Comparison of Chemical Suppressants under Different Atmosphere Temperatures for the Control of Fugitive Dust Emission on Mine Haul Roads

by

David Omane

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Department of Civil and Environmental Engineering
University of Alberta

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ABSTRACT

Dust generated from mine haul roads poses a severe health and safety threat to workers and the environment. Traditionally, to control the dust, water has been applied on mine haul roads. Although environmentally friendly, water lasts for a limited duration due to evaporation. As a result, water has less longevity and requires consistent re-application, leading to an enormous waste of valuable water resources, especially in remote areas where most mine sites are located. Currently, chemical suppressant has been proven by most researchers as a better palliation agent in controlling dust, which is now adopted by many mining industries as a control measure. Among various environmental factors, the temperature of the atmosphere plays an important role in how effective a chemical suppressant is at dust retention on mine haul roads because temperature directly affects water evaporation. However, the past and current research focuses only on the influence of hot temperatures on the performance of chemical suppressants without considering other temperatures (i.e., cold and normal room temperatures). Hence, the objective of this study is to investigate the role of different atmosphere temperatures on the effectiveness of chemical suppressants. In this study, water and selected chemical surfactants—salt, chloride free agents, polymers, and molasses—were tested experimentally for their dust retention efficiency under atmosphere temperatures of 35 ^{o}C (hot), 15 ^{o}C (normal), and -19 ^{o}C (cold), respectively, within a time frame of 72 hours. This study found that water has the retention efficiency of 48.47%, 54.67%, and 99.92% at hot, normal, and cold temperatures, respectively, after 72 hours. Compared with water, a salt solution, chloride free solution, polymer solution, and molasses solution achieved higher efficiencies of 85.85%, 90.15%, 99.78% and 99.98%, respectively, than those of water. This demonstrates that different atmosphere temperatures have an impact on how effective each of the selected chemical suppressants is on fugitive dust. The impact of this research can assist mining companies around the globe in decision-making analysis on different chemical dust suppressants regardless of the atmospheric temperatures present at an area of location of a mine.

PREFACE

This thesis focuses on atmospheric temperatures as a control efficiency parameter on the effectiveness of chemical dust suppressant. The experimental dataset and methodology referred to in chapter 3 was designed by myself, with the assistance of W.V. Liu, and Y. Pourrahimian. The data analysis in chapter 4 and concluding analysis in chapter 5 are my original work, as well as the literature review in chapter 2.

Chapter 3,4, and 5 of this thesis has been submitted for publication as D. Omane, W.V. Liu, and Y. Pourrahimian, "Comparison of Chemical Suppressants under Different Atmosphere Temperatures for the Control of Fugitive Dust Emission on Mine Haul Roads," *International Journal of Mining, Reclamation and Environment*. I was responsible for the data collection and analysis as well as the manuscript composition. W.V. Liu and Y. Pourrahimian were the supervisory authors and were involved with concept formation.

This Thesis is lovingly dedicated:

To the memory of my beloved father, Kofi Attah Amofah
Who showed me the importance of fatherhood

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I am most grateful to the Almighty God for how far he has brought me in life. "PRAISE BE TO HIS NAME". I wish to express my profound gratitude to my supervisors, Dr. Wei Victor Liu and Dr. Yashar Pourrahimian of the School of Mining and Petroleum Engineering, for their guidance, support, and motivation during the preparation of this thesis. Their style of leadership and attention to detail always kept me on the right research track. My sincere thanks and appreciation goes to my advisory committee member, Dr. Clayton Deutsch. Your comments and corrections are appreciated.

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David Omane, June 2017

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BDS	Biological Dust Suppressants
C	Cold Temperature
CDC	Centers for Disease Control and Prevention
H	Hot Temperature
NDS	Non-Biological Dust Suppressant
NIOSH	National Institute for Occupation Safety and Health
NPV	Net Present Value
R	Normal Room Temperature
R_1	Average Dust Retention Efficiency
SIMRAC	Safety in Mines Research Advisory Committee
USEPA	United State Environmental Protection Agency

