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Control of Underground Mining Coal Dust Using Wetting Agents

A dissertation submitted by

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ABSTRACT

This dissertation investigates the control of respirable coal dust in underground mining. The project focuses on investigating the various methods of detection and control in the literature review. A more specific insight into the effectiveness of wetting agents ability to control the fine dust particles is explained throughout the report. The report investigated the necessary theory to conduct wind tunnel experiments, looking at the fluid mechanics of the coal dust. This would then be compared to the data collected from the experiment stage and analysed to show the effectiveness of surfactants working in a wind tunnel environment.

From the testing that was conducted, both positive and negative results were found in relation to the surfactants ability to reduce the horizontal distance the coal particles travelled. The neutrally charged non-ionic surfactant was found to be slightly advantageous over both the positively charged cationic and negatively charged anionic surfactants. The water control stayed consistent with the literature found and proved to be the least effective. Although results were obtained there was large question about the integrity of the results and their reliability. It was therefore recommended that for any conclusive statements to be made that the methodology of the experiment would need to be improved and the tests redone on a larger scale. This report does however server as a guide for future works to better understand the behaviour of respirable coal dust in an underground environment.

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Samuel Hawkins

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CHAPTER 1 INTRODUCTION

1.1 Outline of Study

The need for underground dust control was found when a representative from Rio Tinto suggested that a problem was occurring at an underground coal mine in Central Queensland. It was identified that continuous miners (a machine used for cutting through rock and coal) generate large amounts of dust which can build up where the operators are working. Continuous miners use water to combat this issue, however the addition of specific chemicals added at the surface, can be more effective at controlling dust. There are complications associated to this method, as the chemical can cause dust to build up in the pipes, leading to blockage in water pipes that also feed into the machine's critical cooling systems. In order to address this issue, surfactants must be analysed to discover if their presence is effective at controlling the dust, or if their application are the cause of other complications. A method to better control the issue of coal dust around the continuous miners and also throughout the mine.

1.2 Introduction

Controlling coal dust is an ongoing issue for modern day mining industry. Coal dust not only increases the deterioration of machines through rust on metallic parts, but can also cause long term health problems for humans. As the need for energy continues to grow, so must our commitment to the research and development in regards to safety. Australian mining has built a reputation for having high safety standards, however more can always be done to prevent future issues arising. Mining is a profitable industry, but when a machine is not in operation, it can cost the mine tens of thousands of dollars. That is why it is so important that machines are made to be reliable. The health of workers is another area of great importance, and this means controlling the dust around the work areas. The most vulnerable point of operation for any mine (or any large scale operation) is its workers.

As engineers, potential problems need to be found before they can become a greater issue. A way to solve the big picture problem would be to make as much of the process autonomous and remove the workers from any threat to their health. In a perfect world autonomy would be desirable, however, the reality is complex and the industry still has a way to go in terms of development. Despite great progress in the use of robotics and autonomy, it does not solve the immediate problem of how to keep human workers safe in mines.

With any improvement to safety, the solution must aim to have minimal negative impact on current production levels. Underground mines are a series of intricate processes that allow for the coal to be extracted as quickly as possible. Simple tasks such as shift changes are even carefully planned methods that allow for machines to continue working while a new group of workers take over. For this reason, any proposed changes to current methods are weighed heavily to make sure that they maximum advantage for minimal disruption.

1.3 The Problem

The primary objective of this study is to investigate and better understand how to combat and control dust generated from underground continuous miner machines. The study is based on the specific requirements and conditions of one particular mine operated by the Rio Tinto Mining group. Used as a case study, the findings are designed to be applicable to various mines operating under different standards and machines.

The project was is an attempt at better controlling underground dust around continuous miners. Underground machines already utilise existing spray systems that use water to collect dust in much the same manner that a maintenance team would use on dusty dirt roads. Coal dust however, has different properties to dirt and other minerals that allows the water to slip off the coal particle and continue to be suspended in the air where workers may inhale it. There are chemicals (soaps and foams) that are commonly added to the water systems in mines to compensate for the coal properties, and drag the dust to the floor of the mine. These chemicals are added to the water at the surface of the mine before they are then distributed. Although this system works in the short term, eventually the pipes that feed the system become clogged with dust collected from the water. The purpose of this study is to find a determine better ways of controlling respirable coal dust using either water or wetting agents, including what is an optimal dosage to apply them at.

The report will look at the methods currently used for controlling dust, in order to give a better understanding of what recommendations the industry could take on. To do this, an in-depth look into surfactants was undertaken. From which, experiment were designed and used to test the characteristics of the various surfactants.

1.5 Summary

This dissertation aims to investigate, analyse and come to a conclusion on the effectiveness of current dust control methods. The experimentation uses a Sandvik MB650 Miner Bolter (continuous miner) which serves as a demonstrator in order to investigate the effectiveness of current methods.

Research into the control of coal dust is expected to increase the health and safety of workers in underground coal mines. With an increase in health for the workers being the main objective, the objective of the study is to minimise the time dust may be suspended for.

The success of this project would enable Australian coal mines to improve the working conditions for their employee's safety and long term health. With the increase in cancer (black lung) cases in Australian mines, this study should prove to be beneficial.

CHAPTER 2- LITERATURE REVIEW

2.1 Introduction

This literature review covers the many topics of investigation around the underground mining dust control (UMDC). This dissertation focuses on the investigation and testing, with respect of the many concerns such as coal dust and chemical sprays which are thoroughly analysed.

2.2 Australian Mining

Mining in Australia plays a very large role in the economy, however what most people don't understand within the mining industry is the conditions and environment that mining generates. Within mining there are various resources that are extracted from the ground and numerous processes that are used to do this. Mining as a whole makes up eight percent of Australia's GDP and 60 percent of its exports. The coal industry directly employs around 55,000 people, which is why safety in mining is no small matter.

Within coal mining there are two main processes of extraction; open cut mining and underground mining. These two methods are quite different and can change according to the quality of coal, but predominantly the depth of the coal dictates that method used. Open-cut coal mining is the process used for above ground operations, and is usually carried out using very large machinery. The top soil is removed from a combination of blasting and digging until the layer of coal or coal seam is exposed. This method is cheaper than underground mining, depending on the depth and location of the coal. For coal seams that are less than the 70m below the surface it is generally the preferred method. Once the coal seam reaches the 70 meter mark, open-cut mining becomes uneconomical and companies decide to move to underground mining. Underground mining (as the name suggests) is mining that occurs below the surface. Where open cut mining removes the top layers of the surface, underground mining does not, it instead digs down to the coal seam by only removing the material necessary for the use of roads and laneways. Underground mining occurs when the coal seam is formed at depths of around 50 meter plus. However there is no real limit to the depth it will mine to (within reason), other mineral mines have reached the 4000 meter mark in countries such as South Africa.

The underground environment is quite different to open-cut mining and as such requires many different procedures and equipment to keep the mine running. The mine that is under consideration for this project uses a process called longwall mining. Longwall mining is the more efficient method of underground mining as compared to pillar mining. Longwall mining uses a robust set of machines to support the roof, while a large cutting machine slides along a track which tips the coal onto a convey belt. This allows for large amounts of coal to be cut when the machine is in operation.

For the longwall to be installed, special machines called continuous miners first come in to dig laneways. These laneways are critical for several reasons. They serve as passages for the conveyor belts to carry the coal away, and they also allow access to the longwall machine as it makes its way down the block. The particular continuous miners used in this project are special machines. Not only do these machines cut through both rock and coal to make the lanes or 'gates', but simultaneously drill and bolt the roof and side walls to avoid any material collapsing in on workers and equipment.

The continuous miner (Sandvik MB650) is an electric-powered machine specially designed for underground road way installations and longwall operations. These miners are electrically and hydraulic driven but are cooled using a continuous water feed that circulates throughout the engine. The water held by reservoirs at the surface, supplies piping running all the way down to the coal seam. This water feeds the continuous miner, longwall machine and also a system of sprayers positioned throughout the mine to keep dust down.

2.3 Coal

Coal by definition, is a naturally occurring mineral found in the various layers of the earth relatively close to the surface. It is defined as being more than 50 percent carbonaceous (carbon) matter, formed by the extreme compaction of altered plant remains. The process of coal formation can take as little as 2.6 million years however these are the less valuable varieties such as brown coal. Older era coal are approximately 360 million years old. The coal quality depends on many different factors, these range from the plant type that dictate the coal type, the degree of coalification which determine the rank of the coal, and finally the range of impurities which influence the coal grade. The process in which the coal is formed can have large effects on the way the dust must be controlled. This is due to the properties of the coal, the way they react with chemicals, and the charge the coal holds.

Coal also contains a lot of gases per unit compared to other combustible materials, which is in part why coal is such a great source of energy. Coal contains three main types of gas one of which is very dangerous. Methane or CH_4, is the main gas that is contained within coal and is also very flammable. Other gases include Oxygen O_2 and Nitrogen N_2. The mineral can contain around 50 percent methane when being mined, which is why coal mining must abide by strict rules and regulations. In underground mining the specifications are even more stringent. When mining is in operation methane levels underground may reach so high that an ordinary vehicle engine may continue to run off the ambient air and methane mix that surrounds them. For this reason only special vehicles that have modified engines are permitted to operate underground that have air and fuel cut-off switches. These vehicles also have special exhausts to prohibit even the smallest flames from making contact with the surrounding air. These strict regulations also mean that there is a lot of control as to what chemicals are permitted underground, thus eliminating a lot of wetting agents.

Coal dust continues to cause the mining industry a great deal of issues. Most dust (soil) can easily be contained using water to create a bond between the soil particles, which in turn makes the particles heavy enough to avoid becoming airborne. Coal however is unique in the way that it is hydrophobic or water repellent. Due to this phenomena, it makes the controlling coal dust extremely difficult and more so in underground mining where there is no wind to carry away the fine particles.

2.4 Effects of Coal Dust

Coal dust is no new problem in the world of mining. Although our understanding of coal dust and protections from it has substantially improved, the mining industry still faces the same hazards that have existed for the last 400 years. Recognition of the adverse health effects of coal has been known for some time. Inhalation of coals dust, especially during mining, has caused thousands of cases of health problems and more specifically lung diseases that are only associated to coal and no other minerals (Collis and Gilchrist, 1928 ; Heppleston, 1947). Pneumoconiosis is the disease that is caused by the inhalation of the dust (is more commonly referred to as Coal Worker's Pneumoconiosis (CWP)), affecting the lungs of the body and often resulting in severe cancer. This disease is quite vicious on the human body by inducing lesions on areas of the lungs where gas is exchanged. The disease is grouped as black lung along with obstructive lung diseases such as emphysema which are all commonly found in mining environments. In 1982 a study found that there was a direct relationship between the amount of coal dust inhaled into the respiratory system and the brutality of CWP (Hurley at el., 1982).

There are five factors that are said to initiate and accelerate the disease and Frankelman et al, (2002) describe them as-

- Inhaled coal dust concentrates at the bifurcations of the respiratory bronchioles.
- Local inflammation results in the accumulation of phagocytic cells (alveolar macrophages) that scavenge coal dust particles, forming lung lesions known as coal macules.
- With further exposure, coal macules enlarge to form coal nodules.
- As the lesions condense, surrounding tissue is torn forming scar emphysema.
- Connective tissue becomes associated with these lesions leading to progressive massive fibrosis (PMF).

Controlling the volume of coal dust entering the lungs will definitely reduce the rate of black lung from affecting the work force. However there are some other factors that are still taken into account that also vary the severity of the disease. Most of these factors deal with the specific type of coal being mined. Such as the metal content in the coal, and the correlation of miners who work in mines with higher rank coal have five times the chance of developing CWP as compared to those who are exposed to lower rank coal (Bennett et al., 1979). Other minerals have been found to have minor correlation between CWP such as silica giving a small rise and clay coating on dust particles lowering incidence rates.

2.5 Coal Dust Control Methods

Controlling coal dust is a major part in any operation and to be effective usually requires multiple techniques to physically control the dust. Methods such as mechanical scrubbers, spray nozzles, wetting and digging techniques are currently used in mines to combat dust.

2.5.1 Mechanical Scrubbers

Mechanical scrubbers have played a large role for continuous miners. They allow for the ventilation of air between the cutting operation and the rest of the mine. Mechanical scrubbers are a vent where the polluted air containing contaminates (coal dust), is forced through a filter. Sometimes multiple filters are used in series as well as single action filters. The filters are wetted with water sprays situated in front of the filter panel, which allows for the dust particles to be captured at this point. At the point the particles are removed, the clean filtered air is discharged toward the rear of the continuous miner and is allowed to circulate through the mine. The specific filters inside the scrubber directly influence the performance of the device. The density of the filter and the type of medium used dictate the efficiency of the dust removed and it can be achieved as high as 90 percent.

Although scrubbers have high efficiencies and are capable of handling large amounts of dust they also experience larger maintenance issues. Mechanical scrubbers are said to lose up to a third of the volume airflow after one cut faze (Schultz and Fields 1999). This lose in efficiency stems from the clogging of the filter which forces the continuous miner to shut down temporarily when cleaning is required. Another decrease in efficiency is encountered when the spray nozzles used to wet the filter are not correctly aligned and portions of the filter are not wetted allowing for particles to flow through. Common practice for scrubber cleaning involves cleaning the wetted filter with water twice a shift (12 hours). Once a shift totally replacing wetted filter with back flushed dry filter, also washing the inlets of the vents and ducts with water. Finally once a week the sump, demister and venturi must washed and by doing all this should give maximum efficiency.

2.5.2 Cutting Bits

Stopping coal dust after the coal face has been cut is not the only technique that the industry uses to combat dust. The bit type of the cutting teeth is a critical factor in underground coal mines and can dramatically upset the volume of dust concentrations. Dust is generated at the cutting face when the carbide teeth are worn down creating a flatter cutting angle thus rubbing the coal face more than cutting it. Cutting bits vary slightly however the general principles remain relatively similar. The best angle of attack for the bits ranges from between 30°-45°, this gives the smallest area of contact between the coal and the bit and allows the coal to break off the face with less force. Other factors affect the volume of respirable dust produced by the cutting bit such as the depth of cut. Studies have found that deeper cuts generate larger coal chips while reducing coal dust. Optimal bit spacing also has substantial affect. Bit spacing varies from each machine, however there is a set ratio of bit spacing to cut depth that must be used linearly around the barrel.

2.5.3 Spray Nozzles

Water sprays are currently the most used method for controlling coal dust on both continuous miners and longwall machines. Water sprays are primarily for fire control and cutting teeth cooling however give partial dust suppression as a secondary use, to areas that are difficult to access such as the cutter head and conveyor track. Various nozzle types perform different tasks and most systems incorporate a combination of nozzle types to handle the situation.

Full cone nozzles provide a circular area spray pattern at high velocity which gives the spray trajectory distance as well as coverage. This nozzle type produces a medium to large droplet size which allows for greater distance but less chance of the water wetting the dust particles. Hollow cone as the name suggests, produces a hollowed cone pattern which equates to a ring like spray once it hits the material. Theses sprays produce small to medium size water droplets and increases the chance of saturating the dust. Hollow cones are the most commonly used nozzle type primarily for their anti-clogging characteristics which can be a serious problem in the machines. Solid stream nozzles create a single fast stream of water that has a greater effect even at distance. Despite being more effective at long distances, they are commonly found on the cutting head and in the cutting bits themselves. Having the solid steams close to the cutting area surges that coal with excess water, suppressing the respirable dust before it become airborne. Flat fan nozzles give a wide but flat pattern of water that produce small to medium droplet size. These nozzle types are generally used in narrow areas such as along the sides of the machine but are also effective along the conveyor systems. Flat fan nozzles are another nozzle used more specifically for dust suppression rather than fire prevention. Finally, air atomising nozzles can be used in certain situations which require a very fine mist. Although air atomising nozzle types are the best for dust suppression, these nozzles are not as common as others due to the extra equipment needed such as either hydraulics or air to assist them (Colinet, Rider, Listak, Organiscak and Wolfe 2010).

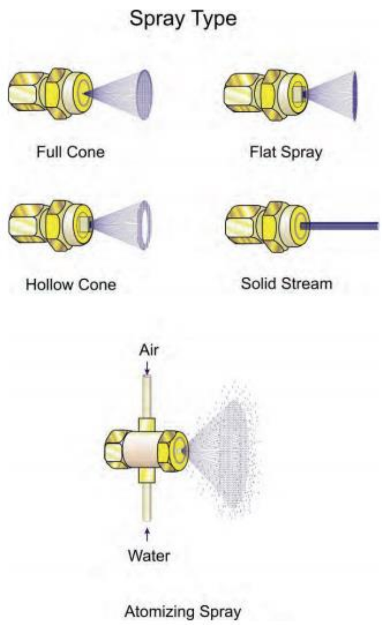


Figure 2.1- Various types of nozzles used on continuous miners (Colinet et al. 2010, Fig 4-1 page42).

Depending on the manufacturer, many of these machines use these nozzle types in combinations. However there are large limitations to the effectiveness of nozzle and water solutions. Because water is hydrophobic (water hating) sometimes all these nozzles achieve during operation is to push the particles around vigorously. Such a phenomenon is known as rollback and is a common occurrence in underground mining even today. Rollback allows the respirable dust to be shot back behind the miner to the operator's position and eventually through the rest of the mine. To eliminate rollback sprays should be located on, above and below the cutting drum. By decreasing the distance the water droplets move, less turbulence is created therefore the dust particles have less chance to be pushed around and expelled out behind the miner. Studies have found (Schroeder et al. 1986) that dust can be reduced as much as 40 percent by relocating the nozzles to the move affective potions.

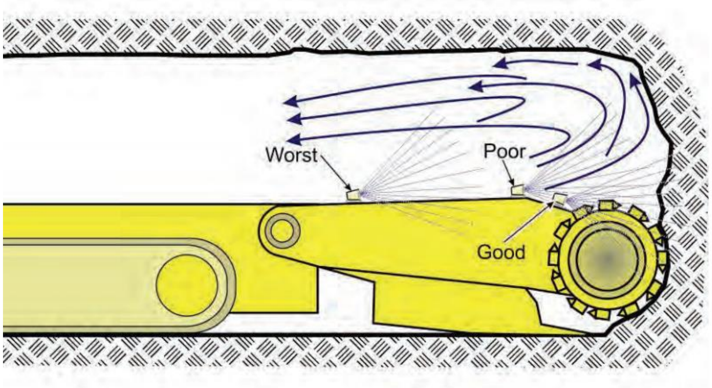


Figure 4-3.—Spray location impact on dust rollback.

Figure 2.2- Showing the effects of spray nozzle location on continuous miners (Colinet et al. 2010, Fig 4-3 page 45).

Research has been conducted into stopping rollback by using lower pressure sprays. High pressure sprays above 100 psi tend to circulate the dust rather than wet it. A majority of the dust should be controlled within the first 30cm of nozzle to cutting face. After this point most respirable dust is rarely controlled using water sprays but positioning flat fan sprays within that 30cm range behind the cutter barrel does show more effectiveness at control and also a secondary benefit of better fire prevention.

2.5.4 Surfactants

Surfactants are a relatively new technology in underground mining and are only sometimes used to combat respirable dust. Surfactants are a chemical wetting agent that is added to the already existing water spray. These agents are specifically for dust suppression in mining and solve many of the problems associated with coal wettability. These agents work by reducing the surface tension of the water, allowing the coal particles and water droplets to bond, thus forcing the dust to fall out of suspension. Some studies have found reductions of 31 percent using only 0.013 percent concentrations of water to agent mix (Hirschi et al. 2002).

2.6 Coal Dust Sampling Methods

Coal dust of the size of 100μm (micrometre or 1x10^{-6} m) or smaller in diameter are defined as float dust or dust that is able to suspend itself in the air, which also makes it hard to measure and detect. This size of dust is the main concern of this dissertation as it is the dust that is capable of inflicting harm on workers. Up until 2000's, dust sampling for mines was done using a brush and pan that took samples off the roof and floor much like a person would cleaning their house. This method is still sometime used however other methods are also used to give better individual readings of personal exposure. For more advanced dust monitoring solutions there are digital dust meters that can be hand held for easy monitoring. However there is some doubt as to accuracy and translation from dirt to coal environment due to their different characteristics.

Because dust levels are not always consistent, samples should be taken at various times over any shift to gain an average reading. Good mining practices would see multiple measurements being taken at various locations both close to and around the miner and throughout the rest of the mine to be thorough. This is not just for safety but rather checks for anomalies that could be altering results such a rollback and changes in geometry of the mine.

2.6.1 Gravimetric Sampler

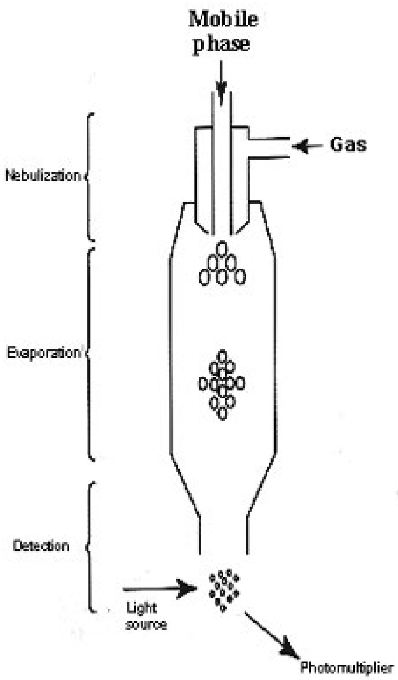
Gravimetric sampling is the most commonly used device for respirable dust measurement in the U.S. and Australia. The device uses a constant flow pump, which pushes the air through the device. The variable cyclone which separates the large coal dust particles from the smaller more harmful respirable dust, where there is variation in opinion but is generally considered to be 74μm in diameter or smaller. Once the large particles have been separated the final contaminants are blown into a PVC filter. These filters are then weighed to determine the mass of dust collected during operation. The mass of the dust is then calculated against the volume of air that was pumped to give a measurement in mg/m^3

(dust/air). The Queensland Coal Mining Safety and Health Regulation of (2001), states that workers must not be exposed to more than 3 mg/m^3 and $0.1 mg/m^3$ for free silica during an 8-hour period or equivalent for extended periods.

Figure 2.3- Gravimetric sampling pump, cyclone and filter assembly.

