42.7697	90.0301	134.7808	181.6234



	CRC, unmodified; 500mM				
P (MPa)		0.0202	0.0405	0.0600	0.0805
weight (g)	17.1678	18.0336	18.8624	20.1762	21.8792
time (sec)		158	57	61	60
Jv (LMH)		40.2594	106.8271	158.2362	208.5306



	PES; 500mM				
P (MPa)		0.0199	0.0399	0.0601	0.0805
weight (g)	17.2174	17.6086	18.1210	18.8999	19.4250
time (sec)		92	60	60	30
Jv (LMH)		31.2405	62.7429	95.3755	128.5959



	CRC, n=3; 500mM				
P (MPa)		0.0201	0.03965	0.06015	0.0796
weight (g)	17.1695	17.5626	18.2213	19.2569	19.9885
time (sec)		67	58	59	32
Jv (LMH)		43.1057	83.4384	128.9575	167.9694