LIST OF NOMENCLATURES

Parameters

Cc & Cu	Co-efficient Curvature and Co-efficient of Uniformity of the soil
Ct	Cost of a dust suppressant
D_{10}, D_{30}, & D_{60}	Diameter of soil sample at 10%, 30%, and 60% on particle size distribution curve (mm)
d	Diameter of the soil particles (mm)
ε	Mass fraction of fugitive dust that escapes the pit (%)
EI	Environmental Impact of each chemical suppressant
F	Application frequency of each chemical suppressant
H	Hot atmospheric temperature
r	Dust retention efficiency (%)
R	Average dust retention efficiency (%)
T	Total fraction of dust generated from the mining activities (%)
v	Volumetric dilution for surfactants (%)
V_d	Settling velocity of the emitted particles (m/s)
ω_1	Weight of the sample before blowing (g)
ω_2	Weight of the sample after blowing (g)

ω_C	Weight of the container (g)
ω_D	Weight of the dried soil sample and container (g)
ω_m	Weight of the moist soil sample and container (g)
ω_p	Weight of the plate (g)
$\Delta\omega$	Weight of the sample loss (g)

CHAPTER 1
Introduction *

This chapter gives an overview of the research. It discusses the background of the study, the problem statement, the study's objectives, context and scope, the proposed methodology, and the contributions of the research.

* A section of this Chapter has been prepared and submitted as a journal manuscript: Omane, D., Liu, W. V., Pourrahimian. Y. (2017) Comparison of chemical suppressants under different atmosphere temperatures for the control of fugitive dust emission on mine haul roads. *International Journal of Mining, Reclamation and Environment*

1.1 Introduction

Surface mining is one of the most dominant methods of minerals extraction in the world. About 70% of the world's ore deposit beneath the earth is extracted through the process of surface mining (Kennedy, 1990). A number of activities are followed during the process of surface mining operation (i.e., drilling, blasting, hauling, dumping, and reclamation). Each operational activity leads to the generation of dust during the operation either by wind effect or through the movement of vehicular equipment (Kennedy, 1990; Thompson, 2011). A major source of dust emission in a surface mining operation is generated during the hauling of materials. Hauling of mined materials either to the processing plant or the waste dump in a surface mining operation is executed using a haul truck, which uses an unpaved mine haul road as the haulage route (Kennedy, 1990; Watson, Chow, & Pace, 2007). Dust is created when fine solid particles of the soil which are added to the wearing course materials of the unpaved road surface, for the filling of the void spaces between the course material to prevent materials displacement gets suspended into the atmosphere. When the suspension of the fine solid particles get caused either by wind effect or human activities, a fugitive dust emission is then generated (Chakradhar, 2005; Watson et al., 2007). The emission of fugitive dust from the road surface is dependent either on the weather condition, surface properties of the road or the activities executed on the road surface (Chakradhar, 2005; Watson et al., 2007; Wetherelt & Wielen, 2006). According to some previous research by Kennedy (1990) and Thompson (2011), truck hauling in surface mining operation constitute 50% of the total operating cost. Hence, there is a need for an optimized way to improve truck efficiency and reduce the related cost of truck usage. According to some previous research by Reed & Organiscak (2008) and the United States Environmental Protection Agency (USEPA), haul trucks on unpaved mine haul roads in a surface mining operation generated about 78% - 97% of the total fugitive dust emission in the mines.

There are a number of problems associated with the fugitive dust during a surface mining operation (Tannant & Regensburg, 2001; Thompson, 2011), fugitive dust may cause poor visibility for haul truck drivers which can lead to road accidents, an increase in road and vehicular maintenance cost, an extension in trucks cycle time, an increase in truck fuel consumption, an increase in haul body vibration of the truck drivers, an increase of mined materials spillage on the roadway, a reduction in truck tire life, an increase in health and safety hazards to mine workers, a reduction in mine productivity and a loss of mining operational license. All these defects of fugitive dust on the unpaved mine haul road can lead to an increase in haul truck operational cost. Moreover, according to statistics from National Institute for Occupational Safety and Health (NIOSH), unpaved mine haul roads contributes 20% of lost time injuries and a 42% of fatal accidents in surface mining operations in the United States of America (Turin, Wiehagen, Jaspal, & Mayton, 2001; Wetherelt & Wielen, 2006). Furthermore, the Safety In Mines Research Advisory Committee (SIMRAC), in South Africa concluded that 74% of accidents in South Africa mines occurs during the hauling of mined materials by haul trucks and the operations of service vehicles (Simpson, Rushworth, Glehn, & Lomas, 1996; Thompson & Visser, 2007). The outcome of the statistics above shows a good maintenance of haul roads and an efficient method of fugitive dust control can have a better influence on the productivity, cost, and operations of the mines. Several measures over the years have been proposed by NIOSH and other researchers as a means of controlling the problem of fugitive dust on mine haul roads. For example, reduction in truck haulage speed, control of haulage truck traffic volume, cab maintenance, consistent haul road maintenance, using of suitable wearing course material for haul road construction, and frequent application of water or chemical suppressants on the road surface (NIOSH, 2013; Thompson & Visser, 2000; Wetherelt & Wielen, 2006).