2.6.2 Light Scattering Method

Light detection is an accurate way of measuring the dust concentration at any particular time. Measuring the dust vie a mechanical means creates abnormalities in tests due to the fluid mechanics of coal dust acting in the air. This is why light sensors are a much more accurate method for measuring the dust samples. Personal DataRam (pDR) are another



device that can be used in dust concentration sampling. These devices are much more compact and less labour intensive than gravimetric samplers which makes them attractive for people to carry on their person. PDR's use scattering light to detect the volume of dust in the air. They work by measuring the amount of light scattered from the solid particles suspended in the air during after evaporation and nebulization (Dreux at el. 1996). These detectors can be used for solutes (particles in solution) that having a lower tendency to evaporate at room temperatures. Scattered light detectors are limited to the size of particles that are measureable and go beyond their capabilities at a range of Nano-gram's. The larger the dust particles that are absorbed during mobile phase, the higher the intensity of light scattered. During operation of the device, physical properties of the liquid, relative velocity and flow rates of the gases and liquids are crucial to give a final reading.

Figure 2.4- Light scattering detector process taking measurements of particle's in air samples.

The benefits of pDR's is that you can obtain a reading instantaneously as compared to a gravimetric sampler which require the results to be processed in a lab and not giving real time values. However one of their drawbacks is that they must be calibrated using gravimetric methods.

Figure 2.5- Personal Data/Ram device for measuring particle concentration.

2.7 Control Spray Chemicals

Chemical control sprays have been known about and utilised in coal mining for a long time, more specifically for the suppression of coal dust in above ground operations. These chemicals are surfactants that are mixed into the water system which is then sprayed over the coal. Surfactants offer many advantages and are relatively simple chemicals to manage. Due to certain properties such as health risks, surfactants are sometimes prohibited from use in underground operations which is why these chemicals are not widely exploited in underground mining.

2.7.1 Surfactant Charge

Surfactants are used for many different applications other than just dust control, because of their unique effects on water they are commonly applied in plant chemicals and even everyday items such as soaps and detergents. Chemically, surfactants are hydrophilic (they like water) and have a great affinity for polar solvents. They are also lipophilic (fear of grease), which combined with hydrophilic, gives these chemicals a dual friendship. This friendship allows the chemical to lower the surface tension of water when mixed. Surfactants fall under three classifications of Anionic, Non-ionic and Cationic. Anionic surfactants (Negatively charged) are the most commonly used of the three, and separate there amphiphilic (water hating and water liking) cation and anion when in water. They make products such as detergents, fatty acid soaps, foaming agent and wetting agents. Non-ionic (neutral charge) surfactants are the next most commonly used of the classes refuse to ionise in water. Finally Cationic surfactants (positively charged) act much like anionic surfactants in that they separate their cation and anion in water but do so as a halogen type (Salager 2002).

Looking at previous studies it can be seen that the characteristic charge of the surfactant has a great influence on the outcome of the results. In a study conducted by Tessum & Raynor (2016), showed that there is a significant difference between anionic (negative charge), Cationic (positively charged) and non-ionic (no charge) surfactants in control of respirable coal dust. The report heavily investigates the electrical effects of the coal and the effectiveness of the surfactant when positively or negatively charged. Highly charged coal particles are some of the main concern for combatting health affects as it they have greater ability to penetrate further into the human lungs as compared to large low charged particles (Tessum & Raynor 2016).

Other studies have also suggested that electrical charges in the coal have impacted the behaviour and efficiency of coal dust suppression surfactant sprays. It is said that the charges that the coal poses can vary from mine to mine depending on its coal and environmental characterises. These factors include ambient humidity, moisture, dust characteristics (e.g. sulphate level, mineral level), process method and particle size. Looking at the effects of charge, the mines individual characteristics play a large role in the effectiveness of surfactants. Some coals will respond differently to other products on the market given their chemical makeup, suggesting that there is no one solution for any application. Tessum et al 2014, found that generally non-ionic surfactants worked best for weakly charged respirable coal dust particles in the range of 0.6-2.1 μm in diameter. However for strongly charged particles, ionic surfactants were the most effective. This may indicate that depending on what dust size that is target, may also dictate the chemical used.

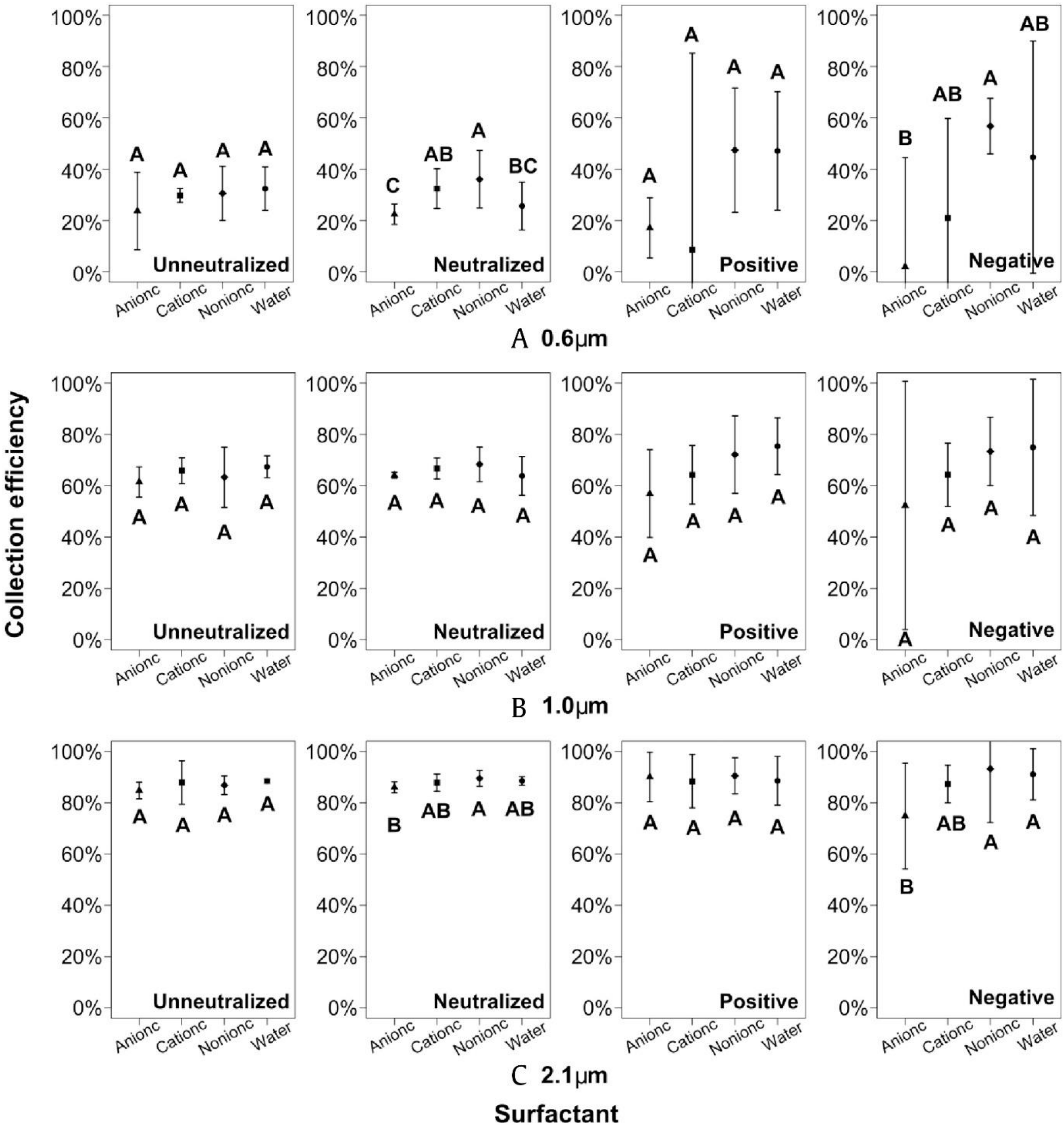


Figure 2.6- (Tessum & Raynor 2016) effectiveness of using anionic, cationic, non-ionic and water aerosols to control respirable coal dust with different electrical charges and dust particles sizes.

2.7.2 Mechanism of water penetration

Water can have a lot of trouble penetrating the pores of coal. This is caused by a number of factors that help the coal body accept or reject the water. Pressure of injection and capillary force have a large influence on the success of the water entering the pores. The capillary force pressure *P_c* relates the surface tension λ of the water and contact angle *cos ϑ*. It can be seen in the equation below why the two parameters are so crucial (Li, Zhou & Liu 2016, page 194) and why we need surfactants to aid the water in dust control.

$$P_c = 2 \lambda \cos \theta / r \text{……..equation 2.7.1}$$

Where P_c is capillary pressure, λ is surface tension, θ is the angle on contact and r is the radius of the coal pore.

2.7.3 Surfactant Type

Choosing a surfactant can be split into the three main groups that are known of cationic, anionic and nonionic. The three classes each hold a positive (cationic), negative (anionic) or neutral (nonionic) charge. Many house hold items contain one or more of the groups in other forms of compounds. The advantage seen in using house hold products is there general safety for human use. Many of the surfactants that are used in domestic applications are less harmful than industrial surfactants which often cause irritation to skin. However, there are still house hold surfactants that do give concern for human health which should be avoided to create any secondary health issues. House hold surfactants are also widely available due to their extensive use in detergents. This often makes them a cheaper than some of their industrial counterparts.

Anionic Surfactants

Anionic surfactants are the most widely available being found in products such as detergents and cleaners. Anionic surfactants contain one or more of the following elements.

- Sodium
- Ammonium
- Magnesium
- Sulfate
- Sulfonate
- Gluconate

These elements can be found in compounds such as sodium lauryl sulfate, linear alkyl benzene sulfonate, dioctyl sodium sulfonate and alcohol ether sulfate (Sioris, L).

Cationic Surfactants

Cationic surfactants are much less common and only account for about 5% – 6% of world surfactant production. Their uses range from a wide field, however they do not make very good detergents unlike anionic and nonionic surfactants. Cationic surfactants are used for purposes such as corrosion inhibitors. Their main use comes from them being a bactericide, which makes them a disinfectant and are often used at hospital level.

- Chloride
- Bromide

These elements can be found in compounds such as alkyl benzene chloride, alkyl dimethyl ammonium chloride and cetylpyridinium chloride (Sioris, L).

Nonionic Surfactants

Nonionic surfactants make up a large portion of total world production, like anionic surfactants they are widely used in cleaning applications. They are mostly used to for their neutral charge characteristics which bind well with extremely small particles that don't hold a strong charge.

- Ethoxylate
- Alkoxylate
- Cocamide

Examples of these can be found in compounds such as alkyl ethoxylate, nonyl phenol ethoxylate and polyethylene glycol stearate (Sioris, L).

2.7.4 Dosage

As there are different products out on the market today that all claim various efficiency's, not all of them work for any one specific situation and can have varying effects to one another and all work at different dosages. Previous studies have shown that there is considerable differences of wettability using water and other wetting agents. These studies even show variations between the different products on market. Field testing is expensive which is why most of the research done so far has been laboratory based. However, from the previous research that has been conducted, most dosage rates have been within the range 0.01% and 0.5% concentration rates. A more specific example was conducted by Kost (et al.,1980) where reductions in coal dust of 27% were achieved using low concentrations. From these in field tests, the results proved to be convincing that wetting agents are a viable solution to given that they are also cost effective. More recent studies conducted by Organiscak (2015) examined three improved wetting agents. Sample A was a non-ionic wetting agent and also a homogenous blend of colloids (large particles dispersed through a second substance). Sample B & C were anionic surfactants, with sample B being a blend with polymers. These agents were applied at concentrations of 0.05%, 0.1% and 0.2% using straight water as a control. The results which can be seen in table 2.1, show variation between the three however indication a positive decrease in time that respirable dust is suspended, with water showing little to no improvement.

Table 1- Keystone Mineral Black sink times with the various wetting agent solutions

Wetting Agent	Water Sample	0.05% Solution	0.1% Solution	0.2% Solution
Sample-A	>900 sec	847 sec	385 sec	191 sec
Sample-A	>900 sec	897 sec	356 sec	215 sec
Sample-A	>900 sec	845 sec	378 sec	173 sec
Sample-B	>900 sec	>900 sec	>900 sec	1,204 sec
Sample-B	>900 sec	>900 sec	>900 sec	1,297 sec
Sample-B	>900 sec	>900 sec	>900 sec	1,214 sec
Sample-C	>900 sec	>900 sec	>900 sec	1,279 sec
Sample-C	>900 sec	>900 sec	>900 sec	1,304 sec
Sample-C	>900 sec	>900 sec	>900 sec	1,320 sec

Other studies conducted by Li, Zhou & Liu (2016) showed that the use of an anodic wetting agent was effective. Although their tests did not release time efficiencies they did see a reduction in respirable dust of 30 percent and a reduction of total dust by also 30 percent when compared to using no wetting agent.

2.7.5 Contact angle

Surfactants although having many characteristics that influence their effectiveness, sever the major purpose of lowering the surface tension of the water to allow a bond to form. Water droplets form a strong round sphere naturally and when it comes in contact with objects the droplets resist any shape change. Contact angle is influenced by the surface roughness of the particle, the particles size and the surface chemical heterogeneities (Qingzhao at el.2012). Qingzhao also suggested, from the testing results shows that contact angle increases extensively with decrease in particle diameter. What this implies is that the wetting ability of fine coal particles is much harder than larger particles due to the increased contact angle. For particles of 10μm or less, wettability drastically diminishes and makes suppression extremely difficult.

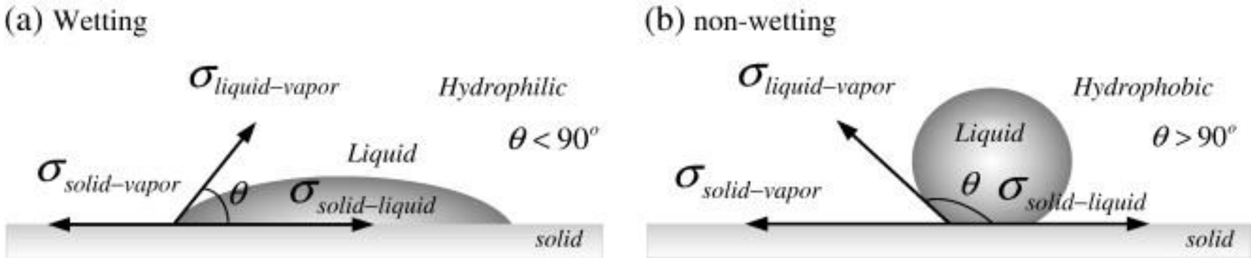


Figure 2.7- The contact angle of a liquid against a solid. Contact angle is small for wettable liquids (hydrophilic) and large for non-wettable liquids (hydrophobic).

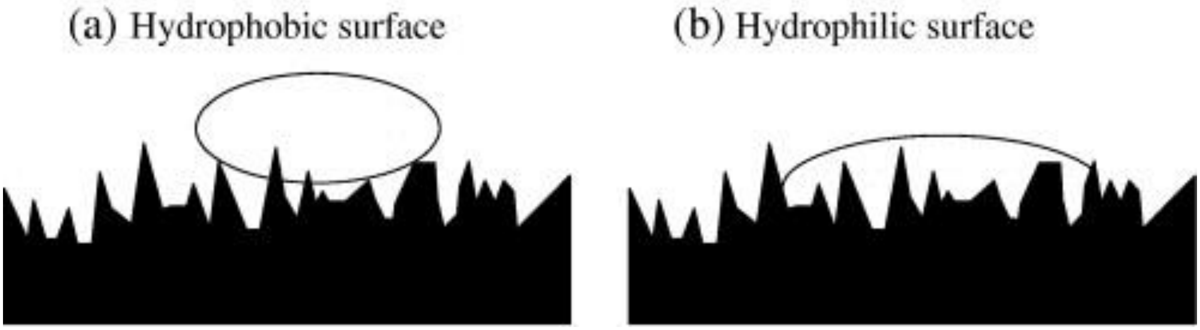
The way in which the contact angle relates to the surface tension of the water can be seen in Young's equation. The equation allows engineers to calculate the wettability of any dust particle in relation to a liquid. The equation can be seen below.

$$\gamma_{d,a} = \gamma_{d,w} + \gamma_{w,a} \cos\theta \quad \text{.......... Equation 2.7.2}$$

where $\gamma_{d,w}$ (mN/m) is the interfacial tension between dust and water, $\gamma_{w,a}$ (mN/m) is the interfacial tension between water and gas, $\gamma_{d,a}$ (mN/m) is the interfacial tension between the dust and gas and θ is the contact angle as seen in figure 2.7.2.

Report by Zhou et al. (2016) 2.0, states that during the wetting of a particle, a new liquid-solid interface occurs between the two as a gas-solid interface. From the above equation, that interface explains the importance of the contact angle of the liquid. The larger the angle the smaller the interfacial tension will be. Mineral or coal dust in classed into three categories of contact angles to better show their wettability also explained in the report. With contact angles of less the 75° water-wet, between 75° – 115° are classes as intermediate-wet and contact angles greater than 115° are gas-wet. These classifications allow all mineral miners to determine the correct chemical application requirements.

The coals physical characteristics can have a large influence over the dust's wettability. Coal dust is different to regular dirt dust under a microscope, and it can be seen why coal dust is a hydrophobic mineral as compared to other compounds. The pores on the surface of coal give the mineral much of its hydrophobic properties. Coal has a very rough surface compared to other elements which is caused by an increased pore volume. The physical properties of the coal particle along with electrical charge account for most of the particles



wettability. Figure 2.8 shows how the liquid interacts with dust particles porous structure and the contact angle that is created between hydrophobic and hydrophilic surfaces.

Figure 2.8- Contact angle between hydrophobic and hydrophilic dust particles (Zhou et al. 2016).

A better understanding of coal surfaces can be seen in the figures 2.7 & 2.8. The picture illustrates the roughness of coal particles surface and the pores that are created by this roughness. There is no indication from other reports that coal is classed into surface roughness types. This suggested that the surface roughness is more or less consistent throughout the mineral classes and not so much from sample to sample.

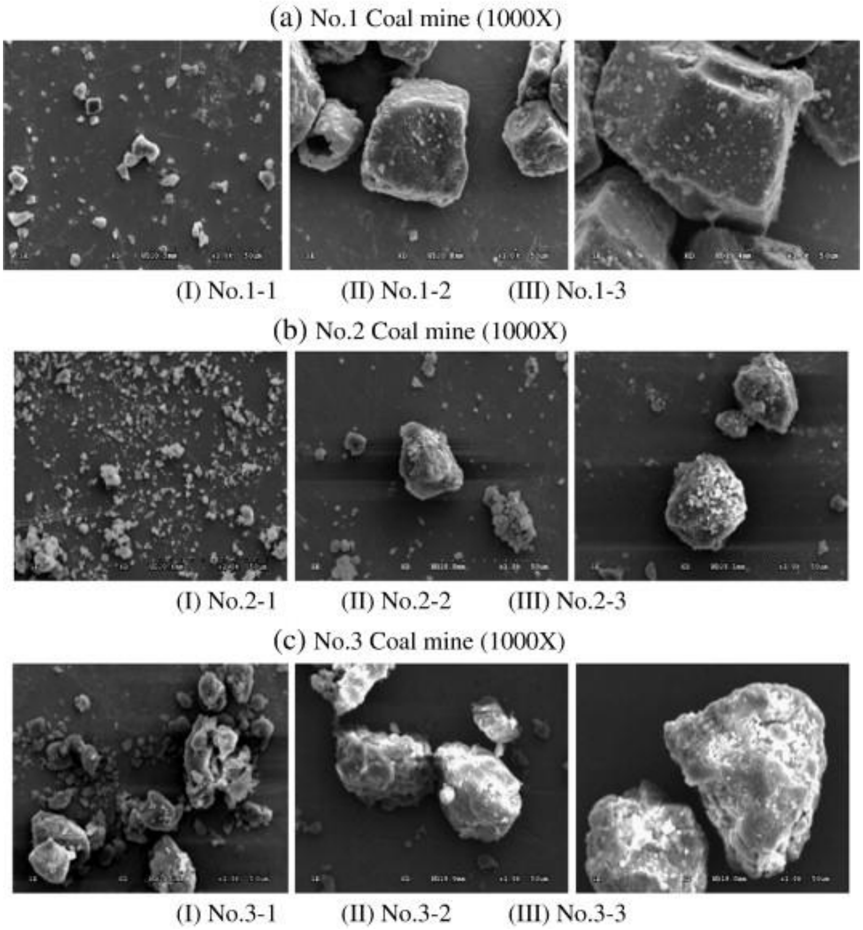


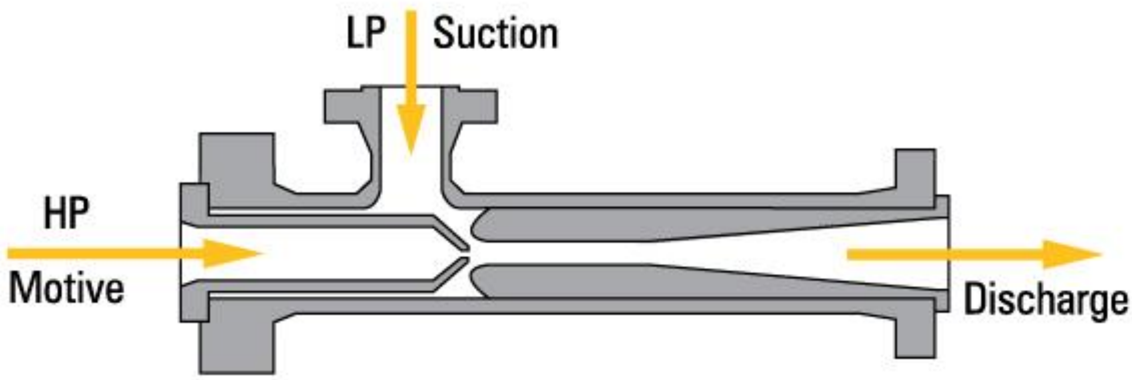
Figure 2.9- Three different coal samples at three different zooms (Li, Q et al. 2016).

2.8 Ejector Nozzles

2.8.1 Ejector Nozzles

This study not only focused on how to chemically control respirable coal dust, but also to solve some of the other problems that are found around dust suppression. Clogging of the water supply system is an ongoing problem found in underground mining. As stated previously in the report, the clogging is caused by the chemical surfactant acting on the dirt particles. This problem is often found in the equipment and solution for this was to remove the chemical from the water supply until the very last point. To do this an ejector nozzle concept was created.

Ejector nozzles or simply ejectors, work on a basis of some simple fluid mechanics. Their purposes have a wide range from chemical mixing to reducing energy consumption in cooling by refrigerant vapour compression. An ejector nozzle works by using high pressure fluid squirted through a larger chamber to create a low pressure or vacuum behind the high pressure flow. The vacuum behind the high pressure fluid then allows for a low pressure



fluid to be automatically extracted and mixed into the high pressure fluid.

Figure 2.8.1: Ejector nozzle, using high pressure (HP) motion to create a vacuum for a low pressure (LP) suction pipe (Transvac 2017).

