Griffith University

Griffith School of Engineering
INDUSTRIAL AFFILIATES PROGRAM

Comparative Performance Analysis of Crushed Recycled Glass as Granular Filtration Media in Swimming Pool Water Treatment

Report Prepared by **Jennifer-Leigh Campbell** (s2624103)
On 17th June 2011, Semester One

Poolrite RESEARCH

For POOLRITE RESEARCH

Wayne Taylor (Industry Supervisor)
Dr Benjamin Mullins (Academic Advisor)

A report submitted in partial fulfillment of the degree of Bachelor of Environmental Engineering/Bachelor of Science

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/watres

Comparative Performance Analysis of Crushed Recycled Glass as Granular Filtration Media in Swimming Pool Water Treatment

Jenifer-Leigh Campbell[a]

[a] Griffith University, Nathan Campus, Kessels Road Mt Gravatt, QLD Australia

Keywords: Recycled Glass, Swimming Pool Water Treatment, Filtration Efficiency, Packed-bed, Granular Media

Abstract

Filtration is essential to reducing the turbidity of swimming pool water caused by suspended particles or contaminants and improve the quality of the water for bather health and safety. One of the most common types of filter to treat swimming pool water is a packed-bed granular media filter, usually filled with sand or zeolite. As a more sustainable media, crushed recycled glass was compared theoretically and experimentally to sand and zeolite media. Theoretically, the glass will perform slightly better but similar to sand. Both media should also perform remarkably better than the grade of zeolite used. To support and verify the theory, experimental testing was conducted using a specially designed column test apparatus. Three column tests were conducted using the designed apparatus which illustrated that overall the glass (DK M10) produced better turbidity reduction and particle removal. Based on the results the glass media (DK M10) was deemed more efficient theoretically and experimentally than traditional sand and zeolite media for use as swimming pool granular filtration media.

1. Introduction

In recent years, there has been an increasing awareness of public health issues as a consequence of poor water quality in recreational waters (Perkins, 2000; Uhl &Hartmann, 2005; WHO, 2006; Croll et al., 2007; Lee et al., 2009; Dorevitch et al., 2011). As a result swimming pool water treatment technology is evolving from a simple stagnant body of water for bathing to full scale water and wastewater treatment processes. The treatment of swimming pool water can differ depending on the type of pool and expected contaminants. In general, the process of treating swimming pool water includes circulation, filtration, chlorination and water balancing (pH correction etc) (Williams &Langley, 2001; PWTAG, 2009). Filtration is essential to reducing the turbidity of the water caused by suspended particles or contaminants and improve the quality of the water (Korkosz et al., 2011). This is vital to reduce ingestion of harmful contaminants whilst swimming and to maintain visibility of swimmers to lifeguards or supervising guardians (WHO, 2006; PWTAG, 2009; Dorevitch et al., 2011)

The most common filters used in swimming pool treatment to collect contaminants are cartridge, diatomaceous earth and medium/high pressure packed-bed granular media filters (Pool Water Treatment Advisory Group (PWTAG), 2009). The granular media used in pool filters is usually sand or zeolite. Each type of media is used in the same way, to create a packed-bed filter in which contaminants are captured within the pore spaces and by adhering to the surface of the grains.

2. Modelling the Theoretical Filtration Efficiency

Various mechanisms act on particles or contaminants while they travel through a filter, sometimes resulting in removal from the flow of water. Using filtration theory and knowledge of these mechanisms, a model for filtration efficiency can be derived. This equation differs amongst the literature and depends ultimately on the application and properties of the filter system.

Three models for clean bed efficiency (YHO, TE and RT) were used to determine the collection efficiency of three different swimming pool filter media (sand, zeolite and glass). The characteristics of the three media are tabulated below (see table 1). These characteristics were then used to compare the media using each model.

The modelling of a single collector using the TE and RT models, predicts similar filtration efficiency for sand and glass with the zeolite performing better than the coarse grade glass. The YHO model shows a larger difference between the sand and glass media performance, predicting glass as the most efficient media.

These results were then used to predict the efficiency of the total filter bed filled with collectors. The above graphs (figure 1) illustrate that when the single collectors are added together in a filter bed the glass will perform slightly better but similar to sand. Both media also perform remarkably better than the zeolite.

Again the YHO model predicts better performance from the glass compared to sand. It is important to note however that the models don't include the chemical conditions within the system nor take into account any screening effects that may occur due to small pore spaces.

Table 1: Filter Grain Characteristics

Filter media	SAND	M10	M20	ZEOLITE
Porosity	0.3923	0.4171	0.4334	0.4436
grain size	0.0013	0.00118	0.0023	0.0016

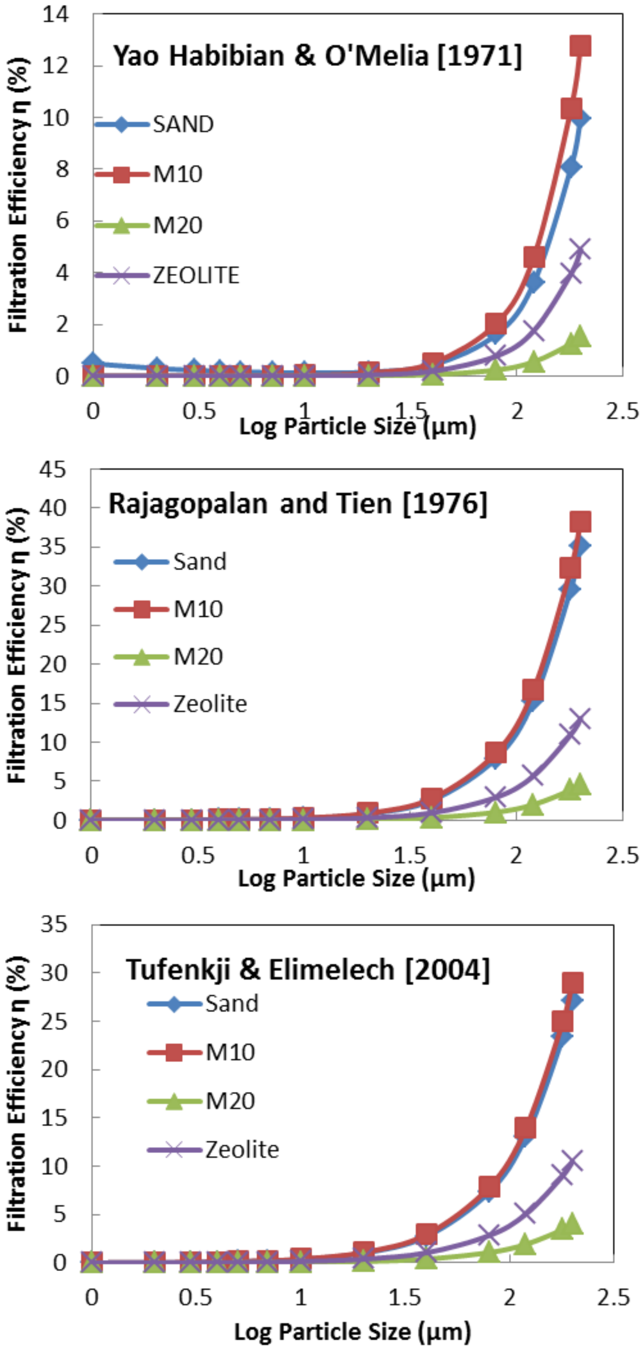


Figure 1: Graphical Representation of the Filtration Efficiency of a Column filled with Collectors (Grains of Filter Media)(Bed Depth 400mm, approach velocity 0.010548m/s, viscosity 0.000891kg/ms, temperature 298K, fluid density 997kg/m^3, Boltzmanns constant 1.38065E-23 m^2 kg/s^{2}K, Hamaker constant 4E-20 kg m^2/s^2, particle density 500kg/m^3)

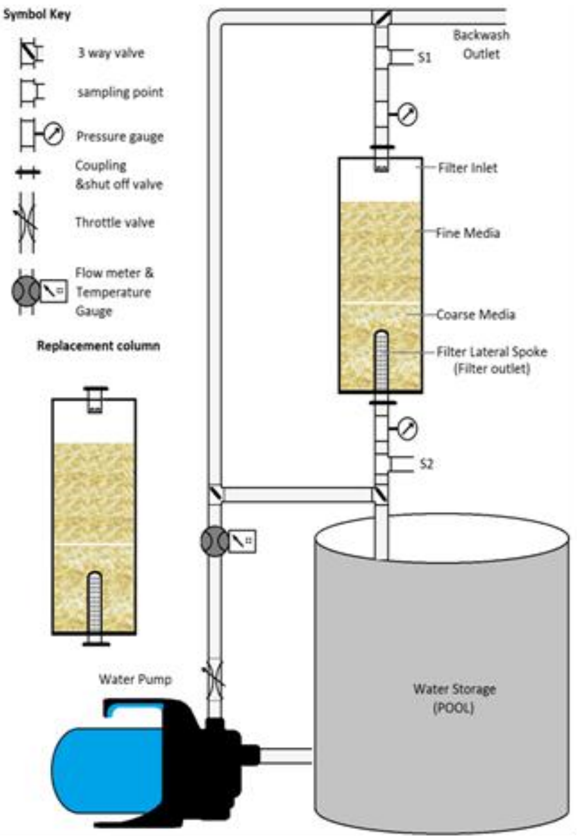


Figure 2: Diagrammatic Representation of the Column Test apparatus design

Methodology

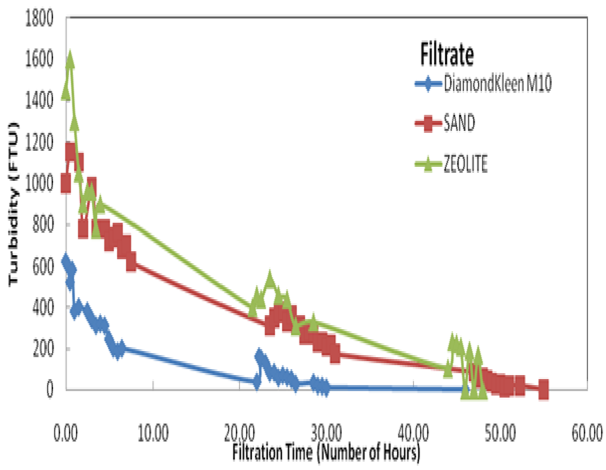
To support and verify the theory discussed experimental testing and assessment of results was conducted. To compare the performance and filtration efficiency a column test apparatus was designed. The design of the column test is shown in figure 2.

Three column tests were conducted using the designed apparatus. Results for pressure difference across the bed, flow rate, turbidity and particle size distribution of samples were obtained from these tests Samples were also collected during the tests. A coulter counter was used to determine the particle size distributions of these samples. These results were then analysed to determine the experimental filtration performance of the granular swimming pool filtration media.

Results

Overall the glass (DK M10) produced better turbidity reduction with no net increase in pressure difference across the bed (figure 3). While the decrease in pressure was probably due to unique conditions occurring in the experimental apparatus, the particle removal percentages and other observations support the claim that glass (DK M10) performs better than the sand or zeolite tested.

The glass (DK M10) filtered quicker than sand and zeolite, taking only 47 hours filtration time to achieve 0 FTU turbidity in the filtrate. This may be a result of lower initial turbidity or because glass (DK M10) filters quicker due to increase filtration efficiency per turnover of the pool water.



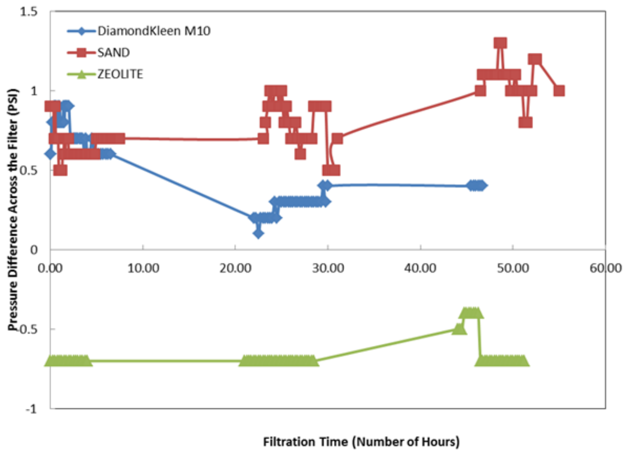


Figure 3: Turbidity Reduction and Changes in Pressure Difference Across the Bed During Filtration

Overall the glass (DK 10) showed efficient removal of particles 3-20 micrometres in size. The largest % of particles remaining in the filtrate at the end of filtration is the size range 0-3 micrometres, which confirms the theoretical removals predicted that the media would be less efficient at removing these smaller particles.

Collection of particles in the glass (DK 10) filter occurred throughout the entire bed whereas the sand filter occurred mostly at the top and bottom of the column, eventually causing screening towards the end of the filtration cycle. The zeolite only collected particles at the bottom.

There was also visible compaction of the sand bed which may have caused the screening effects by decreasing the pore spaces between filter grains. By decreasing the porosity, the filtration efficiency of the sand filter is decreased as shown by the theoretical models.

Korkosz (2011) states that sand also undergoes size reduction from turbulent conditions when washing. This size reduction from filtration and backwash cycling as well as bed compaction during filtration would lead to significant decreases in filtration performance. Therefore the glass (DK 10) will produce better filtration than the sand because there is limited compaction occurring in the filter bed and may experience less grain size reduction.

Conclusions

Based on the results above the glass media (DK M10) is more efficient theoretically and experimentally than traditional sand and zeolite media used in swimming pool granular media filters. It was discussed that this was probably due to the larger porosity maintained by minimal compaction during filtration.

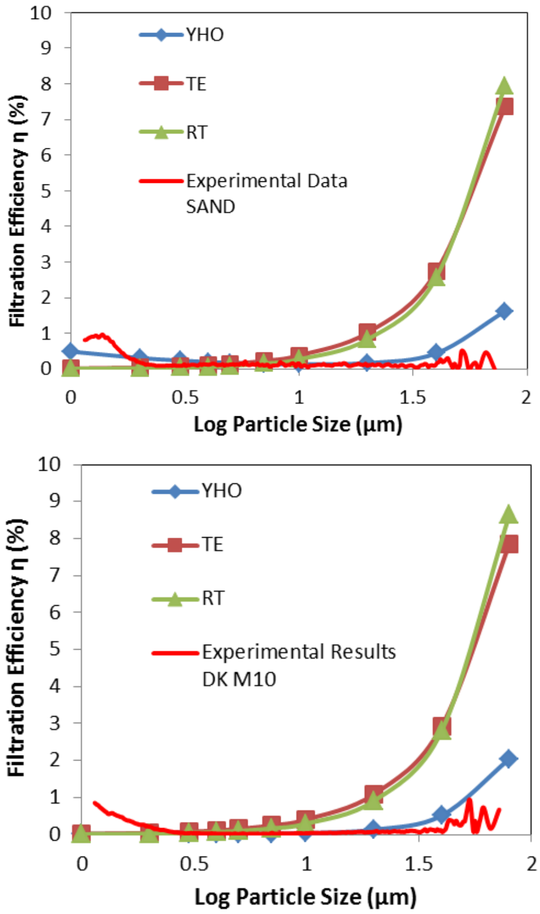


Figure 4: Comparison of the Experimental Results to the Theoretical Models

References

Croll, B. T., C. R. Hayes and S. Moss (2007). "Simulated Cryptosporidium removal under swimming pool filtration conditions." Water and Environment Journal **21**(2): 149-156.

Dorevitch, S., S. Panthi, Y. Huang, H. Li, A. M. Michalek, P. Pratap, M. Wroblewski, L. Liu, P. A. Scheff and A. Li (2011). "Water ingestion during water recreation." Water Research **45**(5): 2020-2028.

Korkosz, A., M. Niewiadomski and J. Hupka (2011). "INVESTIGATION OF PROPERTIES OF SWIMMING POOL WATER TREATMENT SEDIMENTS." Physicochemical Problems of Mineral Processing(46): 243-252.

Lee, J., K. T. Ha and K. D. Zoh (2009). "Characteristics of trihalomethane (THM) production and associated health risk assessment in swimming pool waters treated with different disinfection methods." Science of the Total Environment **407**(6): 1990-1997.

Perkins, P. H. (2000). Water Circulation And Water Treatment. Swimming Pools, Spon Press.

Pool Water Treatment Advisory Group (PWTAG) (2009). Swimming Pool Water: Treatment and Quality Standards for Pools and Spas, Micropress Printers Ltd, London.

Rajagopalan, R. and C. Tien (1976). "Trajectory analysis of deep-bed filtration with the sphere-in-cell porous media model." AIChE Journal **22**(3): 523-533.

Tufenkji, N. and M. Elimelech (2004). "Correlation equation for predicting single-collector efficiency in physicochemical filtration in saturated porous media." Environmental Science & Technology **38**(2): 529-536.

Uhl, W. and C. Hartmann (2005). Disinfection by-products and microbial contamination in the treatment of pool water with granular activated carbon. **52:** 71-76.

Uhl, W. and C. Hartmann (2005). Disinfection by-products and microbial contamination in the treatment of pool water with granular activated carbon. **52:** 71-76.

Williams, L. K. and R. L. Langley (2001). Environmental Health Secrets., Philadelphia, Hanley & Belfus, INC.

World Health Organisation (WHO) (2006). Guidelines for safe recreational waters, Volume 2 - Swimming pools and similar recreational-water environments Chapter 5: Managing Water and Air Quality. Switzerland, WHO Press**:** 80-99

Yao, K. M., M. T. Habibian and C. R. O'Melia (1971). "Water and waste water filtration. Concepts and applications." Environmental Science & Technology **5**(11): 1105-1112.

Griffith UNIVERSITY

Industrial Affiliates Program

Cover Sheet

Section 1: Personal details (student to complete)

Griffith student ID #:	S2624103
Last name:	CAMPBELL
First name:	Jennifer-Leigh
Mobile phone number:	0404949368

Section 2: Course and Assessment details (student to complete)

Course code:	4001ENG
Assessment item name:	Final Project Report
Assessment due date:	20/06/2011
Campus:	Nathan

Section 3: Student declaration (student to complete)

Breaches of academic integrity (cheating, plagiarism, falsification of data, collusion) seriously compromise student learning, as well as the University's assessment of the effectiveness of that learning and the academic quality of the University's awards. All breaches of academic integrity are taken seriously and could result in penalties including failure in the course and exclusion from the University.

Students should be aware that the University uses text-matching software to safeguard the quality of student learning and that your assessment may be checked using this software. Examiners will only award marks for work within this assessment item that is your own original work.

I acknowledge and agree that the examiner of this assessment item may, for the purpose of marking this assessment item:

- Reproduce this assessment item and provide a copy to another Griffith staff member; and/
- Submit this assessment item to a text-matching service. This web-based service will retain a copy of this assessment item for checking the work of other students, but will not reproduce it in any form.

I hereby certify that:

- Except where I have indicated, this assessment item is my own work, based on my personal study and/or research.
- I have acknowledged all materials and sources used in the preparation of this assessment item whether they are books, articles, reports, lecture notes, or any other kind of document or personal communication.
- I have not collaborated with another student or person in planning, developing and writing this assessment item.
- This assessment item has not been submitted for assessment in any other course or at any other time in the same course.
- I have not copied in part or in whole or otherwise plagiarised the work of other students and/or persons.
- I haven't made this piece of work available to another student.
- All of the work covered in this assessment was undertaken during the IAP placement.
- The material/content in this assessment item does not breach the Non-disclosure and Assignment of Intellectual Property Deed I have with the industry partner.
- Providing this declaration falsely is considered a breach of academic integrity.

I have retained a copy of this assessment item for my own records.

Acknowledged by: (After above sections have been completed print and sign form. Ask the Industry Partner to complete section 4)	 (Signature)	**Date:**	20/06/2011

Griffith UNIVERSITY

Industrial Affiliates Program

Section 4: Industry partner/supervisor release (Industry to complete)
(To be completed by the Industry partner/supervisor after the student has fully completed sections 1-3)

The signature of the Industry Partner or Industry Supervisor gives approval for release of information in the assessment item for assessment purposes. It also confirms the assessment as a true representation of the student's work for the organisation.

I give approval for release of this assessment item for assessment purposes:

Industry partner/supervisor name:	WAYNE TAYLOR
Organisation name:	POOLRITE RESEARCH
Industry partner/supervisor signature:	[signature]
Date:	22.6.11

Executive Summary

Poolrite Research Pty Ltd currently uses crushed recycled glass (Product name: DiamondKleen™) as a granular filtration media in packed-bed granular media filters for the treatment of swimming pool water. The reason for using recycled glass opposed to traditional media such as sand or zeolite is to address two social responsibility issues. The first issue is to provide a treatment option to adequately treat swimming pool water to provide safe and clear water to bathe in and second, to provide a more sustainable product. The following report outlines how recycled glass compares to sand and zeolite conceptually, theoretically and in a test environment.

The treatment of swimming pool water can differ depending on the type of pool and expected contaminants. As the water in swimming pools contains anthropogenic contaminants it is sometimes referred to as a wastewater. However because bathers are submerged in the same water and there is a high probability of water ingestion it must therefore be treated to a similar quality as drinking water standards (WHO, 2006; Dorevitch et al., 2011). In general, the process of treating swimming pool water includes circulation, filtration, chlorination and water balancing (pH correction etc) (Williams &Langley, 2001; PWTAG, 2009). Filtration is essential to reduce turbidity of the water caused by suspended particles or contaminants and improve the quality of the water (Korkosz et al., 2011).

The most common filters used in swimming pool treatment to collect contaminants are cartridge, diatomaceous earth and medium/high pressure packed-bed granular media filters (Pool Water Treatment Advisory Group (PWTAG), 2009). The granular media used in pool filters is usually sand or zeolite. Each type of media is used in the same way, to create a packed-bed filter in which contaminants are captured within the pore spaces and by adhering to the surface of the grains. Poolrite Equipment Pty Ltd has patented a form of crushed recycled glass to use in their packed-bed granular filters known as DiamondKleen™. The crushed recycled glass used in DiamondKleen™ is processed from collected soda-lime glass bottles called cullet, which is then heat treated to remove contaminants and residuals (Poolrite Research Pty Ltd, 2011). Conceptually, DiamondKleen™ is comparatively a more socially responsible medium for use in granular filters. The use of recycled glass utilises a waste product therefore encouraging industrial ecology practices while minimising the use of more environmentally harmful raw materials, sand or zeolite.

Various mechanisms act on particles or contaminants while they travel through a filter, sometimes resulting in removal from the flow of water. Using filtration theory and knowledge of these mechanisms, a model for filtration efficiency can be derived. This equation differs amongst the literature and depends ultimately on the application and properties of the filter system. Various models have been derived from these mechanisms to describe the motion of a particle during filtration and therefore determine the overall efficiency of a filter. Three models for clean bed efficiency (YHO, TE and RT) were used to determine the collection efficiency of each media (full model calculations are included in appendix B). The three media were then compared using each model.

The modelling of a single collector using the TE and RT models, predicts similar filtration efficiency for sand and DiamondKleen™ with the zeolite performing better than the coarse grade DiamondKleen™ M20. The YHO model shows a larger difference between the sand and DiamondKleen™ media performance, predicting DiamondKleen™ as the most efficient media. These results are then used to predict the efficiency of the total filter bed filled with collectors. The above graphs illustrate that when the single collectors are added together in a filter bed the DiamondKleen™ will perform slightly better but similar to sand. Both media also perform remarkably better than the zeolite. Again the YHO model predicts better performance from the DK compared to sand. It is important to note however that the models don't include the chemical conditions within the system nor take into account any screening effects that may occur due to small pore space.

To support and verify the theory discussed in the previous section experimental testing and assessment of results was required. Previous internal testing was conducted by the company but upon review there exists an uncertainty when interpreting results and often the interpretation which favours the product is adopted as a final conclusion. A more academic approach to the testing would assist in minimising commercial bias. To compare the performance and filtration efficiency the experimental apparatus was designed utilising the knowledge gained from critiquing previous internal reports and information provided in the academic literature. Three column tests were conducted using the designed apparatus. Results for pressure difference across the bed, flow rate, turbidity and particle size distribution of samples were obtained from these tests (Data and Test Reports provided in appendix D). These results were then analysed to determine the experimental filtration performance of the granular swimming pool filtration media

Overall the DiamondKleen^{TM} produced better turbidity reduction with no increase in pressure difference across the bed. While the decrease in pressure was probably due to unique conditions occurring in the experimental apparatus, the particle removal percentages and other observations support the claim that DiamondKleen^{TM} performs better than the sand or zeolite tested. The DiamondKleen^{TM} filtered quicker than sand and zeolite, taking only 47 hours filtration time to achieve 0FTU turbidity in the filtrate. This may be a result of lower initial turbidity or because DiamondKleen^{TM} filters quicker due to increase filtration efficiency per turnover of the pool water.

Due to time restrictions for testing the samples at the end of the project, only a selection of samples could be tested using the Coulter Counter. Overall the DiamondKleen^{TM} showed efficient removal of particles 3-20 micrometres in size. The largest % of particles remaining in the filtrate at the end of filtration is the size range 0-3 micrometres, which confirms the theoretical removals predicted that the media would be less efficient at removing these smaller particles.

Collection of particles in the DiamondKleen^{TM} filter occurred throughout the entire bed whereas the sand filter occurred mostly at the top and bottom of the column, eventually causing screening towards the end of the filtration cycle. The zeolite only collected particles at the bottom. There was also visible compaction of the sand bed which may have caused the screening effects by decreasing the pore spaces between filter grains. By decreasing the porosity, the filtration efficiency of the sand filter is decreased as shown by the theoretical models. Therefore the DiamondKleen^{TM} will produce better filtration than the sand because there is limited compaction occurring in the filter bed and may experience less grain size reduction. The angularity of the DiamondKleen^{TM} grains (shown in the microscope images) also increases the porosity leading to higher filtration efficiency.

Several recommendations were also made for further improvement of the test apparatus and future testing of DiamondKleen^{TM} to obtain more comprehensive results to support marketing claims. However based on the conclusions drawn from the results it was recommended that the use of DiamondKleen^{TM} in swimming pool filters be continued as it is more efficient and environmentally sustainable than sand or zeolite.

Acknowledgements

The following project would not be possible without the assistance, support and knowledge of numerous people and I would like to acknowledge those people here.

First of all I would like to express immense gratitude to Poolrite Research Pty Ltd for providing the resources required to complete the following project and the opportunity to work with the Quality and Engineering group (QEG) and experience the process of product development. I'd like to thank all the staff at Poolrite for their assistance and support throughout the various stages of the project, especially my industry supervisor, Chief Engineer Wayne Taylor for his technical advice, suggestions and valuable assistance. Special thanks to Alexander Babych and Allen George for their assistance with equipment acquisition, the construction of the test column, assembly of experimental apparatus, and technical advice. Thanks also to fellow student Nonso Okafor who also worked at Poolrite Research for his collaboration with the project and daily work life.

I would also like to acknowledge the support from Griffith University staff. I'm extremely grateful for the time and support from my academic advisor senior lecturer Dr Benjamin Mullins. Thank you for your suggestions, knowledge and patience during project completion. Thank you to the IAP office staff and the IAP academic convener Graham Jenkins for his advice and understanding.

Also thanks to fellow students Mitch Ryan, Jayden Flint and Timothy Sullivan and previous graduates Wendy Tang, Amy Staneke and Melissa Hovey for their advice, knowledge and friendship. Lastly thank you to my family for their support, especially Letitia Campbell for reviewing my endless drafts and my partner Luke Webb for his support and technical advice.

Table of Contents

List of Tables

List of Figures

Nomenclature

A / A_{pwp}	Hamaker Constant
A_S	Parameter from Happel's flow model
a_P	Particle radius
C	Effluent Turbidity
C_O	Influent Turbidi y
d_P	Particle Diameter
d_C	Collector/Gr in Diameter
D_∞	Bulk Diffusion Coefficient
e	Charge of electron
f	Por sity
F_{ad}	Resultant Adhe ive Force
F_B	Born force
F_e	Electrical Double Layer Force
F_h	Hydration Force
F_v	London-va der Waals force
g	Gravitational Acceleration Consta t
h	Empirical cons ant used in hydration force calculation
K_1	Empirical constant used in the hydration forc calculation
K	Boltzmann Constant
N_G	Gravitational/ Sedimentation N mber
N_R	Reynolds Number
N_{Pe}	Pectlet Number
N_{vdW}	a der Waals Number
N_A	Attraction Number (van der Waals and F uid velocity)
N_{LO}	Lo don Number
N_{DL}	Double Layer Number
T	Temperature of Fluid
U	Approach Velocity of Fluid
Z	Charge number of the electrolyte used
z	Separation distance between the particle and the layer of particles attached to the filter grain

Greek Letters:

α	Collision efficiency
ε	Per ittivity o the medium
ζ_P	Zeta Potential of partic es
η	Filtration Efficiency
η_D	Efficiency of collector due to diffusion
η_I	fficienc f collector due to interception
η_G	Efficiency of c llector due to sedimentation
η_O	Single Collector Filtration fficiency
κ	In erse Deb e Length
μ	Viscosity of fluid
ρ_P	Den ity of fluid
ρ_f	Density of particles / contaminants
σ	Collis on Diame e
Ψ_1	Surface Potential of Particle
Ψ_2	Surface Potential of Filter Grain

Project Introduction

Poolrite Research Pty Ltd currently uses crushed recycled glass (Product name: DiamondKleen^{TM}) as a granular filtration media in packed-bed granular media filters for the treatment of swimming pool water. The reason for using recycled glass opposed to traditional media such as sand or zeolite is to address two social responsibility issues. The first issue is to provide a treatment option to adequately treat swimming pool water to provide safe and clear water to bathe in and second, to provide a more sustainable product. The following report aims to outline how recycled glass compares to sand and zeolite conceptually, theoretically and in a test environment.

1 Project Brief

As part of Griffith University's Industrial Affiliates Program run in Semester One of 2011, Poolrite Research (the Industry Partner) requested an investigative comparison of the performance of sand and zeolite with their patented product DiamondKleen^{TM}.

1.1 Project Aim

The main aim of the project is to compare the overall performance of DiamondKleen^{TM} (recycled glass) to sand and zeolite as a swimming pool granular filter media.

1.2 Project Outcomes

To achieve the above aim and support Poolrite's current marketing claims and existing knowledge of the product, the following project outcomes were achieved:

1. Summary of previous research into water filtration using packed-bed granular filters, including filtration theory and prediction modelling.
2. Design an experiment to test swimming pool granular media
3. Completion of experimental testing and technical reports.
4. Presentation of Performance Data:
    a. Pressure drop curves for clean and loaded filters.
    b. Assessment of backwash flow rates and cycle times in terms of water consumption.
    c. Turbidity reduction
    d. Determination of capture efficiency curve
5. Final Report with recommendations for media grading to achieve best performance and preparation of draft journal paper for submission.

2 Report Structure

The following report aims to outline the project offered by Poolrite Research, the resultant outcomes delivered and the conclusion and recommendations arising from the project's completion. A summary of the structure of the report and how the outcomes described above form each section is shown in the following table (**Table 1**).

Table 1: Final Project Report Structure Based on Milestone Report Delivery and Outcomes

Report Section	*Project Outcome/ Deliverable*
Introduction and Project Brief	
Part A: Swimming Pool Water Treatment Options and Conceptual Comparison of Filter Media	1: Literature Review
Part B: Modelling the Theoretical Filtration Efficiency of Granular Filter Media	1: Literature Review
Part C: Determining the Experimental Filtration Efficiency Experiment Design and Construction	2: Experimental Testing
Part D: Determining the Experimental Efficiency Experiment Results and Analysis	2: Experimental Testing 3: Performance Data
Part E: Conclusions and Recommendations	3: Performance Data 4: Report on Performance

PART A: Swimming Pool Water Treatment Options and Conceptual Comparison of Granular Filter Media

3 Swimming Pool Water Treatment

Swimming pools have been used in both the private and public setting for recreation, and fitness since Roman times (Pool Water Treatment Advisory Group (PWTAG), 2009). Elliott (2001b) also claims that local swimming pools are essential for community building and preserving an Australian past-time. In recent years however there has been an increasing awareness of public health issues as a consequence of poor water quality in recreational waters (Perkins, 2000; Uhl &Hartmann, 2005; WHO, 2006; Croll et al., 2007; Lee et al., 2009; Dorevitch et al., 2011). As a result swimming pool water treatment technology is evolving from a simple stagnant body of water for bathing to full scale water and wastewater treatment processes.

3.1 Overview of Swimming Pool Components and Configuration

The modern typical swimming pool setup generally consists of a body of water for bathing in, a treatment system and a recirculation system connecting the components. The treatment system can differ depending on the type of pool and expected contaminants, but in general consists of the following basic components (Poolrite Research Pty Ltd, 2011):

Swimming Pool – The body of water used by people for bathing, swimming, exercise or injury rehabilitation.

Skimmer Box – A box set into the pool edge which contains a weir to allow the top layer of water to be skimmed off the surface. Also contains connections for a vacuum cleaner inlet.

Recirculation System – The connecting pipe work which joins together the swimming pool and the treatment process components. The hydraulics of the circulation system also ensures that the entire body of water is transported through the treatment system.

Pump – Sized according to the swimming pool conditions, the pump is used to transfer water through the treatment process, pulling water through a screen and pushing water through the filter and back to the pool.

Filter – Whilst available in many forms, the filter generally captures contaminants from the pool, which are then removed from the filter by washing or manual removal.

Sanitiser – Chemical treatment process used to kill any micro-organisms present and provide a residual disinfectant to protect bathers from infections and diseases.

Disinfection Controller – an electronic device used to control the application of the sanitiser and water balancing chemicals, for example acid for pH control.

The configuration of the above components is shown in *Figure 2* below.

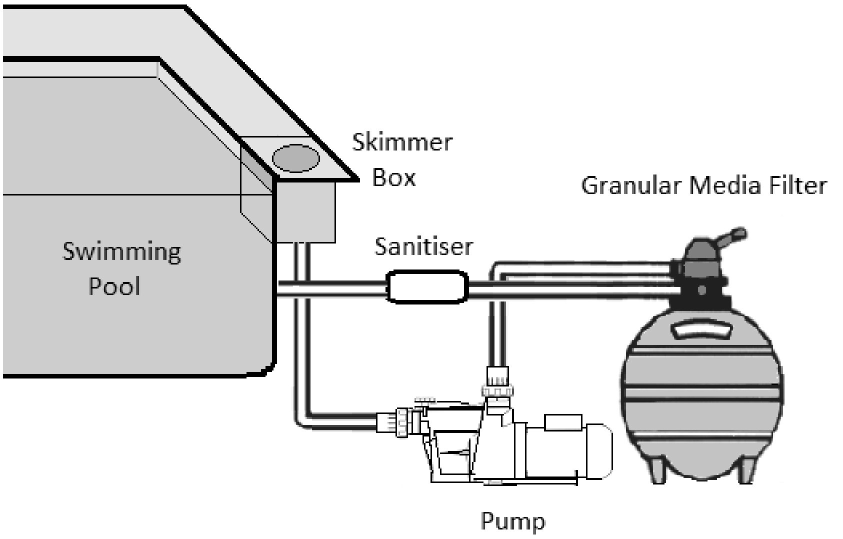


Figure 2: Typical Swimming Pool Configuration of Components

3.2 Swimming Pool Contaminants

The system described above is designed to maintain water quality and aesthetics by removing contaminants from the water which either diminish water clarity or can cause health problems. These contaminants can be suspended or dissolved in the pool water (Korkosz et al., 2011). Some of the sources of the contaminants in swimming pool water include (QLD Health, 2003; World Health Organisation (WHO), 2006; McShane, 2009; Pool Water Treatment Advisory Group (PWTAG), 2009):

- **Bather contaminants**

  (Found in all pools, but main contaminants in indoor commercial pools)
  - Organic – perspiration, urine, mucus from chest and nose, saliva, hair, skin, faecal matter
  - Inorganic – cosmetics, sun screen lotions, clothing particles
- **External contaminants**

  (Usually dominant in outdoor residential pools)
  - Organic - leaves, grass, insects
  - Inorganic - soil, silt, sand

3.3 Pool Water Treatment Process

To remove the above listed contaminants and ensure the water quality in swimming pools is both safe and aesthetically pleasing to bathe in requires recirculation through a treatment process (Williams &Langley, 2001). As the water in swimming pools contains anthropogenic contaminants it is sometimes referred to as a wastewater. However because bathers are submerged in the same water and there is a high probability of water ingestion it must therefore be treated to a similar quality as drinking water standards (WHO, 2006; Dorevitch et al., 2011). Swimming water is often difficult to categorise for this reason, and presents unusual treatment requirements.

In general, the process of treating swimming pool water includes circulation, filtration, chlorination and water balancing (pH correction etc) (Williams &Langley, 2001; PWTAG, 2009). A comparison of this process compared to drinking water and wastewater treatment is outlined in Figure 3 below (Russell, 2006; Hammer, 2008; Binnie &Kimber, 2009; PWTAG, 2009).

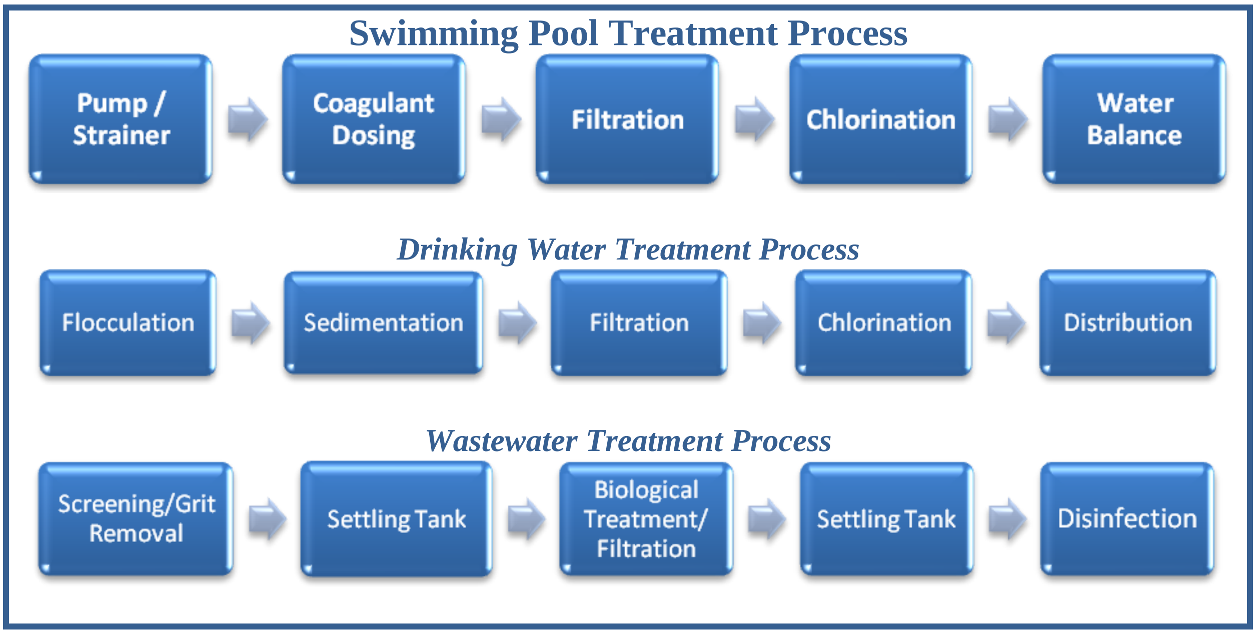


Figure 3: Comparison of Swimming Pool Water Treatment Process to Conventional Drinking Water and Wastewater Treatment

While all steps in the treatment process are essential, the focus of the project and the following final project report is primarily on the filtration aspect of this process.