2.8.2 Ejector Nozzle utility

This device has many advantages over other systems that makes it an ideal solution for mining applications. As stated above, the device only uses pressurised fluid which eliminates the need for any complex mechanical or electrical subsystems to mix the secondary fluid. The device also poses a major advantage and ultimately a solution to any clogging within the pipe work or machine systems with its secondary inlet. The inlet allows the secondary fluid or gas to be added at the point of ejection, keeping the two fluids separated. By eliminating the need for mixing the two fluids prior to ejection i.e. water and the surfactant, it should in theory reduce the occurrence of clogging due to dirt and coal in the water system. However, using these devices in underground mining would require some additional piping and would make the layout of the machines more cluttered having the secondary low pressure hoses. Although being mixed in the ejection chamber the concentration rate can still be controlled allowing for effective use of the wetting agent. Above all they are considered highly reliable, with no moving parts makes maintenance minimal.

A draw back to these devices is that they are generally inefficient due to the changes in pressures. Ejectors usually only reach an energy efficiency of around 35%, which normally would be a big consideration in the design. However, due to the circumstances, the continuous miners work deep below the ground where energy required to pump is small due to pressure created by gravity. At the flow ratio that is required the efficiency is extremely low which can be seen in the efficiency curve however it is still very little in comparison to the pressure due to gravity.

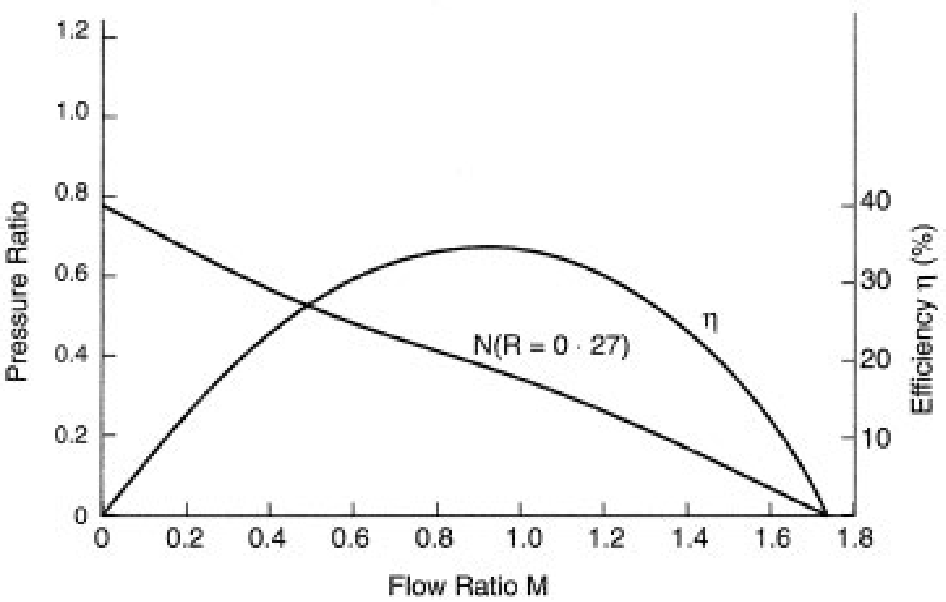


Figure 2.8.2 – Typical ejector efficiency curve chart (Green, A 2011).

3- RESEARCH DESIGN AND METHODOLOGY

This chapter outlines the intended plan, resources and management of the project. The following section will explain the method for testing as well as the apparatus used and the various materials required. A safety analysis is also explained and for all testing and interactive activities.

3.1 Overview and methodology

The following steps were taken to during the project to reach the goal of an improved system for controlling underground dust.

1. Review already existing coal dust control methods and devices for underground mines and investigate their limitations and strengths.

2. Investigate the parameters that influence the effectiveness of dust suppression surfactants.

3. Review coal dust surfactants and their effectiveness of containing coal dust in underground situations.

4. Design and build wind tunnel for testing surfactant effectiveness

5. Wind tunnel experiment: Testing for effectiveness against coal dust. Both water and chemical/water mix. Variable rates.

6. Analysis results and find the most effective, economical or suitable option.

7. Make recommendations based on results from tests to either distribute more water or coal dust spray

If time permits,

8. Conduct secondary testing method of coal water drop test.

9. Test multiple concentrations of surfactant water mix to find efficiency’s.

3.2 Testing

This project set out to analysis and improve methods for controlling respirable coal dust in underground mining. From previous studies it has been found that wetting agents have so far proved to be the most effective method. Although some trials have been conducted, little is still known about the concentration rates of the chemical.

The trials that were conducted tested three wetting agents. These agents would be common house hold surfactants that would demonstrate the difference between the three types. From this, a judgement could be made as to which proves more effective.

Organiscak (2015) used a sink test method to test the efficiency of each wetting agent. A sink test method uses a volume of water, the coal is crushed into very fine particles and then placed on the surface of the water, once released into the water the time is recorded for how long the coal takes to sink once the individual wetting agent is added. This method is the most commonly used method for testing the effectiveness of surfactants. It does not, however, accurately replicate the environment that continuous miners work in which is why for this study a wind tunnel was used to better represent the underground environment.

This experiment aimed to test the effectiveness of one concentration of three surfactants in a wind tunnel situation. The wind tunnel aimed to replicate the environment at the continuous miner with speeds matching that of the particles rolling off the cutting barrel.

3.3 Equipment & Resource List

To complete the research undertaken in project, the following resources were required:

Table 3.1- Resource List

Phase	Item	Amount	Source	Cost
Design	Relevant Mine Material Standards	1 Set	Queensland Mining website	Nil
Testing	Wind Tunnel (PVC pipe Dia 300mm x length 2000mm	1	Reece Pluming	$200
Testing	Elective Fan (simple pedestal fan)	1	Brought from home	Nil
Testing	Test Strips	25m	USQ	$15
Testing	Coal	15kg	Kestrel Mine	Nil
Testing	Camera	1	USQ	Nil
Testing	Fine set of Scales	1	USQ	Nil
Testing	Soil sieve (300μm & 100μm	2	USQ	Nil
Testing	Anemometer (wind speed)	1	USQ	Nil
Testing	Wetting Agent	1 Litre	Hardware Store	$100
Testing	Spray Nozzle	1-3	Hardware store	$10
Testing	Funnel	1	Hardware store	$5
Testing	Length of flexible nosing	2m	Hardware store	$20
Testing	Fire Extinguisher	1	USQ	Nil
Testing	Piping	5m	Hardware Store	$50
Testing	Chemical bucket	1	Hardware Store	$10
Testing	Miscellaneous items	N/A	Hardware Store	$50
Testing	Rubbish bags	10	Super market	$5

3.4 Testing procedure

1. Wind tunnel- A wind tunnel was set up in the USQ laboratory. This wind tunnel consisted of long cylinder with a vacuum at one end. The cylinder was modified for a cone funnel at the start that would release the coal into the tunnel and also a spray nozzle that projected the surfactant horizontally through the pipe.
2. Coal dust- The coal which was sourced from a Central Queensland Mine was finely ground into dust using a fine sieve of 300µm
3. Coal samples were weighed for each test. A sample of 5g was used for each test.
4. The spray nozzle was positioned to sit at the very start of the test section pointed horizontally down the length of the tunnel
5. A pedestal fan was used to give the tunnel the correct air velocity at approximately 1.7m/s.
6. Surfactant was premixed into water at variable rates. Set a 1% for all surfactant tests.
7. **Repeated steps**
8. A 2 meter test strip of house hold absorbent towel would be rolled out the length of the tunnel.
9. Fan would be started (set for air flow at 1.5- 1.8 m/s)
10. The air speed would then be measured and recorded, it would also be corrected if needed.
11. The external town water hose would be switched on to provide the mixing drum with pressure.
12. The spray nozzle would also be switched on with constant stream.
13. Coal will then be released into the testing tunnel
14. Fan and spray nozzle would be switch off.
15. The fan and spray nozzle would then be carefully remove so that photos could be taken down the length of the tunnel for easy viewing.

16. The old test strip would be removed from the tunnel and discarded.
17. The tunnel would be cleaned by pushing a mop down the length of the tunnel.
18. A new test strip would then be added.
19. Once the three tests were completed for the surfactant, the chemical bucket and piping would be emptied and rinsed to remove any surfactant still left in the equipment.
20. A new batch of surfactant would be mixed up at 1% again and the testing would continue.
21. Process would then be repeated for all concentrations.

3.4.2 Wind Tunnel

The wind tunnel was made from a 2 meter length of PCV pipe sourced from a local plumping store. The pipe had a diameter of 300 millimetres which gave a larger distance for the coal particle to drop during testing. The PVC had 180 mm square windows cut from the side of the pipe and replaced with 3 mm (transparent) poly carbonate which allowed for easy viewing.

3.5 Fluids mechanics of Coal Dust

The experiment focused on the basic areas on fluid mechanics of drag force on a particle. The experiment was thought to replicate similar parameters to what a continuous miner would be working in. To find particle velocity, many assumptions were needed to be made with respect to aspects of the miner and how the dust acts in the mine.

3.5.1 Reynolds Number

The particle can be treated as acting in an external viscous flow therefore based on experimental data from charts we can find the drag coefficient C_D. By finding C_D, it can later be used to find the drag force on the particle, which will show the particles trajectory.

The turbulence of the air would have a large influence on the particle and the distance it would travel for the wind tunnel experiments. From fluid mechanics theory, it is stipulated that the larger the Reynolds number Re (higher fluid turbulence) the less drag that the particle will incur. This effect is commonly encountered such a gold balls dimples.

$$Re = \frac{VD}{v} \text{ ....(Equation 3.5.1)}$$

Where:

V - Velocity of fluid or particle (m/s).

D – Diameter of particle (m).

v – Kinematic viscosity (m^2/s).

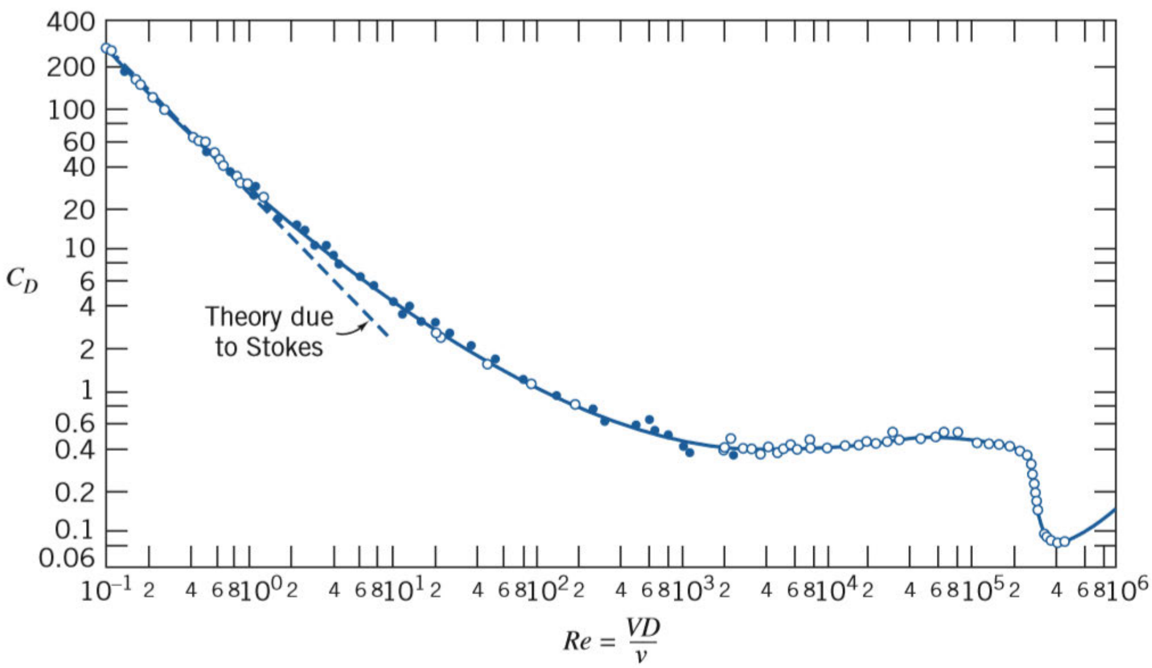


Figure 3.5.1 – Drag coefficient of a smooth sphere as a function of Reynolds number (Schlichting, H 1979).

The Reynolds number gave an indication of how the flow is acting. Taking some assumptions, the Reynolds number could be found at the continuous miner based on ceiling height and other mine conditions.

Assumptions:

- Diameter was taken as maximum height the miner could cut. Although the miner does not cut in circles but rectangles, it was still regarded as accurate for the calculation.
- Temperature was taken at room temperature.
- Velocity of particle was taken to be the linear speed of the cutting drum (see equation 3.5.2).

Particle velocity was found using basic equations seen below.

$$\omega = 2\,\pi\,f \text{ ....(equation 3.5.2)}$$

Where:

ω = angular velocity

f = Frequency

For converting angular velocity into linear velocity the equation below was used.

$$V = \omega * r \text{ ....(equation 3.5.3)}$$

Where:

V = linear velocity

r = radius

For wind tunnel testing, the drag force F_D was found to better understand if the drag on the coal particles would affect the distance the particle would travel.

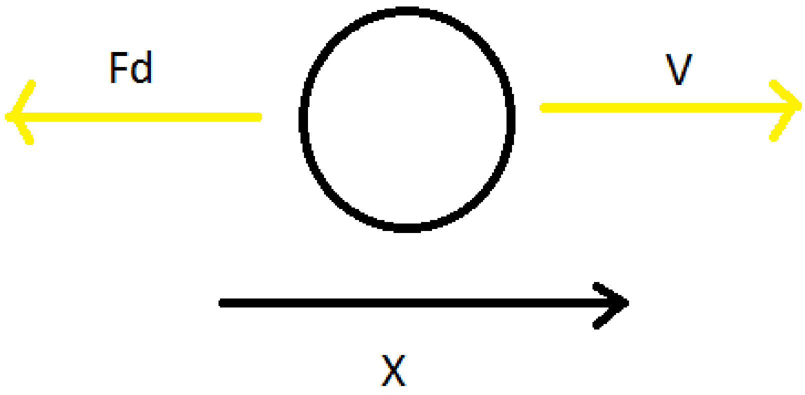


Figure 3.5.2- Forces acting on a particle in motion.

3.5.2 Drag Force

$F_D = ½ * C_D \rho V^2 A$ or $m*dV/dt = m*a = - ½ * C_D \rho V^2 A$ ……… (equation 3.5.4)

Where:

ρ = density of fluid

A = cross-sectional area of particle

m = mass

C_D = Coefficient of drag (see figure 2.9.1)

Equation 3.5.4 can be used to find a drag force. To find a horizontal distance the drag for and the force due to mass are combined to find a resultant that gives an angle. This angle then gave an approximate distance that the coal particle will travel under wind tunnel conditions.

The time for the vertical fall can also be found using the equation below.

$$R = ½ * g * t^2 \text{ .... (Equation 3.5.5)}$$

Where:

R = Height of fall

g = acceleration of gravity (9.81 m/s)

t = time (seconds)

$$\theta = \tan^{-1}(F_D/F_L) \text{ .... (Equation 2.9.6)}$$

Where:

F_D = Drag force

F_L = Lift force (force for weight is this case)

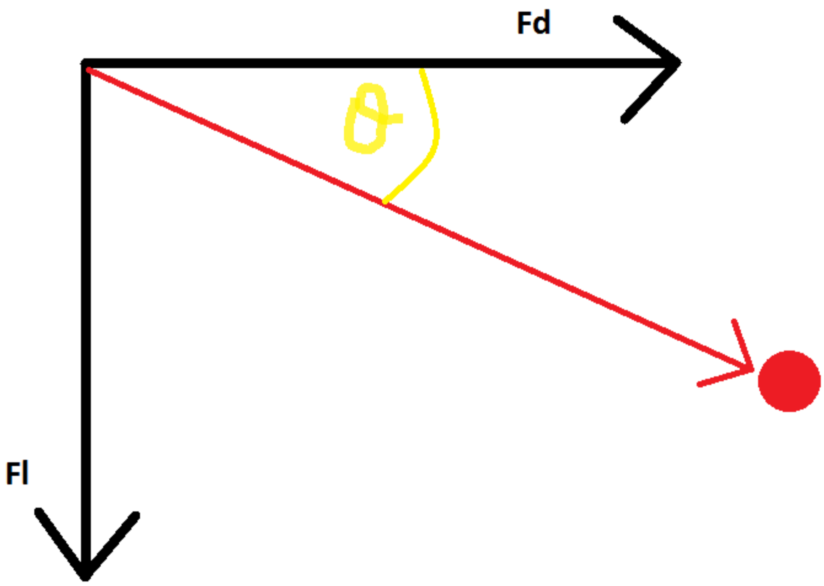


Figure 3.5.3- Trajectory of coal particle.

From experimental data, a coefficient of drag C_D can be found, this then allows the drag force to be found in equation 3.5.4. The coefficient was taken from figure 9.11 of Fox & McDonald's as seen earlier. The C_D was taken as 0.4 for all wind speeds, this was due to such similar wind speeds that the variation made negligible distance. The specific drag forces that were found can be seen in appendix F. The difference between the 12 tests was small however it was noted that some variation exists between them. An average drag force of 5.5×10^{-9} N was found to act on each particle. Using the simple F = ma we found the force due to mass of the particle as seen below in equation 3.5.7.

$$F = ma \quad \ldots\ldots\ldots\ldots\ldots \text{(Equation 3.5.7)}$$

From basic trigonometry the resultant force was then found and the angle theta θ using equation 3.5.6. From this angle the following formula was then used to finally give the horizontal distance using equation 2.5.8.

$$x = -2y \sin\theta\cos\theta + 2\cos\theta\sqrt{hy - y^2 \cos^2\theta} \quad \ldots\ldots\ldots\ldots\ldots \text{(Equation 3.5.8)}$$

Where:

x = horizontal distance

h = original height

y = drop height (same as ‘h’ for this case)

θ = angle from horizontal of the particle

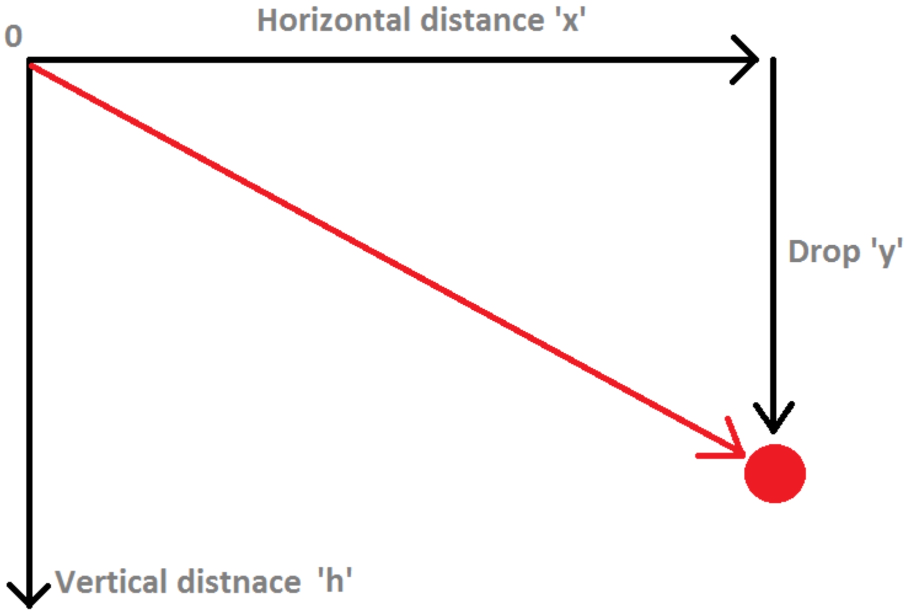


Figure 3.5.4- Trajectory of coal particle using equation 3.5.8.

Using equation 3.5.8 a base horizontal distance of 0.5m, was found for a single coal particle to travel. This assumed that the velocity of the air was 1.65 m/s at 20^0C with coal having a density of 850 kg/m^3. This base line distance allows for the analysis of the coal under no addition of water or surfactant. Theoretically all tests should show a reduction in horizontal distance due to the added force due to mass from water that has bonded with the particle.

3.6 Surfactant

Various constraints induced the use of using house hold surfactants for testing. House hold surfactants were readily available for purchase at the time of testing, as compared to ordering surfactant concentrates from various chemical supply companies only to be held up with testing. It was understood that by finding the right chemicals and using a slightly higher concentration, the agents would still give the same effects as the concentrates. From the research that was conducted in the literature review the following surfactants were selected.

- Cationic- Benzalkonium Chloride

- Anionic- Sodium laureth Sulphate
- Non-ionic- Dimethoxane

3.7 Apparatus

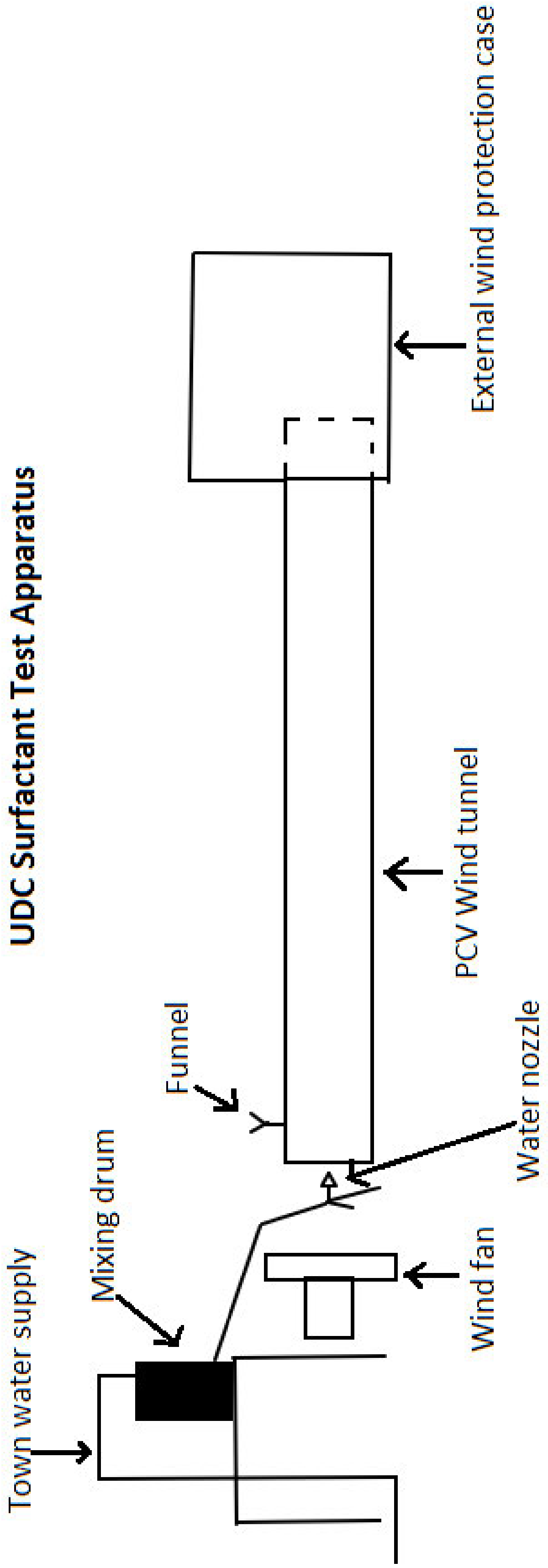


Figure 3.7.1- Apparatus of the wind tunnel testing.