4 Water Filtration Concepts

Filtration is essential to reduce turbidity of the water caused by suspended particles or contaminants and improve the quality of the water (Korkosz et al., 2011). Water clarity has been identified by the (WHO, 2006) as a key factor for ensuring the safety of swimmers by reducing the chance of injury due to poor visibility and increasing the ability to recognise a swimmer in distress. The removal of particulates also assists the disinfection process by removing organic material which can shield microorganisms but also react with disinfectants to form harmful by-products (Glauner et al., 2005; Uhl &Hartmann, 2005; WHO, 2006).

4.1 Diversity of Filter Types

There are many types of filters available for treating water including but not limited to gravity rapid sand, pressure sand, anthracite, diatomaceous earth pressure, vacuum circular disc-, leaf-, and tube-type filters, high permeability depth type and surface type filters (QLD Health, 2003; Salvato et al., 2003; WHO, 2006).

The selection of the type of filter depends on (WHO, 2006):

- The quality of the water source
- Quality of water required at end use
- Amount of area available for the filter
- Filtration conditions (high rate or slow rate required)

4.2 Swimming Pool Filters

The most common filters used in swimming pool treatment to collect contaminants are cartridge, diatomaceous earth and medium/high pressure packed-bed granular media filters (Pool Water Treatment Advisory Group (PWTAG), 2009). A cartridge filter combines a frame and spun-bound polyester or treated paper filter media (Purchas &Sutherland, 2002). The cartridge filter can be either disposable or removed and cleaned (Purchas &Sutherland, 2002), and therefore seen by pool owners and the industry as either a time consuming task for the pool owner or a waste product sent to landfill. Granular media filters used for swimming pools are usually operated at a higher pressure than slow rate water treatment filters to allow for higher turnover rates. These filters usually consist of a filter tank filled with granular media.

4.3 Granular Packed-Bed Filter Media

The granular media used in pool filters is usually sand or zeolite, but the use of the following materials have also been explored in the literature:

- Crushed plant matter (Aksogan et al., 2003),
- Garnet sand, ilmenite, manganese greensand, basalt and tuff, activated carbon, perlite (Uluatam, 1991; Soyer et al., 2010),
- Sphagnum moss (Knighton &Fiegel, 2008; Hahm, 2010),
- Crushed wood charcoal, quartz, diatomaceous earth (Rutledge &Gagnon, 2002),
- Polystyrene (Shin, 2006a), and
- Recycled glass (Gray & Osborne Inc, 1995; Piccirillo &Letterman, 1997; Elliott, 2001b; Elliott, 2001a; Evans et al., 2002; Rutledge &Gagnon, 2002; Wartman et al., 2004; Horan &Lowe, 2007; Gill et al., 2009; Soyer et al., 2010)

Each type of media is used in the same way, to create a packed-bed filter in which contaminants are captured within the pore spaces and by adhering to the surface of the grains. The differences between the media types can result in different filter characteristics and filtration efficiency. For the purpose of this report the focus will be on the specific characteristics and efficiency of crushed recycled glass which is being utilised by Poolrite Equipment Pty Ltd as an environmentally friendly alternative to sand and zeolite.

4.4 DiamondKleen™ Recycled Glass Media

Poolrite Equipment Pty Ltd has patented a form of crushed recycled glass to use in their packed-bed granular filters known as DiamondKleen™. The crushed recycled glass used in DiamondKleen™ is processed from collected soda-lime glass bottles called cullet, which is then heat treated to remove contaminants and residuals (Poolrite Research Pty Ltd, 2011). The chemical composition of the glass is shown in the table below (Table 2) (Poolrite Research Pty Ltd, 2011). A full summary of the characteristics of DiamondKleen™ and a copy of the Material Safety Data Sheet (MSDS) is provided in Appendix A.

Table 2: Chemical Composition of DiamondKleen™	
$Na^2O + K^2O + Li^2O$	12-15%
CaO + MgO	10-13%
Al^2O^3	1-2%
Other OXIDES (except SiO^2)	0-1%
SiO^2 (bound)	Balance

5 Conceptual Comparison of Granular Filter Media

Poolrite Equipment Pty Ltd selected the use of crushed recycled glass in an effort to acknowledge social responsibility for the impacts of swimming pools on the environment. Crushed recycled glass is considered more environmentally friendly and socially responsible for several reasons, which include:

- Minimising extraction and recovery impacts from the use of sand and zeolite
- Minimising waste going to landfill
- Encouraging industrial ecology principles and supporting the recycling industry
- Minimising other resource use – lower amount of media, energy and water required for filtration (depending on application)

5.1 Environmental implications of Sand and Zeolite

Traditionally swimming pool filters were filled with sand and more recently zeolite granular media. The extraction of these resources involves mining, quarrying or dredging processes. The impacts from sand mining and dredging include but are not limited to biodiversity loss, reduced populations of endangered species (De Leeuw et al., 2010), destruction of dune and catchment ecosystems, erosion of dunes or river banks and modification of river flows and flood plains (Thornton et al., 2006; Sreebha &Padmalal, 2011). By minimising the demand for these products the impacts from the recovery of these resources will also be minimised.

In addition to impacts from extraction, transportation of these resources from the extraction location to the swimming pool equipment manufacturer also causes emissions, increasing the carbon footprint (Ruth &Dell'Anno, 1997). In most cases, recycled glass can be sourced locally therefore minimising the emissions from sourcing sand and zeolite.

5.2 Utilising a waste and encouraging industrial ecology

While CRNA (2010) claims there is no definitive target for recycling in Australia, the National Waste Policy (DEWHA, 2009) does recognise the need for increased efforts in recycling and reuse to keep up with growing rates of disposal. One of the key target areas identified in the policy is “Improving the market—Efficient and effective Australian markets operate for waste and recovered resources” (DEWHA, 2009) which demonstrates an awareness to encourage industry to participate in waste recovery markets.

Additionally, one of the strategies to achieve the aims of the policy includes re-use of materials in the commercial and industrial waste stream (DEWHA, 2009). Use of crushed recycled glass in pool filters could provide the means of fulfilling the federal waste policy's intentions to increase recycling efforts by utilising a waste product.

Also, there are limited applications where mixed colour glass, glass with labels or the top part of the bottles are used in recycling so they are usually discarded (Ruth &Dell'Anno, 1997; Elliott, 2001a; Elliott, 2001b). The filter media used in Poolrite's filters is comprised of this waste glass which could not otherwise be used in recycling practices. Use of the waste glass compared to high value glass sorted by colour, reduces the cost of purchasing the media.

By utilising a waste stream instead of raw materials, Poolrite is also encouraging industrial ecology principles. Industrial ecology is defined as closing the loop of industrial systems so that the industrial sector acts like an ecosystem, utilising wastes or by-products from one industry as inputs for another (Ruth &Dell'Anno, 1997). This cycling of resources minimises raw material use and waste to landfill.

Conceptually, DiamondKleen™ is comparatively a more socially responsible medium for use in granular filters. The use of recycled glass utilises a waste product therefore encouraging industrial ecology practices while minimising the use of more environmentally harmful raw materials, sand or zeolite. The use of an unusable waste product also decreases the cost of purchasing raw materials which produces economic savings that can be passed on to the final user. While the community benefits from using recycled glass results in reduced environmental impacts and associated costs, the glass still must perform efficiently as a filter media for health and safety reasons. In the following sections the theoretical and experimental filtration performance and efficiency of glass compared to sand and zeolite is discussed.

PART B: Modelling the Theoretical Filtration Efficiency of Swimming Pool Granular Filter Media

Various mechanisms act on particles or contaminants while they travel through a filter, sometimes resulting in removal from the flow of water. Using filtration theory and knowledge of these mechanisms, a model for filtration efficiency can be derived. This equation differs amongst the literature and depends ultimately on the application and properties of the filter system. Research conducted on filtration theory and the various derived models is summarised below and then applied to swimming pool granular media to derive theoretical filtration efficiency predictions.

6 Filtration Mechanisms and Theory

A particle travelling along a streamline within a flow of water can be removed by the filter in two ways, straining or filtering. Straining by the filter is undesirable and the filter will act more efficiently if the particles to be collected are smaller than the filter pore size (see Figure 4 below). During filtration the particles are collected by transport and attachment mechanisms. The filter efficiency, as discussed below, ultimately depends on the significance and strength of these mechanisms.

6.1 Straining

Particles larger than the pore sizes between filter grains are removed by straining; which results in clogging of the filter forming a mat or cake on the filter surface (Jegatheesan &Vigneswaran, 2005). Clogging of the filter bed can be caused by directly blocking the pore spaces by a large particle or by bridging of small particles (Jegatheesan &Vigneswaran, 2005). A bridge forms when particles accumulate on either side of pore space to eventually cover the pore space (see Figure 4). Kimber et al (2009) state that straining is neither an important removal mechanism nor a desirable one because while it does remove particles, it only requires the filter to be cleaned more frequently.

For the filter to work more efficiently, the contaminants must be smaller than the pore size and be removed from suspension within the filter by being transported to the filter grain and then attaching to the grain by various mechanisms. To achieve this, there should be few particles larger than 20% of the grain size (Kimber et al., 2009).

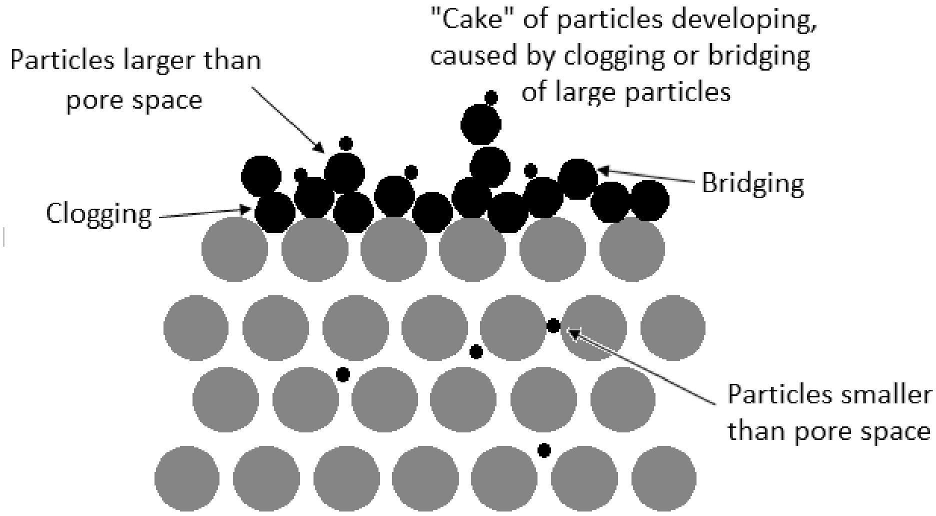


Figure 4: Diagrammatic representation of the screening mechanism in a filter and how this can block the filter bed

6.2 Transport Mechanisms

Transport mechanisms allow particles to move across streamlines to arrive adjacent to a filter grain, otherwise particles would follow flow streamlines of the fluid and avoid touching the filter grains. Particles in suspension are transported near filter grains by either one or a combination of the mechanisms summarised in Table 3 and shown in Figure 2 below.

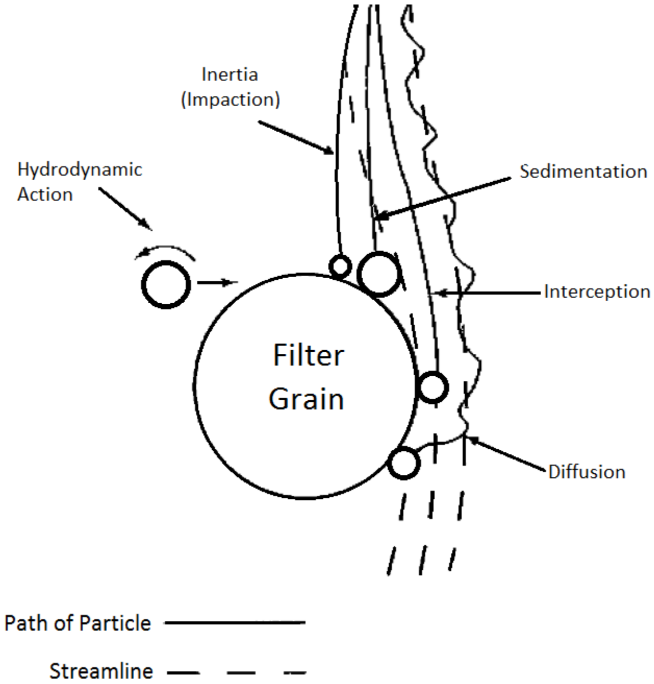


Figure 5: Transport mechanisms acting on a particle in a streamline travelling in a filter - Adapted from (Kimber et al., 2009)

Table 3: Summary of transport mechanisms acting on particles in a granular filter
Summarised from (Stevenson, 1997; Hinds, 1999; Jegatheesan &Vigneswaran, 2005; Gregory, 2006; Kimber et al., 2009)

Transport Mechanism	*Description*	*Dimensionless number used to model mechanism*
Sedimentation:	Motion due to gravitational force When the particle density is greater than that of fluid it is subject to velocity in direction of gravity.	$N_G = (\rho_p - \rho)d_p^2 g/(18\ \mu U)$
Interception:	Motion whereby particles follow streamlines approaching the grain surface within a particle radius, allowing the particle to make contact with the grain surface.	$N_R = d_P/d_c$
Diffusion:	Motion due to Brownian motion (random movement of very small particles due to thermal energy of water. Becomes more significant the smaller the particle).	$N_D = 2N_{Pe}^{-\frac{2}{3}}$ *where,* $N_{Pe} = d_c U/D$
Inertia:	Motion due to inertial forces. Streamlines diverge as flow passes around the grain, if the particle has enough inertia it will maintain its trajectory.	$N_I = \rho_p d_p^2 U/18\ \mu d_c$
Hydrodynamic Effect:	Motion due to pressure differences. Laminar flow in the filter pores with a vertical velocity gradient creates a shear field; the particles rotate because of the shear field causing unpredictable motion.	$\mathrm{Re} = d_c U/\nu$

6.3 Attachment Mechanisms

After transport mechanisms have brought the particles to the filter grain surface there must be an attachment mechanism present to retain the particle in the filter (Hinds, 1999; Jegatheesan &Vigneswaran, 2005). Removal depends on the attachment mechanisms which are determined by which surface forces act between particles and filter grains (Jegatheesan &Vigneswaran, 2005). The attachment mechanisms are summarised below in Table 4.

Table 4: Summary of the attachment mechanisms acting on particles in a filter
Summarised from (Jegatheesan &Vigneswaran, 1997; Gregory, 2006). Equations from (Jegatheesan &Vigneswaran, 1997)

Attachment Mechanism	***Description***	***Equation***
Long Term forces (dominant for separation distance up to 100nm)		
London- van der Waals forces	Attraction between fluctuating dipoles created by the movements of electrons around nuclei.	$F_v = (A_{pwp}/6z)\ [(a_p/z) - 1]$
Electric double layer force	The charged surface of a particle distributes oppositely charged ions from the solution closer to the surface to maintain neutrality. The measurement of this force is by determining the *Zeta Potential* (see below).	$F_e = -64\pi a_p \epsilon \kappa [kT/Ze]^2$ $\tanh[Ze\psi_1/4kT]$ $\tanh[Ze\psi_2/4kT]$ $\exp(-\kappa z)$
Short Term forces (influence for separation distances up to 5nm)		
Born force	Overlap of atom electron clouds at small inter-atomic distances produces a repulsive force. The strength of this force dictates how close atoms or molecules can get.	$F_B = -A_{pwp} a_p \sigma^6 / 180 z^8$
Hydration force	Anions move closer to surfaces because they tend to be less strongly hydrated than cations in solution, disrupting the ordering of water molecules. This can sometimes cause neutral surfaces to become negatively charged in aqueous salt solutions.	$F_h = -2\pi a_p K_f h \exp(-z/h)$

6.3.1 Zeta potential

As described above the surface charge produced by particles in aqueous solutions can modify the distribution of surrounding ions in the solution. This results in a layer of charge different from the rest of the solution. The potential at the point between the electric double layer and the bulk solution is called the zeta potential (see Figure 6) (Jegatheesan &Vigneswaran, 1997; Russell, 2006; Malvern Instruments Ltd, 2011). The strength of this potential is dictated by the concentration and type of ions present in the solution (Russell, 2006).

6.4 Other Filtration Mechanisms

Another mechanism proposed by Camp (1961) to act on particles during filtration is:

- **Orthokinetic flocculation**: the velocity gradient or fluid motion flocculation aggregates particles within pore spaces to increase chances of removal (Camp, 1961).

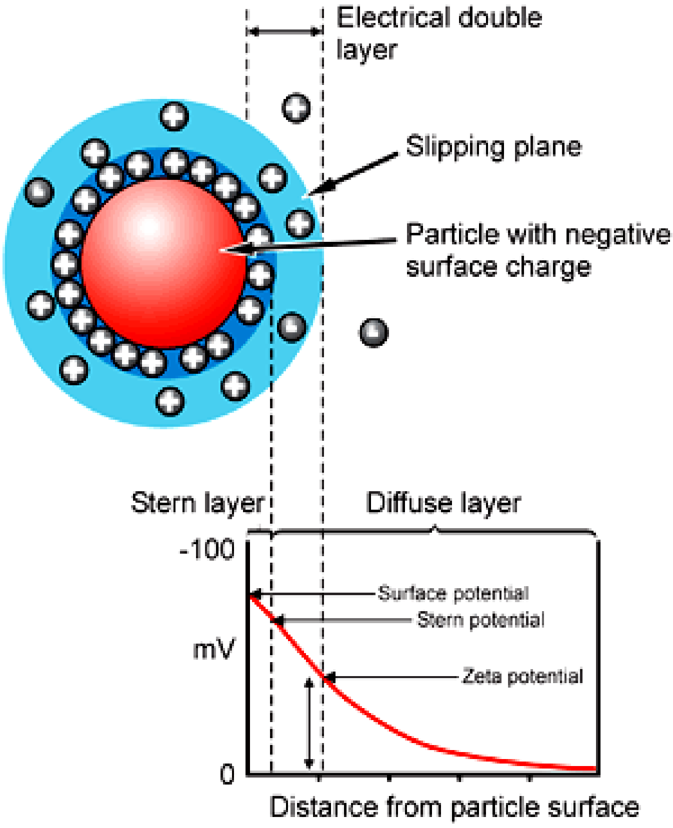


Figure 6: Schematic representation of zeta potential (Malvern Instruments Ltd 2011)

7 Filtration Models

Various models have been derived from these mechanisms to describe the motion of a particle during filtration and therefore determine the overall efficiency of a filter. The majority of the literature examines clean bed filtration which is the efficiency of the filter at the beginning of filtration. However more elaborate models have been proposed to model all stages of filtration. The stages of filtration and the various models are discussed below.

7.1 Stages of Filtration

When the filter bed is clean, particles build up on the filter grains according to the transport and attachment mechanisms discussed above. As particles begin to deposit on the grains they start to contribute to the collection efficiency of the filter bed and increase attachment, this is the ripening stage (stage 1, Figure 7) (O'Melia &Ali, 1978; Jegatheesan &Vigneswaran, 2005). After the filter ripens (stage 2, Figure 7), some particles start to detach as new particles are also attaching (Jegatheesan &Vigneswaran, 2005). The combination of the Ripening Stage and the Effective Filtration Stage is also referred to as the Transient Stage.

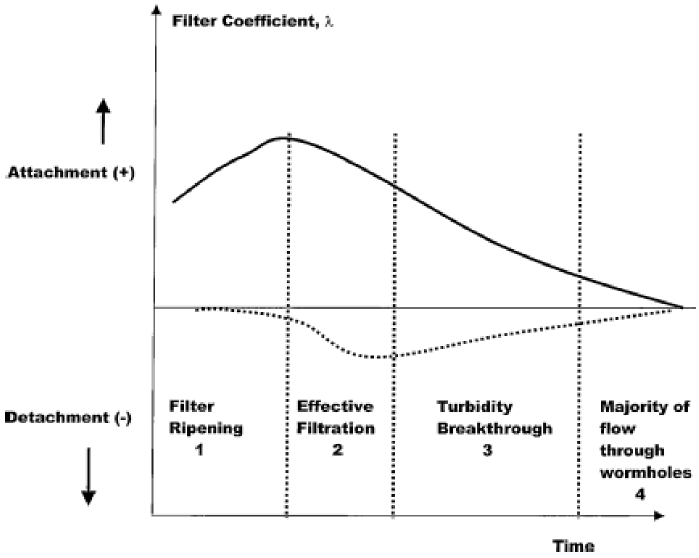


Figure 7: Simulation of particle attachment and detachment at different stages of filtration

After time, the breakthrough stage occurs when accumulation of contaminants declines causing increased turbidity and reduced filtration efficiency (stage 3, Figure 7) (Jegatheesan &Vigneswaran, 2005). The time taken to progress through these stages depends on the filter bed and contaminant characteristics.

7.2 Clean Bed Filtration Efficiency Models

Many researchers have focused their attention on modelling the clean bed filtration efficiency, the condition where the system is free of previously deposited particles or contaminants (Yao et al., 1971; Rajagopalan &Tien, 1976; Darby et al., 1992; Logan et al., 1995; Qi, 1997; Tufenkji &Elimelech, 2004). These models tend to take a microscopic approach and consider the individual particle size and the number of particles, as compared to the macroscopic approach, which focuses on the cumulative collection of deposits (Jegatheesan &Vigneswaran, 2005; Ng et al., 2006).

The three main models used in the literature for filtration through granular media are the Yao-Habibian-O'Melia or YHO model (Yao et al., 1971), the Rajagopolan and Tien or RT Model (Rajagopalan &Tien, 1976) and the Tufenkji and Elimelech or TE model (Tufenkji &Elimelech, 2004). Because there is much discussion on which model is the best to use, for most applications all three are modelled and compared to experimental data (Logan et al., 1995; Logan et al., 1997; Lawler &Nason, 2006; Ng et al., 2006). Therefore the three models have been used to compare the efficiency of the different swimming pool granular media.

7.3 The Yao-Habibian-O'Melia (YHO) Model

The model developed by K.M. Yao, M.T. Habibian, and C.R. O'Melia in 1971 (Yao et al., 1971) is used through subsequent research as the starting model, including the TE and RT models discussed in this report. The YHO model for single collector efficiency (equation 1) is based on the concept that small particles (less than 1μm) are removed by diffusion and large particles (greater than 1μm) by interception or sedimentation. The total efficiency of removal by a single isolated collector (filter grain) will then be the summation of diffusion, interception and sedimentation mechanisms.

$$\eta = \eta_D + \eta_I + \eta_G \qquad (1)$$

By substituting the dimensionless numbers for each mechanism as described in Table 3, the YHO model becomes equation 2. Logan et al (1995) states that some researchers include a correction term known as the Happel correction term derived in 1958, which takes into account the porosity of the bed in determining the collisions due to diffusion. It is mentioned in the same paper the importance of identifying whether or not this correction term is used.

The model described in equation 2 has been used in subsequent modelling conducted for this report and includes the Happel correction ($A_s^{1/3}$) in the diffusion term.

$$\eta = 4A_S^{1/3} N_{Pe}^{-2/3} + \frac{3}{2} N_R^2 + N_G \qquad (2)$$

Yao et al (1971) make the point in their discussion that their model is based on some unrealistic assumptions, including that the "stokes equation for the velocity pattern about an isolated sphere can describe the velocity distribution in a packed-bed". Logan et al. (1995) also comments on this assumption stating that the use of the approach velocity is flawed due to the presence of adjacent collectors which constrict the flow path and increase the pore velocity. Other researchers have also since commented on the limits of the YHO model. Comments include that the model doesn't take into account hydrodynamic drag and London-van der Waals forces (Ng et al., 2006) and that the model generally underestimates the number of collisions occurring in a packed-bed (Logan et al., 1995).

7.4 Rajagopolan and Tien (RT) Model

The model by Rajagopolan and Tien (RT Model) developed in 1976 (Rajagopalan &Tien, 1976) is based on the YHO model but instead of modelling the system by Eulerian methods, the RT model is an application of Langrangian methods. The Eulerian method describes the particle concentration in time and space, whereas the Langrangian method focuses on analysing the trajectory of the particle (Jegatheesan &Vigneswaran, 2005). This method (Langrangian), is based on Newton's second law as the particle approaches the surface of a collector (Jegatheesan &Vigneswaran, 2005). By using this method the RT model calculates the deposition of particles by taking into account the attachment forces as well as the transport of particles.

$$\eta = 4A_S^{1/3}N_{Pe}^{-2/3} + A_S N_{Lo}^{1/8}N_R^{15/8} + 0.00338 A_S N_G^{1.2} N_R^{-0.4} \qquad (3)$$

Rajagopolan and Tien (1976) derived dimensionless parameters to form the RT model based on collection efficiency values obtained from numerical calculations (equation 3 above). Lawler and Nason (2006) state that this model improves on the YHO model by accounting for hydrodynamic interactions of the particles and flowing water near the collectors and also the van der Waals attraction of particles to the collectors.

The first term in this equation is only an approximation of removal by diffusion (Brownian movement) because trajectory analysis is generally applied to non-Brownian particles. Ng et al. (2006) identify this as a flaw in the RT model, because it omits the influences of hydrodynamic and van der Waals interactions on the deposition of particles that are dominated by Brownian diffusion. Lawler and Nason (2006) point out that the RT model is simply using the same equation for Brownian movement (diffusion term) as the YHO model but with the modification proposed by Cookson in 1970. Another issue noted by Logan et al. (1995) is that the "governing equations presented in the paper contain hidden variables as "constant terms" and contained typographical errors". They then claim that the application of this model can then produce inaccurate results (Logan et al., 1995).

7.5 Tufenkji and Elimelech (TE) Model

In 2004, Tufenkji and Elimelech published a paper on a revised model, the TE model shown in equation 4 (Tufenkji &Elimelech, 2004). To develop the model the transport mechanisms were regressed against theoretical single collector efficiency derived from the convective diffusion equation (Tufenkji &Elimelech, 2004; Ng et al., 2006). This method of using a set of regression equations was similar to the development of the RT model, however the difference was essentially including Brownian motion in the simulations of particle motion to improve the model (Lawler &Nason, 2006).

$$\eta_0 = 2.4A_S^{1/3}N_R^{-0.081}N_{Pe}^{-0.715}N_{vdW}^{0.052} + 0.55A_SN_R^{1.675}N_A^{0.125} + 0.22N_R^{-0.24}N_G^{1.11}N_{vdW}^{0.053} \quad (4)$$

Some of the other differences between the RT model and the TE model include:

- TE model removes the porosity-dependant parameter from the equation for sedimentation claiming "η_G barely changes with porosity" (Tufenkji &Elimelech, 2004)
- The sedimentation equation does however include the van der Waals number (Tufenkji &Elimelech, 2004)
- The RT equation significantly overestimates the efficiency of collection of particles in the "Brownian range" (low N_{pe}) (Tufenkji &Elimelech, 2004). The main concern is particles about 2μm the size of cryptosporidium where the RT equation overestimates by upto 60% according to Tufenkji &Elimelech (2004), this limits the application for filtration of microorganisms.

During 2004 and 2005 there was published debate between Tufenkji &Elimelech and Rajagopolan &Tien about whether the claims made above are accurate (Tufenkji &Elimelech, 2004; Rajagopalan &Tien, 2005; Tufenkji &Elimelech, 2005). In the comment made by Rajagopalan and Tien (2005) on the new TE model, they claim that while the TE model includes more precision in the exponents of the dimensionless numbers instead of rounding, these changes are insignificant due to the large variation in the equations. They also claim that the correlation used only applies in the absence of double layer forces(Rajagopalan &Tien, 2005). This is acknowledged by Tufenkji & Elimelech (2005) as flaw but claims the effects of the chemistry of the solution (attraction by double layer forces) is included when examining the attachment efficiency thus separating the physics of filtration from the chemistry of attachment (Tufenkji &Elimelech, 2005).

7.6 Transient Stage Filtration Efficiency Models

Some models have been developed to determine the efficiency after deposition of particles and are often referred to as transient stage models or complete cycle models. In the literature these have not been considered accurate when compared to subsequent experimental data (Darby et al., 1992; Tobiason &Vigneswaran, 1994). Even complex models have difficulty accurately portraying the complex characteristics of real non-monodisperse suspensions and granular media (Tobiason &Vigneswaran, 1994). These models usually still rely on experimental data for guidance and therefore are usually empirical models. While these models aren't used in subsequent modelling for this report they could be used in future research and are discussed briefly below.

One model that addresses the filtration efficiency during ripening developed by O'Melia and Ali in 1978 (Darby et al., 1992; Tobiason &Vigneswaran, 1994). Ripening occurs quickly in granular media and improves the removal of particles. As this model only describes a short space of time after the bed is no longer clean, Vigneswaran and Chang (1989) adapted the model to describe the whole cycle after ripening. This model examines the detachment of particles due to an increase in water velocity between the filter grains caused by the accumulating particles restricting the flow.

Another method by Vigneswaran and Tulachan (1988) examines the change in filtration efficiency differently. This model considers how collection sites on a filter grain become saturated with time, placing a limit to how many particles can be collected(Vigneswaran &Tulachan, 1988; Vigneswaran &Chang, 1989). After this limit is exceeded no more particles are captured.

For simplicity, the swimming pool media discussed in this report were modelled using only the clean bed models. As discussed these models weren't used because of the complex calculations involved and inaccuracies in the model when comparing to experimental data. However, to gain a better understanding of how each media may perform at different stages of the filter cycle, these models could be used.

8 Determining Media Characteristics and Model Parameters

The three clean bed models, YHO, RT and TE, for modelling the filtration efficiency have been used or referenced frequently in the literature, some compare all three methods to experimental data (Rajagopalan &Tien, 1976; Logan et al., 1995; Logan et al., 1997; Tufenkji &Elimelech, 2004; Lawler &Nason, 2006; Ng et al., 2006). To model a swimming pool system with different media, the common system parameters and characteristics of each media were determined. These parameters used in the theoretical comparisons are discussed below. It is important to note these as the outcome of the model can differ greatly depending on the system parameters.

8.1 Common System Parameters

The following tables (Table 5, Table 6 and Table 7) below outline the parameters used in the model calculations. Table 5 outlines the design velocity for the experimental apparatus as calculated in appendix C. This table also outlines the typical conditions in an average swimming pool. Table 6 outlines the standard constants used in the models and table 7 outlines the characteristics of the test particles used. The particles used to contaminate the water are test particles specified by ISO 12103-1 for air and water filter testing (PTI, 2008).

Table 5: Experimental System Characteristics		
Approach velocity	0.010548	m/s
Viscosity	0.000891	kg/ms
Temperature	298	K
Fluid density	997	kg/m^3
Table 6: Constants used in the clean bed efficiency models		
Boltzmann's constant	1.38065×10^{-23}	m^2kg/s^2K
Gravity Constant	9.81	m/s^2
Hamaker constant	4.00×10^{-20}	$kg\ m^2/s^2$
Table 7: ISO Test Particle Characteristics (PTI 2008a; b)		
Particle size	Fine	0-120µm
Particle density	900	kg/m^3

8.2 Swimming Pool Media Properties

To compare the three swimming pool media, sand, zeolite and glass all parameters in the models were kept the same except the porosity and grain size parameters which are unique to each media. To determine these parameters some additional testing was required. The porosity was determined by calculating the size of the pore space which accommodates water. The average porosity determined from this testing is shown in table 8 (test procedure and results are provided in appendix C). The average grain size was determined from the information provided by the supplier (table 8).

Table 8: Average Properties of Swimming Pool Granular Media

Filter media	*SAND*	*DK M10*	*DK M20*	*ZEOLITE*
Porosity	0.3923	0.4171	0.4334	0.4436
Grain size (m)	0.0013	0.00118	0.00236	0.0016

9 Theoretical Comparison of Sand, Zeolite and DiamondKleen™

As discussed above, the three models for clean bed efficiency (YHO, TE and RT) were used to determine the collection efficiency of each media (full model calculations are included in appendix B). The three media were then compared using each model. The resultant differences are discussed below.

For sedimentation to occur the density of the particles or contaminants must be greater than the density of the water, because this was not the case, the sedimentation effects were negligible and therefore did not contribute to the overall filtration efficiency.

The modelling of a single collector using the TE and RT models, predicts similar filtration efficiency for sand and DiamondKleen™ with the zeolite performing better than the coarse grade DiamondKleen™ M20. The YHO model shows a larger difference between the sand and DiamondKleen™ media performance, predicting DiamondKleen™ as the most efficient media. These results are then used to predict the efficiency of the total filter bed filled with collectors. These results are shown in figure 8.

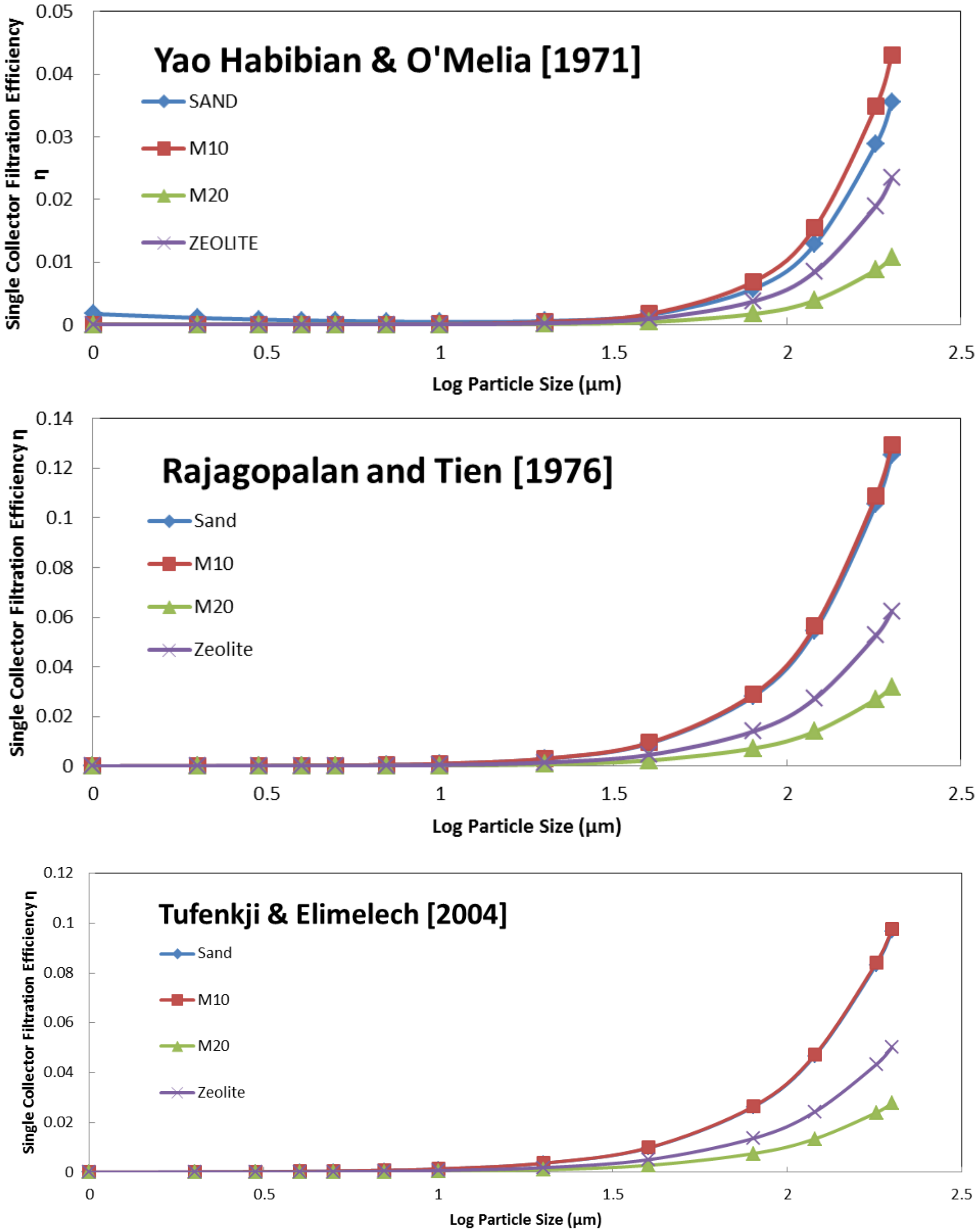


Figure 8: Graphical Representation of the Single-collector Efficiency Using Three Different Models Presented in the Literature

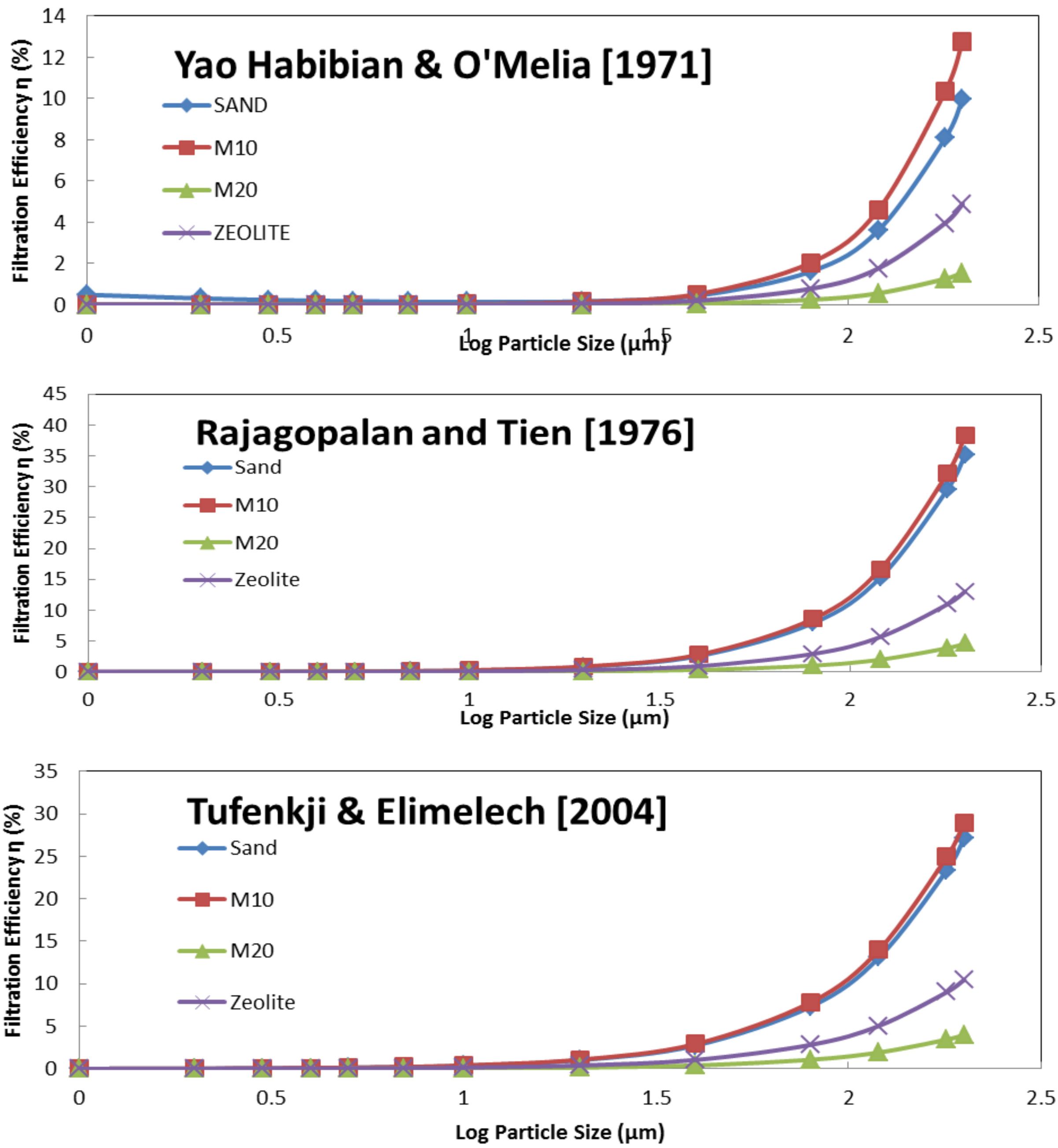


Figure 9: Graphical Representation of the Filtration Efficiency of a Column filled with Collectors (Grains of Filter Media)

The above graphs illustrate that when the single collectors are added together in a filter bed the DiamondKleen^{TM} will perform slightly better but similar to sand. Both media also perform remarkably better than the zeolite. Again the YHO model predicts better performance from the DK compared to sand. It is important to note however that the models don't include the chemical conditions within the system nor take into account any screening effects that may occur due to small pore space, as discussed earlier. It is important to use experimental data to support the theory.

PART C: Designing the Column Test Experiment and Methodology

To support and verify the theory discussed in the previous section experimental testing and assessment of results was required. Poolrite Research has conducted limited experimental testing in the process of developing products and exploring new design options. Some of their marketing claims stem from this testing but most claims are unsupported by formalised testing and experimentation, a common finding in the swimming pool industry. The following section aims to outline the previous testing and research conducted to support industry claims and how the methodology and experimental setup were derived based on previous methods of experimental comparison.

10 Industry Claims

In addition to reducing environmental impacts, many suppliers and product testing claim that crushed glass also exhibits many other beneficial properties. Some of the claims by Glass Recovery Services (2010) include that recycled glass is cleaner and light weight, provides greater improvement in turbidity removal and removal of finer particles from water, it is easier to clean, less likely to block or channel, and will not support bacteria, moss or fungus growth in the media. Wartman et.al, (2004) also claims that recycled glass is more readily available, freely draining, and a relatively low cost material.

Some of the marketing claims made by Poolrite Research and Poolrite Equipment include:

- DiamondKleen™ reduces chemical usage whilst producing brilliant water clarity (Poolrite, 2011b)
- DiamondKleen™ is safer to use, reduces bacteria growth, lowers operating costs, achieves a superior clean, has more efficient backwashing and improves water quality (Poolrite, 2011a)

11 Previous Testing and Experimental Research to Support Claims

While most industry claims used in marketing material are not supported by theory or academic research, some of these claims have been tested in the laboratory or in full scale field testing.

11.1 Summary of Internal Testing

As mentioned above Poolrite Research has a research and development facility which endeavours to provide some comparative testing of its swimming pool filters, sometimes as part of larger experiments or concept design testing. Overall, previous internal testing has been found to be quite sparse and sometimes inconclusive due to time constraints, internal business changes and equipment malfunction. Also, the interpretation of findings is often biased. A summary of the internal reports is provided in appendix C but a short explanation of the key findings and experimental issues are explained below.

The first recorded report on testing of Poolrite's DiamondKleen™ was on the 5th of July 2007. This report (Holloway &Anderson, 2007) measured the flow rate and resultant pressure drop across a filter using sand, zeolite or glass media. Two glass media were tested; Poolrite's DiamondKleen™ and Dryden Aqua's AFM (activated filter media). This report concluded that the best performance was achieved by DK and AFM but the difference in performance of these two media is within the margin of experimental error. Zelbrite performed second best with sand the worst performer in the four filters. Two other reports were completed in 2007, one in August (Raikhel, 2007) and one in November (Liu, 2007) testing the significance of different combinations of equipment including filter media. The August report focused on hydraulic performance including pump and valve type, whereas the November report compared the efficiency of different combinations of media and filters. Both recorded that the DiamondKleen™ media achieved better turbidity reduction than traditional sand media.

Another report was compiled in the following year (Raikhel, 2008) to evaluate the performance of a DiamondKleen™ sand filter as compared to cartridge and diatomaceous earth swimming pool filters. While there were some experimental issues during the conduct of this experiment, the report concludes that the sand filter with DiamondKleen™ filtered to a higher quality (lower particle size at the conclusion of the experiment). However the results show that the back pressure of the DiamondKleen™ sand filter was highest and the amount of turbidity reduction was the same as the cartridge filter but less than the DE filter. The results also show that the final turbidity from the DiamondKleen™ filter was the highest. This may indicate that the final particle size is considered the main indicator of filter performance according to Poolrite. This could be interpreted as a bias towards the company's product when interpreting the results.

These reports indicate short term experiments conducted to assess a current need or concern. In 2010 it was identified that longer term testing was required and an experiment was set up to test the combined effect of Poolrite's Magnapool Mineral Blend for swimming pool water sanitation and use of DiamondKleen^{TM} in the filter (Babych, 2011). The experiment was run with and without the addition of Magnapool minerals and also with a sand, zeolite and DiamondKleen^{TM} filled filter. This experiment was considered inconclusive due to experimental issues with the chosen contaminant Diatomaceous Earth (DE) powder and also with equipment malfunctioning. The use of DE powder was the main concern, as it is normally used as a filter media on its own and could have contributed to the efficiency of the filter. The powder was also too large to obtain meaningful results and is not comparable to actual swimming pool contaminants.

This experiment highlights the difficulty in finding an appropriate contaminant. In water or wastewater pilot plants, the actual waters to be treated are often diverted to a testing facility (Williams et al., 2007). However with swimming pools the water is recirculated so cannot be redirected into a test setup. But also to test an individual component of the system all others must be removed, making the situation unsafe to be exposing bathers to the test environment. Therefore a simulated contamination loading must be used and simulating real contaminants is often a difficult task.

A common trend in the internal reports is that there is no communication of prior understanding, no reference to research or even previous internal reports. Without conducting prior research there exists an uncertainty when interpreting results and often the interpretation which favours the product is adopted as a final conclusion. Ideally what is required is a detailed understanding of what the results mean in terms of filter efficiency and what determines better performance before interpreting the results. This approach requires adequate time allocated to project research as well as experimental testing to successfully achieve this, which is not always possible in a commercial setting.

11.2 Academic Reviews and Experimental testing

The use of recycled glass in filtration systems has been addressed in the academic literature. These reviews or experiments tend to focus on the use of glass in either water filtration or waste water filtration and there exists limited research into swimming pool water treatment. However, the column test apparatus designed was adopted from the experiments discussed in the following studies. The different experimental setups and consequent results were examined.

Numerous studies use different sized columns filled with filter media to compare performance of different filter media for the treatment of various types of water (Gray & Osborne Inc, 1995; Horan &Lowe, 2007; Williams et al., 2007; Dwivedi et al., 2008; Mitrouli et al., 2009; Soyer et al., 2010). These experiments do differ in the dimensions of the column but also the parameters observed, duration and experimental conditions (flow rate, pressurised etc.). The use of a column filter is common in the literature to test not only glass media, but also other new granular filter media types. A summary of some experiment details expressed in the literature is shown in table 9.

Table 9: Summary of Column Dimensions and Measured Parameters from Column Test Experiments Discussed in the Literature

Literature Source	*Media Tested*	*Water source*	*Column diameter*	*Filter bed depth*	*Measured parameters*
(Gray & Osborne Inc, 1995)	Glass, sand	Unchlorinated water	15inch	36inches	Turbidity head loss Microbial
(Horan &Lowe, 2007)	Glass	Wastewater	200mm	90cm	Pressure Flow rate leaving filter
(Soyer et al., 2010)	Glass	Surface water	100mm	2.5m	Turbidity and particle counts
(Williams et al., 2007)	Anthracite sand	Wastewater	20.3cm		Pressure drop Particle count Microbial counts
(Mitrouli et al., 2009)	Expanded clay Sand	Seawater	100mm	3.2m	Particle count Backwash time
(Dwivedi et al., 2008)	Activated carbon	Water with Pb	40mm	60cm	Pb levels

There are mixed results discussed in the literature. This is to be expected because as discussed in the previous section on theoretical modelling, the efficiency of a filter depends on numerous parameters. However tests using recycled glass do agree that glass achieves better results than traditional sand. Rutledge and Gagnon (2002) tested the use of crushed recycled glass as granular media in dual media filters to remove particles and found that glass performed slightly poorer than sand. However, numerous other studies claim that the recycled glass did perform better than traditional media in various treatment applications, taking longer to reach particle breakthrough, lower pressure drops across the filter and more efficient backwashing (more time between and shorter back wash flows) (Gray & Osborne Inc, 1995; Piccirillo &Letterman, 1997; Aquatic Commercial Industries, 1998; Evans et al., 2002; Hu &Gagnon, 2006; Horan &Lowe, 2007; Gill et al., 2009; Soyer et al., 2010).

Most of these studies focus on the treatment of drinking water and waste waters and therefore test the filters by only passing the water through the filter once (single pass test). None of these studies have tested the performance of recycled glass under swimming pool conditions, and therefore haven't assessed the filter media performance in a filter which continuously recirculates the same body of water for a long period of time.

12 Project Experiment Design

To compare the performance and filtration efficiency of Poolrite's DiamondKleen^{TM} to conventional granular media such as sand or zeolite, an experiment design was required which eliminated the bias found in previous internal testing and isolates parameters to assess the media under swimming pool conditions. To achieve this it was decided to test the media in a column test similar to those discussed in the literature above. However due to the unique test conditions required the column test design needed modification. These issues presented several design challenges and specific design requirements for the methodology and equipment construction, these are outlined below.

12.1 Experimental Aims

The main aim of the experiment is to test the performance of DiamondKleen^{TM}, sand, and zeolite in test columns to determine turbidity reduction, filtration efficiency, accuracy of theoretical efficiency and the overall performance of the media.

12.2 Assumptions and Generalised Swimming Pool Aspects

The experimental apparatus design and associated methodology were determined based on numerous assumptions and characteristics of a “typical Swimming pool”. A summary of these assumptions and design criteria are outlined below (Table 10).

Table 10: Assumptions and Characteristics of a "Typical" Swimming Pool used in Experimental Design	
Normal Swimming Pool Operating Conditions	
Pressure	80-100kPa
pH	7.2 – 7.6
Temperature	24-28^{o}C
Alkalinity	80-125ppm
Hardness	200-270ppm
Free chlorine	0.6-1.0ppm
ORP	>700mV
Typical Swimming Pool Design	
Contaminant load	600g (see appendix C for calculations)
Filter	S6000 Sand Filter
Sanitation	Chlorine Disinfection
Hydraulic Specifications	
Flow rate per area	600L/min/m2
Velocity	0.010548m/s (see appendix C for calculations)
Circulation Rate	20L/min (see appendix C for calculations)

12.3 Experimental Apparatus Design

The experimental apparatus was designed utilising the knowledge gained from critiquing previous internal reports and information provided in the academic literature (as discussed above). The design of the test setup was derived in stages and several changes were made in the design through consultation with the project team and further research. Evidence of this development is shown in appendix C but the final design is showed in *Figure 10* below.

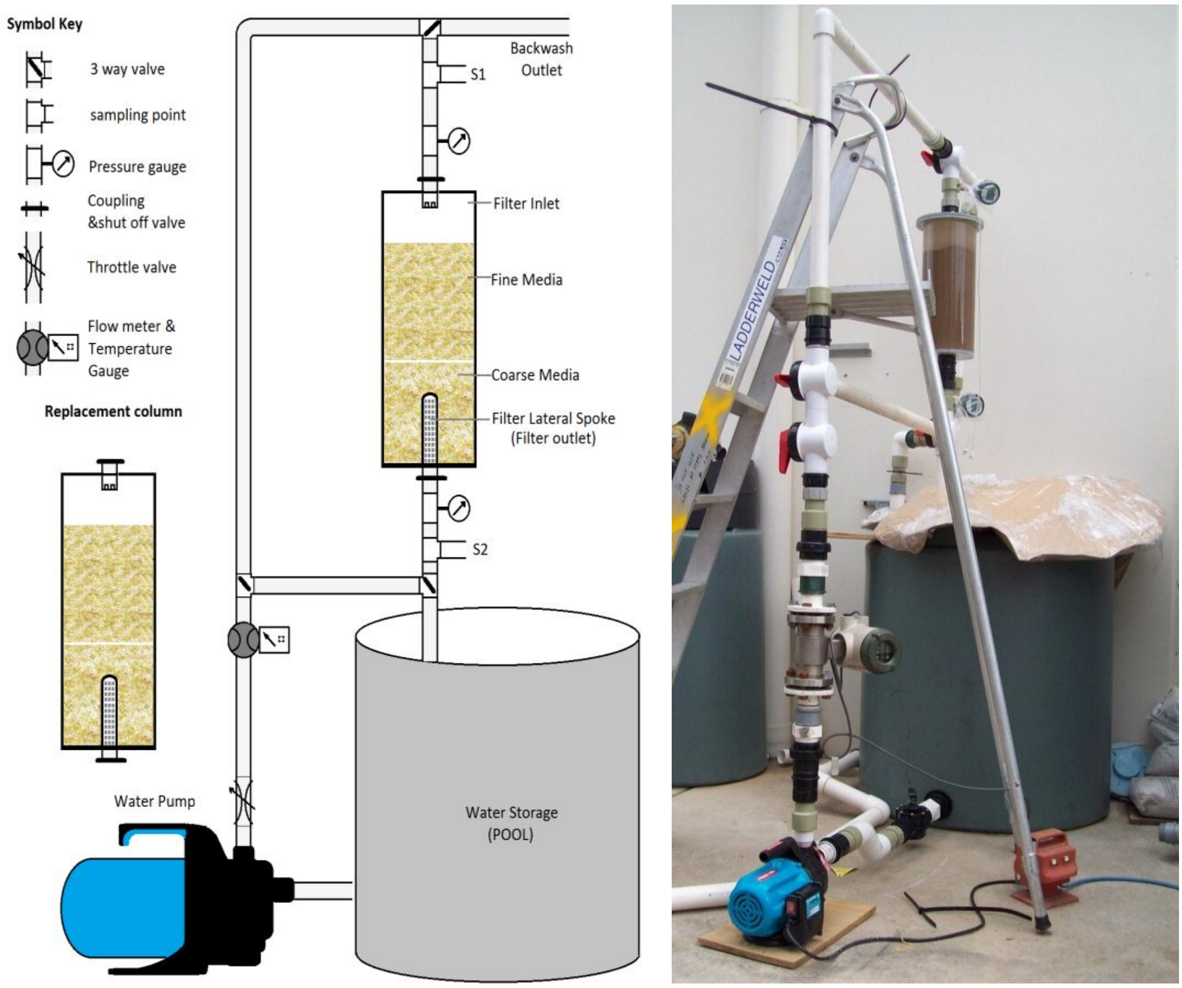


Figure 10: Diagram and Photograph of Test Column Experimental Setup

The original setup was based on a simplified pool circulation system, including a water body (swimming pool), pool pump and a filter. To assess the efficiency of the filter granular media, it was decided to replace the traditional swimming pool sand filter with a clear PVC column to simplify the filter shape and mimic pilot media testing discussed in the literature. To replicate similar conditions of a normal swimming pool filter the inlet and outlet of the column have been designed to mimic the inlet and outlet of a swimming pool sand filter. This meant distributing water at the top similar to a diffuser and allowing the filtrate to exit the column through a lateral spoke. As there are 8 lateral spokes to a normal residential pool filter, the cross sectional filter area is scaled to one eighth because one lateral was used as the outlet. It is important to note that a lateral outlet is usually horizontal in the bottom of a filter, sometime with a slight angle but the lateral used for the filter outlet in the test column is vertical. The change in positioning of the outlet lateral spoke will change the direction of the outlet flow however this was not seen to significantly impact the results.

Calculation of the column dimensions were based on this approximate one eighth scaling. The diameter of the clear PVC pipe to be used was calculated to be approximately 20cm by scaling the effective filter area to one eighth. The length of pipe used was 50cm to allow a similar filter bed depth as a normal swimming pool filter (specifically Poolrite's s6000 rapid sand filter). Calculations of the ideal pipe/column dimensions are provided in appendix C. However, the final dimensions of the PVC pipe depended on the sizes of pipe available therefore the scaling is only approximate.

For this size filter the flow rate was also scaled down according to the flow rate per unit area of 600litres per minute per metre squared. For the filter area proposed the actual flow rate required through the system was calculated to be approximately 20litres per minute (for calculations see appendix C). At such a low flow rate it was no longer feasible to use a normal swimming pool pump, even with a throttle valve to restrict the output flow. It was decided to utilise a small household water transfer pump. This type of pump does not contain a screen and therefore this may impact the results as larger contaminants weren't screened from the water prior to filtration. Contamination by large particles (external sources) was minimised by constructing a "lid" for the water tank/body of water.

The columns were connected to the rest of the system with couplings to allow for removal and changeover of the granular filtration media within. The system was connected to allow for a filtration and backwash configuration to test both filtration efficiency and backwash efficiency claims. Three way valves are used throughout the system to allow for diversion of water flow depending on the configuration required.

12.4 Column Testing Methodology

The column test was setup according to *Figure 10* above. The test column when removed was filled to a depth of 400mm (approximately the working filter depth of a s6000 filter) with the filtration media (sand, zeolite or DiamondKleen^{TM} M10). First a test run was conducted with sand to prime the system and fix issues with the apparatus. The media was then replaced. Measurements of the change in pressure drop with flow rate were recorded and an initial sample was collected at this time.

The system was then set at a flow rate of 20L/min and allowed to stabilise. To stimulate approximately one month's worth of contamination, 600g of ISO Ultrafine test particles were added to the water storage tank and mixed thoroughly to obtain an even distribution of "contaminants". The pressure change and flow rate were recorded every 5 minutes for the first hour after dosing with the particles, and then every 15minutes for the remaining filtration time. Turbidity measurements were also recorded using a Palintest Photometer every 30minutes during filtration and water samples were collected at the beginning, at the end of each day and prior to backwashing. Each test was conducted until the turbidity of the filtrate was less than 2 Formazin Turbidity Units (FTU). The final flow rate and pressure change was recorded before turning the pump off and recording the total filtration time.

The system was then setup for a backwash cycle. The filter was then backwashed until all the water was expelled from the storage tank or "pool". In a normal swimming pool the backwash cycle would run until sufficient clarity of the water flushing the filter is achieved however due to the small volumes of water used in each test a backwash utilised all the water in the tank. The backwash water was collected in a small tank and a sample of the backwash collected was taken. Each sample was then analysed by a Coulter Counter to assess the particle size distribution of the collected samples. The column was then removed from the system and the media changed over. The methodology was repeated for each media type.

The results of these experiments is outlined and analysed in the following section to assess the experimental filtration efficiency.

PART D: Experimental Filtration Efficiency of Swimming Pool Media

Three column tests were conducted using the designed apparatus and according to the methodology outlined in the previous section. Results for pressure difference across the bed, flow rate, turbidity and particle size distribution of samples were obtained from these tests (Data and Test Reports provided in appendix D). These results were then analysed to determine the experimental filtration performance of the granular swimming pool filtration media. These results and the implications are discussed in the following section.

13 Clean Bed Pressure Difference Vs. Flow Curves

To assess the initial conditions of the tests, measurements of pressure difference at corresponding flow rates were recorded when the filter beds were clean. These results were then plotted to obtain a clean bed curve (*Figure 11*). This curve can also be used to compare the media when they are clean.

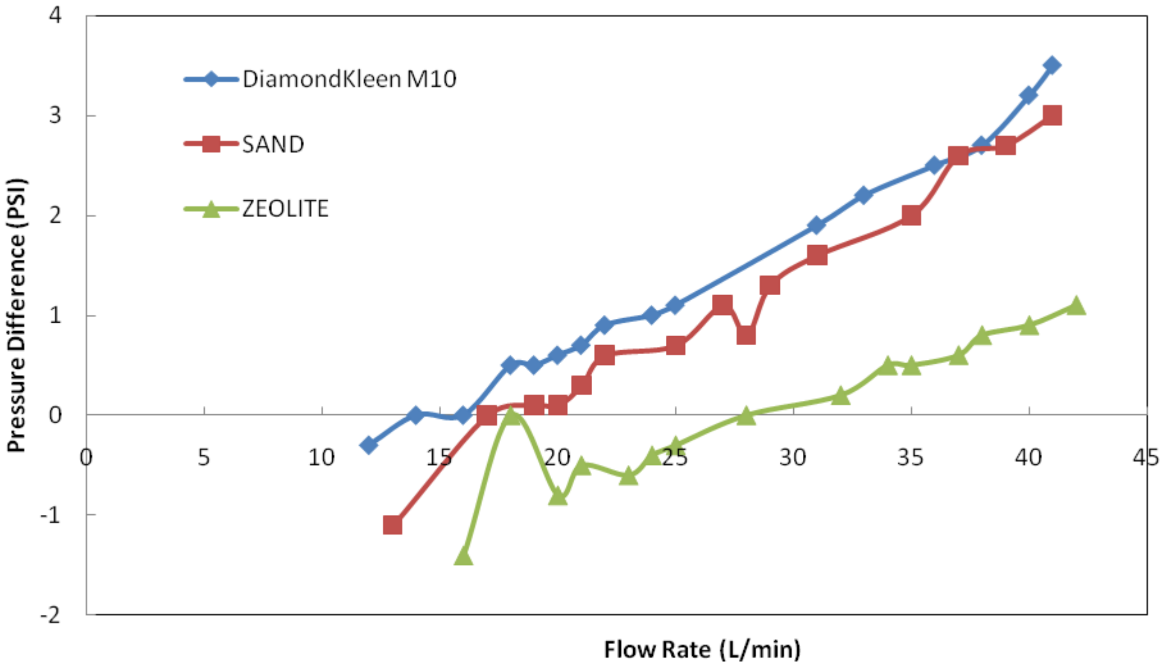


Figure 11: Clean Bed Pressure versus Flow Rate Curve for each Swimming Pool Media Type

As illustrated above in figure 10, The DiamondKleen^{TM} exhibited a higher pressure difference across the bed compared to sand and zeolite, but was similar to the sand curve. The zeolite showed the lowest pressure difference across the bed which is probably due to the higher grain size and pore space volume.

14 Column Test Filtration Performance Results

14.1 Summary of the Initial Data Collected from the Column Tests

The following table (table 11) outlines a summary of the conditions of each test including filtration time and final system conditions. These results illustrate differences between the performances of each media as a whole.

Table 11: Summary of Overall Filtration Results for the Three Tests Performed

Media Type	*Initial Turbidity (FTU)*	*Initial ΔP (PSI)*	*Filtration Run Time*	*Final Turbidity (FTU)*	*Final ΔP (PSI)*
SAND	2150	0.9	55 hours	2	1.2
DIAMONDKLEEN™ M10	1200	0.6	47 hours	0	0.4
ZEOLITE	1450	-0.7	52+ hours	155	-0.7

As shown in table 11, the water in the DiamondKleen™ test, while contaminated with the same dose of particles recorded a much lower initial turbidity level of 1200FTU. There is a large level of error in turbidity readings over 400FTU because turbidity readings over 400FTU required dilution to be read by the photometer. However the difference between initial readings is quit substantial. It is possible that silt and dirt evident in the bags of media was flushed during setup which is contributing to higher initial turgidities. If this is the case, it is evident that the DiamondKleen™ media is a "cleaner" media prior to use compared to sand and zeolite. Usually media is backwashed prior to initial use to remove existing dirt and silt, if DiamondKleen™ is initially cleaner this would mean reduced initial backwashing and therefore reduced water consumption involved with setup.

Overall it also evident that the DiamondKleen™ filtered quicker than sand and zeolite, taking only 47 hours filtration time to achieve 0FTU turbidity in the filtrate. This may be a result of lower initial turbidity or because DiamondKleen™ filters quicker due to increase filtration efficiency per turnover of the pool water. This is discussed further in section 14.3. Overall the sand filter experienced a net increase in pressure differential across the bed of 0.3psi, but the DiamondKleen™ experienced a net pressure difference drop of 0.2psi. The pressure difference in the zeolite media rarely changed at all during filtration time. The zeolite test also took remarkably longer to achieve similar results to sand and DiamondKleen™. These unusual results are discussed further below.

14.2 Pressure Difference Curves for Loaded Filters

The pressure difference results recorded for each test are plotted against filtration time in *Figure 12* below. Data could only be collected during work hour as evident by concentrated data points separated by no data collection.

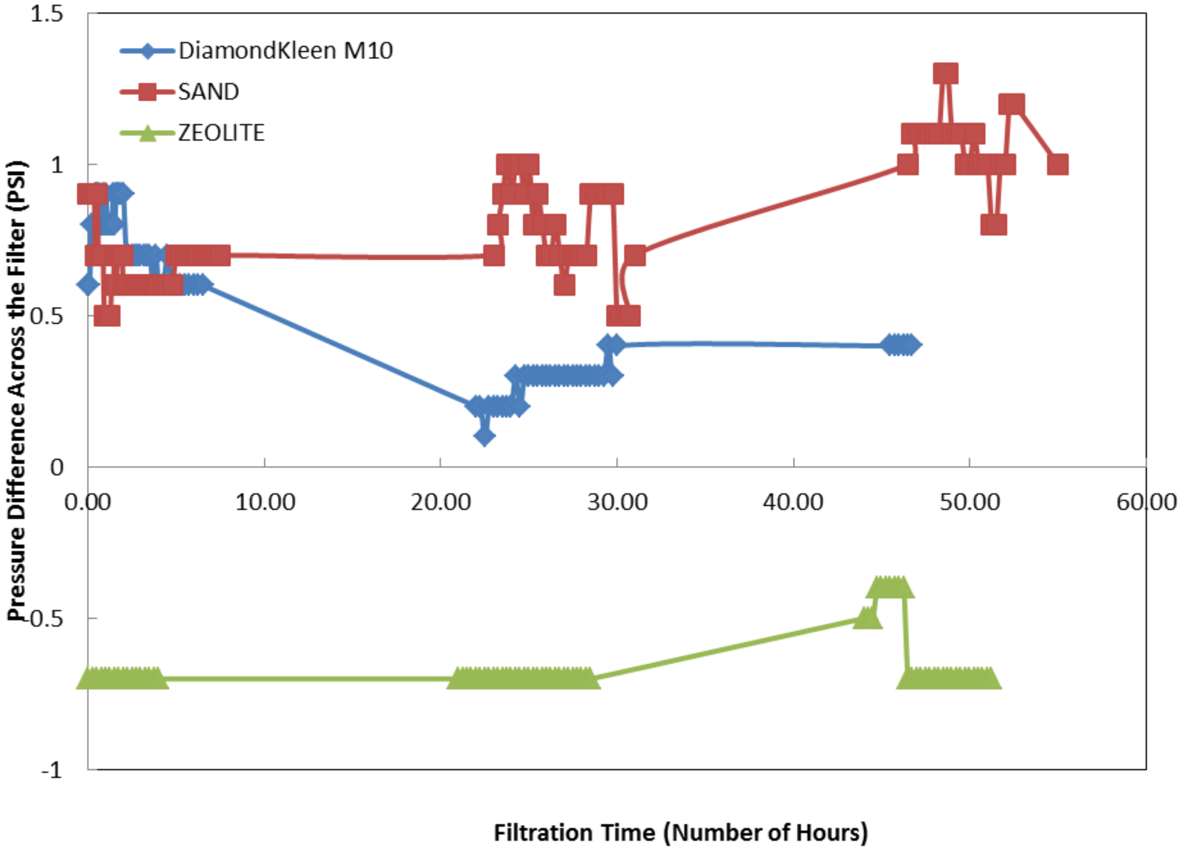


Figure 12: Pressure Difference across the Filter Bed over Time for each Filter Media Type

As evident in *Figure 12* the pressure difference caused by the sand media did increase overall which is consistent with the results from Taylor et al. (1999). However the pressure measurements taken during the day did fluctuate. This could be evidence of particle breakthrough creating a drop in pressure followed by an increase in pressure as the filter recaptures lost particles. The fluctuation in ambient temperature may also have had an impact as the weather conditions fluctuated during the sand test. The DiamondKleen™ shows an overall net decrease in pressure difference. However there was a large decrease in the first 24hours followed by a rise in pressure difference at the end of the filtration cycle.

It was observed that the temperature of the water in the storage tank or "pool" did increase from the heat generated by the pump. This rise in water temperature would have decreased the viscosity of the water in the system leading to a drop in pressure (see *Figure 13*). It is possible that this drop in pressure due to temperature increase was greater than the increase in pressure from particle loading. This would result in an overall decrease in pressure. The rise in pressure after 24 hours was probably a turning point where the resultant pressure from loading up of the filter was greater than the pressure drop created by temperature increase.

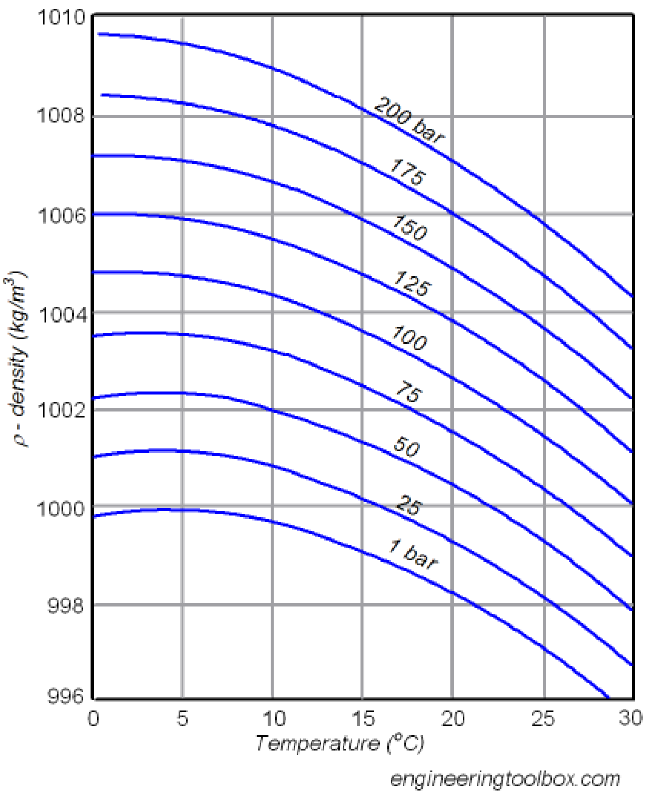


Figure 13: Changes in Density and Pressure Exhibited by Water with Changes in Temperature (Engineering Toolbox, 2011)

The Zeolite media for the majority of the test didn't show any change in pressure difference across the bed, registering a negative 0.7psi. There was a temporary increase in pressure difference after 42 hours but the pressure difference declines again back to the original value. While it was suspected that there was a problem with the pressure gauges for this test, Kimber et al. (2009) state that a head loss greater than the static head of water on the filter bed can result in a negative pressure.

14.3 Turbidity Reduction during Filtration Time

Overall the turbidity results are more conclusive than the pressure difference results. The turbidity readings for the influent to the filter, the filtrate, and the turbidity of the “pool” are shown below.

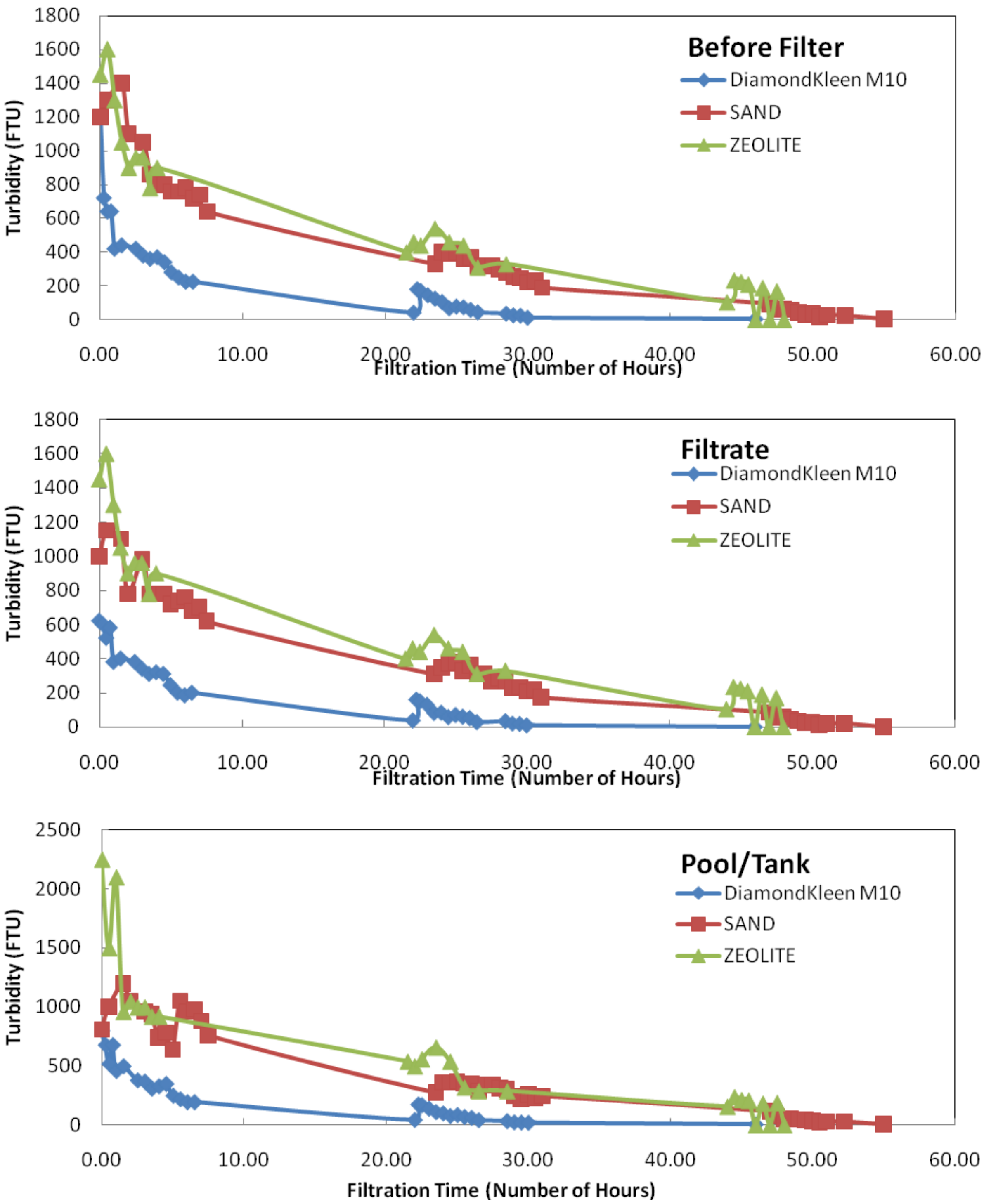


Figure 14: Turbidity Readings during Filtration Time of the Filter Influent, the Filtrate and the "Pool" storage tank

15 Particle Size Distributions from Collected Sample Testing

15.1 Sample Collection Summary

Several samples were collected during the three tests, the time and number of sample collection depended on the performance of the filter media. A summary of the sample collections is illustrated in table 12 below. The samples tested are also indicated. Some samples from the sand test were lost because the sample bottles froze and broke. Some of the samples were retrieved but these could have been contaminated by external particles and so were not tested.