Figure 3.7.2- Photo of the apparatus.

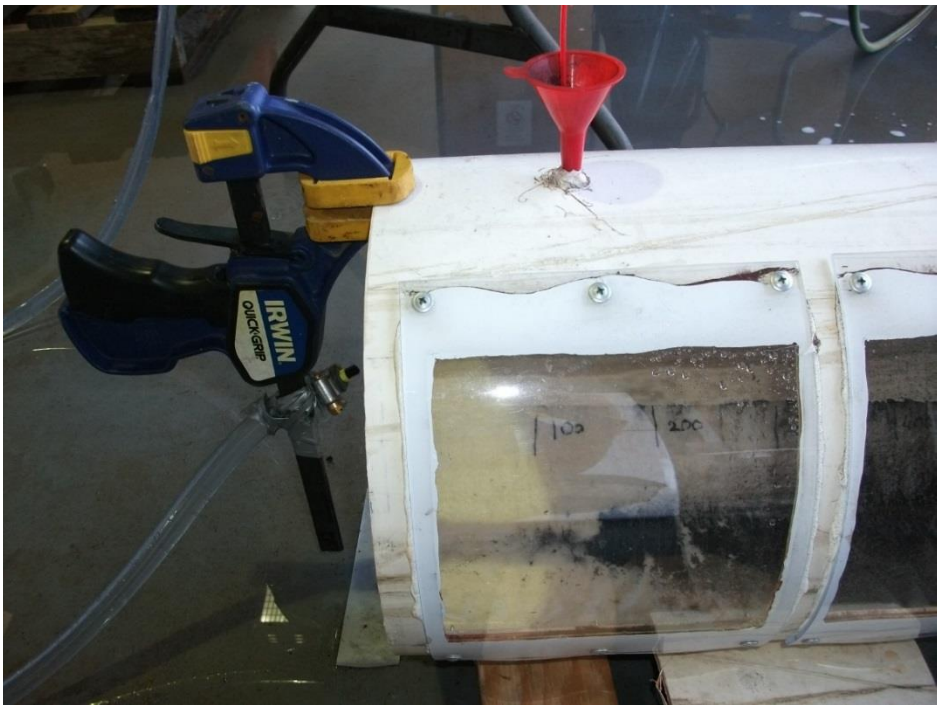


Figure 3.7.3- Photo of the spray nozzle at the entrance of the wind tunnel and the coal dust funnel.

Figure 3.7.4- Chemical mix drum with town water supply coming in at the top and nozzle supply nose at the bottom.

Figure 3.7.5- The apparatus exit and the external wind protection cover.

3.8 Safety Issues

3.8.1 Safety Concerns

This chapter discusses the safety issues and procedures that were involved in this project. Several factors were considered during testing, having to handle hazardous chemicals and also coal dust which in the right circumstances can be a fire hazard.

Although the chances of injury were only minimal, it was noted that there was still a potential for harm. Issues included inhalation of coal dust while the coal was being crushed. The coal had to be broken down from a piece the size of a human foot to dust that was smaller than 300μm in diameter. This required hours of crushing with a hammer and plate, where there was potential to inhale the very fine particles. To prevent this from happening a dust mask was worn during this process that would eliminate the small risk of inhaling respirable coal dust.

Figure 3.8.1 – Crushing the coal into dust.

A consideration that was made for the safety of other people was to expel the coal dust outside during testing. This would ensure that with the fan blowing the dust out the tunnel, the coal particles would remain out of any enclosed areas.

The chemicals themselves did not pose a major threat being house hold items. In the event that they came in contact with eyes, safety showers were located outside the exit doors the test buildings. However, the chemicals were not harmful if they came into contact with skin. Safety charts can be found in appendix A that analyses the tasks and their respected safety risk.

3.8.2 Application

If this study should be implemented in an industry environment, safety should still be taken into consideration around the use of the surfactants and dosage findings. After the release of this dissertation it falls upon the responsibility of the user to ensure that the findings still comply with all updated safety legislation. This report acknowledges the fact that long term health effects of the chemical are unknown however the chemical in use meets current regulatory standards for human health & safety.

4- RESULTS AND ANALYSIS

4.1 Introduction

The results from the experiment that were conducted aimed to show the effectiveness of each type of surfactant. The experiment did not aim to test one particular product against another, but to test the surfactant charged type. By doing this, a better understanding could be made on behalf of the mine and the types of chemical the mine should be looking at for the control of underground coal dust.

The results hopped to show a clear distinction between the surfactant and the straight water mix. This was done by converting the photographs taken of the tests into light images in MATLAB. MATLAB was able to separate the different lights enough to allow for a line of pixel intensities to be plotted giving quantitative results. The plots then showed any trends or patterns from the results eliminating any human judgement. The results however are not straight forward as one would hope and take some thinking in interpreting to show their real data.

4.2 Analysis

The MATLAB code that was used for plotting the data. The code allows for the image to be converted from red, green and blue pixels into hue, saturation and value. The light intensity from these pixels can then be measured which also conveys the concentration of the black coal dust against the white paper towel bottom. Depending on the image, some showed better data using the particular variant of the three. The images that were used in this project gave better accuracy using the ‘v’ mode as compared to the ‘h’ & ‘s’ modes which produce very scattered plots that did not correspond well with the red, green, blue images.

Due to the nature of MATLAB, the image axes are reversed when plotted in graphs and ‘hsv’. The visual axes can be manually reversed however MATLAB will still read the image in the original direction of top to bottom. There is a similar problem with the ‘x’ axis that the data is displayed from right to left when the light intensity is plotted. This was however, corrected and the plots could then be read form left to right. Due to the complexity of the result images, the scaling of the distance was a challenge to obtain in the coding. Because the image was taken down the tunnel length, the image wherefore dies away slightly as the real distance of the tunnel increases. An accurate distance scale was not achieved due to difficulties in the coding. As a substitute, a linear scale was added to the plots that was taken from the start of the test section to the end of the tunnel. This gave a readable scale to the plots although not being completely accurate. An accurate scale would have consisted of an exponential scale of sorts, not being easily obtainable. A linear scale in this situation was considered acceptable, all plots were made in this way which meant that they were all interpreted in an equal field. The MATLAB code can be seen in appendix C &E.

4.3 Results

4.3.1 Captured Results

Figure 4.3.1- Test image 1 for cationic surfactant mix.

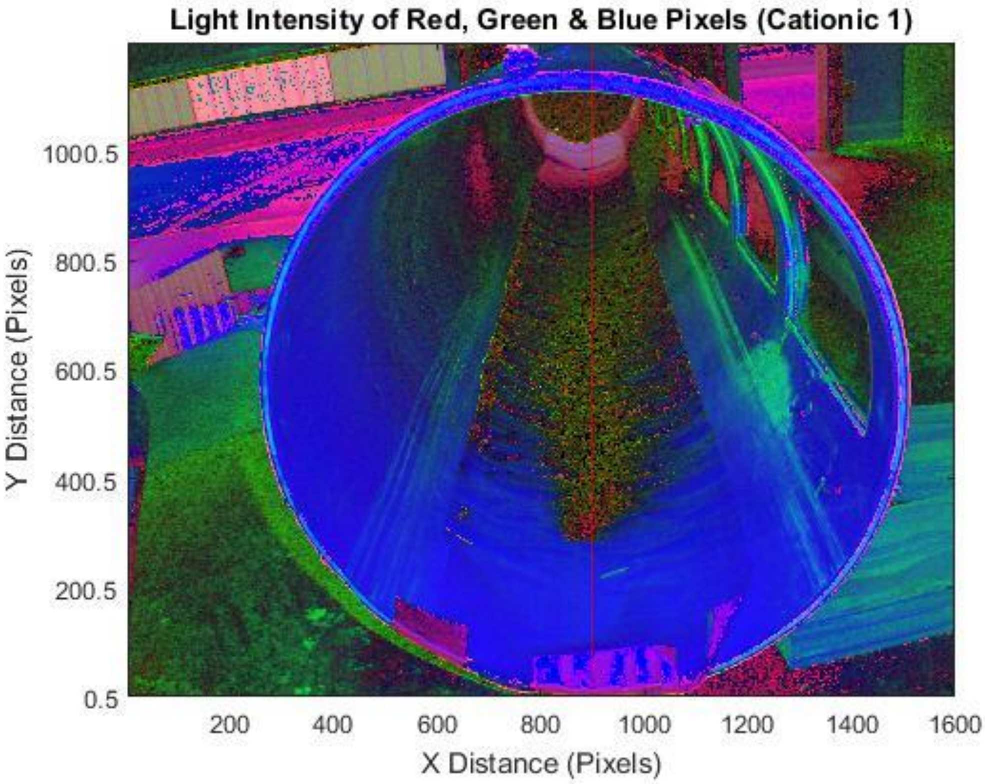


Figure 4.3.2- Test image 1 hue, saturation & value for cationic surfactant.

Figure 4.3.3- Test image 1 for anionic surfactant mix.

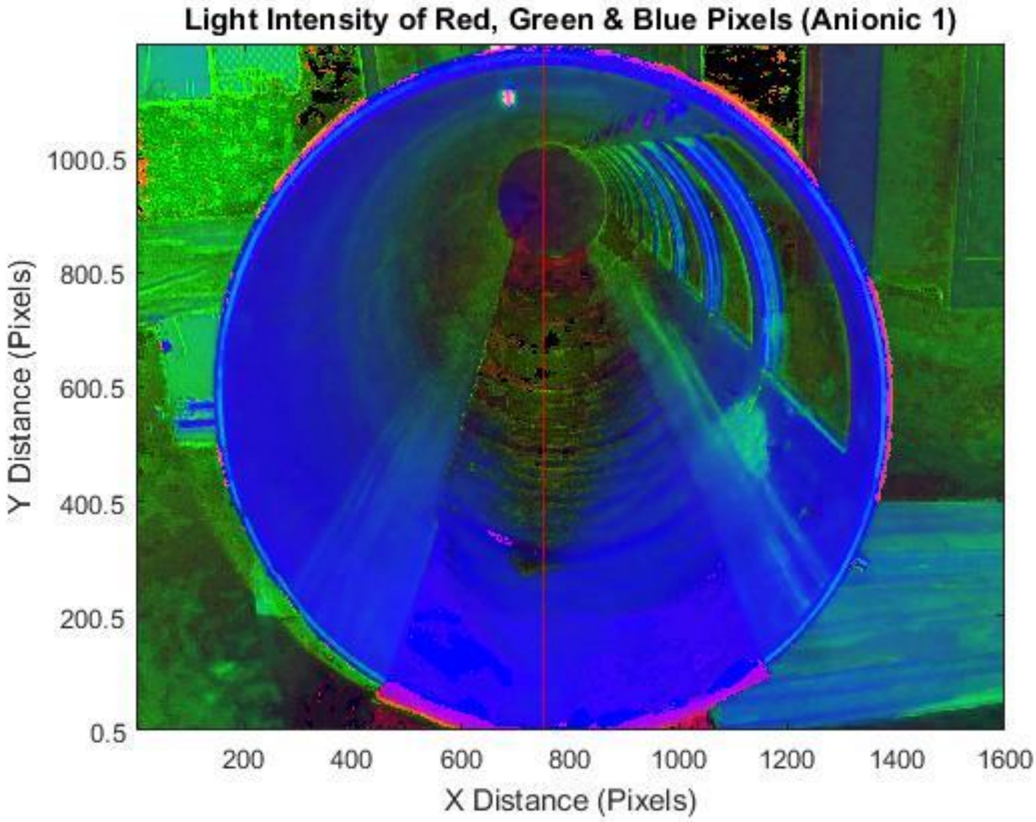


Figure 4.3.4- Test image 1 hue, saturation & value for anionic surfactant.

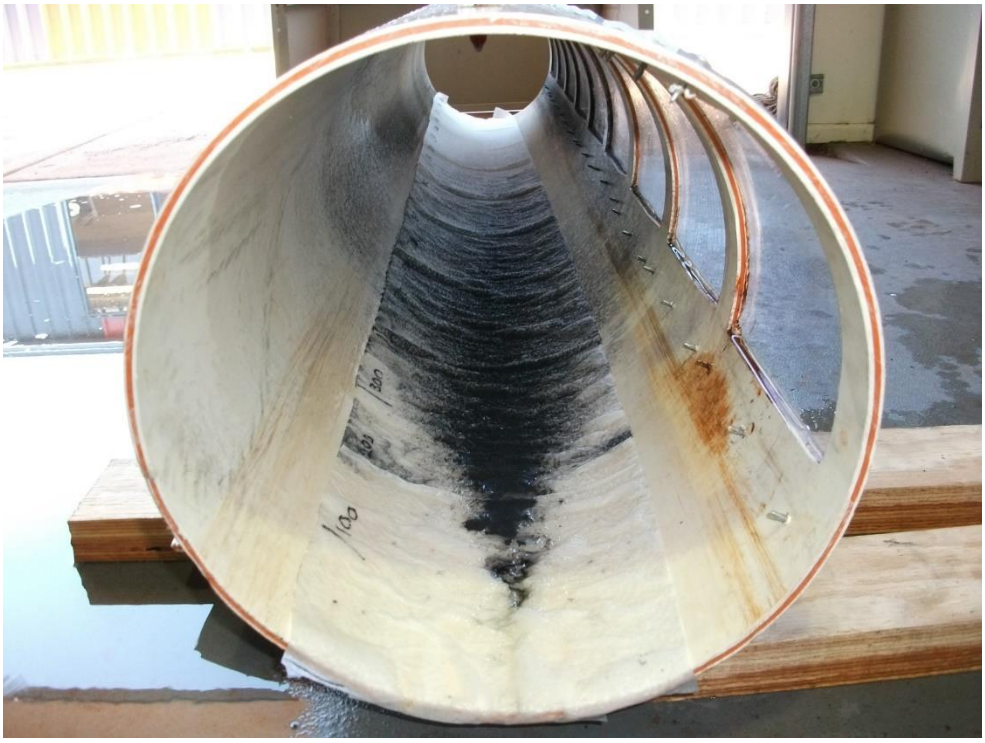


Figure 4.3.5- Test image 1 for non-ionic surfactant mix.

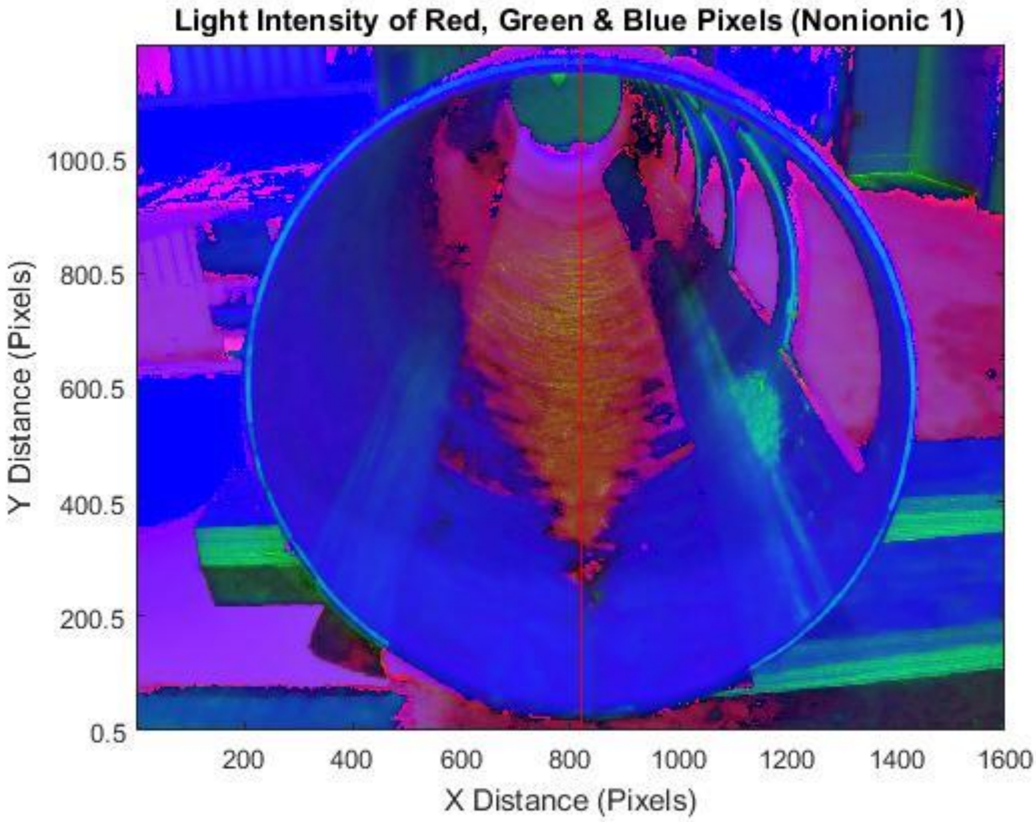


Figure 4.3.6- Test image 1 hue, saturation & value for non-ionic surfactant.

Figure 4.3.7- Test image 1 for water only.

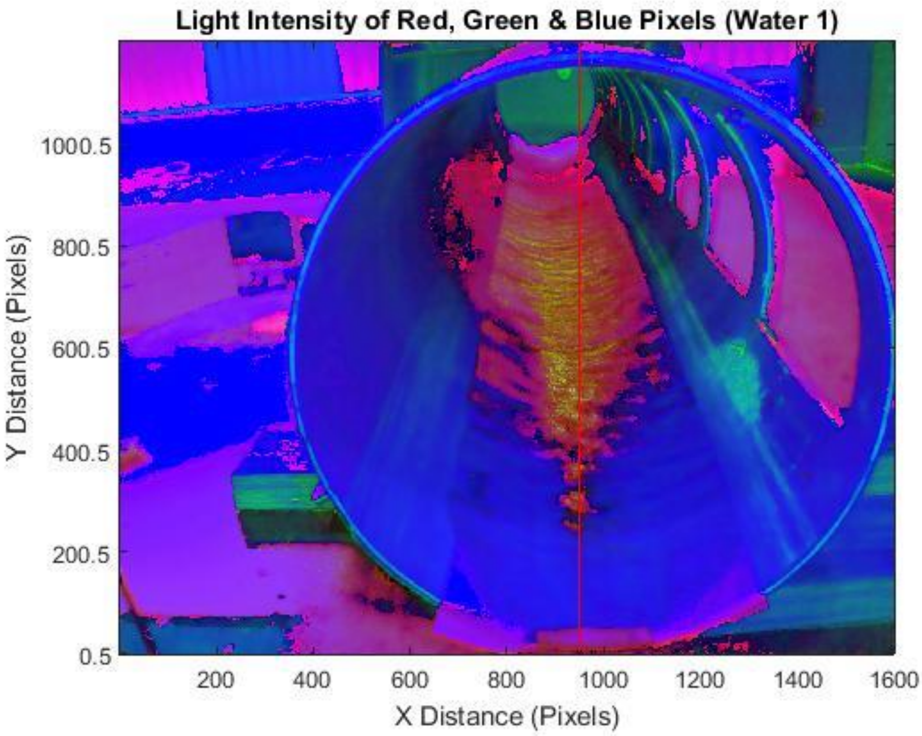


Figure 4.3.8- Test image 1 hue, saturation & value for water only.

4.3.2 Plotted Data

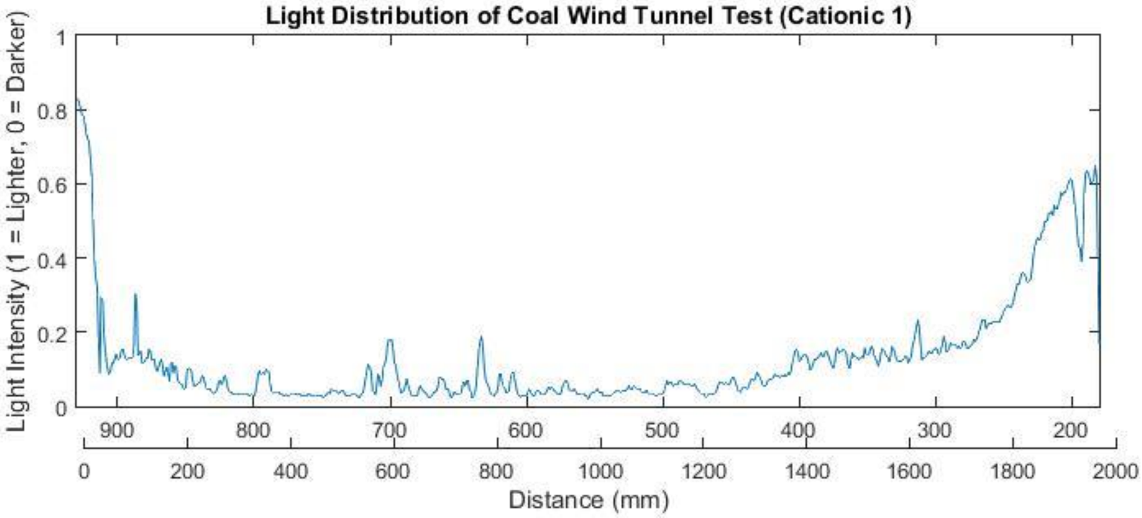


Figure 4.3.9- Cationic test 1 of plotted light intensity.