Table 12: Summary of Sample Collection and Testing for Particle Size Distribution

Sample ID	*Sample Collection Time*	*Sample Point*	*Sample Tested*
Sand 1	Initial	Pre-filter	No
Sand 2	After day 2	Post-filter	No
Sand 3	Prior to backwash	Post-filter	Yes
Sand 4	Backwash	Backwash collection tank	Yes
DiamondKleen™ 1	Initial	Pre-filter	Yes
DiamondKleen™ 2	After day 1	Post-filter	No
DiamondKleen™ 3	After day 2	Post-filter	No
DiamondKleen™ 4	Prior to backwash	Post-filter	Yes
DiamondKleen™ 5	Backwash	Backwash collection tank	Yes
Zeolite 1	Initial	Pre-filter	No
Zeolite 2	After day 3	Post-filter	Yes

Due to time restrictions for testing the samples at the end of the project, only a selection of samples could be tested using the coulter counter. The initial and final were both tested for DiamondKleen™, along with a sample of the collected backwash. The initial sand sample was not tested because it was possibly contaminated due to breakage of the collection bottle. Therefore only the final and the backwash sample for the sand test were tested. It was initially assumed that the sand test final sample could be compared to the DiamondKleen™ test initial sample. However as evident in the turbidity readings, dirt in the sand media could have contributed to some of the contamination of the water initially. Therefore if the filtrate sample is compared to the DiamondKleen™ instead it will show an overestimation of removal percentage rates. Because the zeolite test took longer than the others, sample from the end of day 3 was tested.

15.2 Particle Size Distribution of Samples tested with Coulter Counter

Due to tie restrictions not all samples could be tested as discussed earlier. Because the DiamondKleen^{TM} media is the focus of this report the particle counts at the beginning and end of filtration were examined. A sample of the backwash water was also collected.

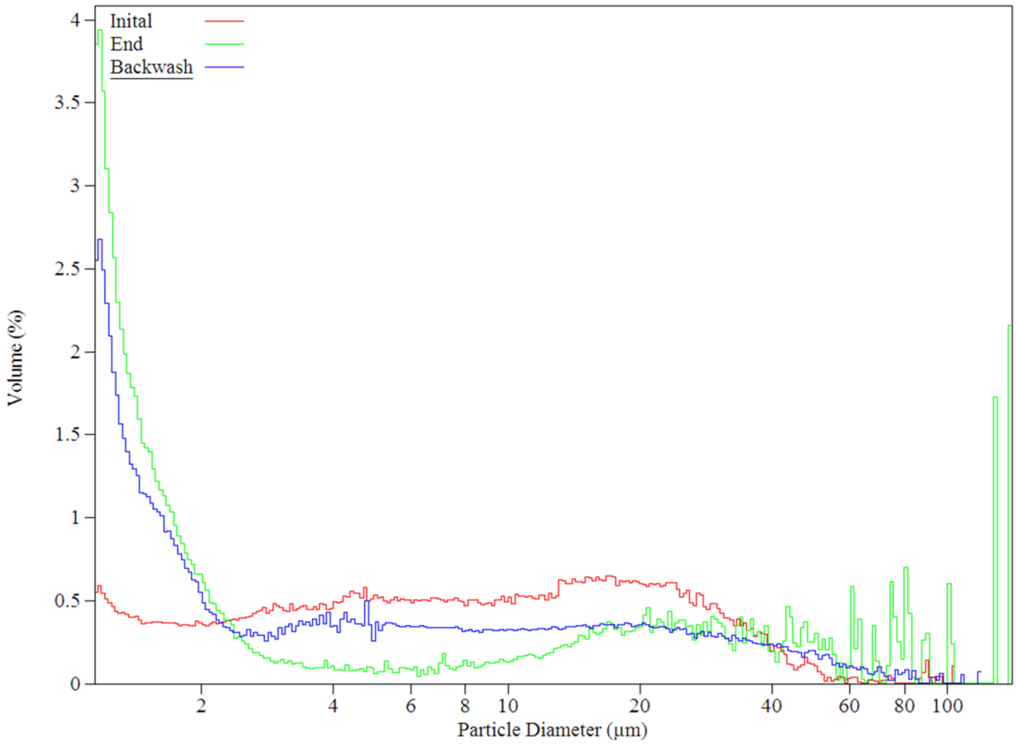
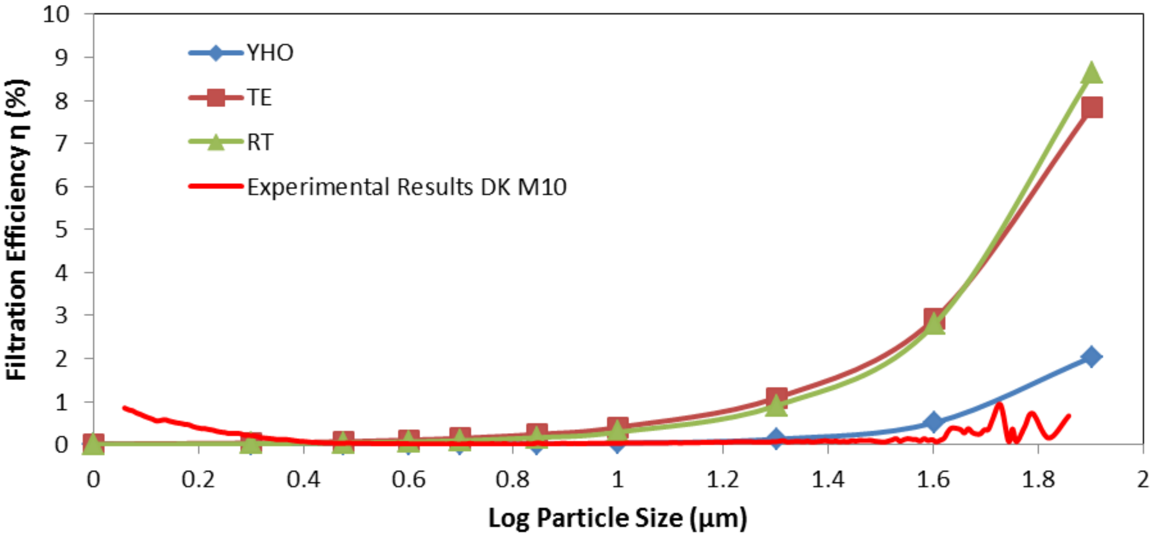


Figure 15: Particle Size Distribution of DiamondKleen^{TM} Samples collected

As would be expected, generally the difference between the initial and final samples is reflected in the particles expelled in the backwash. Overall the DiamondKleen^{TM} showed efficient removal of particles 3-20 micrometres in size. The largest % of particles remaining in the filtrate at the end of filtration is the size range 0-3 micrometres, which confirms the theoretical removals predicted that the media would be less efficient at removing these smaller particles.

16 Swimming Pool Granular Media Capture Efficiency

The particle counts from the sand and DiamondKleen^{TM} test taken at the end of the filtration time were compared to the initial DiamondKleen^{TM} sample particle count. As discussed there is some error in this method because the sand initial sample may have contained higher particle counts due to existing dirt and silt in the media prior to filtration. However because the initial sand sample could not be tested the results were still used to compare the two media. Zeolite was not included in the comparison because it has been identified earlier in the discussion that the zeolite was significantly less efficient.



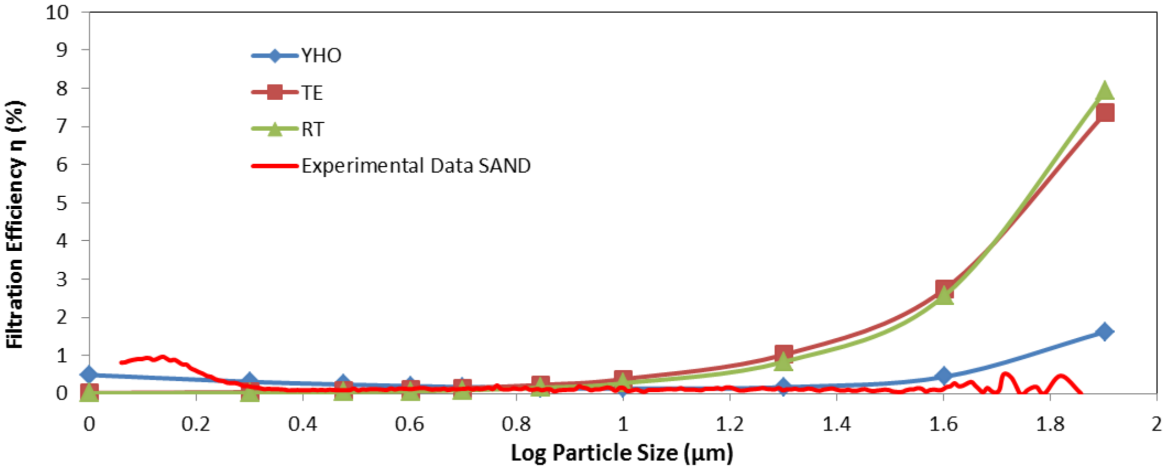


Figure 16: Comparison of Experimental Filtration Efficiency to Theoretical Models

In general the YHO model more closely replicates the experimental results. The DiamondKleen^{TM} achieved higher filtration efficiency however the graphs should illustrate higher efficiencies for both media at collecting the larger sized particles. The samples were screened prior to particle counting to remove large particles; it is possible that there was agglomeration of the larger particles which were then removed from the analysis.

17 Other Experimental Observations

While the main results of interest were the pressure difference change, turbidity reduction and particle removal as discussed above, other results were observed during experimentation or examination of the media. It is believed that these observations are also important to note when comparing the swimming pool filter media and are discussed below.

17.1 Assessment of agglomeration/bio-fouling effects in filter media

An assessment of the agglomeration or "mud-balling" effects within the filter bed was stipulated in the original project brief. It was determined in section C of this report that ISO standard test particles would be used in the testing to simulate contamination in the water. These particles are mostly silicon based (PTI, 2008) (see appendix C for further information on the ISO particles used) and are therefore inorganic in nature. There was no observed agglomeration, bio-fouling or "mud-balling" effects observed in any of the media, which was expected because the contaminants are not organic.

17.2 Contaminant Particle Penetration Depth into the Filter Bed and Visible Collection of Particles

Kimber et al. (2009) state that sand filter initially capture particles high in the bed which penetrate deeper as the filter bed loads up. This loading creates the increase in pressure difference. This is evident in the photos in *Figure 17*, where the majority of particles are accumulating in the top of the bed which eventually leads to screening, and in the bottom of the column (most likely due to sedimentation). In comparison the DiamondKleen™ show a different result. The particles haven't visibly accumulated on the top of the bed to form a screen as with the sand media and instead appear to penetrate the whole filter bed. As illustrated in *Figure 18* there is particle deposition at the bottom, in the middle and near the top of the filter bed.

Figure 17: Photograph of the Sand Media Screening Particles

Top of the filter bed

Middle of the filter bed

Bottom of the filter bed

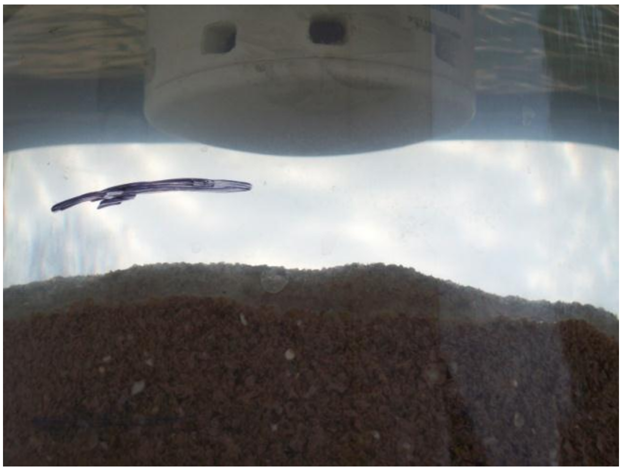
Figure 18: Photographs of Particle Collection in the DiamondKleen™ Media at the Top, Middle and Bottom of the Filter Bed

17.3 Changes in Filter Bed during Filtration and Backwash Cycles

The depth of the filter bed is also important to note, as the depth can greatly impact the filtration efficiency (Lawler &Nason, 2006; Ng et al., 2006; Shin, 2006b).To determine if the filter bed depth changes during filtration, measurements of the depth were recorded at the start and end of each test. As visible in the following photographs (*Figure 19*and *Figure 20*), there was compaction occurring in the sand bed but not in the DiamondKleen™ filter. This compaction of the sand bed may have caused the screening effects (visible in figure *Figure 17*) by decreasing the pore spaces between filter grains. By decreasing the porosity, the filtration efficiency of the sand filter is decreased as shown by the theoretical models.

The top black marking on the left of the photograph was the original fill line. The centre of the bed experienced minimal compaction whereas the outer edges of the bed were compacted up to 30mm.

Figure 19: Photograph of the Compaction in the Sand Filter Bed



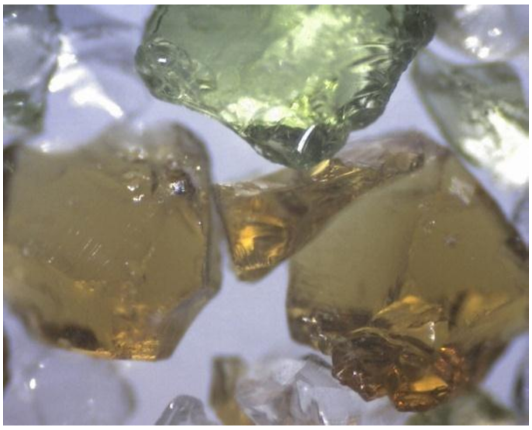
As shown in this photograph the bed remained relatively flat with minimal compaction on the outer edges of the bed. For this test the column wasn't filled to the black line but just below it, so overall the DiamondKleen™ did not compact much at all.

Figure 20: Photograph of the Compaction in the DiamondKleen™ Filter Bed

This might also lead to longer life of the DiamondKleen™ filter media because there may be less size reduction of filter grains. Korkosz (2011) states that sand also undergoes size reduction from turbulent conditions when washing. This size reduction from filtration and backwash cycling as well as bed compaction during filtration would lead to significant decreases in filtration performance. Therefore the DiamondKleen™ will produce better filtration than the sand because there is limited compaction occurring in the filter bed and may experience less grain size reduction.

17.4 Light Microscope Images of Swimming Pool Media

The following images (Figures 16-18) were taken using a light microscope to examine the structure of the different media grains. It is evident in the images that the glass is more angular than the sand and zeolite. Suthaker et al. (1995) explains that the shape of media can greatly impact performance. They claim that greater angularity results in larger bed porosity, and as shown in the theoretical models, greater porosity leads to better filtration efficiency. This evidence of the angularity of the grains of glass explains why the porosity of the M10 grade of DiamondKleen™ is high despite a comparative grain diameter.



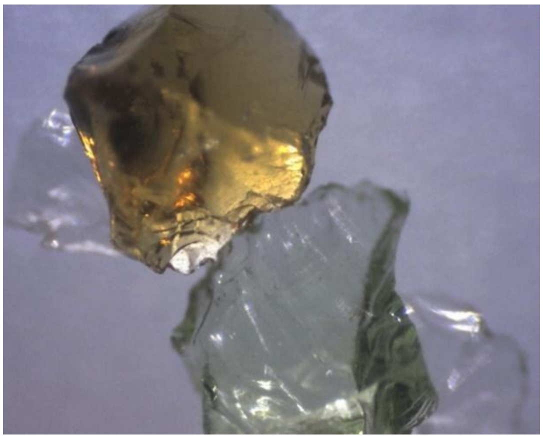


Figure 21: Microscope Images of DiamondKleen™ Glass Media

Figure 22: Microscope Images of Zeolite Media

Figure 23: Microscope Images of Sand Media

PART E: Conclusions and Recommendations for the Use of DiamondKleen™ in Swimming Pool Filters

18 Concluding Comments on the Comparison of Swimming Pool Media

18.1 Summary of Conceptual Comparison of Swimming Pool Media

Conceptually, DiamondKleen™ is comparatively a more socially responsible medium for use in granular filters. The use of recycled glass minimises the use of raw materials, sand and zeolite, and the associated impacts from sourcing these products. Sourcing of sand and zeolite degrade the environment primarily by mining activities and higher emissions from transporting longer distances. DiamondKleen™ utilises waste cullet glass which could not be used in normal recycling processes therefore encouraging industrial ecology practices. The use of an unusable waste product also decreases the cost of purchasing raw materials which produces economic savings that can be passed on to the final user.

18.2 Summary of Theoretical Efficiency of Swimming Pool Media

The theoretical filtration efficiency of sand, zeolite and DiamondKleen™ were modelled using three models discussed in the literature. The models used were the Yao Habibian and O'Melia (1971) Model or YHO Model, the Rajagopolan and Tien (1976) model or RT Model and the Tufenkji and Elimelech (2004) Model or TE Model.

The modelling of a single collector using the TE and RT models, predicts similar filtration efficiency for sand and DiamondKleen™ with the zeolite performing better than the coarse grade DiamondKleen™ M20. The YHO model shows a larger difference between the sand and DiamondKleen™ media performance, predicting DiamondKleen™ as the most efficient media.

When the single collectors are added together in a filter bed the DiamondKleen™ will perform slightly better but similar to sand. Both media also perform remarkably better than the zeolite. Again the YHO model predicts better performance from the DK compared to sand. It is important to note however that the models don't include the chemical conditions within the system nor take into account any screening effects that may occur due to small pore space.

18.3 Summary of Experimental Filtration Efficiency of Swimming Pool Media

Overall the DiamondKleen^{TM} produced better turbidity reduction with no increase in pressure difference across the bed. While the decrease in pressure was probably due to unique conditions occurring in the experimental apparatus, the particle removal percentages and other observations support the claim that DiamondKleen^{TM} performs better than the sand or zeolite tested.

The water in the DiamondKleen^{TM} test, while contaminated with the same dose of particles recorded a much lower initial turbidity level of 1200FTU. This may illustrate that the DiamondKleen^{TM} media is a "cleaner" media prior to use compared to sand and zeolite. Overall it also evident that the DiamondKleen^{TM} filtered quicker than sand and zeolite, taking only 47 hours filtration time to achieve 0FTU turbidity in the filtrate. This may be a result of lower initial turbidity or because DiamondKleen^{TM} filters quicker due to increase filtration efficiency per turnover of the pool water.

The Zeolite media for the majority of the test didn't show any change in pressure difference across the bed, registering a negative 0.7psi. There was a temporary increase in pressure difference after 42 hours but the pressure difference declines again back to the original value.

Due to time restrictions for testing the samples at the end of the project, only a selection of samples could be tested using the coulter counter. Overall the DiamondKleen^{TM} showed efficient removal of particles 3-20 micrometres in size. The largest % of particles remaining in the filtrate at the end of filtration is the size range 0-3 micrometres, which confirms the theoretical removals predicted that the media would be less efficient at removing these smaller particles.

Collection of particles in the DiamondKleenTM Filter occurred throughout the entire bed whereas the sand filter occurred mostly at the top and bottom of the column, eventually causing screening towards the end of the filtration cycle. The zeolite only collected particles at the bottom. There was also visible compaction of the sand bed which may have caused the screening effects by decreasing the pore spaces between filter grains. By decreasing the porosity, the filtration efficiency of the sand filter is decreased as shown by the theoretical models.

This might also lead to longer life of the DiamondKleen^{TM} filter media because there may be less size reduction of filter grains. Korkosz (2011) states that sand also undergoes size reduction from turbulent conditions when washing. This size reduction from filtration and backwash cycling as well as bed compaction during filtration would lead to significant decreases in filtration performance. Therefore the DiamondKleen^{TM} will produce better filtration than the sand because there is limited compaction occurring in the filter bed and may experience less grain size reduction. The angularity of the DiamondKleen^{TM} grains (shown in the microscope images) also increases the porosity leading to higher filtration efficiency.

19 Recommendations for the future use of DiamondKleen™

Based on the conclusions presented in the preceding paragraphs the following is recommended:

- That the use of DiamondKleen^{TM} in swimming pool filters be continued as it is more efficient and environmentally sustainable than sand or zeolite

To improve the existing experimental test apparatus it is recommended:

- The hydraulics of the apparatus be closely examined and designed to maintain the same pressure and flow rate through the system. E.g. Smaller size suction and return pipes
- A tank mixer be employed to maintain particles in suspension for more accurate results
- The temperature of the pool should be controlled to maintain constant temperature and avoid pressure drops due to rising water temperatures caused by the pump.

For further testing of DiamondKleen^{TM} the following is recommended:

- Test the Zeta Potential of the particles in pool water to determine the chemical interactions between swimming pool water contaminants and the filter media.
- Determine the chemical charge of the glass and assess whether this contributes to the efficiency of glass as a medium
- Determine whether the Magnapool minerals modify this chemical interaction (does the Magnapool minerals change the charge of the particles suspended in pool water)
- Test the different swimming pool media using organic contaminants such as backwash sludge to examine agglomeration or mud-balling effects.
- Rerun the tests and collect more comprehensive data for particle sizing.
- Rerun with ‘clean’ media to determine number of backwashes to get media clean and assess true clean bed characteristics.

References

Aksogan, S., A. Basturk, E. Yuksel and O. Akgiray (2003). "On the use of crushed shells of apricot stones as the upper layer in dual media filters." Water Science and Technology **48**(11-12): 497-503.

Aquatic Commercial Industries (1998). Evaluation Of Crushed Recycled Glass Sand Media for High-Rate Sand Filtration. Washington, Clean Washington Center (CWC).

Babych, A. (2011). Technical Report: Turbidity Effect of Magnapool Mineral Mix in Different Filter Medias. Poolrite Research Internal Report, Poolrite Equipment Pty Ltd.

Binnie, C. and M. Kimber (2009). Basic Water Treatment, Thomas Telford.

Camp, T. R. (1961). "Experience with Anthracite-Sand Filters (discussion)." Journal American Water Works Association **53**(12): 1478.

CRNA (2010). Submission of the community recycling network australia to the product stewardship legislation - consultation paper. National Waste Policy: Less Waste, More Resources, Australian Government Department of Sustainability, Environment, Water, Population and Communities

Croll, B. T., C. R. Hayes and S. Moss (2007). "Simulated Cryptosporidium removal under swimming pool filtration conditions." Water and Environment Journal **21**(2): 149-156.

Darby, J. L., R. E. Attanasio and D. F. Lawler (1992). "Filtration of heterodisperse suspensions: Modeling of particle removal and head loss." Water Research **26**(6): 711-726.

De Leeuw, J., D. Shankman, G. F. Wu, W. F. de Boer, J. Burnham, Q. He, H. Yesou and J. Xiao (2010). "Strategic assessment of the magnitude and impacts of sand mining in Poyang Lake, China." Regional Environmental Change **10**(2): 95-102.

DEWHA (2009). A national waste policy: managing waste to 2020: Consultation Paper. DEWHA Waste Policy Taskforce, Canberra, Dept. of the Environment, Water, Heritage and the Arts.

Dorevitch, S., S. Panthi, Y. Huang, H. Li, A. M. Michalek, P. Pratap, M. Wroblewski, L. Liu, P. A. Scheff and A. Li (2011). "Water ingestion during water recreation." Water Research **45**(5): 2020-2028.

Dwivedi, C. P., J. N. Sahu, C. R. Mohanty, B. R. Mohan and B. C. Meikap (2008). "Column performance of granular activated carbon packed bed for Pb(II) removal." Journal of Hazardous Materials **156**(1-3): 596-603.

Engineering Toolbox (2011) Calculating density of fluids when changing pressure and temperature, Retrieved 16/6/2011 from: http://www.engineeringtoolbox.com/fluid-density-temperature-pressure-d_309.html

Elliott, R. W. (2001a). "Evaluation of the use of crushed recycled glass as a filter medium: Part 1." Water-Engineering & Management **148**(7).

Elliott, R. W. (2001b). "Evaluation of the use of crushed recycled glass as a filter medium: Part 2." Water-Engineering & Management **148**(8): 17-20.

Evans, G., P. Dennis, M. Cousins and R. Campbell (2002). "Use of recycled crushed glass as a filtration medium in municipal potable water treatment plants." 3rd World Water Congress: Drinking Water Treatment **2**(5-6): 9-16.

Gill, L., C. Doran, D. Misstear and B. Sheahan (2009). "The use of recycled glass as a filter media for on-site wastewater treatment." Desalination and Water Treatment **4**(1-3): 198-205.

Glauner, T., P. Waldmann, F. H. Frimmel and C. Zwiener (2005). "Swimming pool water - Fractionation and genotoxicological characterization of organic constituents." Water Research **39**(18): 4494-4502.

Gray & Osborne Inc (1995). Evaluation Of Crushed Recycled Glass as a Filtration Medium In Slow Sand Filtration. Washington, Clean Washington Center (CWC).

Gregory, J. (2006). Particles in water: properties and processes. T. F. Group, IWA Publishing.

Hahm, M. (2010). "Moss in the pool isn't such a bad thing: Saint Paul Parks and Recreation embraces unique pool filtration system." Parks & Recreation **45**(8): 43.

Hammer, M. J. (2008). Water and wastewater technology, Pearson/Prentice Hall.

Hinds, W. C. (1999). Aerosol technology: properties, behavior, and measurement of airborne particles, Wiley.

Holloway, C. and S. Anderson (2007). Flow Test Report for Various Filter Media. Poolrite Research Internal Report, Poolrite Equipment Pty Ltd.

Horan, N. J. and M. Lowe (2007). "Full-scale trials of recycled glass as tertiary filter medium for wastewater treatment." Water Research **41**(1): 253-259.

Hu, Z. and G. A. Gagnon (2006). "Impact of filter media on the performance of full-scale recirculating biofilters for treating multi-residential wastewater." Water Research **40**(7): 1474-1480.

Jegatheesan, V. and S. Vigneswaran (1997). "Interaction between organic substances and submicron particles in deep bed filtration." Separation and Purification Technology **12**(1): 61-66.

Jegatheesan, V. and S. Vigneswaran (2005). "Deep bed filtration: Mathematical models and observations." Critical Reviews in Environmental Science and Technology **35**(6): 515-569.

Kimber, M., A. Water and C. Binnie (2009). Basic water treatment, London, Thomas Telford.

Knighton, D. R. and V. D. Fiegel (2008). "Sphagnum Moss, Bacterial Biofilm and Water Quality." Water Conditioning and Purification **50**(11).

Korkosz, A., M. Niewiadomski and J. Hupka (2011). "INVESTIGATION OF PROPERTIES OF SWIMMING POOL WATER TREATMENT SEDIMENTS." Physicochemical Problems of Mineral Processing(46): 243-252.

Lawler, D. F. and J. A. Nason (2006). "Granular media filtration: old process, new thoughts." Water Science and Technology **53**(7): 1-7.

Lee, J., K. T. Ha and K. D. Zoh (2009). "Characteristics of trihalomethane (THM) production and associated health risk assessment in swimming pool waters treated with different disinfection methods." Science of the Total Environment **407**(6): 1990-1997.

Liu, M. (2007). Evaluation of DiamondKleenTM in s8000, s9000 Sand Filter. Poolrite Research Internal Report, Poolrite Equipment Pty Ltd.

Logan, B. E., D. G. Jewett, R. G. Arnold, E. J. Bouwer and C. R. Omelia (1995). "Clarification of Clean-Bed Filtration Models." Journal of Environmental Engineering-Asce **121**(12): 869-873.

Logan, B. E., D. G. Jewett, R. G. Arnold, E. J. Bouwer and C. R. Omelia (1997). "Clarification of clean-bed filtration models - Closure." Journal of Environmental Engineering-Asce **123**(7): 730-731.

Malvern Instruments Ltd. (2011). "Zeta potential measurement using laser Doppler electrophoresis (LDE) " Retrieved 18/05/2011, from http://www.malvern.com/LabEng/technology/zeta_potential/zeta_potential_LDE.htm.

McShane, I. (2009). "The past and future of local swimming pools." Journal of Australian Studies **33**(2): 195-208.

Mitrouli, S. T., A. J. Karabelas, S. G. Yiantsios and P. A. Kjolseth (2009). "New granular materials for dual-media filtration of seawater: Pilot testing." Separation and Purification Technology **65**(2): 147-155.

Ng, W. K., V. Jegatheesan and S. H. Lee (2006). "Influence of particle concentration on initial collection efficiency and surface coverage in porous media filtration." Korean Journal of Chemical Engineering **23**(2): 333-342.

O'Melia, C. R. and W. Ali (1978). "The role of retained particles in deep bed filtration." Progress in Water Technology **10**(5).

Perkins, P. H. (2000). Water Circulation And Water Treatment. Swimming Pools, Spon Press.

Piccirillo, J. B. and R. D. Letterman (1997). Examination of pulverized waste recycled glass as filter media in slow sand filtration. Final Report 97-13, New York State Energy Research and Development Authority (NYSERDA).

Pool Water Treatment Advisory Group (PWTAG) (2009). Swimming Pool Water: Treatment and Quality Standards for Pools and Spas, Micropress Printers Ltd, London.

Poolrite (2011a). All new Revolutionary DiamondKleenTM Glass Filtration Media. Product Brochure. Brisbane, Poolrite Equipment Pty Ltd,.

Poolrite. (2011b). "Polrite Featured Products: DiamondKleenTM." Retrieved 12th May, 2011, from http://www.poolrite.com.au/products/1.

Poolrite Research Pty Ltd (2011). Technical Manual TM-The_Magnapool_System-1 System Description and Compliance Verification. Brisbane, Poolrite Research Pty Ltd,.

PTI (2008). PRODUCT LIST PP2G4: ISO 12103-1 ARIZONA TEST DUST CONTAMINANTS A2 FINE AND A4 COARSE GRADES. Powder Technology Inc. Minnesota.

Purchas, D. B. and K. Sutherland (2002). Handbook of filter media, Elsevier Advanced Technology.

PWTAG (2009). Swimming Pool Water: Treatment and Quality Standards for Pools and Spas, London, Pool Water Treatment Advisory Group (PWTAG),

Micropress Printers Ltd, .

Qi, S. Y. (1997). "Clarification of clean-bed filtration models." Journal of Environmental Engineering-Asce **123**(7): 729-730.

QLD Health (2003). Swimming and Spa Pool Water Quality and Operational Guidelines, Qld Health.

Raikhel, T. (2007). Evaluation of New FiltrationMedia (DiamondKleenTM) in Poolrite Sand Filters. Poolrite Research Internal Report, Poolrite Equipment Pty Ltd.

Raikhel, T. (2008). Filtration Performance Evaluation on Various Poolrite Filters. Poolrite Research Internal Report, Poolrite Equipment Pty Ltd.

Rajagopalan, R. and C. Tien (1976). "Trajectory analysis of deep-bed filtration with the sphere-in-cell porous media model." AIChE Journal **22**(3): 523-533.

Rajagopalan, R. and C. Tien (2005). "Comment on "Correlation equation for predicting single-collector efficiency in physicochemical filtration in saturated porous media"." Environmental Science & Technology **39**(14): 5494-5495.

Russell, D. L. (2006). Practical wastewater treatment, Wiley-Interscience.

Ruth, M. and P. Dell'Anno (1997). "An industrial ecology of the US glass industry." Resources Policy **23**(3): 109-124.

Rutledge, S. O. and G. A. Gagnon (2002). "Comparing crushed recycled glass to silica sand for dual media filtration." Journal of Environmental Engineering and Science **1**(5): 349-358.

Salvato, J. A., N. L. Nemerow and F. J. Agardy (2003). Environmental Engineering John Wiley & Sons.

Shin, C. (2006a). "Filtration application from recycled expanded polystyrene." Journal of Colloid and Interface Science **302**(1): 267-271.

Shin, C. (2006b). "Numerical simulation for particle penetration depth distribution in deep bed filtration." Chemical Engineering & Technology **29**(8): 905-909.

Soyer, E., Ö. Akgiray, N. Ö. Eldem and A. M. Saatçı (2010). "Crushed recycled glass as a filter medium and comparison with silica sand." CLEAN – Soil, Air, Water **38**(10): 927-935.

Sreebha, S. and D. Padmalal (2011). "Environmental Impact Assessment of Sand Mining from the Small Catchment Rivers in the Southwestern Coast of India: A Case Study." Environmental Management **47**(1): 130-140.

Stevenson, D. G. (1997). "Flow and filtration through granular media--the effect of grain and particle size dispersion." Water Research **31**(2): 310-322.

Suthaker, S., D. W. Smith and S. J. Stanley (1995). "Evaluation of Filter Media for Upgrading Existing Filter Performance." Environmental Technology **16**(7): 625 - 643.

Taylor, K., A. G. Smith, S. Ross and M. Smith (1999). The Prediction of Pressure Drop and Flow Distribution in Packed Bed Filters. Second International Conference on CFD in the Minerals and Process Industries, CSIRO. **:** 273-280.

Thornton, E. B., A. Sallenger, J. C. Sesto, L. Egley, T. McGee and R. Parsons (2006). "Sand mining impacts on long-term dune erosion in southern Monterey Bay." Marine Geology **229**(1-2): 45-58.

Tobiason, J. E. and B. Vigneswaran (1994). "Evaluation of a modified model for deep bed filtration." Water Research **28**(2): 335-342.

Tufenkji, N. and M. Elimelech (2004). "Correlation equation for predicting single-collector efficiency in physicochemical filtration in saturated porous media." Environmental Science & Technology **38**(2): 529-536.

Tufenkji, N. and M. Elimelech (2005). "Response to comment on "Correlation equation for predicting single-collector efficiency in physicochemical filtration in saturated porous media"." Environmental Science & Technology **39**(14): 5496-5497.

Uhl, W. and C. Hartmann (2005). Disinfection by-products and microbial contamination in the treatment of pool water with granular activated carbon. **52:** 71-76.

Uluatam, S. S. (1991). "Assessing Perlite as a Sand Substitute in Filtration." Journal American Water Works Association **83**(6): 70-71.

Vigneswaran, S. and J. S. Chang (1989). "Experimental testing of mathematical models describing the entire cycle of filtration." Water Research **23**(11): 1413-1421.

Vigneswaran, S. and R. K. Tulachan (1988). "MATHEMATICAL-MODELING OF TRANSIENT-BEHAVIOR OF DEEP BED FILTRATION." Water Research **22**(9): 1093-1100.

Wartman, J., D. G. Grubb and A. S. M. Nasim (2004). "Select engineering characteristics of crushed glass." Journal of Materials in Civil Engineering **16**(6): 526-539.

WHO (2006). Guidelines for safe recreational waters, Volume 2 - Swimming pools and similar recreational-water environments Chapter 5: Managing Water and Air Quality. Switzerland, World Health Organisation (WHO) Press**:** 80-99

Williams, G. J., B. Sheikh, R. B. Holden, T. J. Kouretas and K. L. Nelson (2007). "The impact of increased loading rate on granular media, rapid depth filtration of wastewater." Water Research **41**: 4535-4545.

Williams, L. K. and R. L. Langley (2001). Environmental Health Secrets., Philadelphia, Hanley & Belfus, INC.

World Health Organisation (WHO) (2006). Guidelines for safe recreational waters, Volume 2 - Swimming pools and similar recreational-water environments Chapter 5: Managing Water and Air Quality. Switzerland, WHO Press**:** 80-99

Yao, K. M., M. T. Habibian and C. R. O'Melia (1971). "Water and waste water filtration. Concepts and applications." Environmental Science & Technology **5**(11): 1105-1112.

APPENDICES

Appendix A: Background Information

A - 1. DiamondKleen™/ Magnapool System Characteristics

A - 2. DiamondKleen™ Material Safety Data Sheet (MSDS)

A - 1. DiamondKleen™/ Magnapool System Characteristics

Normal operating characteristics			
pressure	80-100kPa	Components:	Purpose:
pH	7.2 – 7.6	Body of pool water	Swimming
Temperature	24-28°C	Suction & return lines	recirculation
Alkalinity	80-125ppm	Pumps	recirculation
hardness	200-270ppm	Primary filter	turbidity reduction
Free chlorine	0.6-1.0ppm	Secondary filter	back wash settling and recycling
ORP	>700mV	Collector tank	Rainwater replenishment
		Sanitiser	Disinfection
		Disinfection controller	pH/ORP reading balance water quality

DiamondKleen Filtration Media				
	M10	M20	Sand	Gravel
Colour and shape	Brown and green sub-angular granules	Brown and green sub-angular granules		
Grain size	0.75mm – 1.70mm	1.70mm – 3.00mm		
Grain density	2500 kg/m^3	2500 kg/m^3		
Bulk density – loose	1250 kg/m^3	1250 kg/m^3		
Bulk density – packed	1450 kg/m^3	1450 kg/m^3		
Packed bed voidage – loose	0.48 to 0.54	0.48 to 0.54		
Packed bed voidage -packed	0.40 to 0.46	0.40 to 0.46		
Uniformity coefficient (d60/d10)	1.18mm/0.75 mm = 1.57	2.00mm/1.30 mm = 1.54	0.60mm/0.33 mm = 1.82	

Supporting Equipment (cost folder)				
	S5000	S6000	S8000	S9000
Tank diameter –	522mm (20in)	635mm (25in)	770mm (30in)	813mm (32in)
Max flow rate L/Hr	13200	18000	27000	33000
Fine Media Weight kg	45	90	120	150
Coarse media weight kg	30	45	45	60
Pump model	SQI-400	SQI-500	SQI-600	SQI-700
Pump hp	1.0	1.25	1.5	2.0
kW output	0.75	0.96	1.1	1.5
Min suction pipe size mm	40	40-50	40-50	50 only
Pump weight kg	16.6	18	18.4	18.6
Pump dimensions	720 x 220 x 340	720 x 220 x 340	720 x 220 x 340	720 x 220 x 340

A - 2. DiamondKleen™ Material Safety Data Sheet (MSDS)

MATERIAL SAFETY DATA SHEET
DIAMOND KLEEN FILTER MEDIA

PAGE 1 OF TOTAL 2 DATE OF ISSUE: JULY 2010

SUPPLIER DETAILS

Name	Poolrite Equipment
Address	415 Creek Road, Mt Gravatt QLD 4122
Telephone No	(07) 3323 6555
Facsimile No	(07) 3323 6526
Contact	Stuart Anderson

IDENTIFICATION

Product Name	Diamond Kleen	**UN Number:**	None Allocated
Other Names		**Hazchem Code:**	None Allocated
Use	Filter Media	**Dangerous Goods:**	None Allocated
		Class and Sub-risk:	None Allocated
		Poisons Schedule:	Not Scheduled

Physical Description/Properties

Appearance	Crushed Translucent Granules	**Flashpoint (0ºC):**	Not Combustible
		Flammability Limits (%):	Not Relevant
Melting Point (0ºC)	800ºC	**Solubility in Water (g/L):**	Non-Soluble

Other Properties

Hardness	6.0 Mhos
Chlorides	<5 ppm
Specific Gravity	2.46
Free Silica (alpha quartz)	Nil

Packaging

15kg Bags

HEALTH HAZARD INFORMATION

HEALTH EFFECTS

Acute	Swallowed:	Non Toxic
	Eye:	Mechanical irritant
	Skin:	Direct contact with material under pressure may abrade or damage skin.
	Inhaled:	May irritate if exposure is excessive. Prolonged exposure to high level may have debilitating effect on the lungs.
First Aid	Swallowed:	Rinse mouth thoroughly with water. Seek medical attention if large quantities have been Ingested.
	Eye:	Remove foreign body, flush with water
	Skin	Clean and dress open wounds
	Inhaled:	Move to fresh air
	First Aid Facilities:	General first aid equipment for treatment of cuts and abrasions
Advice to Doctor		Treat Symptomatically

DIAMOND KLEEN FILTER MEDIA

 DATE OF ISSUE: JULY 2010

PRECAUTIONS FOR USE

Exposure Standards

Australian Regulations nominate TLV (TWA) 10mg/m^3 as total dust, 5 mg/m^3 as respirable dust.

Engineering Controls

- Ensure ventilation is adequate to maintain dust exposure below the exposure standard for personnel adjacent to the grit blasting area.
- Ensure that all blast cleaning equipment complies with Workcover and all appropriate Regulatory Authority Regulations and Codes of Practice.

Personal Protection

Operator must wear Abrasive Blast Helmet Air Line Respirator of a type complying with AS1716. A protective Leather Jacket or suit, Leather Hand and Foot protection with Steel Toe Cap inserts. Use hearing protection when working in blast cleaning operations.

Flammability

Not flammable.

SAFE HANDLING INFORMATION

Storage and Transport

Bags to remain closed and bulk loads covered to avoid dusting. Use good housekeeping practices to reduce dust.

Spills and Disposal

No special storage or Transport requirements necessary.
Sweep or vacuum material for disposal. Prevent generation of dust during clean up. Disposal through approved land waste site. **MATERIAL CONTAMINATED IN USE MAY REQUIRE SPECIAL HANDLING.**

Fire/Explosion Hazard

Avoid contact with hydrofluoric acid.
As with any dust, there is the potential for a dust explosion and thus ventilation should be such that gross levels of dust do not accumulate.

●●●

IMPORTANT NOTE

This information is furnished without warranty, representation, endorsement or license of any kind, except that it is accurate to the best of Poolrite Equipment knowledge or obtained from sources believed by Poolrite Equipment to be accurate and Poolrite Equipment does not assume any legal responsibility for use or reliance upon same. Users are encouraged to conduct their own tests before using or disposal of this product.

●●●

Appendix B: Theoretical Modelling

B - 1. Model Parameters

System Characteristics		
Approach velocity	0.010548	m/s
Viscosity	0.000891	kg/ms
Temperature	298	K
Fluid density	997	kg/m3

Constants		
Boltzmanns constant	1.38065E-23	m2 kg/s2K
Gravity Constant	9.81	m/s2
Hamaker constant	4E-20	kg m^2/s^2

Particle Characteristics		
particle size	Ultrafine	0-20µm
	Fine	0-120µm
particle density	500	kg/m3

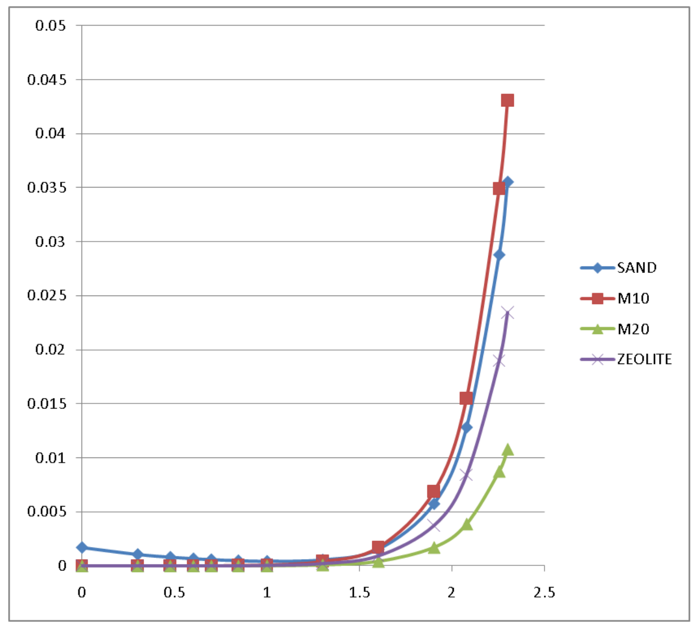
Filter Grain characterisitics				
Filter media	SAND	M10	M20	ZEOLITE
Porosity	0.3923	0.4171	0.4334	0.4436
grain size	0.0013	0.00118	0.00236	0.0016

B - 2. Calculations for the YHO, RT and TE models

Yao et al. [1971]	$\eta_o = \eta_1 + \eta_G + \eta_D$	$\eta = 4N_{Pe}^{-2/3} + \frac{3}{2} N_R^2 + N_G$

	SAND				M10				M20				ZEOLITE			
Particle Size Distribution	I	D	G	η	I	D	G	η	I	D	G	η	I	D	G	η
0.000001	8.87574E-07	4.36E-05	0.00000000	0.00173615	1.07728E-06	4.64682E-05	0.00000000	0.00004755	2.69319E-07	2.92731E-05	0.00000000	0.00002954	5.85938E-07	3.79313E-05	0.00000000	0.00003852
0.000002	3.5503E-06	2.74E-05	0.00000000	0.00109670	4.30911E-06	2.92731E-05	0.00000000	0.00003358	1.07728E-06	1.84409E-05	0.00000000	0.00001952	2.34375E-06	2.38952E-05	0.00000000	0.00002624
0.000003	7.98817E-06	2.09E-05	0.00000000	0.00084222	9.69549E-06	2.23396E-05	0.00000000	0.00003204	2.42387E-06	1.40731E-05	0.00000000	0.00001650	5.27344E-06	1.82354E-05	0.00000000	0.00002351
0.000004	1.42012E-05	1.73E-05	0.00000000	0.00070284	1.72364E-05	1.84409E-05	0.00000000	0.00003568	4.30911E-06	1.16171E-05	0.00000000	0.00001593	0.000009375	1.5053E-05	0.00000000	0.00002443
0.000005	2.21893E-05	1.49E-05	0.00000000	0.00061564	2.69319E-05	1.58919E-05	0.00000000	0.00004282	6.73298E-06	1.00113E-05	0.00000000	0.00001674	1.46484E-05	1.29723E-05	0.00000000	0.00002762
0.000007	4.34911E-05	1.19E-05	0.00000000	0.00051770	5.27866E-05	1.26986E-05	0.00000000	0.00006549	1.31966E-05	7.99964E-06	0.00000000	0.00002120	2.87109E-05	1.03657E-05	0.00000000	0.00003908
0.00001	8.87574E-05	9.39E-06	0.00000000	0.00046261	0.000107728	1.00113E-05	0.00000000	0.00011774	2.69319E-05	6.30671E-06	0.00000000	0.00003324	5.85938E-05	8.17204E-06	0.00000000	0.00006677
0.00002	0.00035503	5.91E-06	0.00000000	0.00059054	0.000430911	6.30671E-06	0.00000000	0.00043722	0.000107728	3.97298E-06	0.00000000	0.00011170	0.000234375	5.14806E-06	0.00000000	0.00023952
0.00004	0.001420118	3.72E-06	0.00000000	0.00156848	0.001723643	3.97298E-06	0.00000000	0.00172762	0.000430911	2.50282E-06	0.00000000	0.00043341	0.0009375	3.24308E-06	0.00000000	0.00094074
0.00008	0.005680473	2.35E-06	0.00000000	0.00577394	0.006894571	2.50282E-06	0.00000000	0.00689707	0.001723643	1.57668E-06	0.00000000	0.00172522	0.00375	2.04301E-06	0.00000000	0.00375204
0.00012	0.012781065	1.79E-06	0.00000000	0.01285239	0.015512784	1.91001E-06	0.00000000	0.01551469	0.003878196	1.20323E-06	0.00000000	0.00387940	0.0084375	1.55911E-06	0.00000000	0.00843906
0.00018	0.028757396	1.37E-06	0.00000000	0.02881183	0.034903763	1.45761E-06	0.00000000	0.03490522	0.008725941	9.18236E-07	0.00000000	0.00872686	0.018984375	1.18982E-06	0.00000000	0.01898556
0.0002	0.035502959	1.27E-06	0.00000000	0.03555370	0.043091066	1.35874E-06	0.00000000	0.04309242	0.010772766	8.55952E-07	0.00000000	0.01077362	0.0234375	1.10912E-06	0.00000000	0.02343861

	SAND	M10	M20	ZEOLITE
0	0.001736	4.75455E-05	2.95425E-05	3.85172E-05
0.301029996	0.001097	3.35822E-05	1.95182E-05	2.62389E-05
0.477121255	0.000842	3.20351E-05	1.64969E-05	2.35089E-05
0.602059991	0.000703	3.56773E-05	1.59262E-05	2.4428E-05
0.698970004	0.000616	4.28238E-05	1.67443E-05	2.76207E-05
0.84509804	0.000518	6.54852E-05	2.11963E-05	3.90766E-05
1	0.000463	0.000117739	3.32386E-05	6.67658E-05
1.301029996	0.000591	0.000437217	0.000111701	0.000239523
1.602059991	0.001568	0.001727616	0.000433413	0.000940743
1.903089987	0.005774	0.006897073	0.001725219	0.003752043
2.079181246	0.012852	0.015514694	0.003879399	0.008439059
2.255272505	0.028812	0.034905221	0.008726859	0.018985565
2.301029996	0.035554	0.043092425	0.010773622	0.023438609



Tufenkji & Elimelech

$$\eta_o=2.4\,A_S^{1/3}N_R^{-0.081}N_{Pe}^{-0.715}N_{vdW}^{0.052}+0.55A_S\,N_R^{1.675}N_A^{0.125}+0.22\,N_R^{-0.24}N_G^{1.11}N_{vdW}^{0.053}$$

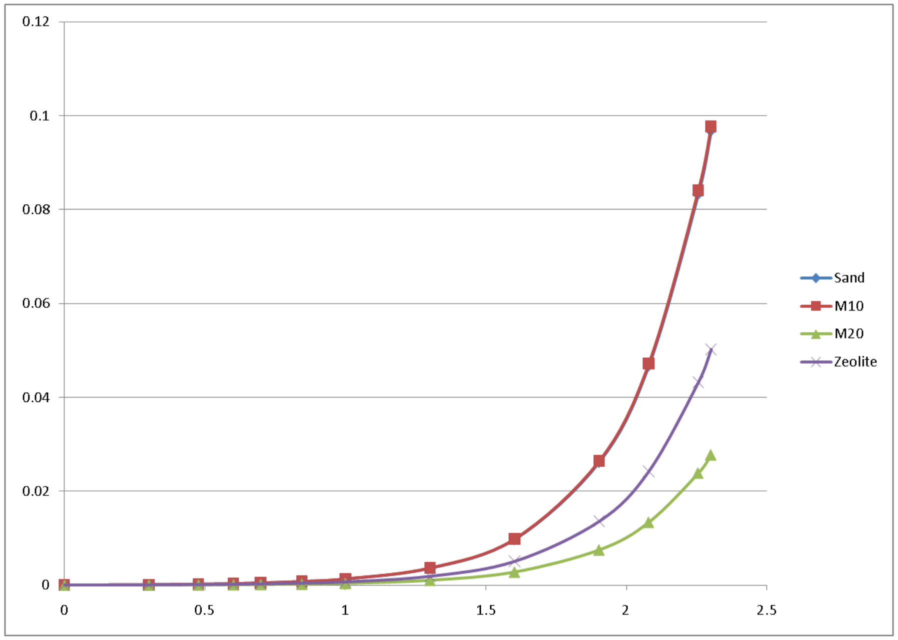
Particle Size Distribution		Sand N_R	Sand N_{pe}	Sand N_{vdW}	Sand N_A	Sand N_G	Sand η
1	0.000001	0.000769	72767205544	9.722099	4.516E-04	0.00000000	5.1169E-05
2	0.000002	0.001538	72767205544	9.722099	1.129E-04	0.00000000	0.0001369
3	0.000003	0.002308	72767205544	9.722099	5.018E-05	0.00000000	0.00024376
4	0.000004	0.003077	72767205544	9.722099	2.822E-05	0.00000000	0.00036714
5	0.000005	0.003846	72767205544	9.722099	1.806E-05	0.00000000	0.00050448
7	0.000007	0.005385	72767205544	9.722099	9.216E-06	0.00000000	0.00081469
10	0.00001	0.007692	72767205544	9.722099	4.516E-06	0.00000000	0.00135418
20	0.00002	0.015385	72767205544	9.722099	1.129E-06	0.00000000	0.00363576
40	0.00004	0.030769	72767205544	9.722099	2.822E-07	0.00000000	0.00976217
80	0.00008	0.061538	72767205544	9.722099	7.056E-08	0.00000000	0.02621247
120	0.00012	0.092308	72767205544	9.722099	3.136E-08	0.00000000	0.04671286
180	0.00018	0.138462	72767205544	9.722099	1.394E-08	0.00000000	0.08324644
200	0.0002	0.153846	72767205544	9.722099	1.129E-08	0.00000000	0.09673195

Particle Size Distribution	DK M10 N_R	DK M10 N_{pe}	DK M10 N_{vdW}	DK M10 N_A	DK M10 N_G	DK M10 η
1	0.000847458	6E+10	9.7221	0.000452	0.00000000	5.17279E-05
2	0.001694915	6E+10	9.7221	0.000113	0.00000000	0.000138364
3	0.002542373	6E+10	9.7221	5.02E-05	0.00000000	0.000246343
4	0.003389831	6E+10	9.7221	2.82E-05	0.00000000	0.000371025
5	0.004237288	6E+10	9.7221	1.81E-05	0.00000000	0.000509811
7	0.005932203	6E+10	9.7221	9.22E-06	0.00000000	0.000823286
10	0.008474576	6E+10	9.7221	4.52E-06	0.00000000	0.001368449
20	0.016949153	6E+10	9.7221	1.13E-06	0.00000000	0.003674041
40	0.033898305	6E+10	9.7221	2.82E-07	0.00000000	0.009864916
80	0.06779661	6E+10	9.7221	7.06E-08	0.00000000	0.026488335
120	0.101694915	6E+10	9.7221	3.14E-08	0.00000000	0.047204467
180	0.152542373	6E+10	9.7221	1.39E-08	0.00000000	0.084122519
200	0.169491525	6E+10	9.7221	1.13E-08	0.00000000	0.097749949

Particle Size Distribution	DK M20 N_R	DK M20 N_{pe}	DK M20 N_{vdW}	DK M20 N_A	DK M20 N_G	DK M20 η
1	0.000424	2.4E+11	9.7221	0.000452	0	1.47E-05
2	0.000847	2.4E+11	9.7221	0.000113	0	3.94E-05
3	0.001271	2.4E+11	9.7221	5.02E-05	0	7.01E-05
4	0.001695	2.4E+11	9.7221	2.82E-05	0	0.000106
5	0.002119	2.4E+11	9.7221	1.81E-05	0	0.000145
7	0.002966	2.4E+11	9.7221	9.22E-06	0	0.000234
10	0.004237	2.4E+11	9.7221	4.52E-06	0	0.000389
20	0.008475	2.4E+11	9.7221	1.13E-06	0	0.001045
40	0.016949	2.4E+11	9.7221	2.82E-07	0	0.002805
80	0.033898	2.4E+11	9.7221	7.06E-08	0	0.007533
120	0.050847	2.4E+11	9.7221	3.14E-08	0	0.013424
180	0.076271	2.4E+11	9.7221	1.39E-08	0	0.023923
200	0.084746	2.4E+11	9.7221	1.13E-08	0	0.027799

Particle Size Distribution	Zeolite N_R	Zeolite N_{pe}	Zeolite N_{vdW}	Zeolite N_A	Zeolite N_G	Zeolite η
1	0.000625	1.1E+11	9.7221	0.000452	0	2.66E-05
2	0.00125	1.1E+11	9.7221	0.000113	0	7.12E-05
3	0.001875	1.1E+11	9.7221	5.02E-05	0	0.000127
4	0.0025	1.1E+11	9.7221	2.82E-05	0	0.000191
5	0.003125	1.1E+11	9.7221	1.81E-05	0	0.000262
7	0.004375	1.1E+11	9.7221	9.22E-06	0	0.000423
10	0.00625	1.1E+11	9.7221	4.52E-06	0	0.000703
20	0.0125	1.1E+11	9.7221	1.13E-06	0	0.001889
40	0.025	1.1E+11	9.7221	2.82E-07	0	0.005071
80	0.05	1.1E+11	9.7221	7.06E-08	0	0.013616
120	0.075	1.1E+11	9.7221	3.14E-08	0	0.024266
180	0.1125	1.1E+11	9.7221	1.39E-08	0	0.043244
200	0.125	1.1E+11	9.7221	1.13E-08	0	0.050249

		Sand	M10	M20	Zeolite
1	0	5.11688E-05	5.17E-05	1.47E-05	2.6626E-05
2	0.30103	0.000136904	0.000138	3.94E-05	7.116E-05
3	0.477121	0.000243759	0.000246	7.01E-05	0.00012667
4	0.60206	0.000367143	0.000371	0.000106	0.00019076
5	0.69897	0.000504484	0.00051	0.000145	0.0002621
7	0.845098	0.000814694	0.000823	0.000234	0.00042324
10	1	0.00135418	0.001368	0.000389	0.00070349
20	1.30103	0.003635763	0.003674	0.001045	0.00188868
40	1.60206	0.009762166	0.009865	0.002805	0.00507112
80	1.90309	0.026212466	0.026488	0.007533	0.01361645
120	2.079181	0.046712856	0.047204	0.013424	0.02426566
180	2.255273	0.083246437	0.084123	0.023923	0.04324352
200	2.30103	0.096731949	0.09775	0.027799	0.05024875

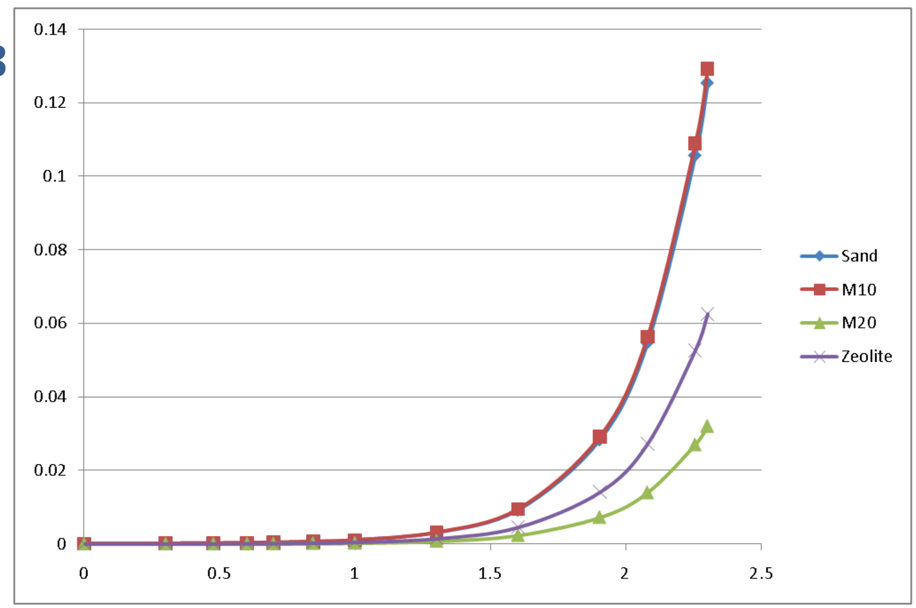


Appendix B

Rajagopalan and Tien [1976]	$\eta_o = 4 A_s^{1/3} N_{Pe}^{-2/3} + (1-f_o)^{2/3} A_s N_{Lo}^{1/8} N_R^{15/8} + 3.375\times10^{-3} (1-f_o)^{2/3} A_s N_G^{1.2} N_R^{-0.4}$																			
	Sand					DK M10					DK M20					Zeolite				
Particle Size Distribution	N_R	N_{pe}	N_{Lo}	N_G	η	N_R	N_{pe}	N_{Lo}	N_G	η	N_R	N_{pe}	N_{Lo}	N_G	η	N_R	N_{pe}	N_{Lo}	N_G	η
0.000001	0.00077	7.3E+10	0.0006	0.00000000	2.4E-05	0.00085	6E+10	0.0006	0.00000000	2.4E-05	0.00042	2.4E+11	0.0006	0	6.2E-06	0.00063	1.1E+11	0.0006	0	1.2E-05
0.000002	0.00154	7.3E+10	0.00015	0.00000000	7.1E-05	0.00169	6E+10	0.00015	0.00000000	7.3E-05	0.00085	2.4E+11	0.00015	0	1.8E-05	0.00125	1.1E+11	0.00015	0	3.6E-05
0.000003	0.00231	7.3E+10	6.7E-05	0.00000000	0.00014	0.00254	6E+10	6.7E-05	0.00000000	0.00014	0.00127	2.4E+11	6.7E-05	0	3.5E-05	0.00188	1.1E+11	6.7E-05	0	6.8E-05
0.000004	0.00308	7.3E+10	3.8E-05	0.00000000	0.00022	0.00339	6E+10	3.8E-05	0.00000000	0.00022	0.00169	2.4E+11	3.8E-05	0	5.6E-05	0.0025	1.1E+11	3.8E-05	0	0.00011
0.000005	0.00385	7.3E+10	2.4E-05	0.00000000	0.00031	0.00424	6E+10	2.4E-05	0.00000000	0.00032	0.00212	2.4E+11	2.4E-05	0	8E-05	0.00313	1.1E+11	2.4E-05	0	0.00016
0.000007	0.00538	7.3E+10	1.2E-05	0.00000000	0.00054	0.00593	6E+10	1.2E-05	0.00000000	0.00056	0.00297	2.4E+11	1.2E-05	0	0.00014	0.00438	1.1E+11	1.2E-05	0	0.00027
0.00001	0.00769	7.3E+10	6E-06	0.00000000	0.00096	0.00847	6E+10	6E-06	0.00000000	0.00099	0.00424	2.4E+11	6E-06	0	0.00025	0.00625	1.1E+11	6E-06	0	0.00048
0.00002	0.01538	7.3E+10	1.5E-06	0.00000000	0.00297	0.01695	6E+10	1.5E-06	0.00000000	0.00306	0.00847	2.4E+11	1.5E-06	0	0.00076	0.0125	1.1E+11	1.5E-06	0	0.00148
0.00004	0.03077	7.3E+10	3.8E-07	0.00000000	0.00917	0.0339	6E+10	3.8E-07	0.00000000	0.00945	0.01695	2.4E+11	3.8E-07	0	0.00234	0.025	1.1E+11	3.8E-07	0	0.00457
0.00008	0.06154	7.3E+10	9.4E-08	0.00000000	0.02829	0.0678	6E+10	9.4E-08	0.00000000	0.02914	0.0339	2.4E+11	9.4E-08	0	0.00722	0.05	1.1E+11	9.4E-08	0	0.0141
0.00012	0.09231	7.3E+10	4.2E-08	0.00000000	0.05467	0.10169	6E+10	4.2E-08	0.00000000	0.05633	0.05085	2.4E+11	4.2E-08	0	0.01394	0.075	1.1E+11	4.2E-08	0	0.02724
0.00018	0.13846	7.3E+10	1.9E-08	0.00000000	0.10565	0.15254	6E+10	1.9E-08	0.00000000	0.10885	0.07627	2.4E+11	1.9E-08	0	0.02695	0.1125	1.1E+11	1.9E-08	0	0.05265
0.0002	0.15385	7.3E+10	1.5E-08	0.00000000	0.12538	0.16949	6E+10	1.5E-08	0.00000000	0.12918	0.08475	2.4E+11	1.5E-08	0	0.03198	0.125	1.1E+11	1.5E-08	0	0.06248

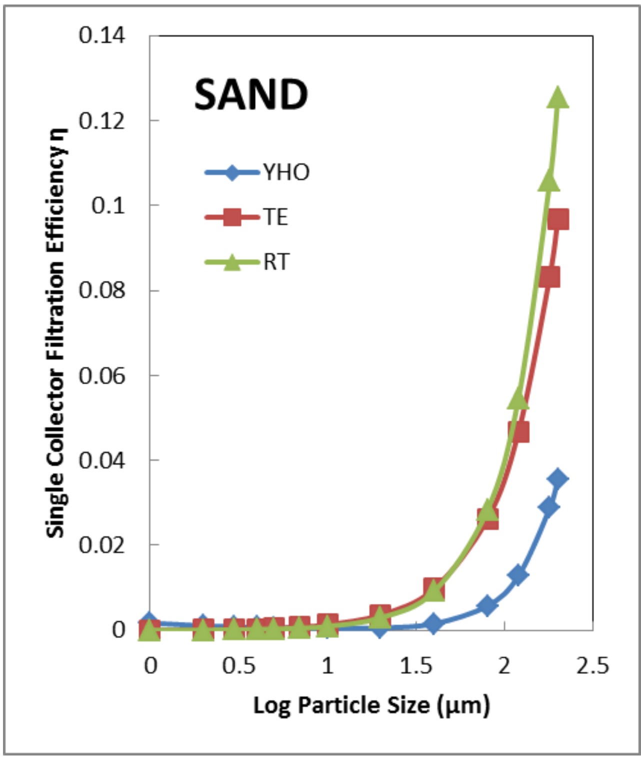
		Sand	M10	M20	Zeolite
1	0	2.4E-05	2.44E-05	6.2E-06	1.2E-05
2	0.30103	7.1E-05	7.3492E-05	1.8E-05	3.6E-05
3	0.47712	0.00014	0.00014124	3.5E-05	6.8E-05
4	0.60206	0.00022	0.00022491	5.6E-05	0.00011
5	0.69897	0.00031	0.00032285	8E-05	0.00016
7	0.8451	0.00054	0.00055715	0.00014	0.00027
10	1	0.00096	0.00099402	0.00025	0.00048
20	1.30103	0.00297	0.00306422	0.00076	0.00148
40	1.60206	0.00917	0.00944958	0.00234	0.00457
80	1.90309	0.02829	0.02914473	0.00722	0.0141
120	2.07918	0.05467	0.05632513	0.01394	0.02724
180	2.25527	0.10565	0.10885475	0.02695	0.05265
200	2.30103	0.12538	0.12918222	0.03198	0.06248

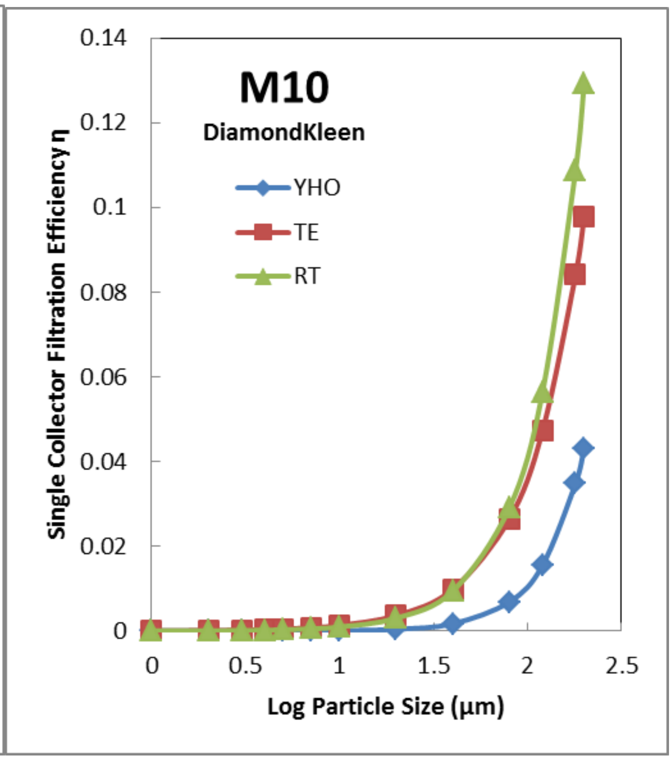
B

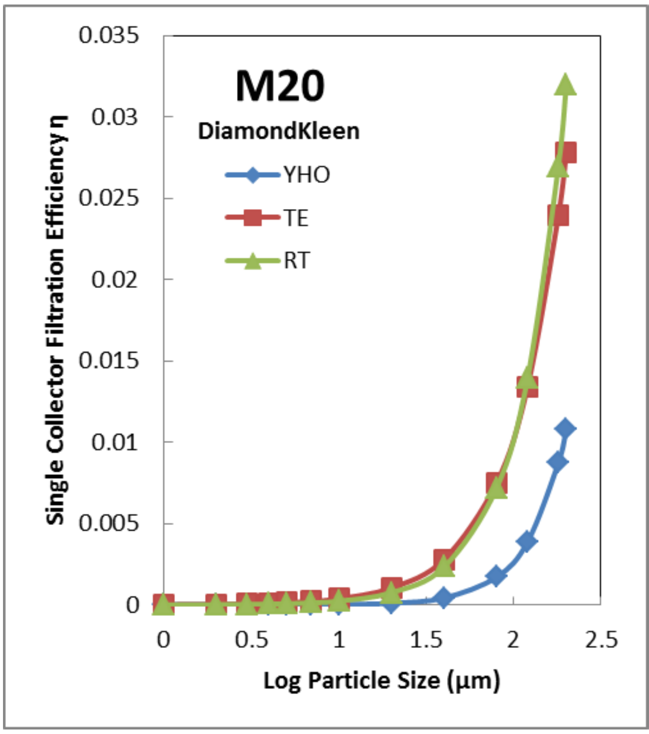


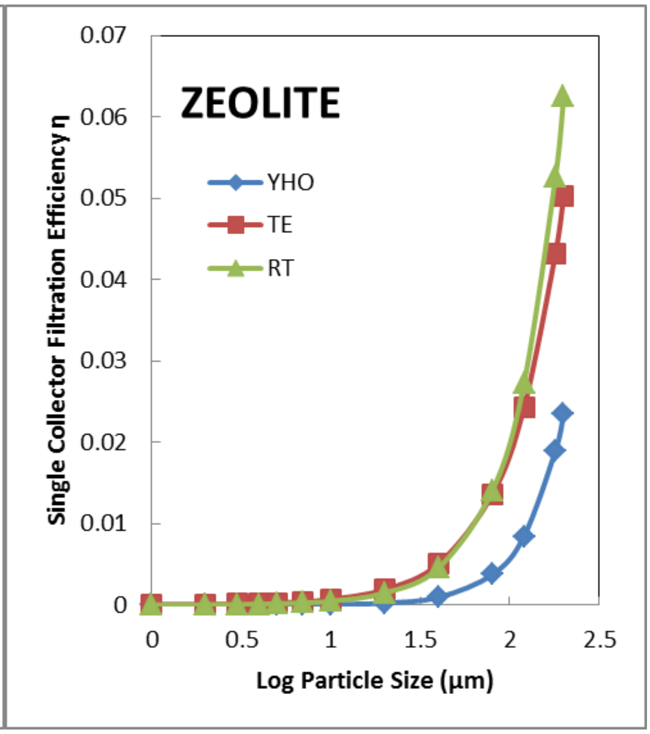
Appendix B

B - 4. Comparison of the Models – Single Collector efficiency

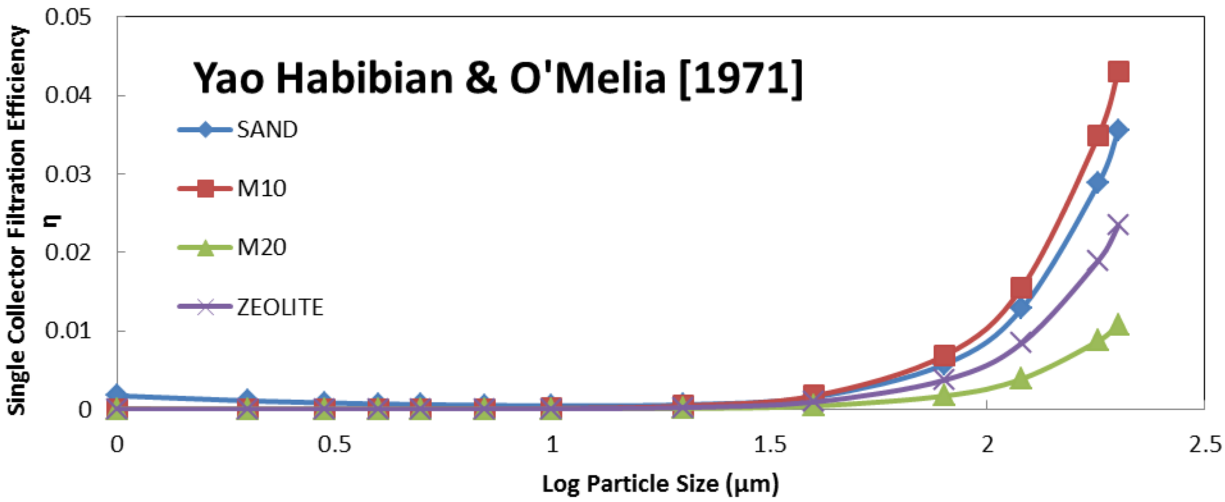


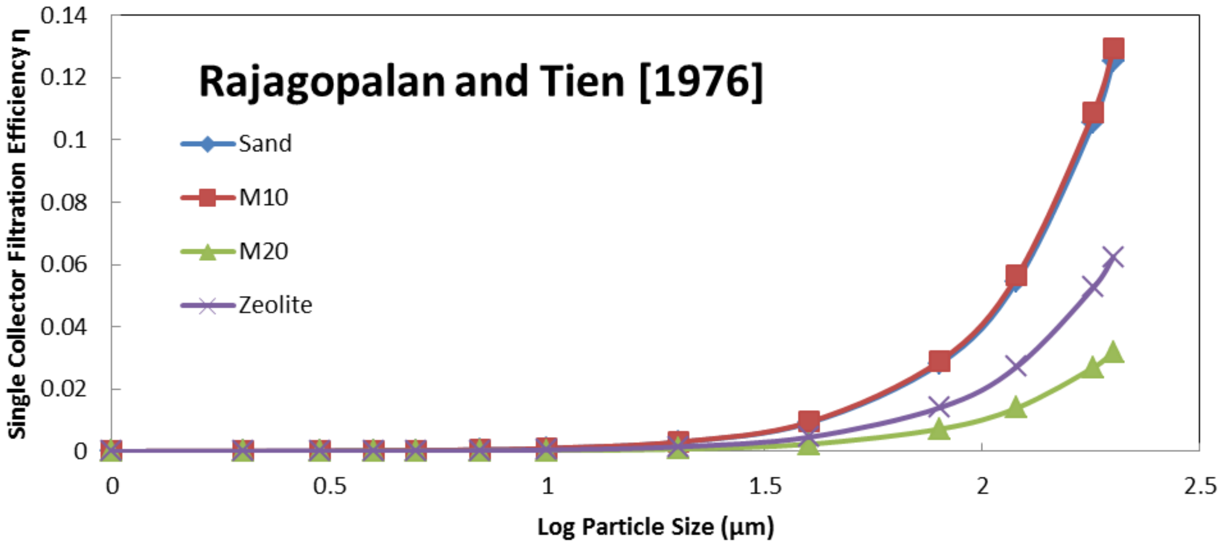


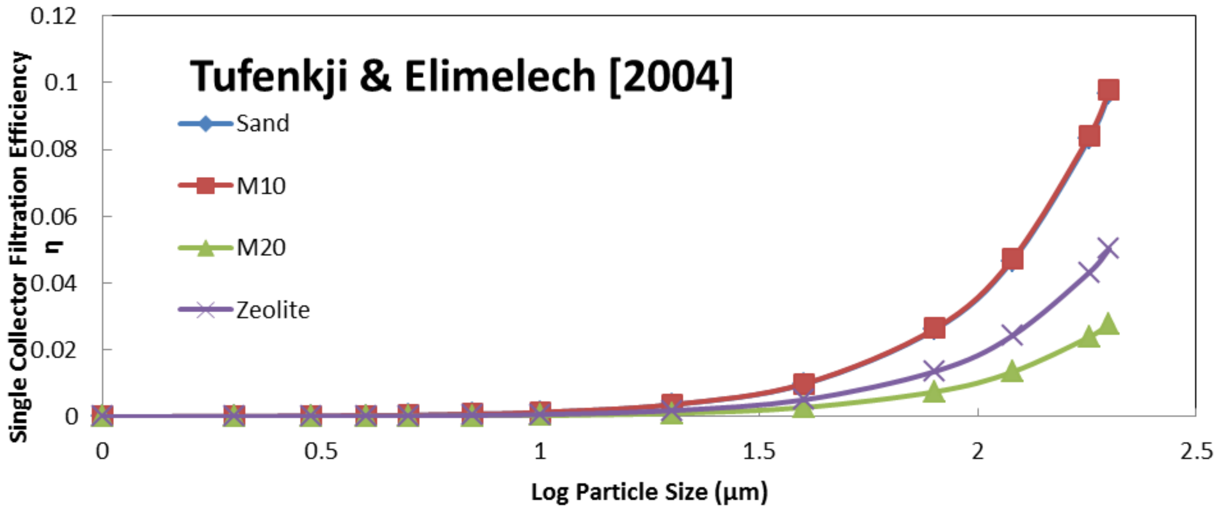




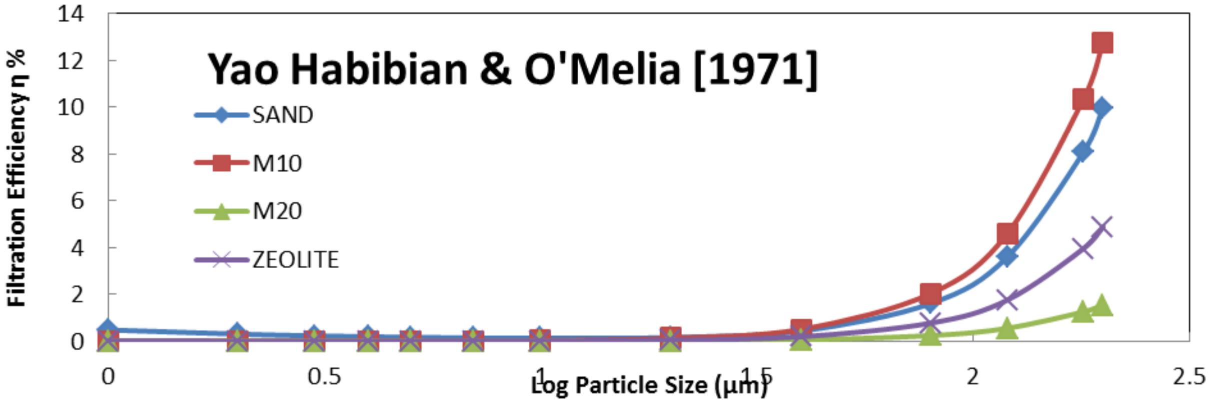
B - 5. Comparison of the Media –Single Collector efficiency