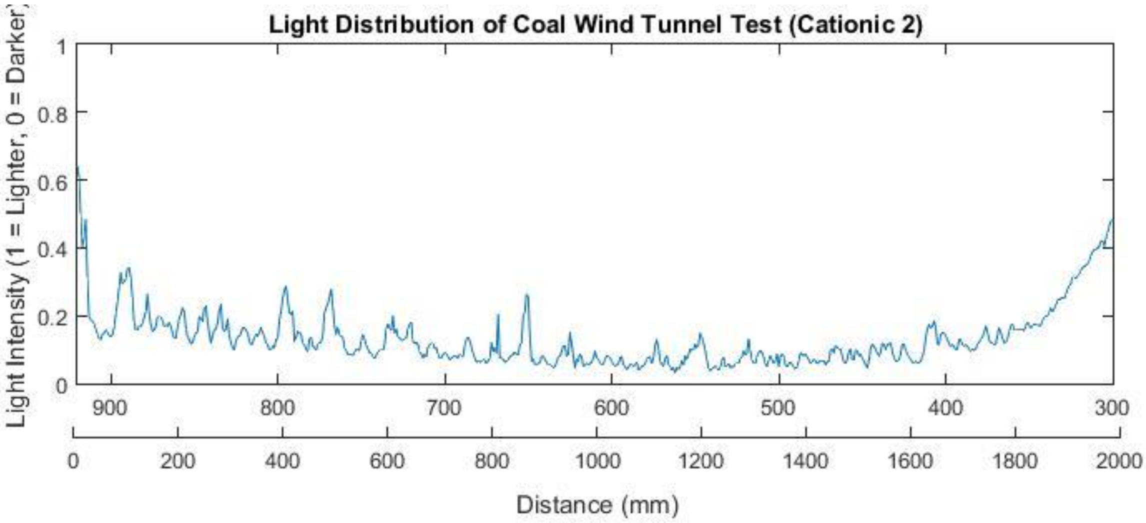


Figure 4.3.10- Cationic test 2 of plotted light intensity.

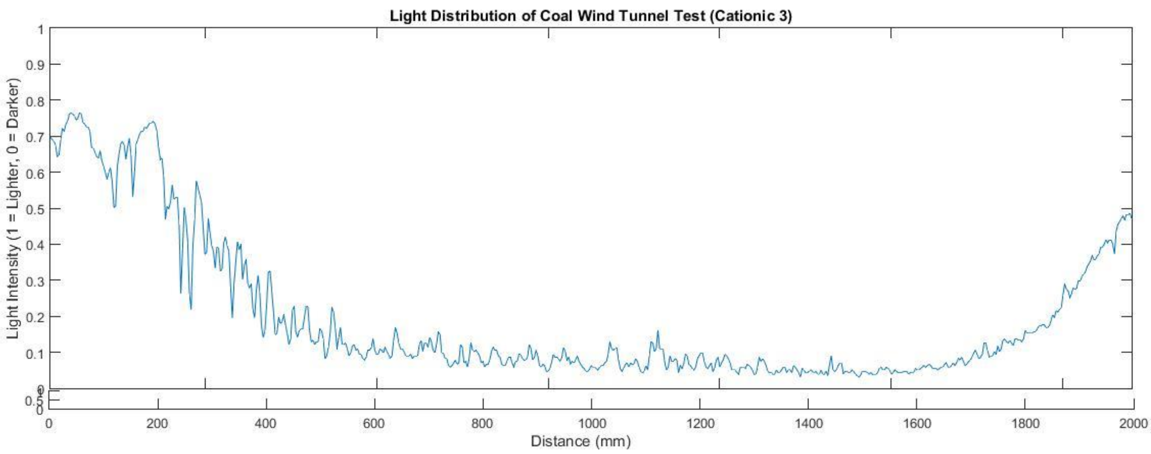


Figure 4.3.11- Cationic test 3 of plotted light intensity.

4.3.2 Cationic

Looking at the plots in section 4.3.2 some trends do become apparent in terms of success. The cationic tests showed varied results to what was expected from what was found in the literature review. Figures 4.3.9, 4.3.10 and 4.3.11 all showed relatively gradual drops in light intensity. Viewing the figures, the majority of the coal concentrations are displayed further towards the middle instead of having effective early drop in the test section. This lack of activity from the cationic wetting agent is contrary to what was found in literature. From past studies the positively charged surfactant has generally been found to be a better at controlling the dust. Tessum & Raynor 2016, conducted test of surfactants and found cationic surfactants to be as effective as anionic surfactants. There are two things this could suggest. Firstly it could suggest that there are fewer negatively charged coal particles found in the coal sample. Secondly and more likely it could be evidence that the tests are invalid. The latter of the two is suspected of being the culprit in these circumstances, it will be mentioned in further detail in section 8.4 of why the tests are incorrect. However, it was theorised that the chemical used may not have been in high enough concentrations of their primary surfactant.

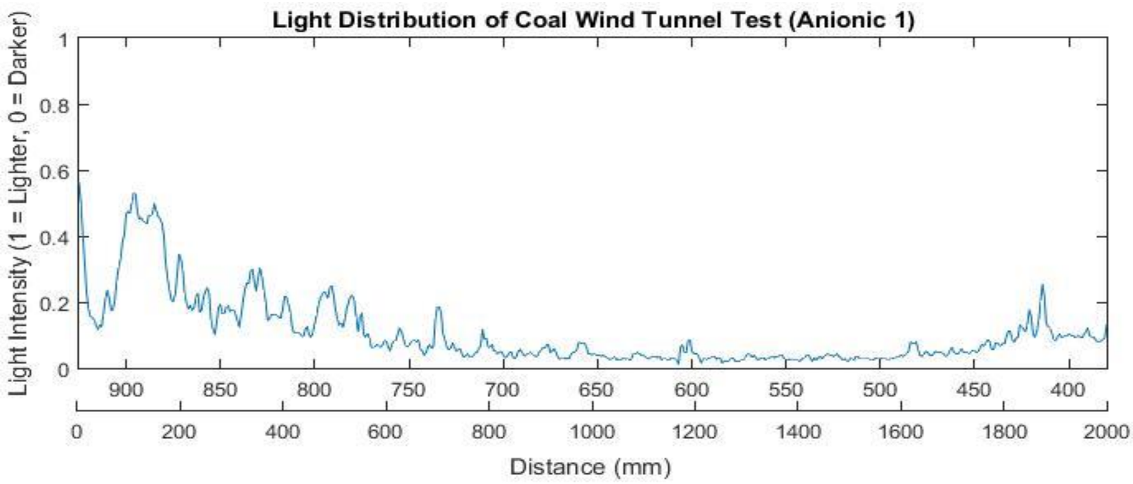


Figure 4.3.12- Anionic test 1 of plotted light intensity.

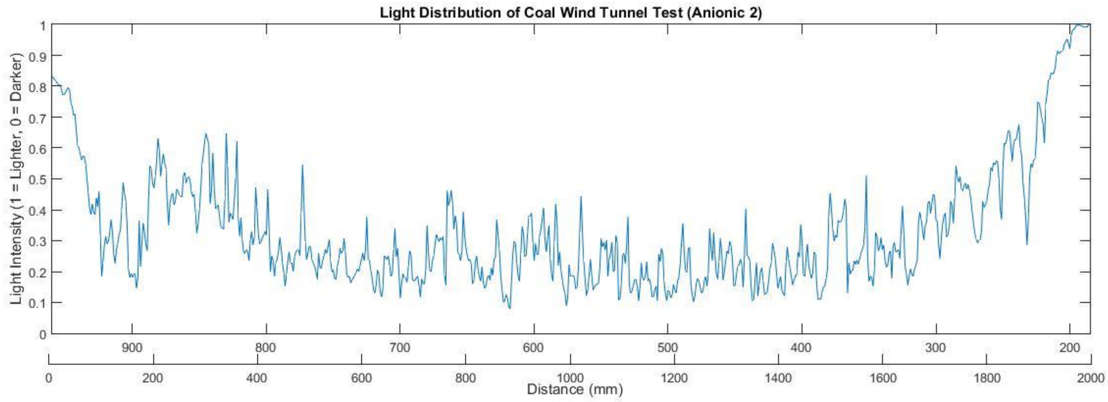


Figure 4.3.13- Anionic test 2 of plotted light intensity.

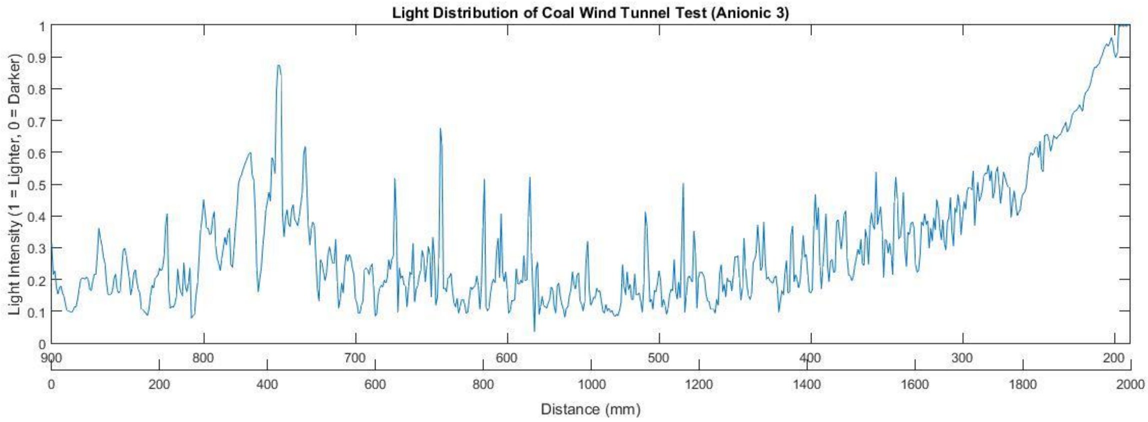


Figure 4.3.14- Anionic test 3 of plotted light intensity.

4.3.3 Anionic

The negatively charged anionic surfactant tests showed marginally better results than that of positively charged cationic tests. Looking at the plots in figures 4.3.12, 4.3.13 & 4.3.14 there tended to be marginally better drops in light intensity earlier in the plots. Not only did the plots show earlier drops, but they showed the light intensity rising again sooner. This rise indicates that the majority of the dust has settled. Once again it should be noted that the rise in light intensity only indicates a majority of the dust. Small traces of dust were seen to have gotten through that were not been picked up in MATLAB photos. In the data plots, a noteworthy observation was seen between the cationic and anionic test, where the different variances in light intensity ('y' axis of plots) between them. The cationic tests showed a smaller variance over the length of the test section compared to the large variance seen in the anionic tests. It is difficult to make any kind of assumption as to whether this variance indicates anything towards the results however. It is suspected that the variance is more likely a problem in regards to the methodology of the experiment, rather than a potential positive or negative attribute of the results themselves.

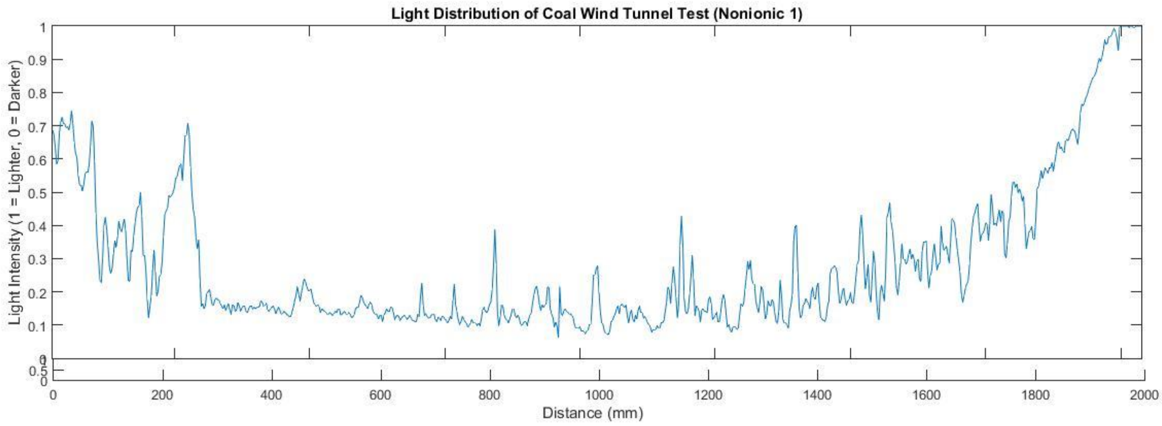


Figure 4.3.15- Non-ionic test 1 of plotted light intensity.

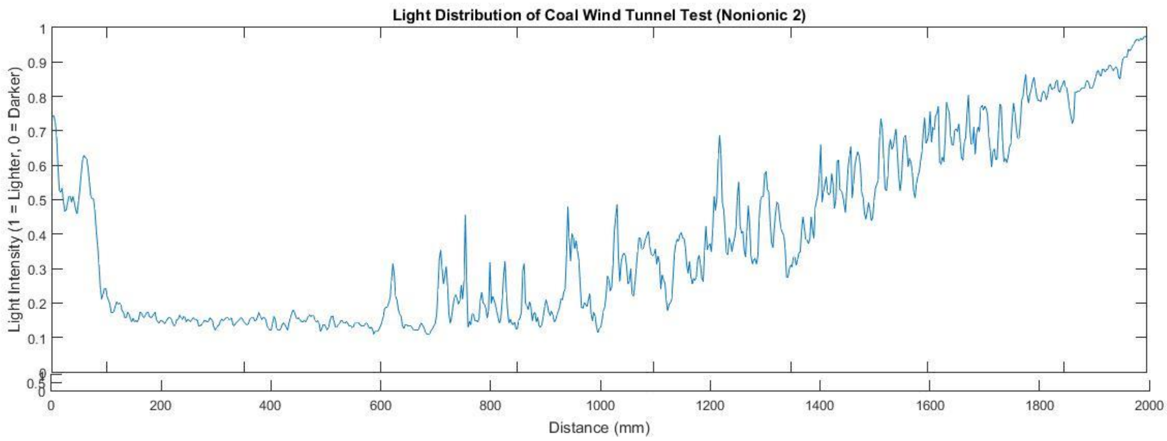


Figure 4.3.16- Non-ionic test 2 of plotted light intensity.

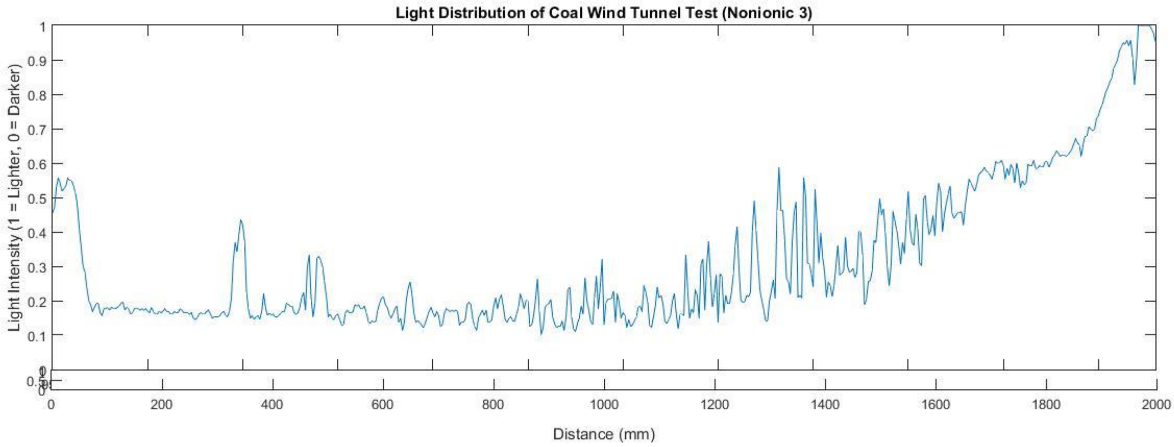


Figure 4.3.17- Non-ionic test 3 of plotted light intensity.

4.3.4 Non-ionic

Perhaps one of the more surprising aspects of the project to be unvalued during the course of these trials was the results that came from the non-ionic tests. The non-ionic tests showed remarkable change in both initial drop and tailing light intensity rise. Examining plots 4.3.15, 4.3.16 & 4.3.17 there are some notable differences toward the first two wetting agents (cationic & anionic). The dust in these tests, seems to react very quickly with the chemical giving a very low light intensity early in the plots. This is especially seen in tests 2 & 3 or figures 4.3.16 & 4.3.17. Another supporting argument in favour of the non-ionic surfactant is that the average light intensity increases rapidly after the initial drop. This would suggest that in these tests the coal dust has been captured much sooner and obviously having a smaller horizontal distance. The difference in the tailing intensity change was as much as approximately 300mm closer to the start in the case of non-ionic test 2 (figure 4.3.16) compared with that of either the cationic or anionic tests. Having two of the tests gather similar data supports the effectiveness of the non-ionic surfactant as an effective means for controlling the dust. The fact that their data followed very similar trends is perhaps, the most convincing evidence of any of the tests. This is not to say that the test could have two special cases that worked out in favour of the wetting agent. To make a better conclusion on this occurrence, several more trails would have to be carried out. Due to the method and apparatus of testing, it is hard to be convinced of any credible data that could have been produced.

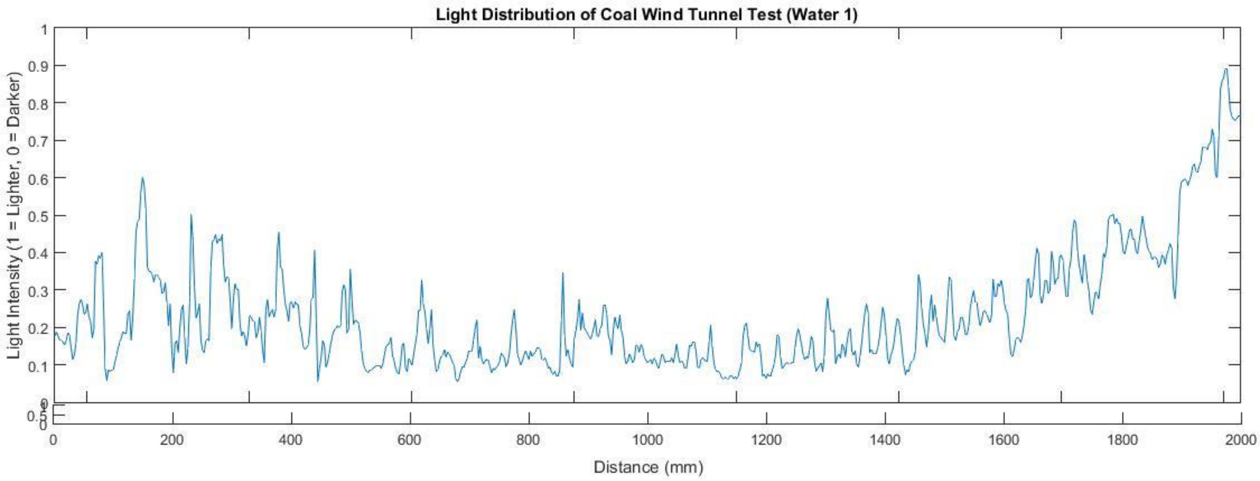


Figure 4.3.18- Water test 1 of plotted light intensity.

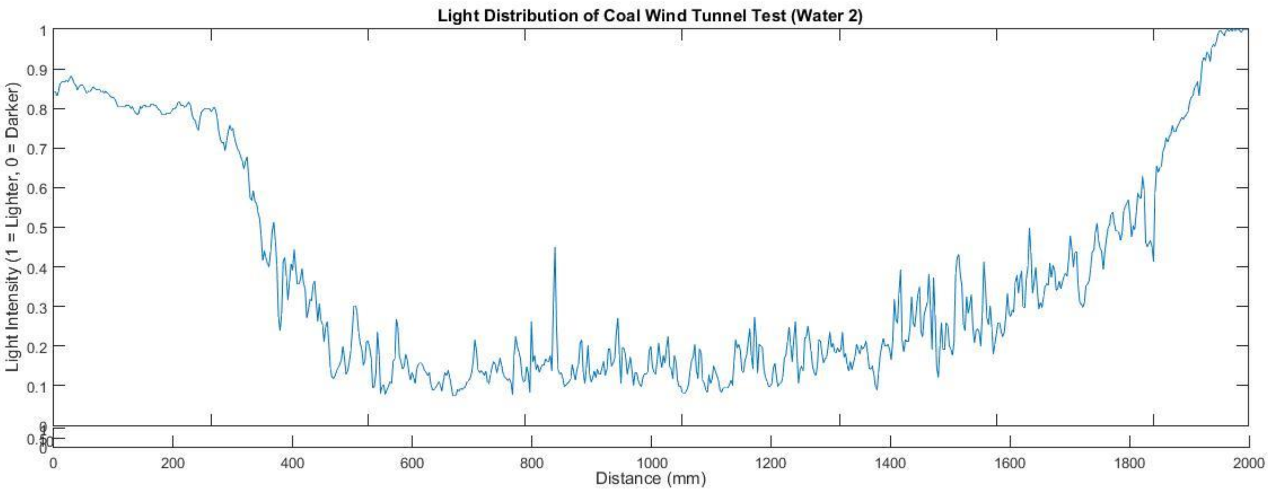


Figure 4.3.19- Water test 2 of plotted light intensity.

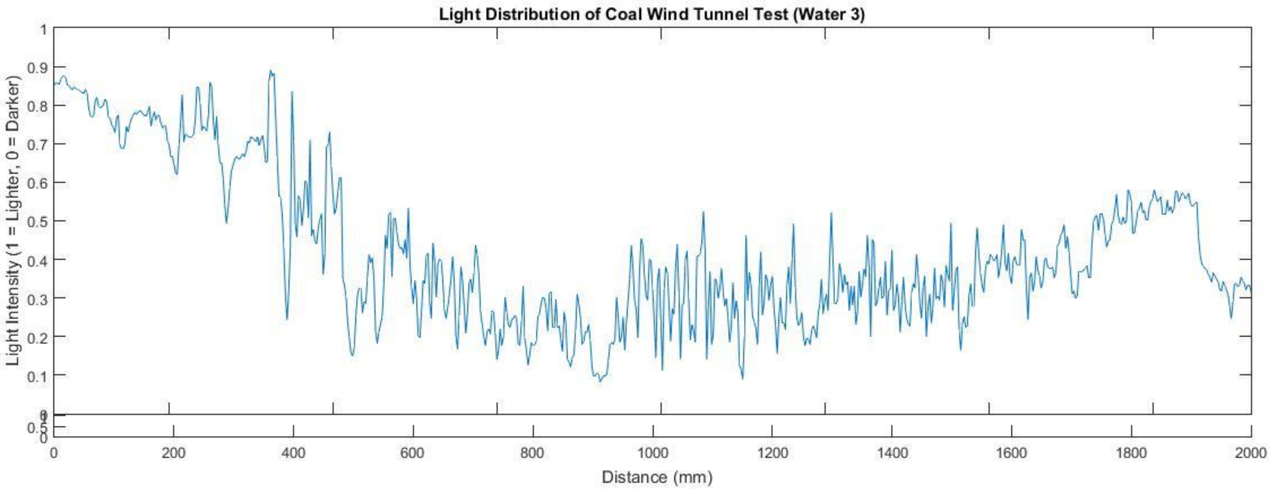


Figure 4.3.20- Water test 3 of plotted light intensity.