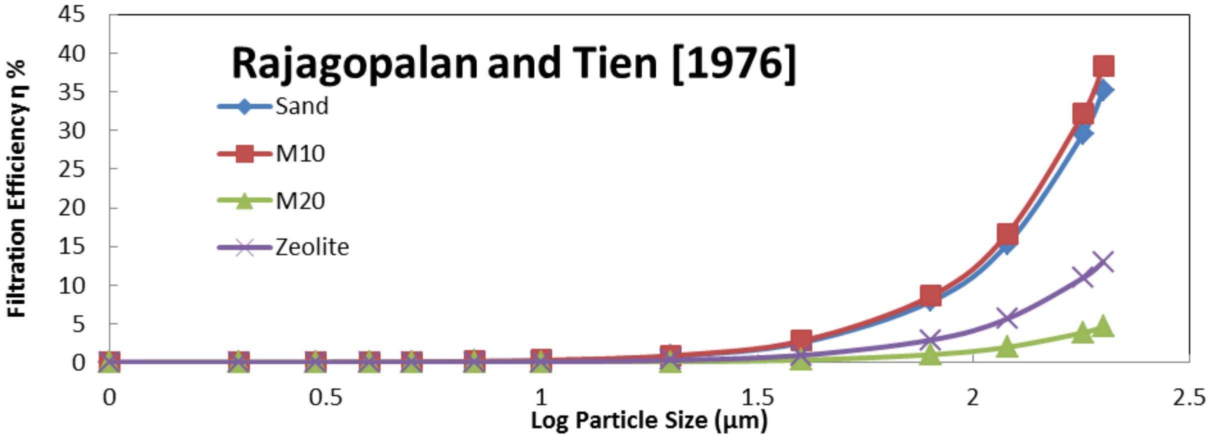


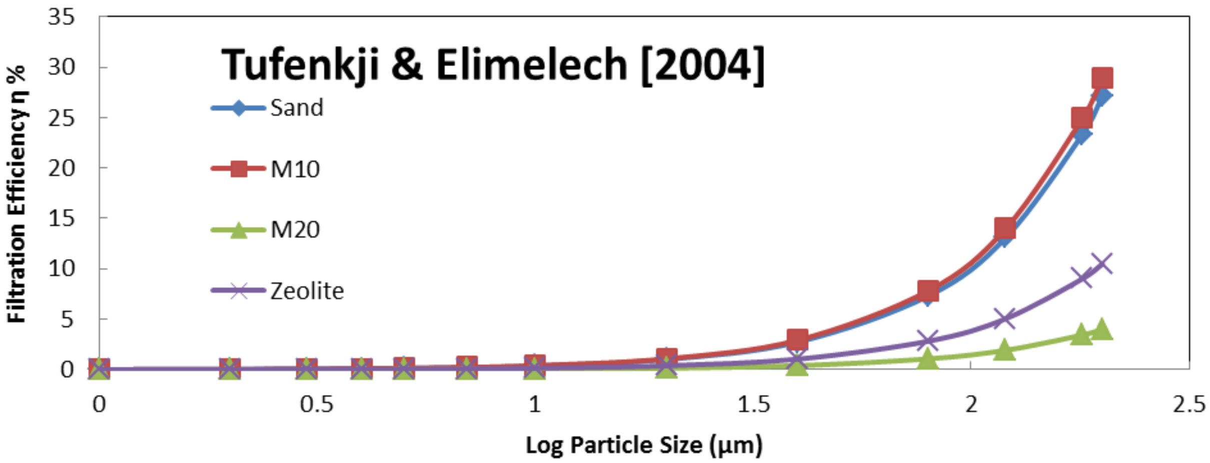




B - 6. Comparison of the Media – Test Column Filter Efficiency







Appendix C: Experimental Design and Calculations

C - 1. Summary of Internal Test Reports

C - 2. Column Test Apparatus Design Stages

C - 3. Experiment System Calculations

C - 4. ISO Fine Test Particles MSD and Supplier Information

C - 1. Summary of Internal Test Reports

<table>
<tr><td>29th March 2011</td><td colspan="2">Turbidity Effect of Magnapool Mineral Mix in different Filter Medias</td></tr>
<tr><td>Purpose</td><td colspan="2">To Test the flocculation affect of magnesium minerals (magnapool minerals)</td></tr>
<tr><td>Runtime/Duration</td><td colspan="2">5months</td></tr>
<tr><td>Contaminants</td><td colspan="2">Diatomaceous earth powder</td></tr>
<tr><td>Parameters measured</td><td>Turbidity</td><td></td></tr>
<tr><td></td><td>Pressure</td><td>Difference depending on contaminant loading</td></tr>
<tr><td>Filters used</td><td>S6000</td><td>Sand</td></tr>
<tr><td></td><td>S6000</td><td>Zeolite</td></tr>
<tr><td></td><td>S6000</td><td>DiamonKleen</td></tr>
<tr><td colspan="3">Conclusions/findings
The sand and DiamonKleen fine clogged forming a thick crust of DE powder
Zeobrite (zeolite) had the lowest pressure differential
DE powder penetration was highest in the DiamondKleen
The combination of DK and magnapool minerals results in the highest pressure differential
Issues with the experiment
There were problems with the multiport diffuser in the zeobrite
The DE powder probably contributed to the filter efficiency because it is a filter media itself
The filters clogged to quickly with the DE powder, the use of DE powder as a contaminant is probably not comparable to actual pool contaminants.</td></tr>
<tr><td>16th July 2008</td><td colspan="2">Filtration performance evaluation on various Poolrite filters</td></tr>
<tr><td>Purpose</td><td colspan="2">Test performance</td></tr>
<tr><td>Runtime/Duration</td><td colspan="2">96hours (approx 4 days)</td></tr>
<tr><td>Contaminants</td><td colspan="2">Brickie loam</td></tr>
<tr><td>Parameters measured</td><td>turbidity</td><td>Taken at beginning and end</td></tr>
<tr><td></td><td>pressure</td><td>Inlet and outlet</td></tr>
<tr><td></td><td>Particle size</td><td>From samples taken before and after</td></tr>
<tr><td>Filters used</td><td>S6000 with M15</td><td>Granular glass</td></tr>
<tr><td></td><td>Watermiser 400</td><td>Cartridge</td></tr>
<tr><td></td><td>XL-60 DE filter</td><td>Diatomaceous earth</td></tr>
<tr><td colspan="3">Conclusions/findings
The sand filter with DK filtered to a higher quality (lower particle size at the conclusion of the experiment)
The back pressure of the DK sand filter was highest and the amount of turbidity reduction was the same as the cartridge filter but less than the DE filter
The finishing turbidity level of the DK filter was also the highest
Issues with the experiment
There were problems with the DE filter and due to a malfunction in the equipment unfiltered water passed through the system.
There was some bias in the interpretation of results</td></tr>
<tr><td>9th November 2007</td><td colspan="2">Evaluation of DiamondKleen in s8000, s9000 sand filters</td></tr>
<tr><td>Purpose</td><td colspan="2">Performance of glass vs sand</td></tr>
<tr><td>Runtime/Duration</td><td colspan="2">6hrs per test</td></tr>
</table>

Contaminants	"dirt" (sand, soil and bark)	
Parameters measured	Turbidity reduction	
	Flow rate	
	Pressure	Inlet and outlet
Filters used	S8000	Sand
	S8000	DiamondKleen
	S9000	sand
	S9000	DiamondKleen

Conclusions/findings

- Turbidity reduction in both types of filter with both types of pumps was the highest for DiamonKleen
- The highest reduction occurred using DK with a s9000 filter and SQI 600 pump to obtain a turbidity reduction of 71.21%

22nd august 2007	**Evaluation of new filtration media (DiamondKleen) in Poolrite sand filters**	
Purpose	Performance of traditional sand vx glass	
Runtime/Duration	6hrs per test	
Contaminants	"dirt" (soil, sand, bark)	
Parameters measured	Hydraulic testing	Different valves (SQI 500+smart valve 9210 and SQI-600+ s9000valve)
	Turbidity	
	Flow rate	
	pressure	Inlet and outlet
Filters used	S6000	Sand
	S5000	Glass
	S6000	Zelbrite (not tested only used to compare)

Conclusions/findings

- No significant difference hydraulically between s6000 and a 1 ¼ HP pump and a s5000 and a ¾ HP pump
- The zelbrite filter performed the best with the highest turbidity reduction
- DK in the s5000 performed better than the sand for turbidity reduction
- Final recommendation was to replace tradtional sand s6000 filter with 1 ¼ HP pump with a DK s5000 filter with ¾ pump

5th July 2007	**Flow test report for various filter media**	
Purpose	Test pressure drop only	
Runtime/Duration	Not specified assumed 1 day	
Contaminants	Not specified	
Parameters measured	Flow rate	
	pressure	Inlet and outlet
Filters used	EN450	DiamondKleen
	EN450	AFM
	EN450	Sand
	EN450	Zeolite (zelbrite)

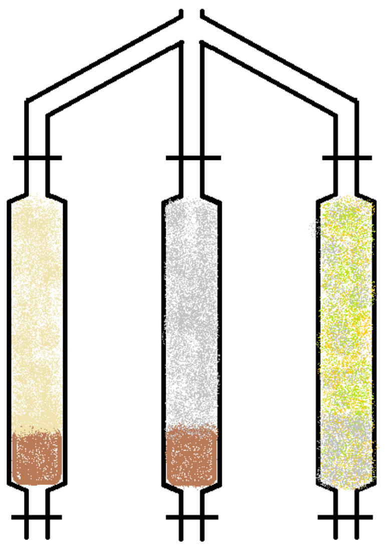
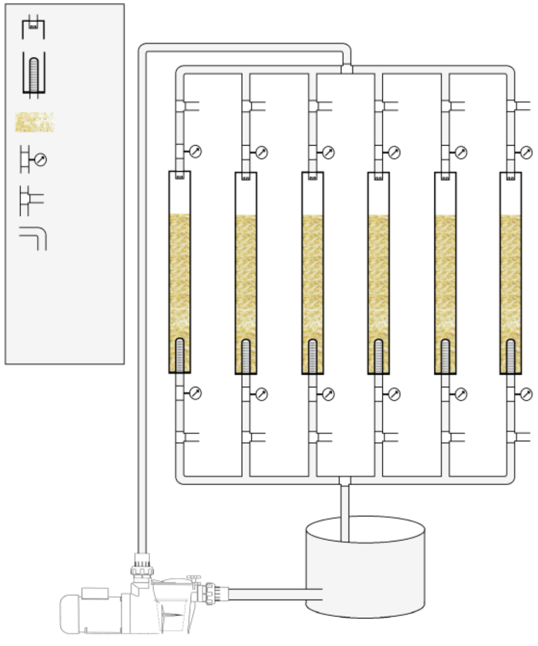
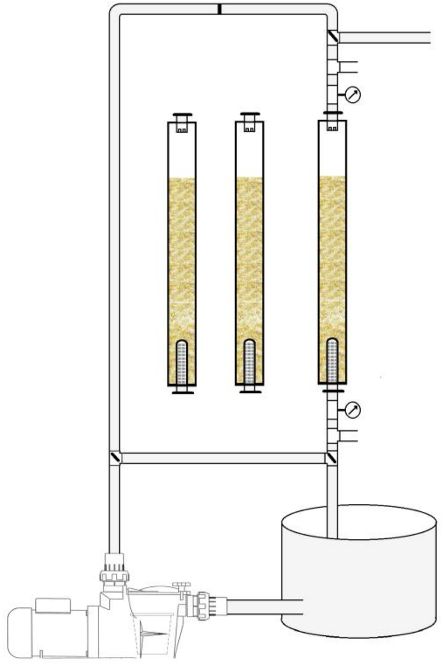
Conclusions/findings

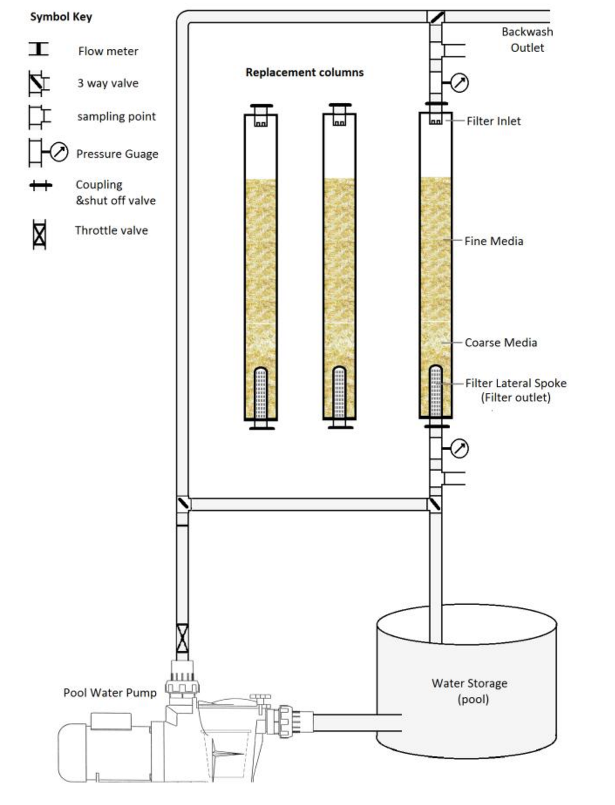
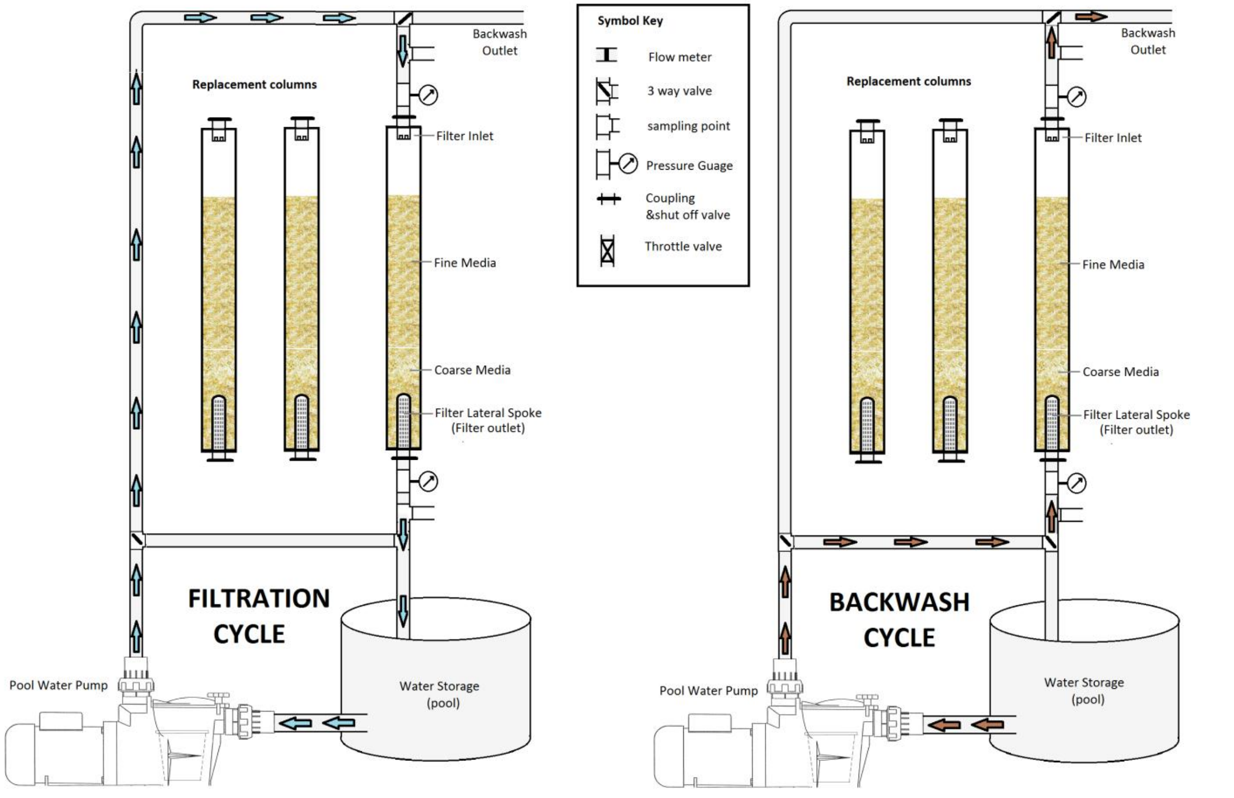
- The best performance was achieved by DK and AFM (activated filter media)
- The difference in performance of these two media is within the margin of experimental error
- Zelbrite performed second best with sand the worst

Other comments

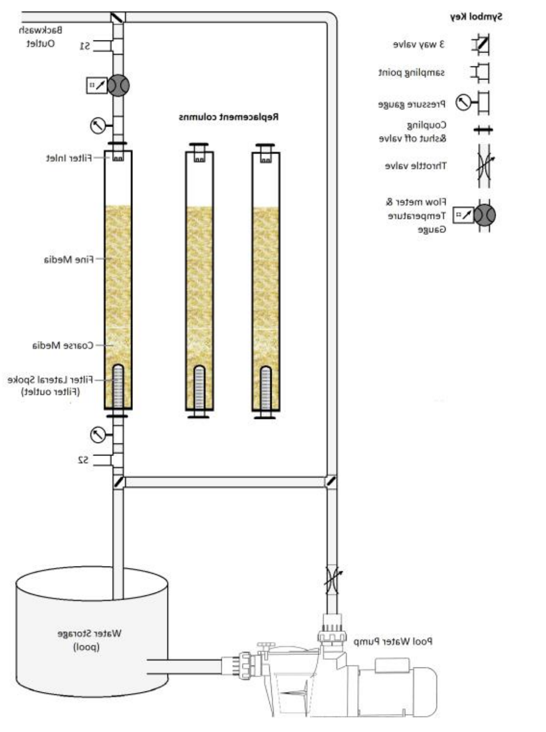
- This report is the most detailed with regard to explaining the methodology and experimental setup.

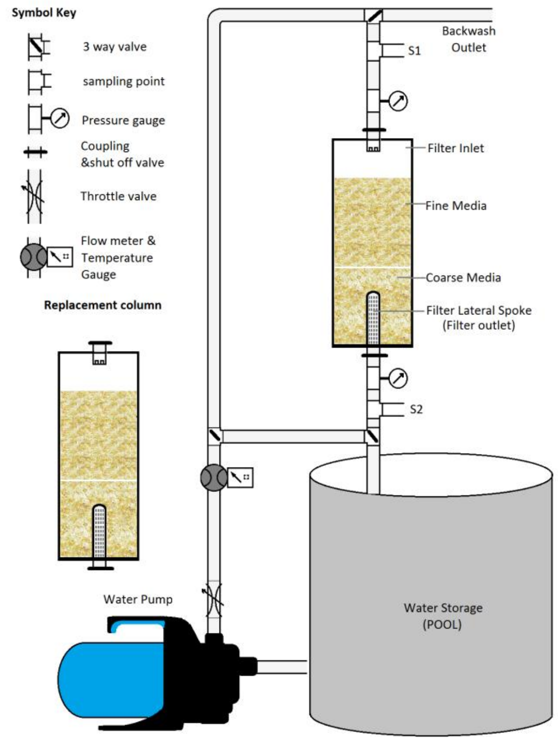
C - 2. Column Test Apparatus Design Stages

		
23/3/2011 • Initial ideas sketch • Three columns ○ 1 – sand ○ 1 – zeolite ○ 1 - DiamondKleen	31/3/2011 • Increase number of columns to introduce a duplicate to eliminate bias • Connected to allow all filters to test at the same time under identical conditions • Pump, body of water and columns required • Concerns that a pressure gauge and sample point needed for each column section – are these resources available	1/4/2011 • Changed the configuration to have only on column at a time because if all are connected at the same time they will act as components in parallel. • The columns will be ended with couplings to allow for disconnecting and reconnecting of a new column • This configuration lowers the amount of equipment required eg. Pressure gauges • Backwash loop has also bee added to test backwash claims the outlet at the top allows for disposal of backwash water • Concern that backwash cycle uses water from filter cycle

	
3/4/2011 • Labelling of components added • Throttle valve added to pipe after pump to slow flow rate for this system • Need to fix flow meter symbol • Need to add temperature gauge	3/4/2011 • Representation of filtration and backwash cycle

Appendix C

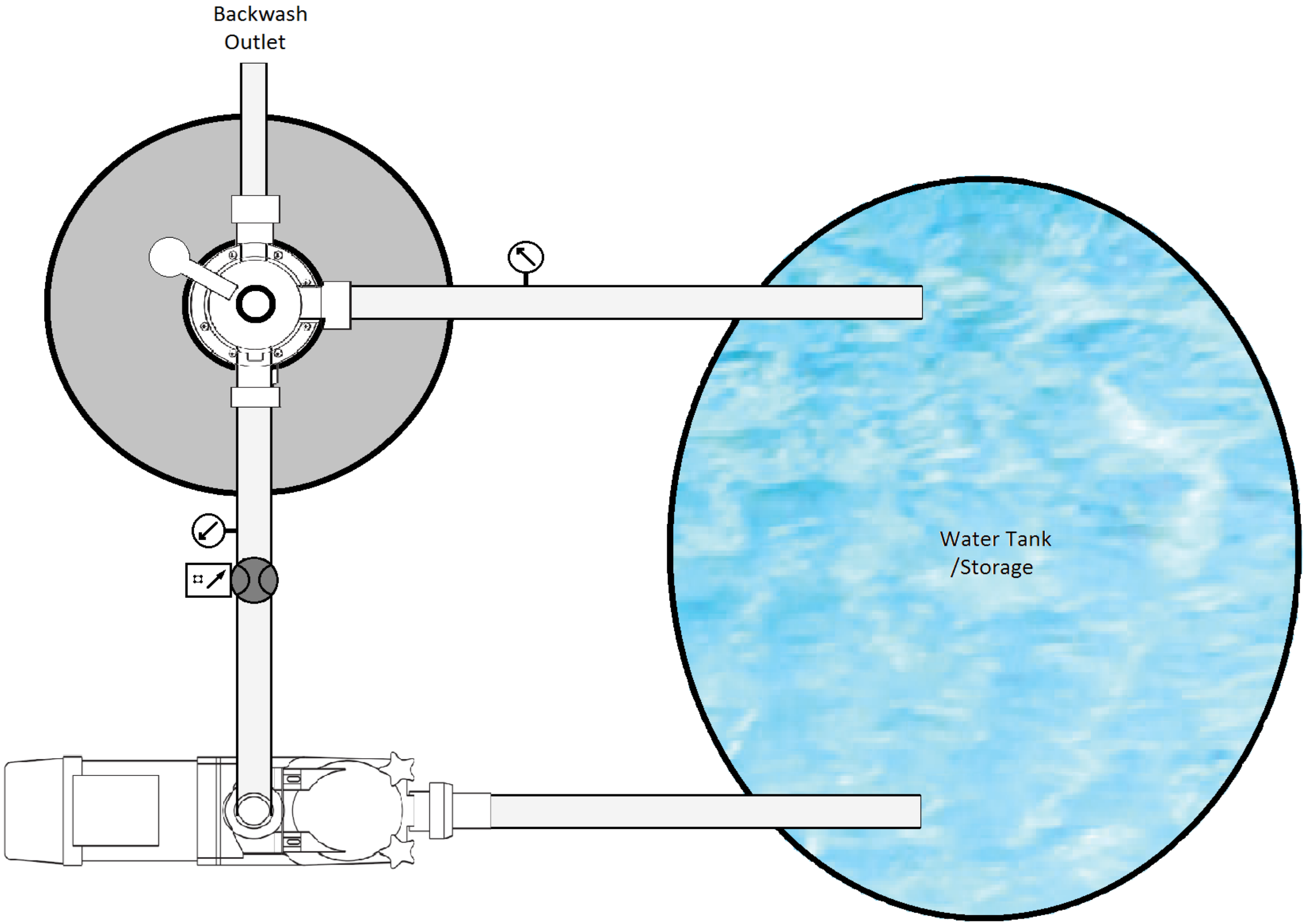




7/4/2011 • Incorporated new flow meter symbol • Move placement of flow meter	5/5/2011 • Change diagram of pump to show different type of pump • Move flow meter because of its size • Adjust visual representation of the column to show wider diameter Change size of tank

Appendix C

Proposed Full Scale Filter Test



Appendix C

C - 3. Experiment System Calculations

<u>Calculating column diameter:</u>

S6000 filter diameter = 635mm

Filter area:

$$A = \frac{\pi D^2}{4} = \frac{\pi(0.635m)^2}{4} = 0.316m^2$$

The test column will be approximately 1/8 scale of a normal pool filter.

Test Column Filter Area

$$A = 0.316m^2 \times {}^1/_8 = 0.0395m^2$$

Test Column Diameter

$$D = \sqrt[2]{\frac{4 \times 0.0395m^2}{\pi}} = 0.224m \approx 20cm$$

Therefore using a 20cm diameter column the filtration area is

$$A = \frac{\pi D^2}{4} = \frac{\pi(0.2m)^2}{4} = 0.0314m^2$$

<u>Calculating flow rate:</u>

Normal operating Flow rate

$$Q = 200L/min$$

Flow rate per unit area

$$Q' \approx 600L/min/m^2$$

Or Velocity

$$V = 0.010548m/s$$

If column is 20cm in diameter, flow rate through test setup will be

$$Q = 0.010548m/s \times 0.0314m^2 = 3.3138 \times 10^{-4}m^3/s = 19.88L/min$$

So, a pump is required that can deliver or be restricted to deliver approximately a 20L/min flow rate.

<u>Length of column</u>

L = 0.5m

C - 4. ISO Fine Test Particles MSD and Supplier Information

COULTER® MULTISIZER AccuComp® 1.19

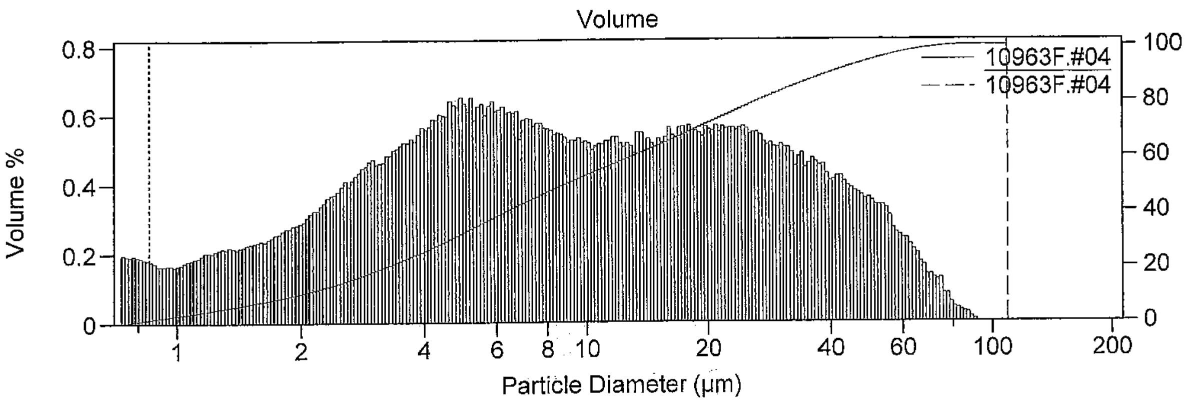
9 May 2011

POWDER TECHNOLOGY, INC.

PTI POWDER TECHNOLOGY INC.
14331 Ewing Avenue South Burnsville, Minnesota 55306
Phone: 952-894-8737

Filename:	10963F.#04	Sample Number:	267
Group ID:	10963F		
Sample ID:	10963F		
Comment:	ISO 12103-1, A2 FINE TEST DUST, NIST TRACEABLE		
Operator:	JDF		
Acquired:	11:55 7 May 2011		

Edited size data



LC= 0.852 µm UC= 109.2 µm {98.48%}

Volume Statistics (Geometric) 10963F.#04

Calculations from 0.729 µm to 109.2 µm

Volume	2.402e9 µm^3		
Mean:	8.827 µm	S.D.:	18.4 µm
Median:	8.830 µm		
Mean/Median Ratio:	1.000		
Mode:	4.911 µm		

10963F.#04

Particle Diameter µm	Volume % <	Particle Diameter µm	Volume % <
1	2.89	200	100.00
2	10.74		
3	18.54		
4	25.92		
5	32.82		
7	43.32		
10	53.34		
20	72.12		
40	90.31		
80	99.82		
120	100.00		
180	100.00		

10963F.#04

Channel Number	Particle Diameter µm	Cum < Volume %	Diff Number %	Cum < Number %	Diff Volume %
9	0.852	1.52	15.61	35.62	1.01
15	0.958	2.53	10.97	51.23	1.01
21	1.078	3.54	8.77	62.20	1.15
27	1.212	4.69	6.76	70.96	1.26
33	1.363	5.96	4.95	77.73	1.31
39	1.533	7.27	3.76	82.68	1.42
45	1.724	8.69	2.97	86.43	1.60
51	1.938	10.28	2.35	89.40	1.80
57	2.180	12.08	1.93	91.75	2.10
63	2.451	14.19	1.56	93.68	2.41
69	2.757	16.59	1.24	95.24	2.72
75	3.100	19.32	0.922	96.47	2.89
81	3.487	22.20	0.707	97.40	3.14
87	3.921	25.35	0.547	98.10	3.46
93	4.410	28.81	0.416	98.65	3.74
99	4.959	32.55	0.293	99.07	3.73
105	5.577	36.29	0.204	99.36	3.72
111	6.272	40.00	0.138	99.56	3.54
117	7.053	43.54	0.094	99.70	3.46
123	7.932	47.00	0.063	99.80	3.28
129	8.921	50.28	0.042	99.86	3.14
135	10.03	53.42	0.029	99.90	3.08
141	11.28	56.50	0.021	99.93	3.13
147	12.69	59.63	0.015	99.95	3.12
153	14.27	62.75	0.010	99.96	3.17
159	16.05	65.92	0.008	99.98	3.31
165	18.05	69.23	0.005	99.98	3.31
171	20.29	72.54	0.004	99.99	3.36
177	22.82	75.89	0.003	99.99	3.35
183	25.67	79.24	0.002	99.99	3.19
189	28.87	82.43	0.001	100.00	3.02
195	32.46	85.45	0.001	100.00	2.79
201	36.51	88.24	0.001	100.00	2.62
207	41.06	90.86	0.0033	100.00	2.41
213	46.17	93.27	0.0021	100.00	2.14
219	51.92	95.41	0.0013	100.00	1.84
225	58.39	97.24	6.6E-5	100.00	1.36
231	65.67	98.61	2.9E-5	100.00	0.859
237	73.85	99.47	1.1E-5	100.00	0.426
243	83.06	99.89	1.9E-6	100.00	0.107
249	93.40	100.00	0	100.00	0
255	105.0	100.00	0	100.00	0

MATERIAL SAFETY DATA SHEET

Section 1: Product/Company Information

Identity: Arizona sand including Arizona Test Dust, Arizona Road Dust, Arizona Silica, AC Fine and AC Coarse Test Dusts, SAE Fine and Coarse Test Dusts, J726 Test Dusts, ISO 12103-1, A1 Ultrafine Test Dust, ISO 12103-1, A2 Fine Test Dust, ISO 12103-1, A3 Medium Test Dust and ISO 12103-1, A4 Coarse Test Dust, MIL STD 810F Blowing Dust.

Mfg. Name: Powder Technology Inc.
14331 Ewing Avenue S.
Burnsville, MN 55306

Emergency Number: (952) 894-8737
Number for Info: (952) 894-8737
Date Updated: 3 January 2011

Section 2: Emergency and First Aid

Eyes: Immediately flush eye thoroughly with water. Seek medical attention if irritation persists.

Skin: Wash with soap and water. Seek medical attention if irritation persists.

Inhalation: Remove person to fresh air. If breathing is difficult, administer oxygen. If not breathing, give artificial respiration. Seek medical help if coughing and other symptoms do not subside.

Ingestion: Do not induce vomiting. If conscious, have the victim drink plenty of water and call a physician if discomfort is experienced.

Section 3: Composition Information

Typical chemical composition:

Chemical	CAS Number	Percent of Weight
SiO_2	14808-60-7	68-76%
Al_2O_3	1344-28-1	10-15%
Fe_2O_3	1309-37-1	2-5%
Na_2O	1313-59-3	2-4%
CaO	1305-78-8	2-5%
MgO	1309-48-4	1-2%
TiO_2	13463-67-7	0.5-1.0%
K_2O	12136-45-7	2-5%

Loss on Ignition 2 - 5 %

All components of this material are included on the TSCA Inventory.

Section 4: Hazardous Ingredients/Identity Information

This product contains free silica. Inhalation of dust may be harmful to your health. NIOSH has recommended an REL (Recommended Exposure Limit) of 0.05 mg/m^3 as determined by a full shift sample up to 10 hours working day, 40 hours per week.

H.M.I.S. ratings: Health – * Flammability – 0 Reactivity - 0
* see Section 5 of this MSDS for further information on health effects

Section 5: Hazard Identification

Potential Health Effects: Potential health effects may vary depending upon the duration and degree of exposure. To reduce or eliminate health hazards associated with this product, use exposure controls or personal protection methods as described in Section 12.

Eye Contact: (Acute/Chronic) Exposure to airborne dust may cause immediate or delayed irritation or inflammation of the cornea.

Inhalation: (Chronic) Inhalation exposure to free silica may cause delayed lung injury, including silicosis, a disabling and potentially fatal lung disease, and/or cause or aggravate other lung diseases or conditions.

Carcinogenic Potential: This product contains free silica, which IARC classifies as a known human carcinogen. The NTP, in its Ninth Annual Report on Carcinogens, classified "silica, crystalline (respirable)" as a known carcinogen.

Section 6: Accidental Release Measures

Use clean-up methods that do not disperse dust into the air. Avoid inhalation of dust and contact with eyes. Use exposure control and personal protection methods as described in Section 12.

Section 7: Physical/Chemical Data

Boiling Point:	4040^0 F
Specific Gravity (H_20 = 1.0):	2.65
Vapor Pressure:	Not applicable
Solubility in Water:	Insoluble
Appearance:	Tan, Brown, Light Brown, Reddish Brown.
Odor:	No Odor
Physical State:	Solid
Vapor Density:	Not applicable

Section 8: Fire and Explosion Hazard Data

Flash Point: None

Auto ignition Temperature: Not combustible

Flammable Limits: N/A

Extinguishing Media: Not Combustible

Hazardous Combustion Products: None

Lower Explosive Limit: None

Upper Explosive Limit: None

Special Fire Fighting Procedures: None

Unusual Fire and Explosion Hazards: None

Section 9: Stability and Reactivity Data

Stability:	Product is stable
Incompatibility (Materials to Avoid):	Strong oxidizing agents and acids
Hazardous Decomposition:	Will not occur
Hazardous Polymerization:	Will not occur

Section 10: Handling and Storage

Handle and store in a manner so that airborne dust does not exceed applicable exposure limits. Use adequate ventilation and dust collection. Use exposure control and personal protection methods as described in Section 12.

Section 11: Toxicological Information

Inhalation:
-Silicosis
The major concern is silicosis, caused by the inhalation and retention of respirable crystalline silica dust. Silicosis can exist in several forms, chronic (or ordinary), accelerated, or acute. Chronic or Ordinary Silicosis (often referred to as Simple Silicosis) is the most common form of silicosis, and can occur after many years of exposure to relatively low levels of airborne respirable crystalline silica dust. It is further defined as either simple or complicated silicosis. Simple silicosis is characterized by lung lesions (shown as radiographic opacities) less than 1 centimeter in diameter, primarily in the upper lung zones. Often, simple silicosis is not associated with symptoms, detectable changes in lung function or disability.

Simple silicosis may be progressive and may develop into complicated silicosis or progressive massive fibrosis (PMF). Complicated silicosis or PMF is characterized by lung lesions (shown as radiographic opacities) greater than 1 centimeter in diameter.

Although there may be no symptoms associated with complicated silicosis or PMF, the symptoms, if present, are shortness of breath, wheezing, cough and sputum production. Complicated silicosis or PMF may be associated with decreased lung function and may be disabling.

Advanced complicated silicosis or PMF may lead to death. Advanced complicated silicosis or PMF can result in heart disease secondary to the lung disease (corpumonale). Accelerated Silicosis can occur with exposure to high concentrations of respirable crystalline silica over a relatively short period; the lung lesions can appear within five (5) years of initial exposure. Progression can be rapid. Accelerated silicosis is similar to chronic or ordinary silicosis, except that lung lesions appear earlier and progression is more rapid.

Acute Silicosis can occur with exposures to very high concentrations of respirable crystalline silica over a very short time period, sometimes as short as a few months. The symptoms of acute silicosis include progressive shortness of breath, fever, cough and weight loss. Acute silicosis is fatal.

Carcinogenic Potential: IARC - The International Agency for Research on Cancer ("IARC") concluded that there was "*sufficient evidence* in humans for the carcinogenicity of crystalline silica in the forms of quartz or cristobalite from occupational sources", and that there is "*sufficient evidence* in experimental animals for the carcinogenicity of quartz and cristobalite." The overall IARC evaluation was that "crystalline silica inhaled in the form of quartz or cristobalite from occupational sources is *carcinogenic to humans* (*Group 1*)." The IARC evaluation noted, "Carcinogenicity was not detected in all industrial circumstances studies. Carcinogenicity may be dependent on inherent characteristics of the crystalline silica or on external factors affecting its biological activity or distribution of its polymorphs." For further information on the IARC evaluation, see IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 68, and "Silica, Some Silicates..." (1997).