4.3.5 Water

The water only trials served as a core control for the experiment and assisting in the judgement of the three wetting agents. These trials were found to be in accordance with what was expected with a water only control method. From the literature, water was found to have a struggle bonding with the coal dust due to the high surface tension. This phenomenon was supported with the data found from these tests. Examining the plots from the water only test in figures 4.3.18, 4.3.19 & 4.3.20, it can be seen that the initial distance for the light intensity to drop is much greater than what is seen by the surfactant tests. Finding this data has helped to possibly validate the other trials in the test series, confirming what is consistent with not only the theory but other trials.

Table 4.3.1 Corresponding Wind speeds of tests.

Test Type	Wind Speed (m/s)
Cationic 1	1.65
Cationic 2	1.7
Cationic 3	1.65
Anionic 1	1.6
Anionic 2	1.7
Anionic 3	1.7
Non-ionic 1	1.8
Non-ionic 2	1.8
Non-ionic 3	1.7
Water 1	1.7
Water 2	1.7
Water 3	1.7

4.4 Conclusion

In conclusion, the results of the testing were obtained and the photos that were taken gave some useable data to allow for analysis and better understanding. Although the data was not discrete, it still provided the necessary evidence that the surfactants were either working or not. In compiling the results, it was sometimes hard to find consistency is making equal opportunities for each trial to show their best results due to several factors. For the results to have equal opportunities several plots would have to been made of each trial in order to capture any outlying data that should be recognised. The size of the project was the limiting factor in this instance and is why more plots were not conducted.

5- DISCUSSION

5.1 Introduction

This project saw some interesting observations throughout its duration, with results that would give some insight into the effectiveness of the control of underground respirable coal dust. From the literature review, an understanding and background of respirable coal dust was found, a comprehensible discussion can be made on the data and plots that found from the testing phase of the project. Using the theory found earlier in the report, conclusions can be made between the positive data as well as understandings of the negative data. This discussion highlights the importance of not just whether the data proves or disproves the effectiveness of wetting agents and water, but whether the results have any credibility to them to make any assumption of that nature. This discussion also hoped to analyse the trends that the data displays and relate the trend back to the theory in the hope of validating the overall experiment.

5.2 Data & Results

Over the course of the experimentation it was generally seen that using any of the control methods that were used had a positive impact on the control of the coal dust. More specifically, the objective of using the wetting agent and the water was to decrease the distance travelled by each individual coal particle. By decreasing the distance travelled, proportionally decreases the time that the particle could hypothetically be suspended in the air, reducing the risk of being inhaled which was the overall aim of this project. An initial trial was conducted that showed little control of the respirable coal dust. Finding a large portion of the coal towards the 1m mark (middle of wind tunnel) and the latter half. Some of the smaller coal particles were found even at the very end of the tunnel which suggested that coal could have gone passed the end and no longer traceable. In saying this, portions of the dust were found close to the start however these tended to be the larger particles towards the 300μm diameter size. Refereeing back to section 3.5, the theoretical horizontal distance that the coal particle should have travelled at 100μm in diameter was approximately 0.5m. This theory was supported by the dry control test that was carried out initially.

Given the difficult nature of the testing that was carried out, the data that was collected showed reasonable response to the conditions that were set. Examining the images in section 4.3, gives a first look at what is happening in regards to the coal dust. In this section the original images are paired with their converted light intensity image. Looking at these images, it is hard to pick any particular differences in regards to change in distance. Across all four tests, there were positive signs of coal increases in the first quadrant of the tunnel section. Once again, much like the dry control test there were obvious signs of the larger particles very close to the starting position of the tunnel. As seen in figure 4.3.1 there is a high concentration of particles found within the first 300mm. This would indicate that the surfactant has controlled a majority of the dust in comparison to the dry control. To help establish a criteria of success, the results have to be compared so that the wetting agents reduce the largest portions of coal dust with the least distance travelled. Because the apparatus and testing method does not adequately allow for the latter half of the tunnel section to be screened, means that there could be data could be missing or that was not picked up from the medium resolution camera that was used. This means that to compensate for this, the data plot displayed in 4.3.2 should indicate where the major changes in light intensity are.

5.3 Surfactants

The project aimed to focus on a single type of surfactant for each test in order to build an understanding of the effectiveness of the wetting agents. The three surfactants used in these tests were simple house hold surfactants, making their procurement easy. The cationic surfactant (positive charge) used benzalkonium chloride as the active constituent. This compound was found in off the shelf Glitz, which is a disinfectant concentrate. The anionic wetting agent (negative charge) used for the trials had sodium laureth sulphate as the active constituent, and was also found in a chemical as simple as Glitz hand wash. Finally the non-ionic wetting agent (neutral charge) used Dimethoxane as the main ingredient for the non-ionic surfactant, found in Rug Doctor Anti-foam which is a carpet cleaning product.

Figure 5.3.1 – The three house hold surfactants used, from left to right, non-ionic, cationic and anionic.

Other studies that have been found typically use the pure surfactant for the trial. This project originally aimed to test one surfactant at different concentrations to find an efficiency in the wetting agent for better control of the dust. Due to unforeseen circumstance the project was adjusted to test the three agents instead. The change in testing method left the project on a tight time line which made the procurement of pure surfactants difficult. For this reason the decision was made to use house hold surfactants. Using these surfactants in place of the active concentrates was a quick and cheap alternative, and it was assumed that the results would still be transferable in analysis. Leading on from this point, there was some query as to the effects on the surface tension lowering ability of the other chemicals found in the products. All three of the chemicals had a percentage of other compounds, and the affects and influence to the trials were unknown. Most of the added indigents to the chemicals were things such as fragrances however it cannot be said if they had any extra positive or negative affect.

There was question as to the concentration of surfactant being used was a reasonable amount. In previous studies, surfactants were used at concentrations of around 0.05% - 0.2% for testing. This project used a single concertation at 1% (surfactant in water) which is obviously much higher than other studies. The reasons why this experiment used such high concertation's was in part due to the setup of the experiment. As mentioned in the methodology, town water was piped into the surfactant drum in order to achieve enough pressure for the spray. Doing this however lowered the concentration of the surfactant slightly during each test. The idea was to start with a high concentration and by the second and third tests the mix would still be within the desired range. Another reason the concentrations were made so high was to accommodate for the uncertainty of the chemicals used. Because the chemical were off the shelf house hold surfactants, the concentrations of the active constituent was not 100%. This then influenced the decision to increase the concentration used. Because the project was not able to test for efficiency in each individual surfactant, the use of a high concentration does not entirely destroy the integrity of the experiment. The objective of the experiment was to observe which type of control method offered the best result. The use of high concentrations still provides evidence of this with possible exaggeration to allow for better differentiation between agents.

5.4 Errors

The experimentation process for this project presented errors and flaws that is believed to be why the data holds little integral value. The previous sections made points about why the trials have produced the trends and anomalies in the results. To better understand why the results are sceptical, the methodology and apparatus needs to be closely examined.

5.4.1 Coal dust size

As found in the literature, respirable coal dust is the dust that is smaller than 100μm in diameter. This size dust has the ability to enter the respirable system of humans and become trapped in the organs such as the lungs where they develop health problems. For the trials conducted in this experiment, sizes of 300μm were used to help give a better visual analysis of what the dust was doing. In doing this, it was later believed that the larger dust sizes may have affected the wetting ability of the smaller particles, there for obscuring the results. Whether or not the size of the particles completely ruined the results is debatable. Although the surfactants showed these large particles with very little horizontal distance, two of the three water only control trials showed a prolonged time before these larger particles fell. So potentially, the size of the particles, although not being classified as respirable dust, could still indicate the effectiveness of the surfactants. However, this can neither be confirmed nor denied which makes the circumstance difficult.

Figure 5.4.1 – A lump of coal that was crushed down to the size of 300μm in diamter.

5.4.2 Spray Nozzle

Research was conducted in the literature review on the spray nozzles that are used on underground continuous miners. The spray nozzles that was used for this testing was a simple garden type spray nozzle that produced a circular spray pattern. This nozzle was chosen due to, firstly, time and money, having little of each prompted a simple nozzle as compared to a more sophisticated expensive nozzle. Secondly, having a small scale test where only 5g of dust was used for each trial, a nozzle that would produce fine enough droplets had to be used. This gave another problem of getting enough pressure through the liquid system to then capture the dust particles. For this reason, it is believed that there may not have been enough pressure behind the water to grab the quickly moving coal particles. It can be seen in appendix figure that the small particles were not captured possibly for this reason.

Figure 5.4.2 – The garden style spray nozzle that was used made it hard to get enough pressure.

5.4.3 Imagery

The imagery method that was used is believed to be a large root cause of the disbelief in the integrity of the data collected. The photos used in generating the data plots, were taken with a normal digital camera. This camera was able to take good images close in, but as the image extends further away, naturally the image quality decreases. Looking at figures in appendix 2D, it can be seen that dust has made it back however not been picked up in the MATLAB plots. This problem could also have been attributed to the lack of light in the tunnel. The converter in MATLAB works best when there is a large difference in light intensity. Towards the end of the tunnel, the light from the flash of the camera diminishes, leaving the image bright at the front of the tunnel and dark at the back of the tunnel where the smaller particles have fallen. From comparing the original photos taken and the plotted data this problems stands to reason. Further evidence of this can be seen between individual trials. The difference in day light can be seen in the anionic test and ion-ionic test in figures 4.3.3 and 4.3.5 respectively. The bright light of the day in the non-ionic test helped distinguish between the black coal and the white paper.

5.4.4 Winds Speed Influences

The trials were conducted using a trial wind speed of 1.7m/s which was calculated from the cutting drums on the continuous miner specified in the project. The testing was conducted partially indoors to help accommodate for any influences from the wind. Due to safety from respirable dust inhalation, the exit of the tunnel was directed outside for the very small traces of dust to dissipate in. The outside influence however, began to affect the tunnel wind speed despite good attempts to block it, such as barriers. These small changes in wind speed from test to test, could have affected the horizontal distance the particle travelled. Stated in the fluid mechanics of coal dust, the larger the horizontal force the further it will travel. When the outside wind creates negative force, obviously this reduces the distance the particles travels giving false data. The stated wind speed in table 4.3.1 is only the wind speed that was taken at the start of each run, it does not guarantee that the wind remained consistent during the time of trial.

5.5 Suggested Improvements for Testing

For this project to be run again in the hope of achieving better control of underground coal dust, several aspects of the project would have to be improved. Time played a large influencer over the testing stage. Because of time, house hold surfactants were used instead of surfactant concentrates. A step in achieving valid results would be to obtain these concentrates to remove any doubt of the chemicals affects.

A further step would be to obtain finer coal dust below the 100μm diameter range. This would eliminate the problem as mentioned in the previous section of heavier coal particles falling short and giving unrealistic data. This would be achieved using a special crushing piece of equipment such as a mortar bowel, as compared to a hammer and a plastic chopping board which was used.

Wind protection is something that needed to be addressed during this project, with time so short, the best attempt was made to shield the apparatus. If the testing had been done in doors somehow, the wind would not have had any influence in the results as discussed earlier.

5.6 Predictions and Recommendations

5.6.1 Surfactant of Choice

From the experiments that were conducted, several recommendations were made that are supported by the data collected. The tests showed that non-ionic surfactants had the most influence on controlling the coal dust. This was supported by two out of three trials that showed very similar results. This came as a surprise, as from the literature, it suggested that non-ionic surfactants are generally used for controlling small weakly charged particles. The water only as predicted showed poor results. Using water only could be an inefficient method for controlling the dust, having to supply more water to achieve the same result. The amount of extra water needed is not covered in this project, but the project has given further evidence of water's lack of effectiveness.

The data found that this report is not enough alone to make any justifiable conclusions but would recommend further investigation into non-ionic surfactants. Because the evidence is there, it would seem productive to look further into the non-ionic types and aim to either replicate the results or improve the efficiency of the concentrations. An addition to this, the use of different types of non-ion surfactant such as Alkyl Ethoxylate, Nonyl Phenol Ethoxylate or Polyethylene glycol Stearate and look for a possible improvement across the range.

5.6.2 Ejector nozzle

The project has intensely covered the control of coal dust by chemical means but has not covered the mechanical problems with controlling coal dust. Mentioned at the beginning of this report, the use of surfactants in underground coal mining can be difficult. This is due to the surfactants creating dirt clogs in the water supply systems when they are added above the surface and pumped down. To combat this problem, the system would have to remove the surfactant from as much of the system, but then having the surfactant added at the point of water ejection. From the literature review the simplest way of adding the chemical at the point of ejection was to use an ejector nozzle as seen in figure 2.8.1. An ejector nozzle using the forward pressure of a high velocity fluid to create a section from which point the surfactant could then easily be added at any specified concentration. The ejector nozzle offers a simple mechanical solution to the problem without the hassle of complex systems to add the surfactant at some point near the point of ejection. Working a fluid mechanics principles the device has no moving parts which also means that maintenance wouldn't be a large factor. Although the mechanical side of the project has only been touched on, it is still worth mentioning the possibility of integrating the idea of an effective surfactant type, into use with an improved way of distribution.

5.7 Conclusion

In conclusion, the data that was obtained showed both positive and negative results. Some of the data matched the theoretical data that was found in other studies. All the surfactants generally produced either similar or smaller horizontal distance than the water which was expected from the theory found. The non-ionic surfactant was the more promising wetting agent of the three which was not entirely expected. It was believed however that there was an issue with the integrity of the results due to several factors. The coal size, image processing, spray nozzles and control of wind speed all were suspected culprits of producing inadequate data. It was suggested that improvements needed to be made to the methodology and apparatus of the experiment in order to obtain more encouraging results. To possibly help improve the spray method system, it was suggested that an ejector nozzle should be used to help with a side problem of underground water systems clogging from surfactant dirt build up. However this topic was only touched on in the hope that future works might be conducted at a more in depth level.

6- CONCLUSION

6.1 Summary of project

The project set out to investigate the effectiveness of controlling respirable coal dust using chemical wetting agents. Although the method of testing that was conducted in this project was unique to conventional surfactant testing methods, the research that was found gave a strong foundation to build this project off. The information found on the various methods of controlling coal dust, gave the project and appreciation for what obstacles would have to be overcome.

Looking at the evidence that was collected there is no certain yes or no answer that the project was successful or not. The results that were obtained through experimentation showed both positive and negative attributes to the theory that was researched in the literature review. The non-ionic surfactant showed the best results of controlling the dust quickly. This was only confirmed, however, in two of the three trials producing similar results, which is not enough to make any large assumptions on. For this reason, the results produced from this project should only be taken as a possibility rather than a conclusive argument. The cationic and anionic surfactants both performed adequately in some trials however their results varied dramatically which is why the no major conclusions were made on them.

From the experiment no major recommendations could be made due to the integrity of the results. The biggest lesson that can be taken away from this project should be around the methodology of the experimentation. There were a lot of factors that influenced the end results, and could have made the difference. Learning from these factors could help to produce reliable data of surfactant effectiveness in a wind tunnel environment.

6.2 Future Work

There are several things that would be recommended for future work following the completion of this project.

- All three surfactants would be tested again several times over to see if more definite trends emerge from the data.
- Different concentrations of the surfactants would provide efficiencies on the wetting agents and provide quantitative data for other studies to compare against.
- One scope of the project that was unfortunately only touched on was the delivery and mixing system of the surfactant. A project in itself would be to design and test an ejector nozzle that is capable of producing the correct water droplet type, while still mixing the surfactant at the point of ejection.

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8 APPENDICES

Appendix A Project Specification

ENG 4111/4112 Research Project

Project Specification

For: Sam Hawkins

Title: Underground Dust Control Unit

Major: Mechanical

Supervisor:

Enrolment: ENG4111- OnC S1, 2017

ENG4112- OnC S2, 2017

Project Aim: To investigate the effectiveness of surfactants at controlling respirable coal in underground coal mines.

Programme: Version 4, 10th May 2017

1. Review already existing coal dust control methods and devices for underground mines and investigate their limitations and strengths.

2. Investigate the parameters that influence the effectiveness of dust suppression surfactants.

3. Review coal dust surfactants and their effectiveness of containing coal dust in underground situations.

4. Design and build wind tunnel for testing surfactant effectiveness

5. Wind tunnel experiment: Testing for effectiveness against coal dust. Both water and chemical/water mix. Variable rates.

6. Analysis results and find the most effective, economical or suitable option.

7. Make recommendations based on results from tests to either distribute more water or coal dust spray

If time permits,

8. Conduct secondary testing method of coal water drop test.

9. Test multiple concentrations of surfactant water mix to find efficiency's.

Appendix B Time Line

This project consisted of four core sections that enabled the progression of the project.

- Start-up Phase- This phase involved gathering and compiling information that was vital to the project by conducting a thorough literature review that covered a wide field of areas.
- Testing Phase- Experimental test were conducted on comparing water to wetting agents and the dosage rates at which they can be applied.
- Analysis – The results were analysed to find if the practical results were matching the theoretical literature.
- Write-up Phase- An extensive write up of the literature what was found, the results from testing and a dissection of the design were all compiled to construct the dissertation.

Table B1- Showing essential phases and critical steps.

Essential Phase	Critical Steps
Start-up	
1.1	Resource check: Conduct a literature review on relevant information that will assist with the testing and design of an underground dust control unit. This will consist of coal dust and its health effects, already existing control methods, wetting agents and sampling methods.
1.2	Collect Mine Specific Information
Testing	
2.1	Collect Resources necessary for testing.
2.2	Construct or modify wind tunnel to suit the project specific tests.
2.3	

2.4	Wind tunnel test took place at USQ labs. This testing entailed a comparison of water as a control method compared to a wetting agent specifically formulated for underground mining. Formulate results: Various dosage rate were tested using the wetting agent to discover if there is an efficiency in the product. The results from which would dictate which method would be chosen.
Analysis and Design	
3.1	Results: The results would then be analysed for water savings cost efficiency and health benefits.
3.2	Design: A design of a surfactant concertation mix was made from the findings of the results.
Write-up	
4.1	Dissertation Draft: Construct a draft submission to be reviewed and critiqued by supervisor.
4.2	Final Dissertation: Review and correct and feedback given from supervisor and finalise the document for submission.

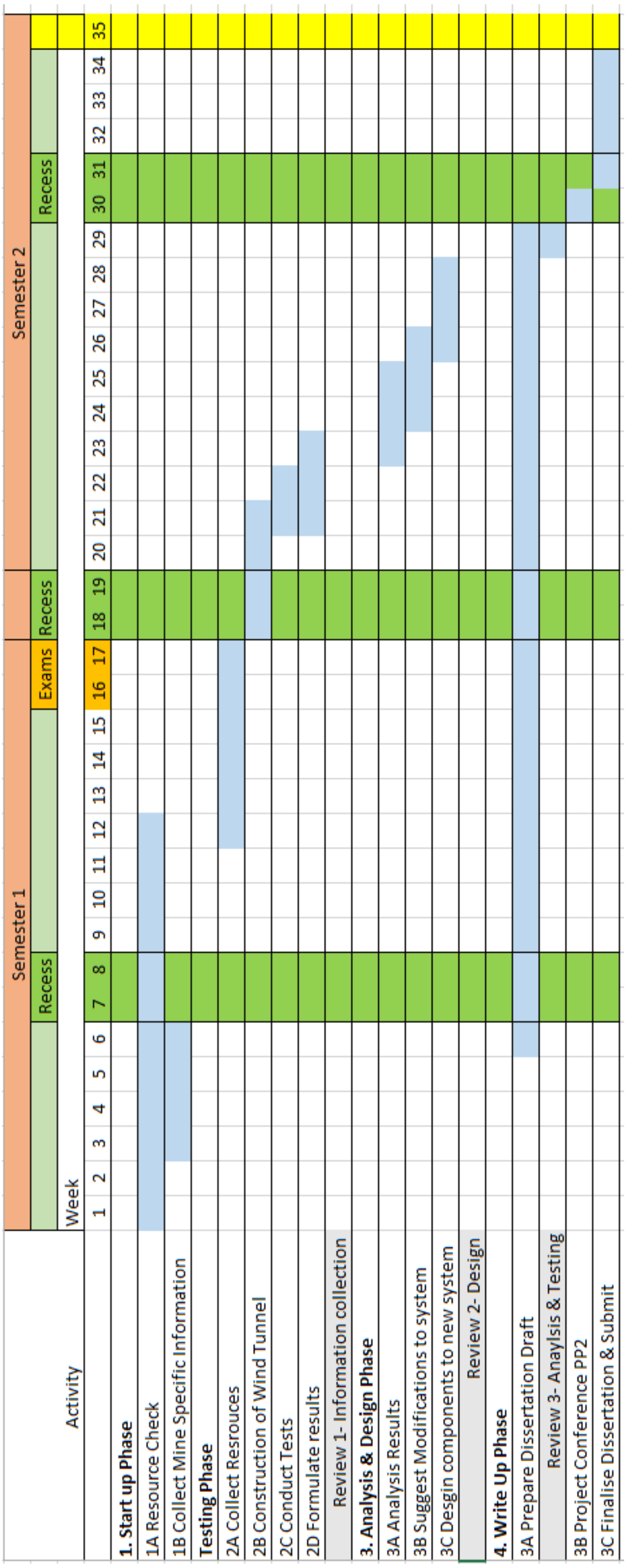

Figure B1- Graph of timeline

Appendix C- First trial MATLAB Code

```
clear all;
close all;
% Test 3.1_Cationic
A = imread('DSCF8738_C1.JPG');
B = rgb2hsv(A);

figure(1)
image(B);
hold on
plot([900 900],[1 1200],'r')
h = B(600,:,1);
s = B(600,:,2);
v = B(:,900,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick
values and
                                      % subtract them from the
upper
                                      %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick
values to
                                         % string and update
the y axis
                                         % labels.
title('Light Intensity of Red, Green & Blue Pixels (Cationic
1)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')
```

```
figure(2)
% plot([1:1600],h)
% figure(3)
% plot([1:1600],s)
% figure(4)
plot([1:1200],v)
title('Light Distribution of Coal Wind Tunnel Test (Cationic
1)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (Pixels)')
```

Figure C1- MATLAB code used to obtain light intensity plots (Credit: Professor David Buttsworth).