Section 12: Exposure Control/Personal Protection

Respiratory Protection: Use local exhaust or general dilution ventilation to control dust levels below applicable exposure limits. Minimize dispersal of dust into the air. Use appropriate NIOSH approved respiratory protection for respirable crystalline silica. NIOSH recommends the use of half-facepiece particulate respirators with N95 or better filters for airborne exposures to crystalline silica at concentrations less than or equal to 0.5 milligrams per cubic meter of air (mg/m^3).

Eye Protection: Wear safety glasses with side shields or goggles to avoid contact with the eyes. In extremely dusty environments and unpredictable environments, wear tight-fitting unvented or indirectly vented goggles to avoid eye irritation or injury.

Section 13: Disposal Considerations

All disposal methods must be in accordance with all Federal, State/Provincial and local laws and regulations. Regulations may vary in different locations. Waste characterization and compliance with applicable laws are the responsibility solely of the waste generator.

Section 14: Transportation Data

Arizona Test Dust is not hazardous under U.S. DOT or TDG regulations.

Section 15: Other Regulatory Information

Status under US OSHA Hazard Communications Rule 29 CFR 1910.1200:	Silica sand is considered a hazardous chemical under this regulation and should be included in the employer's hazard communication program.
Status under CERCLA/Superfund, 40 CFR 117 and 302:	Not listed
Hazard Category under SARA (Title III), Sections 311 and 312:	Silica sand qualifies as a hazardous substance with delayed health effects.
Status under SARA (Title III), Section 313:	Not subject to reporting requirements under Section 313
Status under Canadian Environmental Protection Act:	Not listed.

Section 16: Other Information

The information and recommendations contained herein are based upon data believed to be correct. However, no guarantee or warranty of any kind, express or implied, is made with respect to the information contained herein. It is the user's obligation to determine the conditions of safe use of this product.

Appendix D: Column Test Experimental Results

D - 1. Porosity Test Results

D - 2. Test Report – Sand Media

D - 3. Test Report – DiamondKleen^{TM} M10

D - 4. Test Report – Zeolite Media

D - 5. Sample Analysis Results

D - 1. Porosity Test Results

To test the porosity of the granular media, a 300mL jar was filled with dry media. The dry weight was recorded. The jar with media was then slowly filled with water to replace the air spaces with water. This wet weight was then recorded. The pore space was determined by dividing the difference between the wet and dry weight by the density of water. This value was divided by the volume of the jar to determine the porosity.

Media	Dry Weight	Wet Weight	Difference	Average	/density of water	Unit Convert	/Volume =Porosity
Sand	466.25	583.8	117.55				
	454.55	572.6	118.05				
	451.4	568.9	117.5	117.7	0.1177	0.0001177	0.392333
M10	407.15	530.45	123.3				
	403.55	528	124.45				
	402.15	529.8	127.65	125.133	0.125133333	0.000125133	0.417111
M20	404.9	534.8	129.9				
	412.05	541.4	129.35				
	400.5	534.1	133.6	130.025	0.130025	0.000130025	0.433417
Zeolite	370.5	498.4	127.9				
	360.55	495.8	135.25				
	363.6	499.7	136.1	133.083	0.133083333	0.000133083	0.443611

D - 2. Test Report – Sand Media

Test Summary

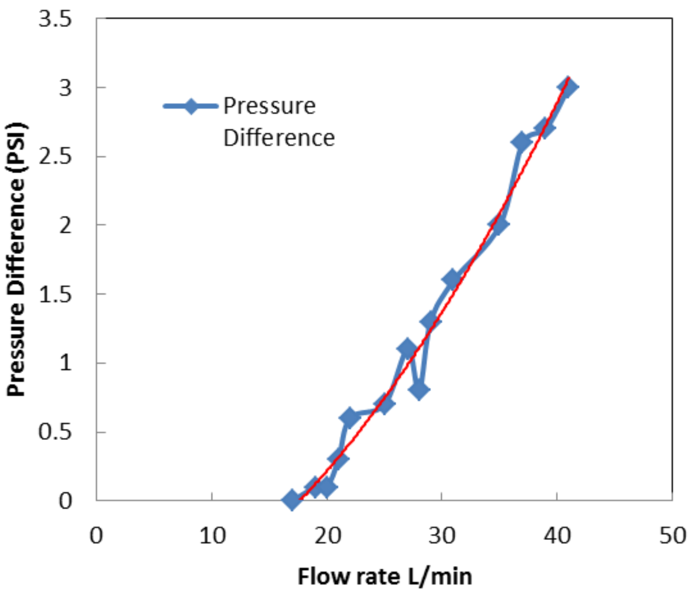
Media Tested	**SAND**
Start Date and Time	1st June 2011 9:25am
Finish Date and Time	3rd June 2011 3:45pm
Depth of Bed (Dry)	400mm (80% of Column depth)
Depth of Bed (Wet)	370mm
Flow Rate (L/min)	20L/min
Contaminant	600g ISO Fine Test Particles

Results Summary

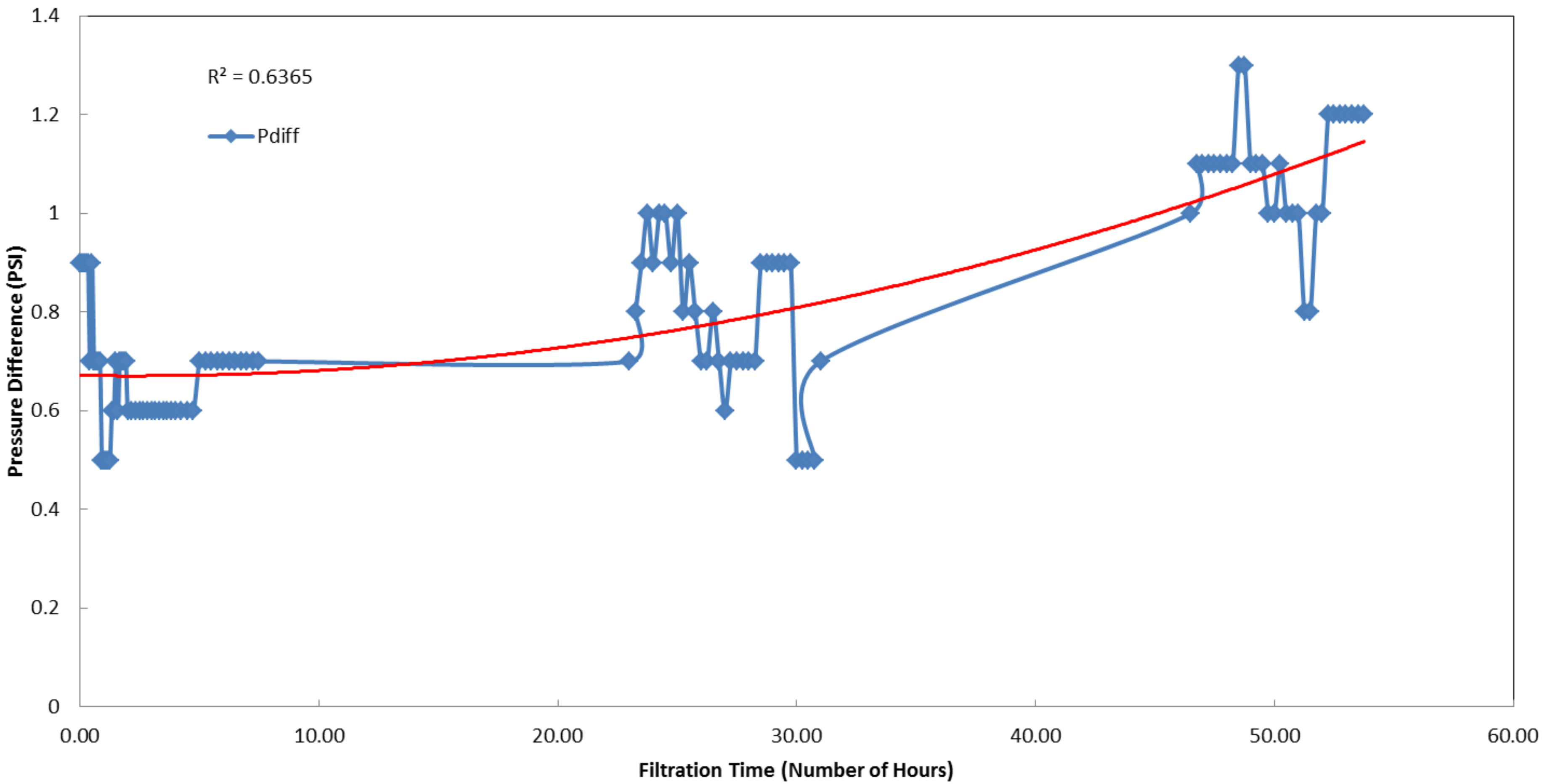
Maximum Turbidity	2150 FTU
Minimum Turbidity	2 FTU
Total Turbidity Reduction	2148 FTU
Minimum Pressure Difference	0.3 PSI
Maximum Pressure Difference	1.4 PSI
Total change in ΔP	1.1 PSI

Clean Bed Pressure Vs. Flow curve

Flow (L/min)	Pressure 1 (PSI)	Pressure 2 (PSI)	Pressure Difference
13	-1.1	0	-1.1
17	0.4	0.4	0
19	1.1	1	0.1
20	1.4	1.3	0.1
21	1.8	1.5	0.3
22	2.1	1.5	0.6
25	3.3	2.6	0.7
27	4.2	3.1	1.1
28	4.1	3.3	0.8
29	4.9	3.6	1.3
31	6.2	4.6	1.6
35	7.8	5.8	2
37	9.4	6.8	2.6
39	10.5	7.8	2.7
41	11.7	8.7	3



Pressure Difference over Time



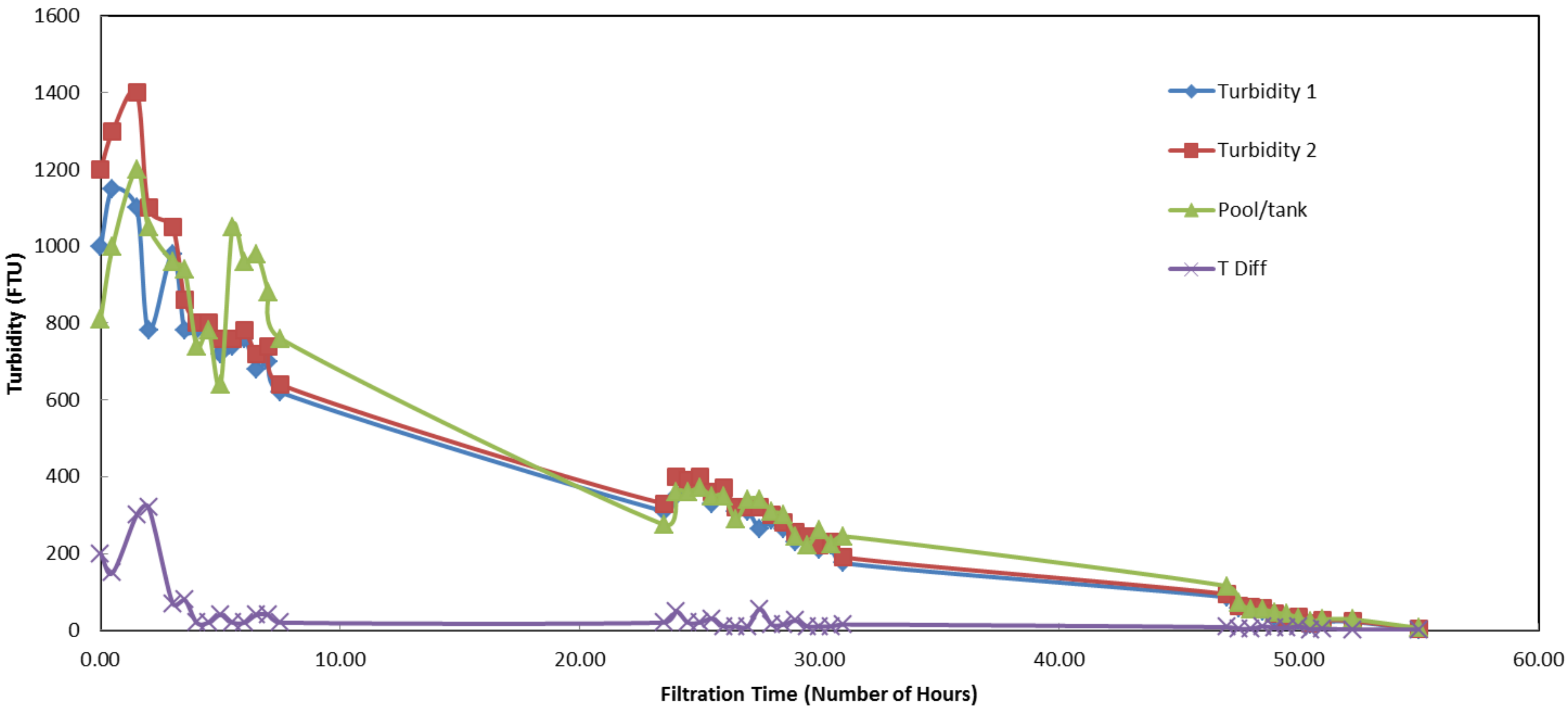
Appendix D

SAND										
	TIME	Actual Time	Flow Rate	Pressure 1	Pressure 2	Pdiff	Turbidity 1	Turbidity 2	T Diff	Pool
LOADING	-0.75	9:30	20	2.1	1.7	0.4	10	16	6	
	-0.50	9:35	20	2.3	1.7	0.6			0	
	-0.25	9:40	20	2.4	1.7	0.7			0	
FILTERING	0.00	9:45	20	2.6	1.7	0.9	1000	1200	200	810
	0.08	9:50	20	2.6	1.7	0.9			0	
	0.17	9:55	20	2.6	1.7	0.9			0	
	0.25	10:00	20	2.6	1.7	0.9			0	
	0.33	10:05	20	2.6	1.7	0.9			0	
	0.42	10:10	21	2.4	1.7	0.7			0	
	0.50	10:15	20	2.6	1.7	0.9	1150	1300	150	
	0.58	10:20	21	2.4	1.7	0.7			0	
	0.67	10:25	21	2.4	1.7	0.7			0	
	0.75	10:30	20	2	1.3	0.7			0	
	0.83	10:35	20	2	1.3	0.7			0	
	0.92	10:40	20	1.8	1.3	0.5			0	
	1.00	10:45	20	1.8	1.3	0.5	1150	2150	1000	1000
	1.08	10:50	20	1.8	1.3	0.5			0	
	1.17	10:55	20	1.8	1.3	0.5			0	
	1.25	11:00	20	1.8	1.3	0.5			0	
	1.33	11:05	20	1.7	1.1	0.6			0	
	1.42	11:10	20	1.7	1.1	0.6			0	
	1.50	11:15	20	1.8	1.1	0.7	1100	1400	300	1200
	1.58	11:20	20	1.7	1.1	0.6			0	
	1.67	11:25	20	1.7	1	0.7			0	
	1.75	11:30	20	1.7	1	0.7			0	
	1.83	11:35	20	1.8	1.1	0.7			0	
	1.92	11:40	20	1.8	1.1	0.7			0	
	2.00	11:45	20	1.7	1.1	0.6	780	1100	320	1050
	2.17	11:55	21	1.7	1.1	0.6			0	
	2.33	12:05	21	1.7	1.1	0.6			0	
	2.50	12:15	20	1.7	1.1	0.6	1000	1800	800	1150
	2.67	12:25	21	1.7	1.1	0.6			0	
	2.83	12:35	21	1.7	1.1	0.6			0	
	3.00	12:45	20	1.7	1.1	0.6	980	1050	70	960
	3.17	12:55	21	1.7	1.1	0.6			0	
	3.33	13:05	21	1.7	1.1	0.6			0	
	3.50	13:15	21	1.7	1.1	0.6	780	860	80	940
	3.67	13:25	21	1.7	1.1	0.6			0	
	3.83	13:35	21	1.7	1.1	0.6			0	

SAND									
Time	Actual Time	Flow Rate	Pressure 1	Pressure 2	Pdiff	Turbidity 1	Turbidity 2	T Diff	Pool
4.00	13:45	20	1.7	1.1	0.6	780	800	20	740
4.25	14:00	20	1.7	1.1	0.6			0	
4.50	14:15	21	1.7	1.1	0.6	780	800	20	780
4.75	14:30	20	1.7	1.1	0.6			0	
5.00	14:45	21	1.8	1.1	0.7	720	760	40	640
5.25	15:00	21	1.8	1.1	0.7			0	
5.50	15:15	21	1.8	1.1	0.7	740	760	20	1050
5.75	15:30	21	1.8	1.1	0.7			0	
6.00	15:45	21	1.8	1.1	0.7	760	780	20	960
6.25	16:00	21	1.8	1.1	0.7			0	
6.50	16:15	21	1.8	1.1	0.7	680	720	40	980
6.75	16:30	21	1.8	1.1	0.7			0	
7.00	16:45	21	1.8	1.1	0.7	700	740	40	880
7.25	17:00	21	1.8	1.1	0.7			0	
7.50	17:15	21	1.8	1.1	0.7	620	640	20	760
23.00	8:45	20	1.7	1	0.7			0	
23.25	9:00	20	1.8	1	0.8			0	
23.50	9:15	20	1.7	0.8	0.9	310	330	20	275
23.75	9:30	20	1.8	0.8	1			0	
24.00	9:45	20	1.7	0.8	0.9	350	400	50	360
24.25	10:00	20	1.8	0.8	1			0	
24.50	10:15	21	1.8	0.8	1	370	390	20	360
24.75	10:30	21	1.7	0.8	0.9			0	
25.00	10:45	21	1.8	0.8	1	380	400	20	370
25.25	11:00	21	1.8	1	0.8			0	
25.50	11:15	21	1.7	0.8	0.9	330	360	30	350
25.75	11:30	21	1.8	1	0.8			0	
26.00	11:45	21	1.7	1	0.7	360	370	10	350
26.25	12:00	21	1.7	1	0.7			0	
26.50	12:15	21	1.8	1	0.8	310	320	10	290
26.75	12:30	21	1.7	1	0.7			0	
27.00	12:45	21	1.7	1.1	0.6	310	320	10	340
27.25	13:00	21	1.8	1.1	0.7			0	
27.50	13:15	21	1.8	1.1	0.7	265	320	55	340
27.75	13:30	21	1.8	1.1	0.7			0	
28.00	13:45	21	1.8	1.1	0.7	285	300	15	310
28.25	14:00	21	2	1.3	0.7			0	
28.50	14:15	21	2	1.1	0.9	265	280	15	300

SAND									
Time	Actual Time	Flow Rate	Pressure 1	Pressure 2	ΔP	Turbidity 1	Turbidity 2	T Diff	Pool
28.75	14:30	21	2	1.1	0.9			0	
29.00	14:45	21	2	1.1	0.9	230	255	25	245
29.25	15:00	21	2	1.1	0.9			0	
29.50	15:15	21	2	1.1	0.9	235	245	10	220
29.75	15:30	21	2	1.1	0.9			0	
30.00	15:45	20	1.5	1	0.5	210	220	10	260
30.25	16:00	20	1.5	1	0.5			0	
30.50	16:15	20	1.5	1	0.5	220	230	10	225
30.75	16:30	20	1.5	1	0.5			0	
31.00	16:45	20	1.7	1	0.7	175	190	15	245
46.50	8:15	20	1.8	0.8	1				
46.75	8:30	20	1.8	0.7	1.1				
47.00	8:45	20	1.8	0.7	1.1	86	94	8	115
47.25	9:00	20	1.8	0.7	1.1			0	
47.50	9:15	20	1.8	0.7	1.1	58	62	4	72
47.75	9:30	20	1.8	0.7	1.1			0	
48.00	9:45	20	1.8	0.7	1.1	56	60	4	54
48.25	10:00	20	1.8	0.7	1.1			0	
48.50	10:15	20	2	0.7	1.3	48	58	10	54
48.75	10:30	20	2	0.7	1.3			0	
49.00	10:45	20	1.8	0.7	1.1	36	42	6	46
49.25	11:00	20	1.8	0.7	1.1			0	
49.50	11:15	20	1.8	0.7	1.1	24	30	6	42
49.75	11:30	20	1.8	0.8	1			0	
50.00	11:45	20	1.8	0.8	1	26	36	10	32
50.25	12:00	20	1.8	0.7	1.1			0	
50.50	12:15	20	1.8	0.8	1	16	18	2	22
50.75	12:30	20	1.8	0.8	1			0	
51.00	12:45	20	1.8	0.8	1	22	26	4	28
51.25	13:00	20	1.8	1	0.8			0	
51.50	13:15	20	1.8	1	0.8			0	
51.75	13:30	20	2	1	1			0	
52.00	13:45	20	2	1	1			0	
52.25	14:00	20	2	0.8	1.2	22	24	2	28
52.50	14:15	20	2	0.8	1.2			0	
55.00	16:45	19	1.8	0.8	1	2	4	2	6

Turbidity of Filtrate over Time



Appendix D

Time	Turbidity 1	Turbidity 2	Turbidity Difference	Pool/tank
0.00	1000	1200	200	810
0.50	1150	1300	150	1000
1.50	1100	1400	300	1200
2.00	780	1100	320	1050
3.00	980	1050	70	960
3.50	780	860	80	940
4.00	780	800	20	740
4.50	780	800	20	780
5.00	720	760	40	640
5.50	740	760	20	1050
6.00	760	780	20	960
6.50	680	720	40	980
7.00	700	740	40	880
7.50	620	640	20	760
23.50	310	330	20	275
24.00	350	400	50	360
24.50	370	390	20	360
25.00	380	400	20	370
25.50	330	360	30	350
26.00	360	370	10	350
26.50	310	320	10	290
27.00	310	320	10	340
27.50	265	320	55	340
28.00	285	300	15	310
28.50	265	280	15	300
29.00	230	255	25	245
29.50	235	245	10	220
30.00	210	220	10	260
30.50	220	230	10	225
31.00	175	190	15	245
47.00	86	94	8	115
47.50	58	62	4	72
48.00	56	60	4	54
48.50	48	58	10	54
49.00	36	42	6	46
49.50	24	30	6	42
50.00	26	36	10	32
50.50	16	18	2	22
51.00	22	26	4	28
52.25	22	24	2	28
55.00	2	4	2	6

Backwash Notes

Backwash		
top pressure	-0.8	
Bottom pressure	1.5	
flow rate	20l/min	
Backwash turbidity	365	Mid stream
time to empty tank	9min 11 sec	
at 8:38 flow rate dropped rapidly to 5l/min, not enough water in suction line		

Comments/Observations

- Insufficient data on backwash due to short time taken to empty tank, there was an interruption during the backwash cycle for approx 20sec
- Water warmed during testing, temperature rise may have impacted results
- Flow rate fluctuated in the beginning up to 22L/min this was changed after 1 hour of filtration time to 20L/min
- Samples were collected before filtration, after 31 hours of filtration, after 55hours of filtration and from the collected backwash
- The first 2 samples broke due to freezing but some of the water sample was recovered from the ice, there may be some contamination or loss of sediment from the water.
- After filtering over night there was some sedimentation of particles in the bottom of the tank because it could not be mixed overnight. This resulted in lower turbidity readings before mixing.
- Spikes in turbidity and drops in pressure difference may have been caused by filter bed break through, where a break in the bed allowed filtered particles to return to the pool/water tank
- The depth of the bed changes by 30mm due to compaction during filtering
- The level of the top of the bed was not flat caused by the initial flow of water into the filter column
- The initial increase in turbidity may have been caused by flushing of dirt from the media itself, which was then filtered out again before having an effect on the pool contaminants. It is reasonable to assume that sand would contain a high portion of fines because it was sourced from river sands.

D - 3. Test Report – DiamondKleen™ M10

Test Summary

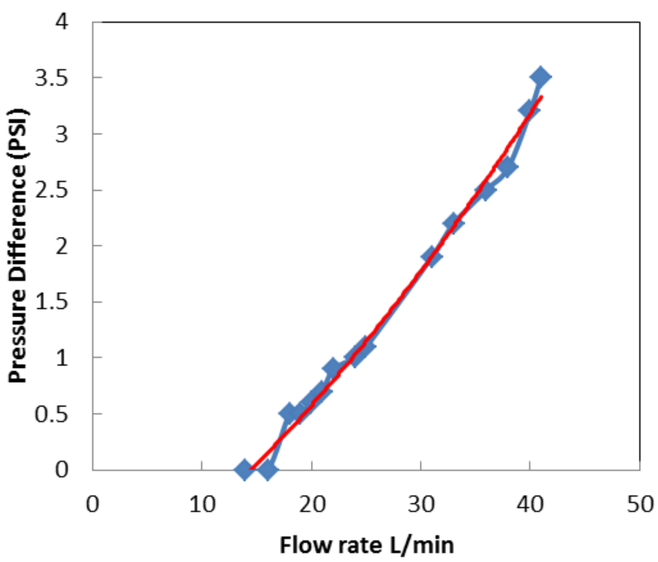
Media Tested	**DiamondKleen M10**
Start Date and Time	6th June 2011 10:30am
Finish Date and Time	8th June 2011 9:30am
Depth of Bed (Dry)	380mm
Depth of Bed (Wet)	378mm
Flow Rate (L/min)	20L/min
Contaminant	600g ISO Fine Test Particles

Results Summary

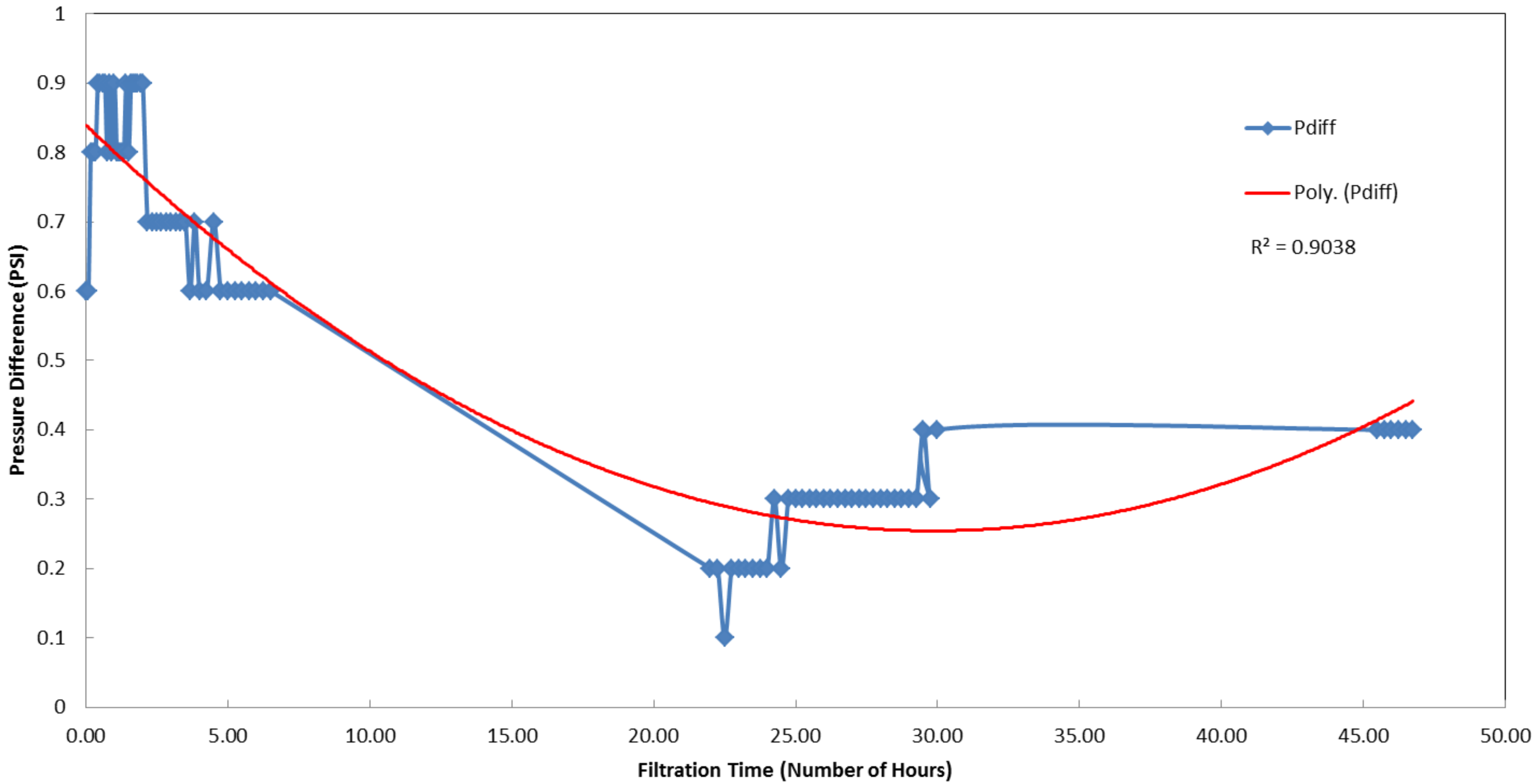
Maximum Turbidity	1200 FTU
Minimum Turbidity	0 FTU
Total Turbidity Reduction	1200 FTU
Minimum Pressure Difference	0.1 PSI
Maximum Pressure Difference	0.9 PSI
Total change in ΔP	0.8 PSI

Clean Bed Pressure Vs. Flow curve

Flow (L/min)	Pressure 1 (PSI)	Pressure 2 (PSI)	Pressure Difference
12	-1.7	-1.4	-0.3
14	0	0	0
16	0	0	0
18	0.5	0	0.5
19	1	0.5	0.5
20	1.1	0.5	0.6
21	1.7	1	0.7
22	2.4	1.5	0.9
24	3	2	1
25	3.1	2	1.1
31	5.9	4	1.9
33	6.9	4.7	2.2
36	8.5	6	2.5
38	9.5	6.8	2.7
40	10.8	7.6	3.2



Pressure Difference over Time



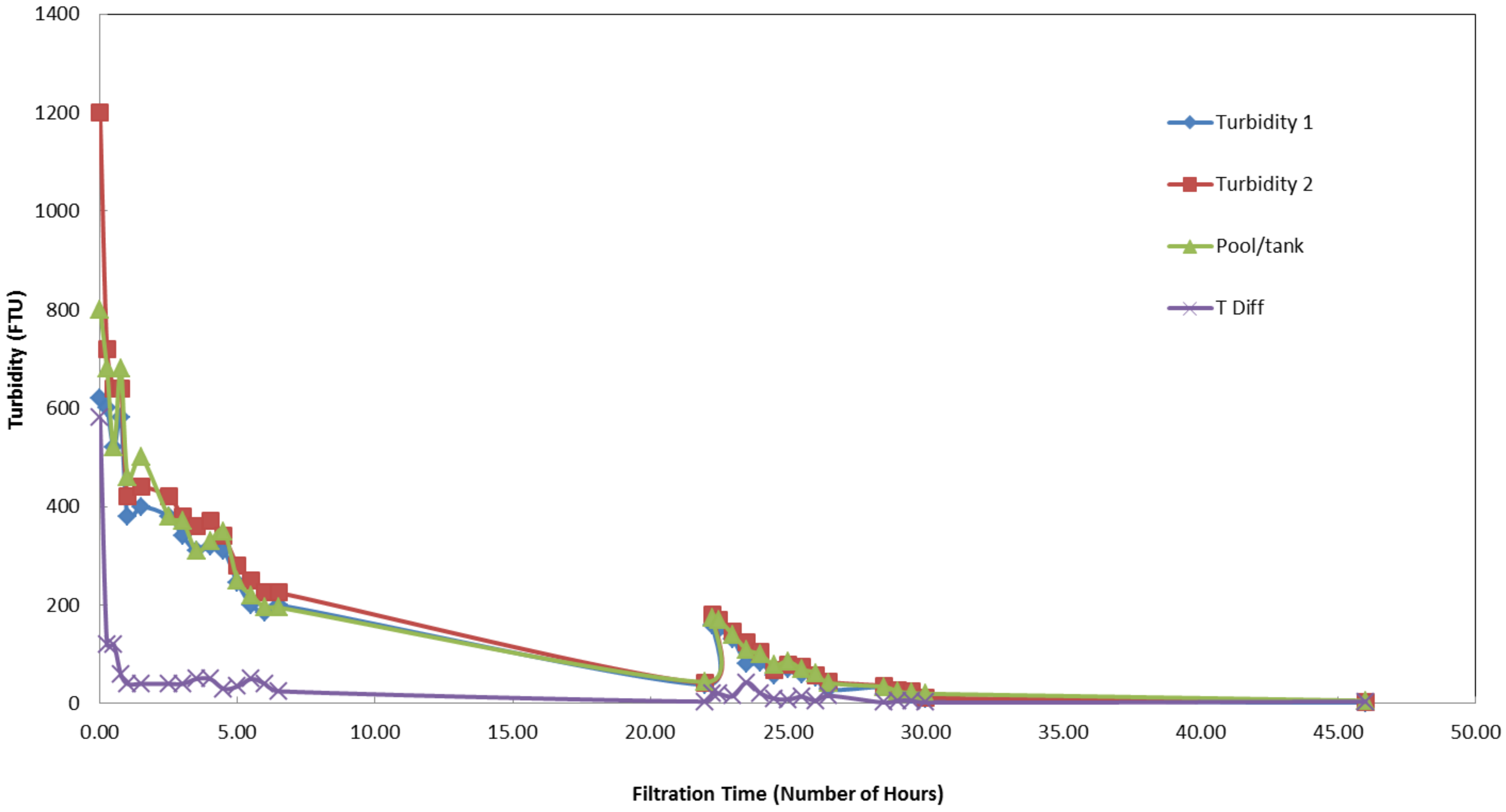
Appendix D

DiamondKleen M10										
	TIME	Actual Time	Flow Rate	Pressure 1	Pressure 2	ΔP	Turbidity 1	Turbidity 2	T Diff	Pool
LOADING	-0.75	10:30	20	0.8	0.5	0.3				4
	-0.50	10:35	20	1	0.5	0.5				
	-0.25	10:40	20	1.1	0.5	0.6				
FILTERING	0.00	10:45	20	1.1	0.5	0.6	620	1200	580	800
	0.08	10:50	20	1.1	0.5	0.6			0	
	0.17	10:55	20	1.3	0.5	0.8			0	
	0.25	11:00	20	1.3	0.5	0.8	600	720	120	680
	0.33	11:05	20	1.3	0.5	0.8			0	
	0.42	11:10	20	1.4	0.5	0.9			0	
	0.50	11:15	20	1.4	0.5	0.9	520	640	120	520
	0.58	11:20	20	1.4	0.5	0.9			0	
	0.67	11:25	20	1.4	0.5	0.9			0	
	0.75	11:30	19	1.3	0.5	0.8	580	640	60	680
	0.83	11:35	19	1.4	0.5	0.9			0	
	0.92	11:40	20	1.3	0.5	0.8			0	
	1.00	11:45	19	1.4	0.5	0.9	380	420	40	460
	1.08	11:50	20	1.3	0.5	0.8			0	
	1.17	11:55	19	1.3	0.5	0.8			0	
	1.25	12:00	19	1.3	0.5	0.8			0	
	1.33	12:05	19	1.3	0.5	0.8			0	
	1.42	12:10	20	1.4	0.5	0.9			0	
	1.50	12:15	19	1.3	0.5	0.8	400	440	40	500
	1.58	12:20	20	1.4	0.5	0.9			0	
	1.67	12:25	20	1.4	0.5	0.9			0	
	1.75	12:30	20	1.4	0.5	0.9			0	
	1.83	12:35	20	1.4	0.5	0.9			0	
	1.92	12:40	20	1.4	0.5	0.9			0	
	2.00	12:45	20	1.4	0.5	0.9			0	
	2.17	12:55	20	1.4	0.7	0.7			0	
	2.33	13:05	20	1.5	0.8	0.7			0	
	2.50	13:15	20	1.4	0.7	0.7	380	420	40	380
	2.67	13:25	20	1.5	0.8	0.7			0	
	2.83	13:35	20	1.5	0.8	0.7			0	
	3.00	13:45	19	1.5	0.8	0.7	340	380	40	370
	3.17	13:55	19	1.5	0.8	0.7			0	
	3.33	14:05	20	1.5	0.8	0.7			0	
	3.50	14:15	20	1.5	0.8	0.7	310	360	50	310
	3.67	14:25	20	1.4	0.8	0.6			0	
	3.83	14:35	20	1.5	0.8	0.7			0	
	4.00	14:45	20	1.4	0.8	0.6	320	370	50	330
	4.25	15:00	20	1.4	0.8	0.6			0	

TIME	Actual Time	Flow Rate	Pressure 1	Pressure 2	ΔP	Turbidity 1	Turbidity 2	T Diff	Pool
4.50	15:15	19	1.4	0.7	0.7	310	340	30	350
4.75	15:30	20	1.4	0.8	0.6			0	
5.00	15:45	20	1.4	0.8	0.6	245	280	35	250
5.25	16:00	20	1.4	0.8	0.6			0	
5.50	16:15	20	1.4	0.8	0.6	200	250	50	220
5.75	16:30	20	1.4	0.8	0.6			0	
6.00	16:45	20	1.4	0.8	0.6	185	225	40	195
6.25	17:00	20	1.4	0.8	0.6			0	
6.50	17:15	20	1.4	0.8	0.6	200	225	25	195
22.00	8:45	20	1	0.8	0.2	38	42	4	44
22.25	9:00	20	1	0.8	0.2	160	180	20	175
22.50	9:15	19	0.8	0.7	0.1	150	170	20	170
22.75	9:30	20	1	0.8	0.2			0	
23.00	9:45	20	1	0.8	0.2	130	145	15	140
23.25	10:00	20	1	0.8	0.2			0	
23.50	10:15	20	1	0.8	0.2	82	125	43	110
23.75	10:30	20	1	0.8	0.2			0	
24.00	10:45	20	1	0.8	0.2	84	105	21	100
24.25	11:00	20	1	0.7	0.3			0	
24.50	11:15	20	1	0.8	0.2	58	68	10	78
24.75	11:30	20	1	0.7	0.3			0	
25.00	11:45	20	1	0.7	0.3	70	78	8	86
25.25	12:00	20	1	0.7	0.3			0	
25.50	12:15	20	1	0.7	0.3	60	74	14	70
25.75	12:30	20	1	0.7	0.3			0	
26.00	12:45	20	1	0.7	0.3	52	58	6	62
26.25	13:00	20	1	0.7	0.3			0	
26.50	13:15	20	1	0.7	0.3	28	44	16	42
26.75	13:30	20	1	0.7	0.3			0	
27.00	13:45	20	1	0.7	0.3			0	
27.25	14:00	20	1	0.7	0.3			0	
27.50	14:15	20	1	0.7	0.3			0	
27.75	14:30	20	1	0.7	0.3			0	
28.00	14:45	20	1	0.7	0.3			0	
28.25	15:00	20	1	0.7	0.3			0	
28.50	15:15	20	1	0.7	0.3	34	36	2	34
28.75	15:30	20	1	0.7	0.3			0	
29.00	15:45	20	1	0.7	0.3	20	26	6	24
29.25	16:00	20	1	0.7	0.3			0	
29.50	16:15	20	1.1	0.7	0.4	18	24	6	22
29.75	16:30	20	1	0.7	0.3			0	
30.00	16:45	20	1.1	0.7	0.4	10	12	2	20