Appendix 1D Results photos

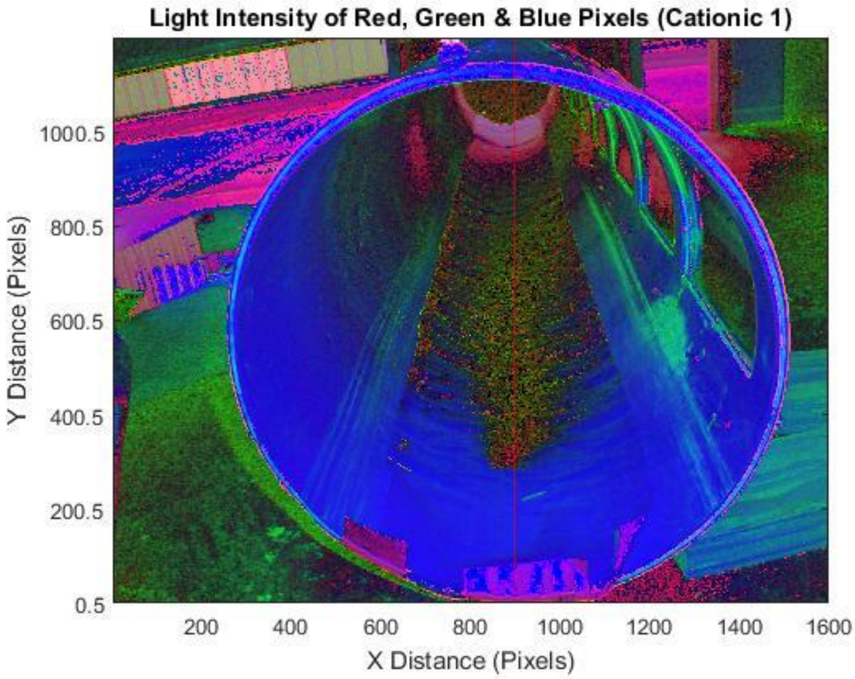

Figure D1- Cation 1 result

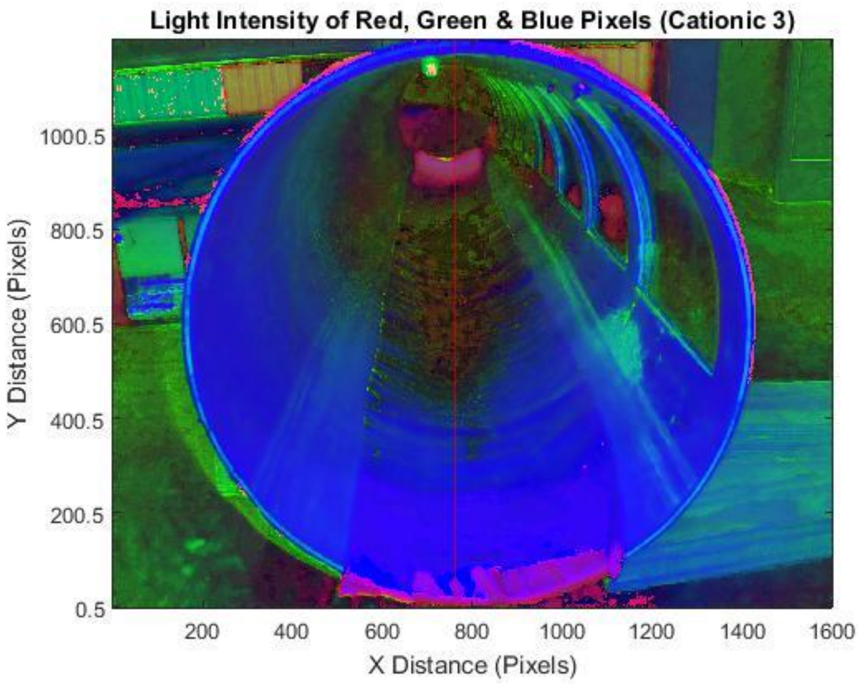

Figure D3- Cation 3 result

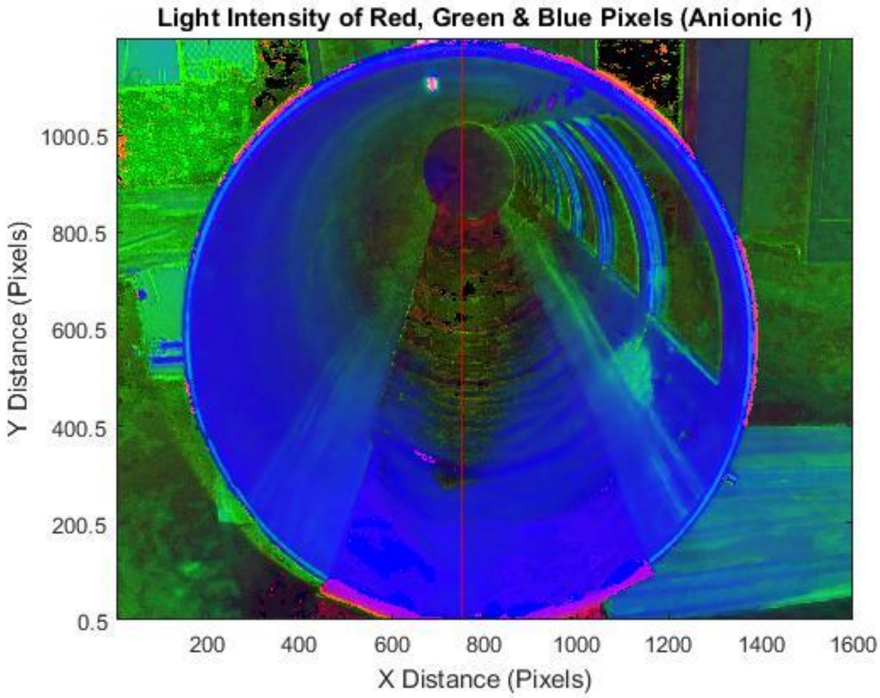

Figure D4- Anionic 1 result

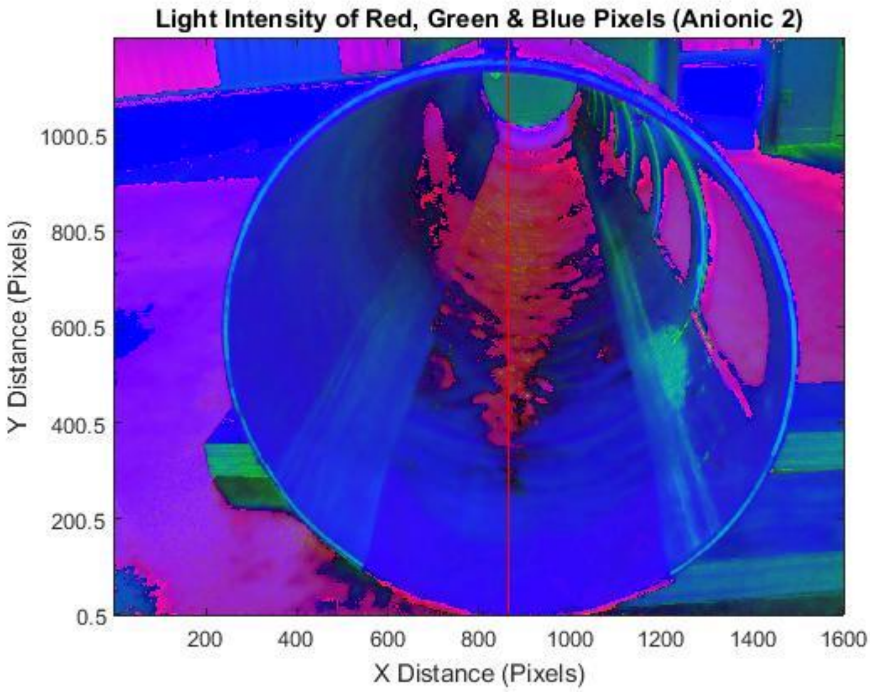

Figure D5- Anionic 2 result

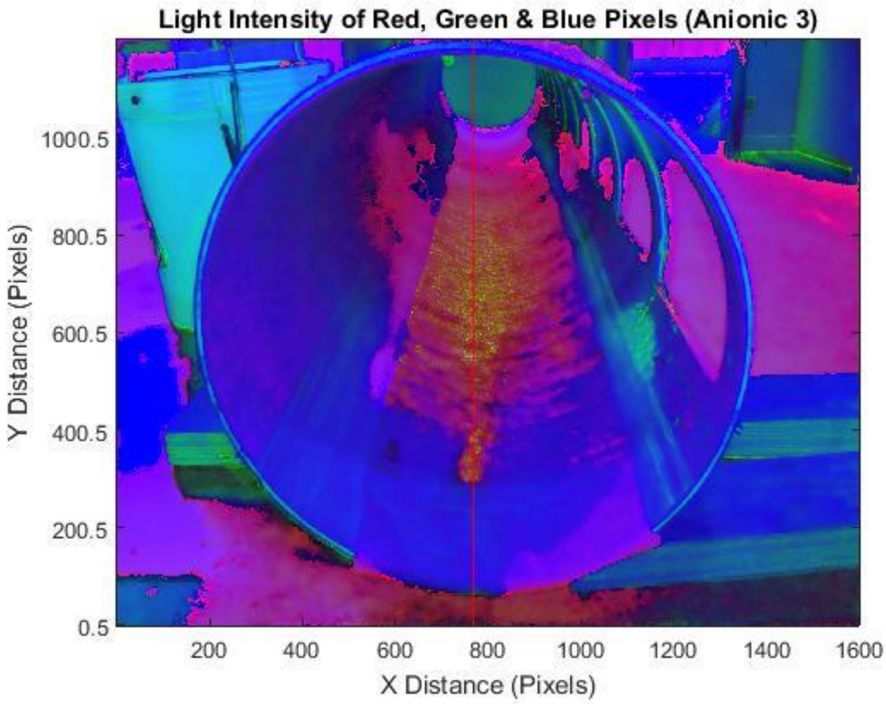

Figure D6- Anionic 3 result

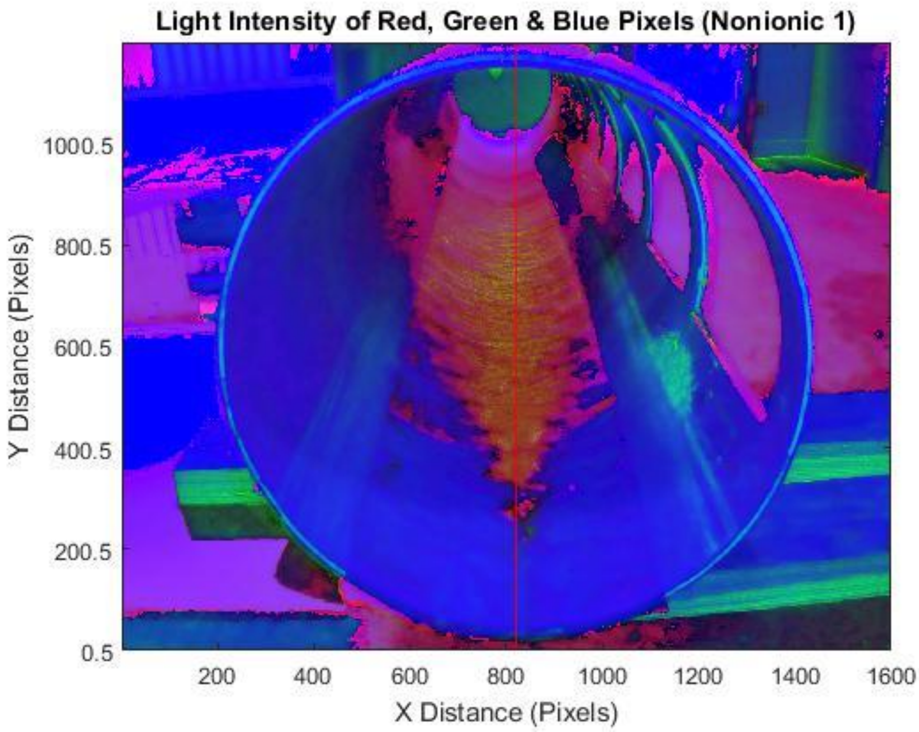

Figure D7- Non-ionic 1 result

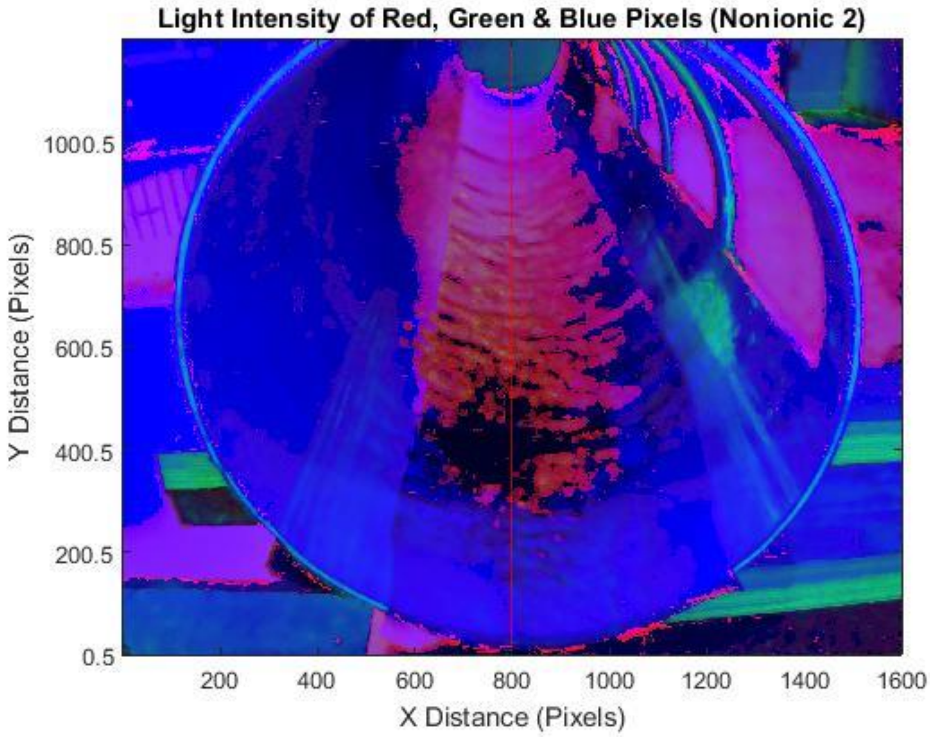

Figure D8- Non-ionic 2 result

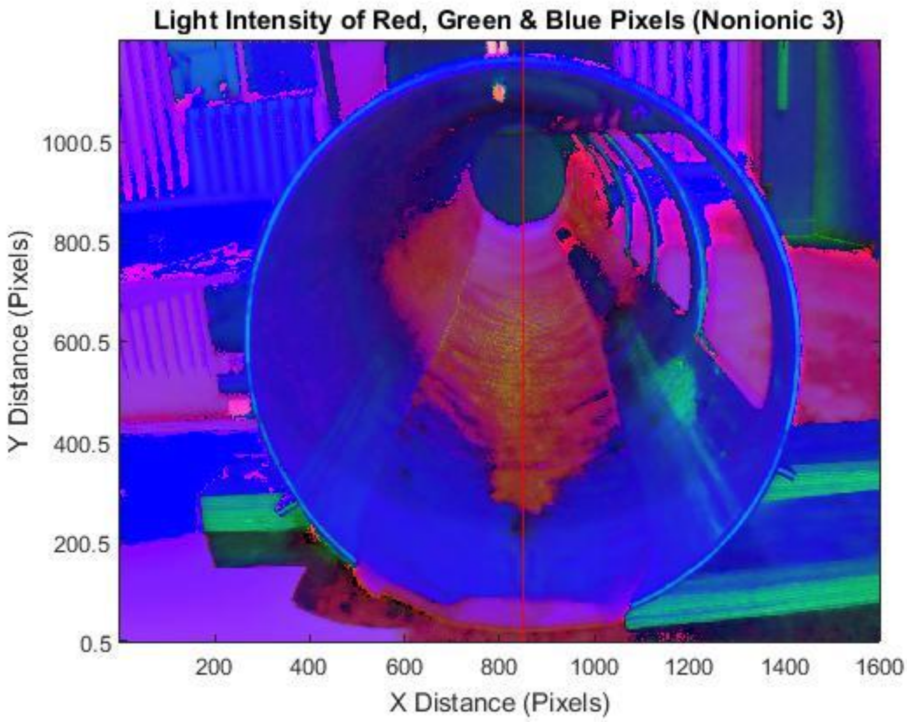

Figure D9- Non-ionic 3 result

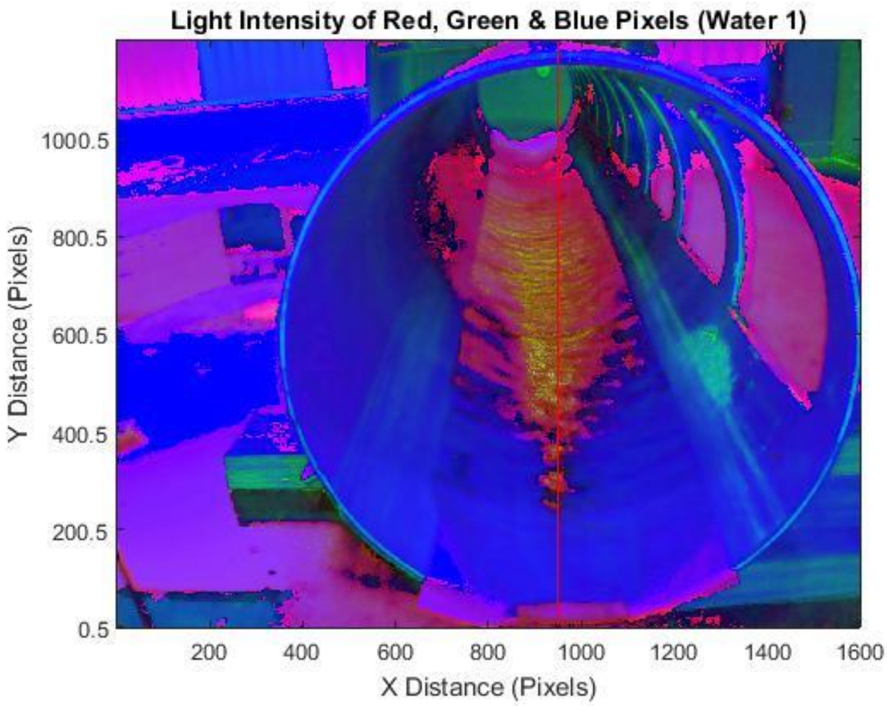

Figure D10- Water only 1 result

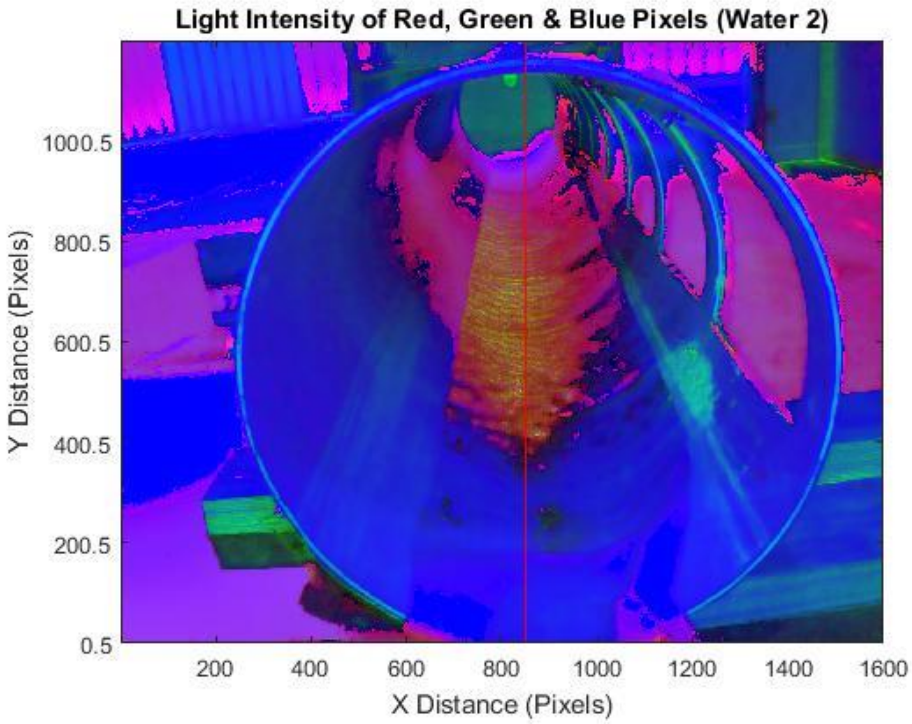

Figure D11- Water only 2 result

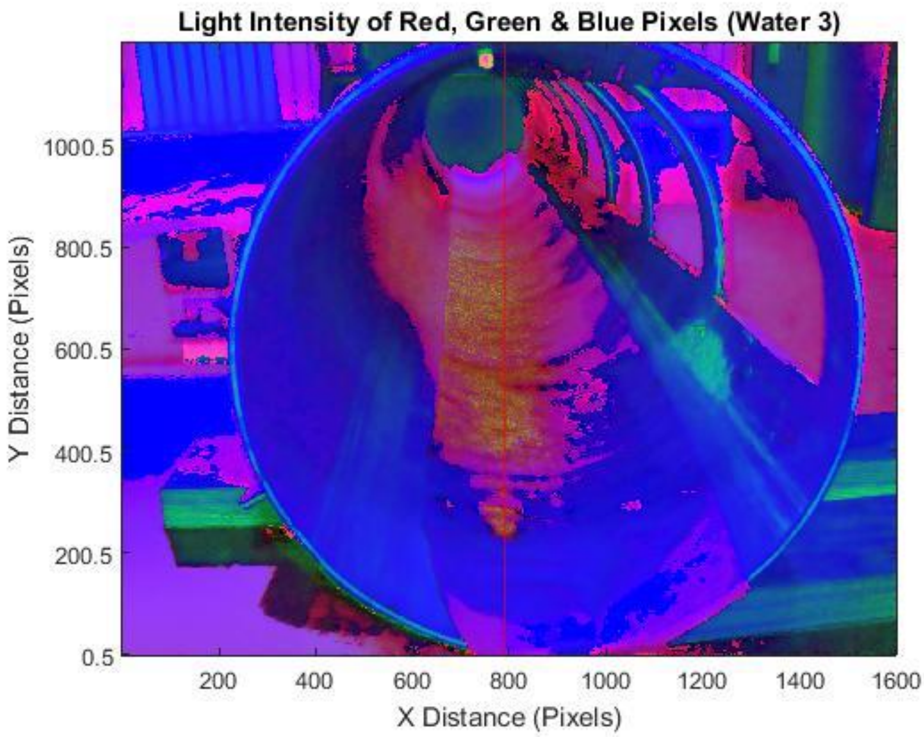

Figure D12- Water only 3 result

Appendix 2D Untranslated images

Figure D13- Cationic 1 result

Figure D14- Cationic 2 result

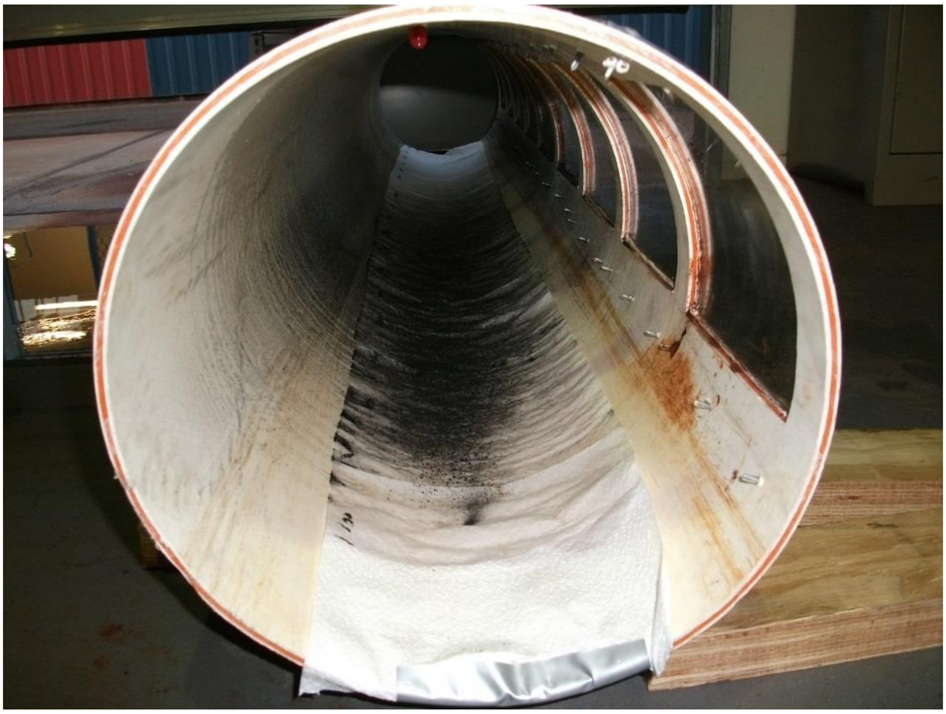

Figure D15- Cationic 3 result

Figure D16- Anionic 1 result

Figure D17- Anionic 2 result

Figure D18- Anionic 3 result

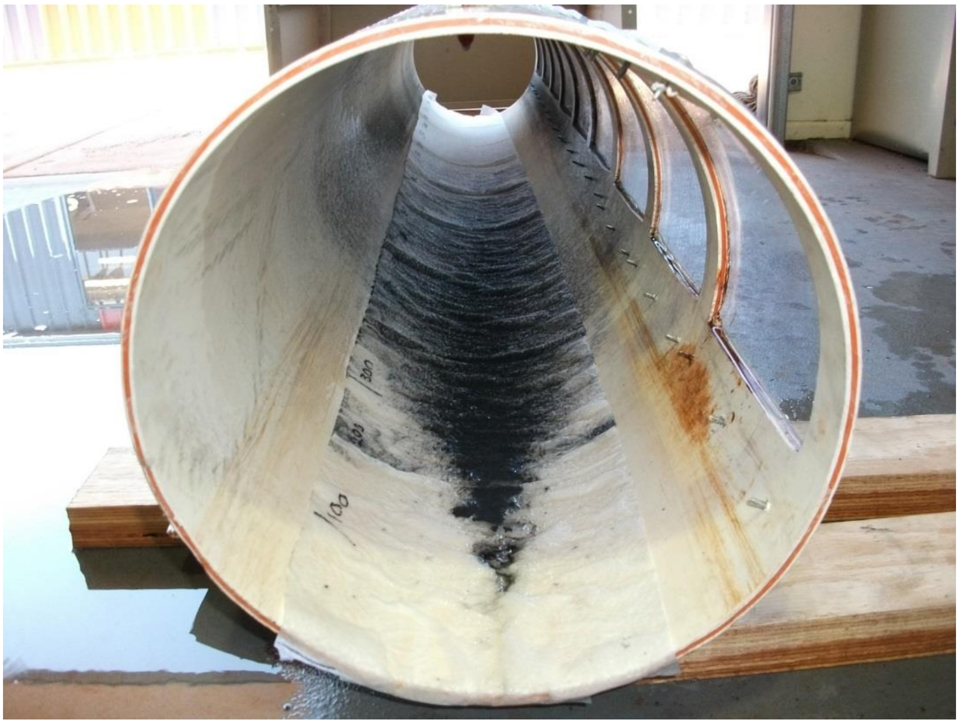

Figure D19- Non-ionic 1 result

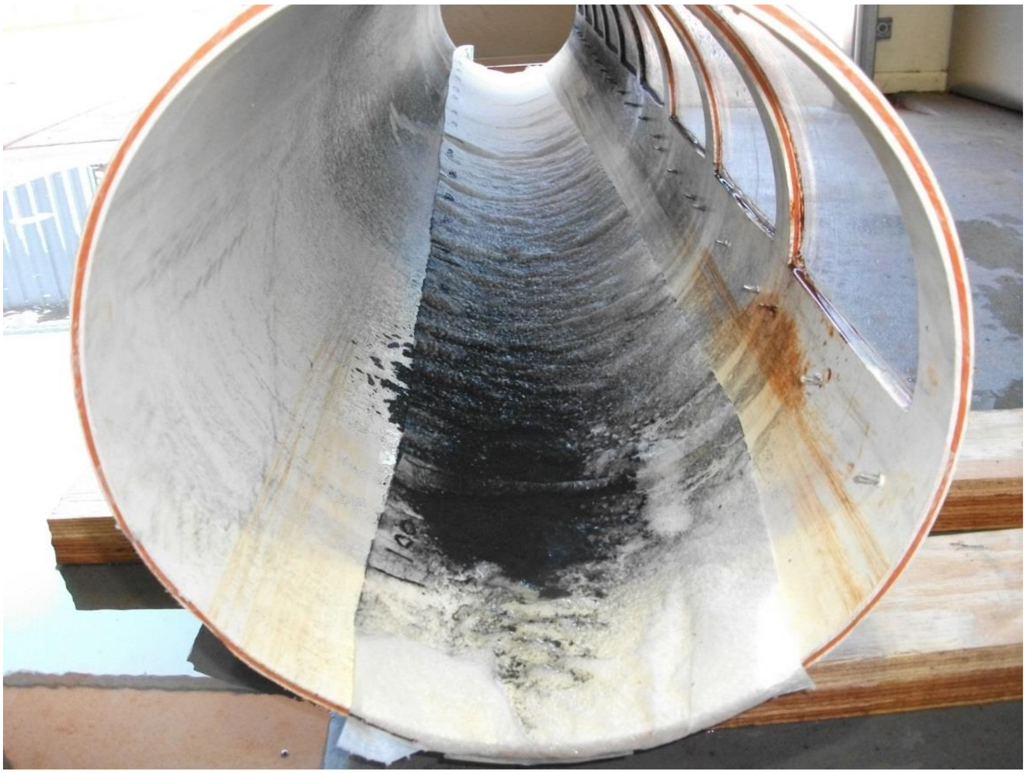

Figure D20- Non-ionic 2 result

Figure D21- Non-ionic 3 result

Figure D22- Water only 1 result

Figure D23- Water only 2 result

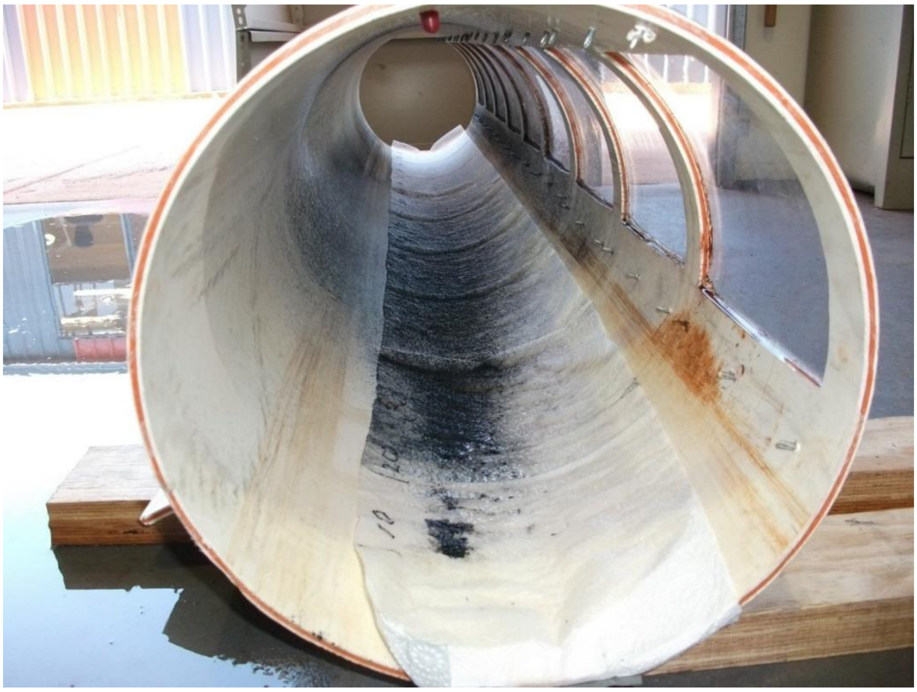

Figure D24- Water only 3 result

Appendix E MATLAB Code

```
clear all;
close all;
% Test 3.1_Cationic
A = imread('DSCF8738_C1.JPG');
B = rgb2hsv(A);

figure(1)
image(B);
hold on
plot([900 900],[0 1200],'r')
h = B(600,:,1);
s = B(600,:,2);
v =  B(:,900,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
                                      % subtract them from the upper
                                      %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                         % string and update the y axis
                                         % labels.
title('Light Intensity of Red, Green & Blue Pixels (Cationic 1)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')



figure(2)
% plot([1:1600],h)
% figure(3)
% plot([1:1600],s)
% figure(4)
h1 = axes;
plot([1:1200],v)
set(h1, 'Xdir', 'reverse')
```

```
axis([180 930 , 0 1]);
%axis([0 250 500 750 1000 1250 1500 17500]);
title('Light Distribution of Coal Wind Tunnel Test (Cationic 1)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (mm)')
```

Figure E1- Cationic 1 code

```
clear all;
close all;
% Test 3.1_Cationic
A = imread('DSCF8747_C2.JPG');
B = rgb2hsv(A);

figure(1)
image(B);
hold on
plot([820 820],[0 1200],'r')
h = B(600,:,1);
s = B(600,:,2);
v =  B(:,820,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
                                      % subtract them from the upper
                                      %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                         % string and update the y axis
                                         % labels.
title('Light Intensity of Red, Green & Blue Pixels (Cationic 2)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')



figure(2)
% plot([1:1600],h)
% figure(3)
% plot([1:1600],s)
```

```
% figure(4)
h1 = axes;
plot([1:1200],v)
set(h1, 'Xdir', 'reverse')
axis([300 920 , 0 1]);
%axis([0 250 500 750 1000 1250 1500 17500]);
title('Light Distribution of Coal Wind Tunnel Test (Cationic 2)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (mm)')
```

Figure E2- Cationic 2 code

```
clear all;
close all;
% Test 3.3_Cationic
A = imread('DSCF8758_C3.JPG');
B = rgb2hsv(A);

figure(1)
image(B);
hold on
plot([760 760],[0 1200],'r')
h = B(600,:,1);
s = B(600,:,2);
v =  B(:,760,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
                                      % subtract them from the upper
                                      %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                         % string and update the y axis
                                         % labels.
title('Light Intensity of Red, Green & Blue Pixels (Cationic 3)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')



figure(2)
```

```
% plot([1:1600],h)
% figure(3)
% plot([1:1600],s)
% figure(4)
h1 = axes;
plot([1:1200],v)
set(h1, 'Xdir', 'reverse')
axis([260 890 , 0 1]);
title('Light Distribution of Coal Wind Tunnel Test (Cationic 3)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (mm)')
```

Figure E3- Cationic 3 code

```
clear all;
close all;
% Test 3.1_Cationic
A = imread('DSCF8767_A1.JPG');
B = rgb2hsv(A);

figure(1)
image(B);
hold on
plot([750 750],[1 1200],'r')
h = B(:,750,1);
s = B(:,750,2);
v =  B(:,750,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
                                      % subtract them from the upper
                                      %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                         % string and update the y axis
                                         % labels.
title('Light Intensity of Red, Green & Blue Pixels (Anionic 1)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')
```

```
figure(2)
% plot([1:1200],h)
% figure(3)
% plot([1:1200],s)
% figure(4)
h1 = axes;
plot([1:1200],v)
set(h1, 'Xdir', 'reverse')
axis([380 925 , 0 1]);
title('Light Distribution of Coal Wind Tunnel Test (Anionic 1)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (mm)')
```

Figure E4- Anionic 1 code

```
clear all;
close all;
% Test 4.2_Anaionic
A = imread('DSCF8783_A2.JPG');
B = rgb2hsv(A);

figure(1)
image(B);
hold on
plot([865 865],[1 1200],'r')
h = B(:,750,1);
s = B(:,750,2);
v =  B(:,865,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
                                       % subtract them from the upper
                                       %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                          % string and update the y axis
                                          % labels.
title('Light Intensity of Red, Green & Blue Pixels (Anionic 2)')
ylabel('Y Distance (Pixels)')
```

```
xlabel('X Distance (Pixels)')


figure(2)
% plot([1:1200],h)
% figure(3)
% plot([1:1200],s)
% figure(4)
h1 = axes;
plot([1:1200],v)
set(h1, 'Xdir', 'reverse')
axis([185 960 , 0 1]);
title('Light Distribution of Coal Wind Tunnel Test (Anionic 2)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (mm)')
```

Figure E5- Anionic 2 code

```
clear all;
close all;
% Test 4.3_Anaionic
A = imread('DSCF8794_A3.JPG');
B = rgb2hsv(A);

figure(1)
image(B);
hold on
plot([770 770],[1 1200],'r')
h = B(:,750,1);
s = B(:,750,2);
v =  B(:,770,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
                                      % subtract them from the upper
                                      %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                         % string and update the y axis
```

```
                                                          % labels.
title('Light Intensity of Red, Green & Blue Pixels (Anionic 3)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')




figure(2)
% plot([1:1200],h)
% figure(3)
% plot([1:1200],s)
% figure(4)
h1 = axes;
plot([1:1200],v)
set(h1, 'Xdir', 'reverse')
axis([190 900 , 0 1]);
title('Light Distribution of Coal Wind Tunnel Test (Anionic 3)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (mm)')
```

Figure E6- Anionic 3 code

```
clear all;
close all;
% Test 5.1 Nonionic
A = imread('DSCF8836_N1.JPG');
B = rgb2hsv(A);

figure(1)
image(B);
hold on
plot([820 820],[1 1200],'r')
h = B(600,:,1);
s = B(600,:,2);
v =  B(:,820,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
```

```
                                            % subtract them from the upper
                                            %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                            % string and update the y axis
                                            % labels.
title('Light Intensity of Red, Green & Blue Pixels (Nonionic 1)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')