	TIME	Actual Time	Flow Rate	Pressure 1	Pressure 2	ΔP	Turbidity 1	Turbidity 2	T Diff	Pool
	45.50	8:15	20	1.1	0.7	0.4			0	
	45.75	8:30	20	1.1	0.7	0.4			0	
	46.00	8:45	20	1.1	0.7	0.4	0	4	4	6
	46.25	9:00	20	1.1	0.7	0.4	0	8	8	4
	46.50	9:15	20	1.1	0.7	0.4	0	8	8	4
	46.75	9:30	20	1.1	0.7	0.4	0	2	2	2

Turbidity of Filtrate over Time



Time	Turbidity 1	Turbidity 2	Turbidity Difference	Pool/tank
0.00	620	1200	580	800
0.25	600	720	120	680
0.50	520	640	120	520
0.75	580	640	60	680
1.00	380	420	40	460
1.50	400	440	40	500
2.50	380	420	40	380
3.00	340	380	40	370
3.50	310	360	50	310
4.00	320	370	50	330
4.50	310	340	30	350
5.00	245	280	35	250
5.50	200	250	50	220
6.00	185	225	40	195
6.50	200	225	25	195
23.25	160	180	20	175
23.50	150	170	20	170
24.00	130	145	15	140
24.50	82	125	43	110
25.00	84	105	21	100
25.50	58	68	10	78
26.00	70	78	8	86
26.50	60	74	14	70
27.00	52	58	6	62
27.50	28	44	16	42
29.50	34	36	2	34
30.00	20	26	6	24
30.50	18	24	6	22
31.00	10	12	2	20
47.00	0	4	4	6
47.50	0	8	8	4

Backwash Notes

Backwash			
top pressure	0		
Bottom pressure	1.5	/1.7	
flow rate	20l/min		225Lleft
Backwash turbidity	3.16	50	
	3.44	42	150L left
	4.57	30	
	5.02	26	
	6.17	22	
	6.38	24	
	7.52	18	
time to empty tank	8min 52sec		

Comments/Observations

D - 4. Test Report – Zeolite Media

Test Summary

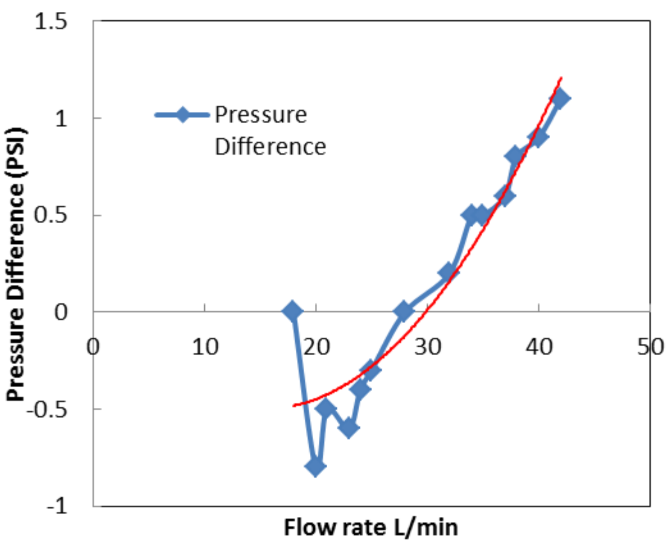
Media Tested	**ZEOLITE**
Start Date and Time	8/06/2011, 12:00pm
Finish Date and Time	10/06/2011, 5:00pm
Depth of Bed (Dry)	400mm
Depth of Bed (Wet)	
Flow Rate (L/min)	20L/min
Contaminant	600g ISO Fine

Results Summary

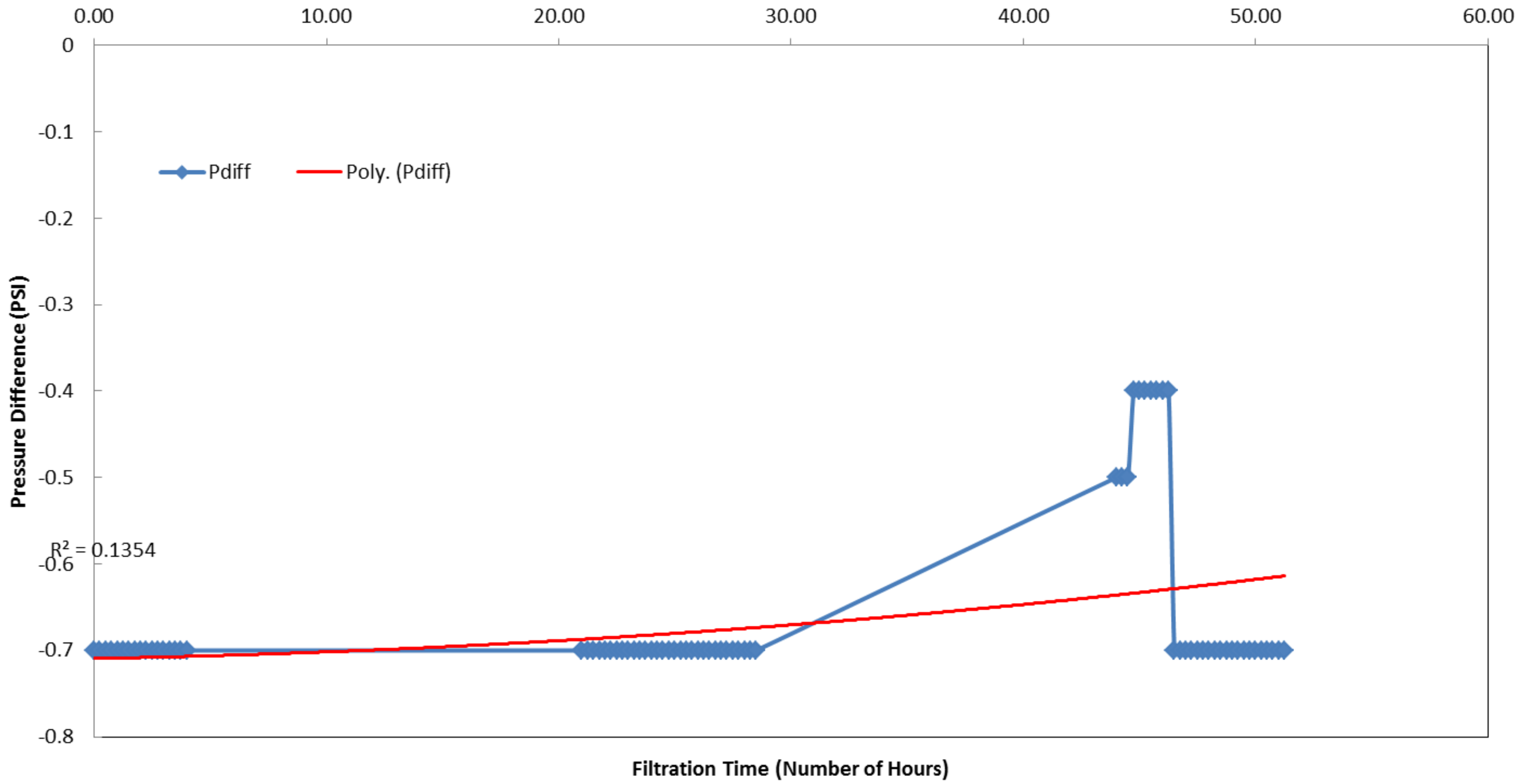
Maximum Turbidity	2250FTU
Minimum Turbidity	105FTU
Total Turbidity Reduction	
Minimum Pressure Difference	-0.7 PSI
Maximum Pressure Difference	-0.7 PSI
Total change in ΔP	0.0 PSI

Clean Bed Pressure Vs. Flow curve

Flow (L/min)	Pressure 1 (PSI)	Pressure 2 (PSI)	Pressure Difference
16	-1.4	0	-1.4
18	0	0	0
20	0	0.8	-0.8
21	0.5	1	-0.5
23	0.5	1.1	-0.6
24	1.3	1.7	-0.4
25	1.4	1.7	-0.3
28	2.6	2.6	0
32	4.2	4	0.2
34	5.2	4.7	0.5
35	5.5	5	0.5
37	6.2	5.6	0.6
38	6.8	6	0.8
40	7.8	6.9	0.9
42	9.2	8.1	1.1



Pressure Difference over Time



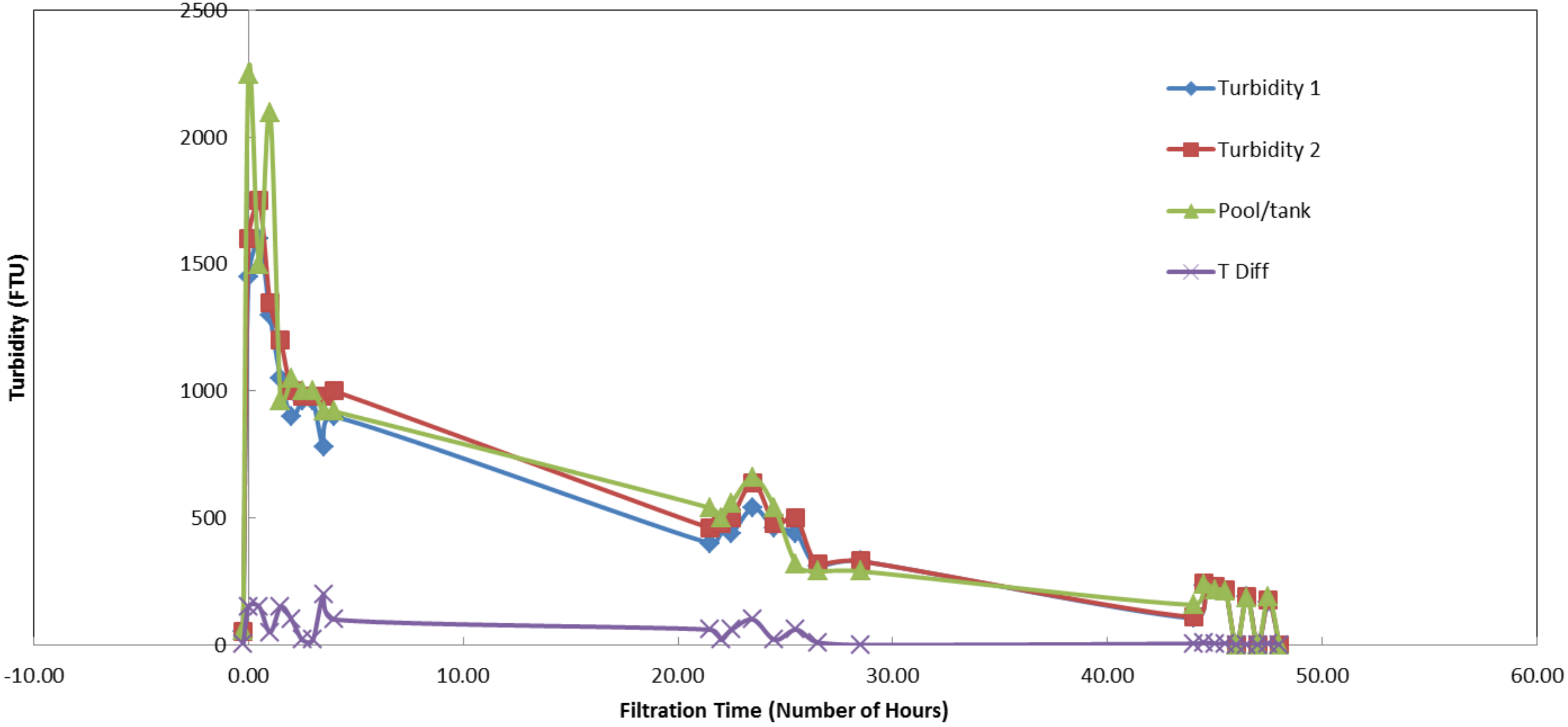
Appendix D

	Actual	ZEOLITE								
	Time	Flow Rate	Pressure 1	Pressure 2	Pdiff		Turbidity 1	Turbidity 2	T Diff	Pool
0.1	12:00	20	0	0.7	-0.7		52	54	2	56
0.1	12:15	20	0	0.7	-0.7		1450	1600	150	2250
0.1	12:30	20	0	0.7	-0.7				0	
0.1	12:45	20	0	0.7	-0.7		1600	1750	150	1500
0.1	13:00	20	0	0.7	-0.7				0	
0.1	13:15	20	0	0.7	-0.7		1300	1350	50	2100
0.1	13:30	20	0	0.7	-0.7				0	
0.1	13:45	20	0	0.7	-0.7		1050	1200	150	960
0.1	14:00	20	0	0.7	-0.7				0	
0.1	14:15	20	0	0.7	-0.7		900	1000	100	1050
0.1	14:30	20	0	0.7	-0.7				0	
0.1	14:45	20	0	0.7	-0.7		960	980	20	1000
0.1	15:00	20	0	0.7	-0.7				0	
0.1	15:15	20	0	0.7	-0.7		960	980	20	1000
0.1	15:30	20	0	0.7	-0.7				0	
0.1	15:45	20	0	0.7	-0.7		780	980	200	920
0.1	16:00	20	0	0.7	-0.7				0	
0.1	16:15	20	0	0.7	-0.7		900	1000	100	920
0.1	9:15	20	0	0.7	-0.7				0	
0.1	9:30	20	0	0.7	-0.7				0	
0.1	9:45	20	0	0.7	-0.7		400	460	60	540
0.1	10:00	20	0	0.7	-0.7				0	
0.1	10:15	20	0	0.7	-0.7		460	480	20	500
0.1	10:30	20	0	0.7	-0.7				0	
0.1	10:45	20	0	0.7	-0.7		440	500	60	560
0.1	11:00	20	0	0.7	-0.7				0	
0.1	11:15	20	0	0.7	-0.7				0	
0.1	11:30	20	0	0.7	-0.7				0	
0.1	11:45	20	0	0.7	-0.7		540	640	100	660
0.1	12:00	20	0	0.7	-0.7				0	
0.1	12:15	20	0	0.7	-0.7				0	
0.1	12:30	20	0	0.7	-0.7				0	
0.1	12:45	20	0	0.7	-0.7		460	480	20	540
0.1	13:00	20	0	0.7	-0.7				0	
0.1	13:15	20	0	0.7	-0.7				0	
0.1	13:30	20	0	0.7	-0.7				0	
0.1	13:45	20	0	0.7	-0.7		440	500	60	320

ZEOLITE

0.1	14:00	20	0	0.7	-0.7				0	
0.1	14:15	20	0	0.7	-0.7				0	
0.1	14:30	20	0	0.7	-0.7				0	
0.1	14:45	20	0	0.7	-0.7		310	320	10	290
0.1	15:00	20	0	0.7	-0.7				0	
0.1	15:15	20	0	0.7	-0.7				0	
0.1	15:30	20	0	0.7	-0.7				0	
0.1	15:45	20	0	0.7	-0.7				0	
0.1	16:00	20	0	0.7	-0.7				0	
0.1	16:15	20	0	0.7	-0.7				0	
0.1	16:30	20	0	0.7	-0.7				0	
0.1	16:45	20	0	0.7	-0.7		330	330	0	290
0.3	8:15	20	0	0.5	-0.5		105	110	5	158
0.3	8:30	20	0	0.5	-0.5				0	
0.3	8:45	20	0	0.5	-0.5		235	245	10	240
0.4	9:00	20	0	0.4	-0.4				0	
0.4	9:15	20	0	0.4	-0.4		225	230	5	215
0.4	9:30	20	0	0.4	-0.4				0	
0.4	9:45	20	0	0.4	-0.4		210	215	5	210
0.4	10:00	20	0	0.4	-0.4				0	
0.4	10:15	20	0	0.4	-0.4				0	
0.4	10:30	20	0	0.4	-0.4				0	
0.1	10:45	20	0	0.7	-0.7		190	190	0	185
0.1	11:00	20	0	0.7	-0.7				0	
0.1	11:15	20	0	0.7	-0.7				0	
0.1	11:30	20	0	0.7	-0.7				0	
0.1	11:45	20	0	0.7	-0.7		170	175	5	190
0.1	12:00	20	0	0.7	-0.7				0	
0.1	12:15	20	0	0.7	-0.7				0	
0.1	12:30	20	0	0.7	-0.7				0	
0.1	12:45	20	0	0.7	-0.7				0	
0.1	13:00	20	0	0.7	-0.7				0	
0.1	13:15	20	0	0.7	-0.7				0	
0.1	13:30	20	0	0.7	-0.7				0	
0.1	13:45	20	0	0.7	-0.7		185	190	5	160
0.1	14:00	20	0	0.7	-0.7				0	
0.1	14:15	20	0	0.7	-0.7				0	
0.1	14:30	20	0	0.7	-0.7				0	
0.1	14:45	20	0	0.7	-0.7		168	170	2	180
0.1	15:00	20	0	0.7	-0.7				0	
0.1	15:15	20	0	0.7	-0.7				0	
0.1	15:30	20	0	0.7	-0.7				0	
0.1	15:45	20	0	0.7	-0.7		155	160	5	155

Turbidity of Filtrate over Time



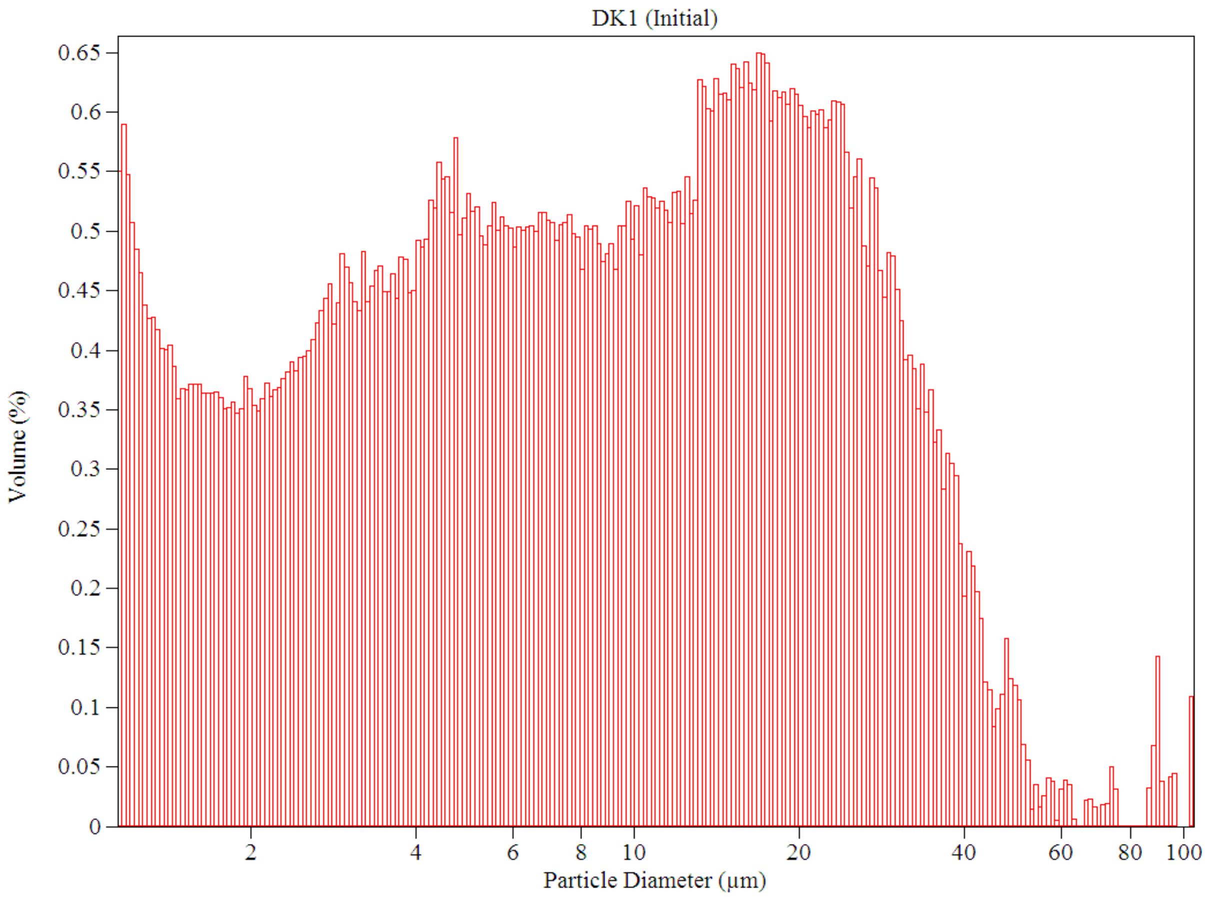
Appendix D

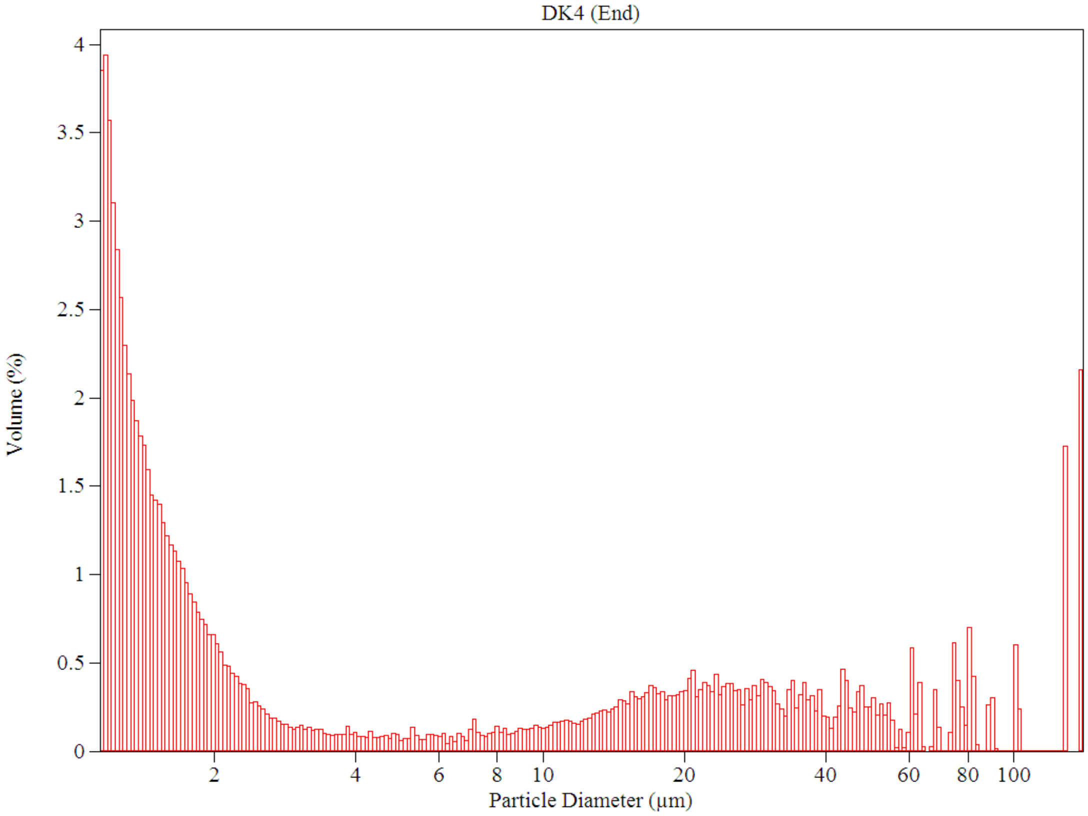
Time	Turbidity 1	Turbidity 2	T Diff	Pool/tank
-0.25	52	54	2	56
0.00	1450	1600	150	2250
0.50	1600	1750	150	1500
1.00	1300	1350	50	2100
1.50	1050	1200	150	960
2.00	900	1000	100	1050
2.50	960	980	20	1000
3.00	960	980	20	1000
3.50	780	980	200	920
4.00	900	1000	100	920
21.50	400	460	60	540
22.00	460	480	20	500
22.50	440	500	60	560
23.50	540	640	100	660
24.50	460	480	20	540
25.50	440	500	60	320
26.50	310	320	10	290
28.50	330	330	0	290
44.00	105	110	5	158
44.50	235	245	10	240
45.00	225	230	5	215
45.50	210	215	5	210
46.00	0	0	0	0
46.50	190	190	0	185
47.00	0	0	0	0
47.50	170	175	5	190
48.00	0	0	0	0

Appendix D

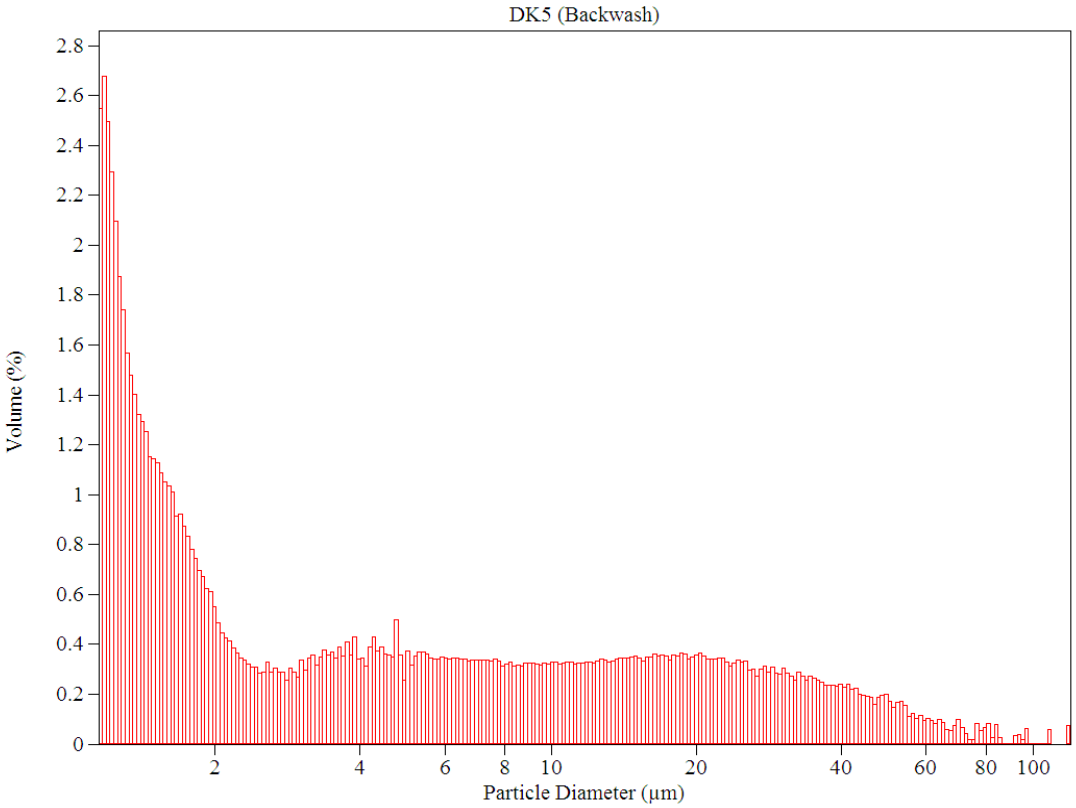
D - 5. Sample Analysis Results

Sample Date	Lab Number	Sample Identifier	Sample location	Sample Type	Tubes	Dispersion
16/06/2011	R722	DK1 (Initial)	Griffith Lab	Pool Filters	280,140 and 50	Minimally Dispersed
16/06/2011	R723	DK4 (End)	Griffith Lab	Pool Filters	280,140 and 50	Minimally Dispersed
16/06/2011	R724	DK5 (Backwash)	Griffith Lab	Pool Filters	280,140 and 50	Minimally Dispersed
16/06/2011	R725	Sand 3 (End)	Griffith Lab	Pool Filters	280,140 and 50	Minimally Dispersed
16/06/2011	R726	Sand 4 (Backwash)	Griffith Lab	Pool Filters	280,140 and 50	Minimally Dispersed
16/06/2011	R727	Zeolite (End)	Griffith Lab	Pool Filters	280,140 and 50	Minimally Dispersed

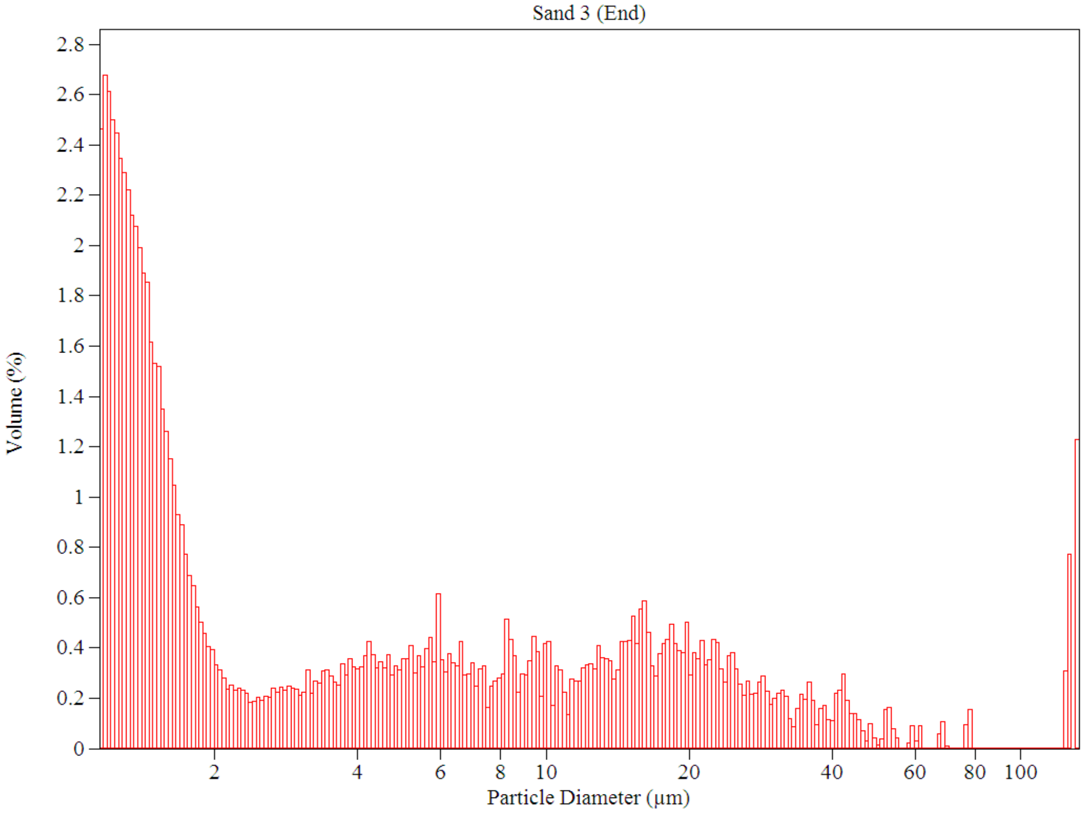


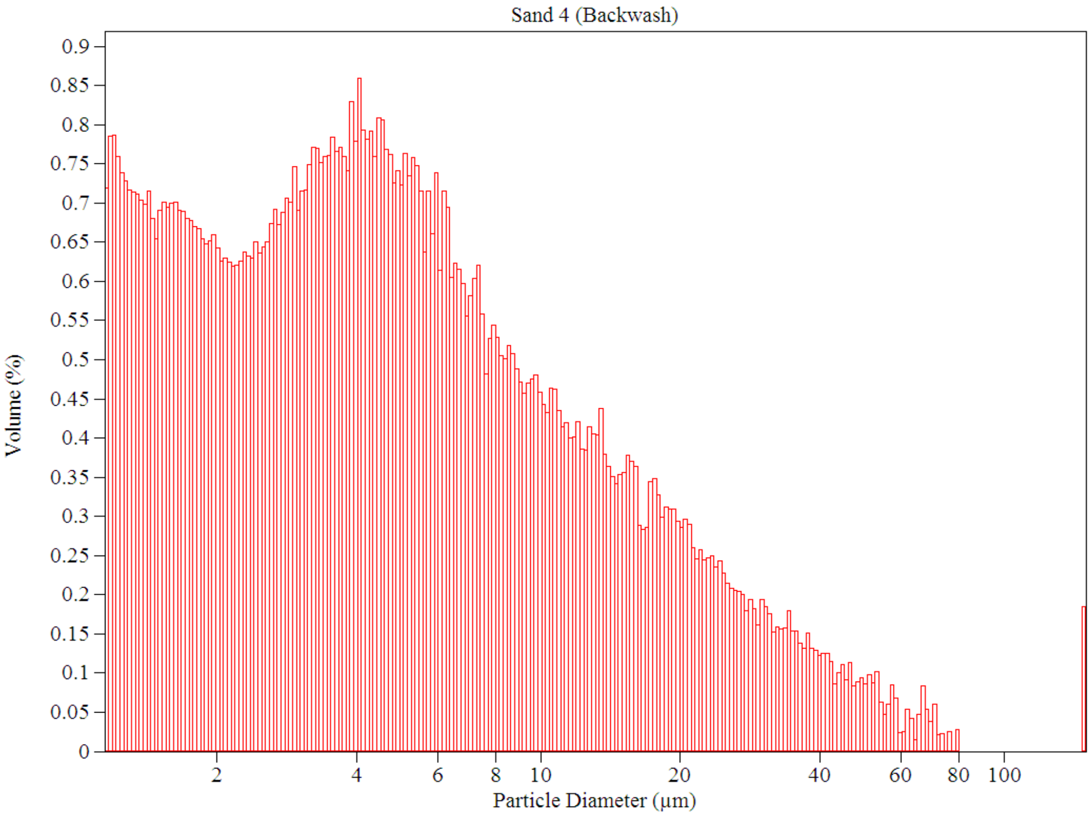


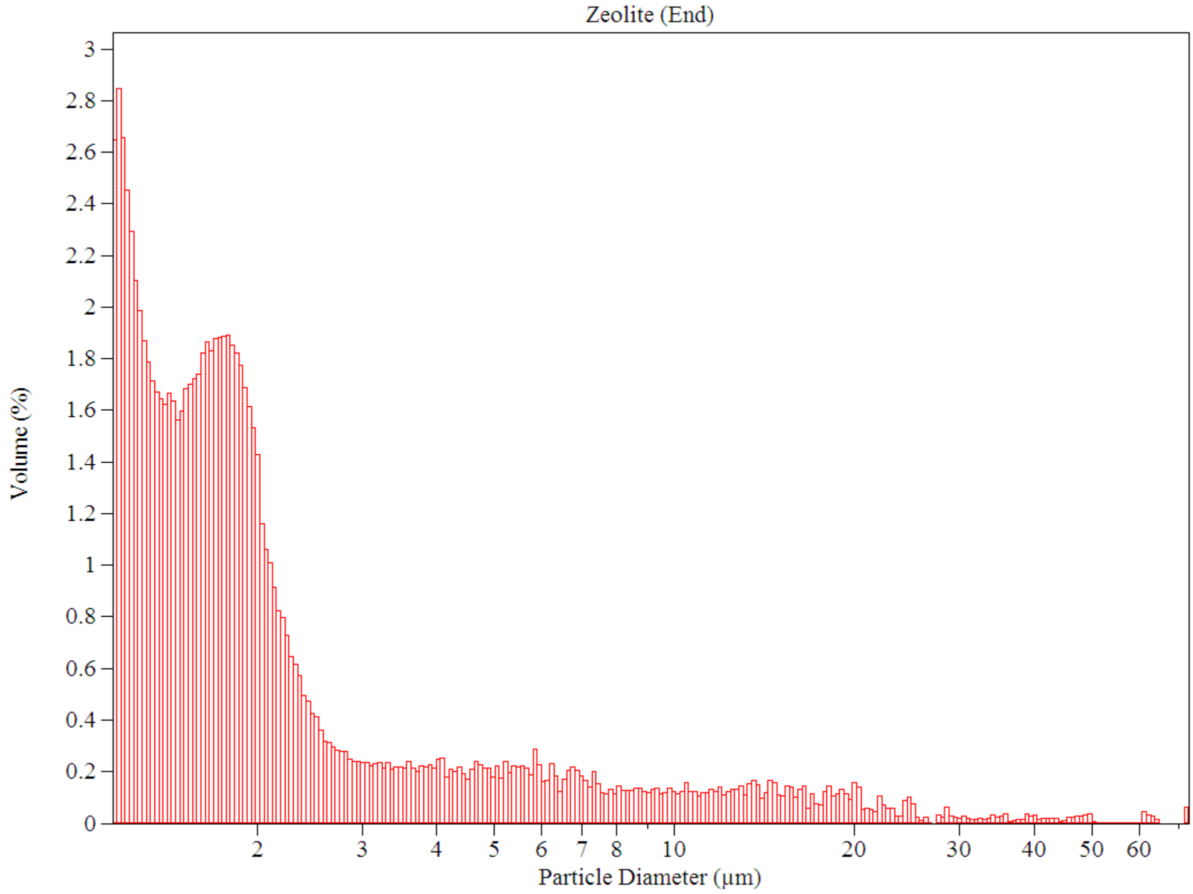
DK4 (End)
Volume (%)
0
0.5
1
1.5
2
2.5
3
3.5
4
2
4
6
8
10
20
40
60
80
100
Particle Diameter (μm)



DK5 (Backwash)
Volume (%)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
2
4
6
8
10
20
40
60
80
100
Particle Diameter (μm)


Sand 3 (End)
Volume (%)
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2
4
6
8
10
20
40
60
80
100
Particle Diameter (µm)


Sand 4 (Backwash)
Volume (%)
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2
4
6
8
10
20
40
60
80
100
Particle Diameter (µm)


Zeolite (End)
Volume (%)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2
3
4
5
6
7
8
10
20
30
40
50
60
Particle Diameter (µm)

Appendix D