figure(2)
% plot([1:1600],h)
% figure(3)
% plot([1:1600],s)
% figure(4)
plot([1:1200],v)
title('Light Distribution of Coal Wind Tunnel Test (Nonionic 1)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (Pixels)')
```

Figure E7- Non-ionic 1 code

```
clear all;
close all;
% Test 5.2 Nonionic
A = imread('DSCF8846_N2.JPG');
B = rgb2hsv(A);

figure(1)
image(B);
hold on
plot([800 800],[1 1200],'r')
h = B(:,750,1);
s = B(:,750,2);
v =  B(:,800,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
```

```
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
                                      % subtract them from the upper
                                      %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                         % string and update the y axis
                                         % labels.
title('Light Intensity of Red, Green & Blue Pixels (Nonionic 2)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')

figure(2)
% plot([1:1200],h)
% figure(3)
% plot([1:1200],s)
% figure(4)
h1 = axes;
plot([1:1200],v)
set(h1, 'Xdir', 'reverse')
axis([140 940 , 0 1]);
title('Light Distribution of Coal Wind Tunnel Test (Nonionic 2)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (mm)')
```

Figure E8- Non-ionic 2 code

```
clear all;
close all;
% Test 5.3 Nonionic
A = imread('DSCF8857_N3.JPG');
B = rgb2hsv(A);

figure(1)
image(B);
hold on
plot([850 850],[1 1200],'r')
h = B(:,750,1);
s = B(:,750,2);
v =  B(:,850,3);
```

```
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
                                      % subtract them from the upper
                                      %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                         % string and update the y axis
                                         % labels.
title('Light Intensity of Red, Green & Blue Pixels (Nonionic 3)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')



figure(2)
% plot([1:1200],h)
% figure(3)
% plot([1:1200],s)
% figure(4)
h1 = axes;
plot([1:1200],v)
set(h1, 'Xdir', 'reverse')
axis([370 950 , 0 1]);
title('Light Distribution of Coal Wind Tunnel Test (Nonionic 3)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (mm)')
```

Figure E9- Non-ionic 3 code

```
clear all;
close all;
% Test 6.1 Water
A = imread('DSCF8804_W1.JPG');
B = rgb2hsv(A);

figure(1)
image(B);
hold on
```

```
plot([950 950],[1 1200],'r')
h = B(:,750,1);
s = B(:,750,2);
v =  B(:,950,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
                                      % subtract them from the upper
                                      %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                         % string and update the y axis
                                         % labels.
title('Light Intensity of Red, Green & Blue Pixels (Water 1)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')



figure(2)
% plot([1:1200],h)
% figure(3)
% plot([1:1200],s)
% figure(4)
h1 = axes;
plot([1:1200],v)
set(h1, 'Xdir', 'reverse')
axis([190 920 , 0 1]);
title('Light Distribution of Coal Wind Tunnel Test (Water 1)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (mm)')
```

Figure E10- Water Only 1 code

```
clear all;
close all;
% Test Water 6.2
A = imread('DSCF8814_W2.JPG');
B = rgb2hsv(A);

figure(1)
```

```
image(B);
hold on
plot([850 850],[1 1200],'r')
h = B(600,:,1);
s = B(600,:,2);
v =  B(:,850,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
                                      % subtract them from the upper
                                      %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                         % string and update the y axis
                                         % labels.
title('Light Intensity of Red, Green & Blue Pixels (Water 2)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')



figure(2)
% plot([1:1600],h)
% figure(3)
% plot([1:1600],s)
% figure(4)
plot([1:1200],v)
title('Light Distribution of Coal Wind Tunnel Test (Water 2)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (Pixels)')
```

Figure E11- Water Only 2 code

```
clear all;
close all;
% Test 6.3 Water
A = imread('DSCF8825_W3.JPG');
B = rgb2hsv(A);
```

```
figure(1)
image(B);
hold on
plot([790 790],[1 1200],'r')
h = B(:,750,1);
s = B(:,750,2);
v =  B(:,850,3);
yLimits = get(gca,'YLim'); % Get the y axis limits
yTicks = yLimits(2)-get(gca,'YTick'); % Get the y axis tick values and
                                      % subtract them from the upper
                                      %nlimit.
set(gca,'YTickLabel',num2str(yTicks.')); % Convert the tick values to
                                         % string and update the y axis
                                         % labels.
title('Light Intensity of Red, Green & Blue Pixels (Water 3)')
ylabel('Y Distance (Pixels)')
xlabel('X Distance (Pixels)')



figure(2)
% plot([1:1200],h)
% figure(3)
% plot([1:1200],s)
% figure(4)
h1 = axes;
plot([1:1200],v)
set(h1, 'Xdir', 'reverse')
axis([240 970 , 0 1]);
title('Light Distribution of Coal Wind Tunnel Test (Water 3)')
ylabel('Light Intensity (1 = Lighter, 0 = Darker)')
xlabel('Distance (mm)')
```

Figure E12- Water Only 3 code

Appendix F Drag Forces and Trajectory Angle

Wind Speed (m/s)		Hight (h)	Hight (y)	Pi	Mass	Lift Force (Fl)			Reynolds	Cd	Drag force (Fd)	Theta θ (radians)	Theat (Degrees)	
1.65		0.3	0.3	3.141593	4.45059E-10	4.36603E-09			10.50955	0.4	5.13179E-09	0.704947029	40.39048955	
1.7									10.82803	0.4	5.44752E-09	0.675636999	38.71114854	
1.65									10.50955	0.4	5.13179E-09	0.704947029	40.39048955	
1.6									10.19108	0.4	4.82549E-09	0.735452553	42.13832732	
1.7									10.82803	0.4	5.44752E-09	0.675636999	38.71114854	
1.7									10.82803	0.4	5.44752E-09	0.675636999	38.71114854	
1.8									11.46497	0.4	6.10726E-09	0.620650814	35.56067219	
1.8									11.46497	0.4	6.10726E-09	0.620650814	35.56067219	
1.7									10.82803	0.4	5.44752E-09	0.675636999	38.71114854	
1.7									10.82803	0.4	5.44752E-09	0.675636999	38.71114854	
1.7									10.82803	0.4	5.44752E-09	0.675636999	38.71114854	
1.7									10.82803	0.4	5.44752E-09	0.675636999	38.71114854	
850 kg/m^3														
1.2 kg//m^3														
			1.069161											

Appendix G Safety

Table A1: Hazard Likelihood and Consequences Chart.

		Consequences			
		A: Minor First Aid or Medical attention required	B: Moderate Advanced medical attention required	C: Major Sever Health Outcome or Injury	D: Extreme Death or Permanent Injury
Hazard Likelihood	1: Rare	A1	B1	C1	D1
	2: Unlikely	A2	B2	C2	D2
	3: Likely	A3	B3	C3	D3
	4: Almost certain	A4	B4	C4	D4
	Legend	Low Risk	Medium Risk	High Risk	

Table A2: Assessment of Personal Risk

Task	Hazard	Risk	Precaution Measure
All Phases	Paper Cuts and similar small injuries due to stationary equipment	A1	Caution must be taken during all aspects of this project including personal conduct and behaviour
All Phases	Muscle and back pain due to being seated for long periods of time	A1	During the Design and Write-up phases, take regular breaks to stretch, relax and get some air.
All Phases	Sore eyes from increased contact with screens	A2	During the Design and Write-up phases, take regular breaks to stretch, relax and get some air.
All Phases	Dehydration	B1	During the Design and Write-up phases, take regular breaks to stretch, relax and rehydrate.

Testing	Exposure to respirable coal dust	A4	Store coal dust in sealed containers and keep away from windy environments until use.
Testing	Fire hazard from coal dust	C1	During testing a fire extinguisher will be stationed near the apparatus. Remembering there will only be a very small amount of coal used.
Testing	Skin irritation from wetting agent	A3	Chemical gloves should be worn as well as other PPE equipment e.g. eye protection.
Testing	Falling objects	A2	Protective steel cap footwear should be worn.
Testing	Inhalation of coal dust	A4	The experiment was conducted in open space to allow the dust to quickly disperse.