There are many ways reducing the level of fugitive dust during truck haulage. First of all, a reduction in truck haulage speed during a mining operation can minimize the emission of fugitive dust on an unpaved road. According to a study by Countess (2006), when the speed of haulage truck on an unpaved haul road is limited to 25 mph, it contributes to a reduction of fugitive dust on the road by 44%. In another study, reducing the speed of a haul truck from 25 mph to 10 mph decreases the generation of fine dust particles of diameter less than 10 µm into the atmosphere by 58% (Watson, 1996). Also, a reduction from 25 mph to 15 mph translates into a reduction of 42% of fugitive dust (Watson, 1996). However, this measure of control approach is a mitigation action, and it does not prevent the problem from occurring. Furthermore, implementing this method can lead to an increase in truck cycle time, which can translate into a reduction in truck productivity and mines production.

A second measure is to use traffic control for the reduction of fugitive dust on mine haul roads. A previous study by Reed & Organiscak (2006), showed a 20 seconds time interval between leading truck and the follow-up truck can lead to a 52% reduction of fugitive dust from haul roads into the atmosphere. Also, a 20 seconds' time interval between trucks, can allow generated dust particles from the lead truck to dissipate into the atmosphere to ensure clear visibility of the following truck (Reed & Organiscak, 2006). Nonetheless, traffic control can only serve as a mitigation action without halting the generation of fugitive dust on the roads. Furthermore, truck traffic control will increase truck cycle time, which will minimize production.

Thirdly, consistent cab maintenance of operational haulage truck reduces the exposure of the truck operator to the generated fugitive dust from the haul road. A previous study by Chekan & Colinet (2003), explained that a proper maintenance of haulage truck cabs could reduce respirable dust exposure of the operator by 59% to 84%. According to the Centers for Disease Control and Prevention (CDC), a study performed in central Pennsylvania concluded that a higher proportion of dust-related disease cases (e.g. Silicosis) recorded were associated with mine workers who were operating mobile mining equipment without any proper cab maintenance (CDC, 2000). Implementation of the measure can reduce the percentage of mine workers affected by the dust-related disease each year. However, cab maintenance can only reduce respirable dust exposure to the truck operator but cannot prevent the emission of fugitive dust from the road surface into the atmosphere.

Among all the proposed dust control measures, the most effective options are the selection of appropriate wearing course materials for road construction, application of suitable dust suppressant and a proper haul road maintenance according to some recent research (NIOSH, 2013; Tannant & Regensburg, 2010; Thompson, 2011; Wetherelt & Wielen, 2006). For example, a selection of appropriate wearing course material and a suitable dust suppressant will assist in protecting mine haul roads from deterioration such as potholing, which decreases the efficiency of haul trucks. Moreover, it contributes to a reduction in mine haul road maintenance time and cost. A study by Thompson (2011), explained that statistics show it takes 500% more time in maintaining a deteriorated road than the time spent in building it. Non-avoidance of the deficiency of consistent road maintenance can lead to a delay in mine production and a loss of productivity on the part of the workers and the vehicular equipment (i.e., haul trucks) that uses the haul road. Selection of appropriate wearing course material depends on the area of the mining operation and the weight of the vehicular equipment that will be using the road (Tannant & Regensburg, 2010). Application of a suitable dust suppressant on an appropriate wearing course material is dependent on factors such as cost efficiency, dust retention efficacy and atmospheric temperature (Amponsah-Dacosta, 1997; Edvardsson, Gustafsson, & Magnusson, 2011; Kavouras et al., 2009a; Thompson & Visser, 2007). Different dust suppressants such water and chemical suppressants has been used over the years in controlling the emission of fugitive dust on mine haul roads (Gillies et al., 1999; Kavouras et al., 2009a; Reed & Organiscak, 2008; Valenzuela, Palma, & Vega, 2014; Visser, 2013; Watson, 1996).

Water over the years is used as the traditional dust suppressant in controlling fugitive dust on an unpaved mine haul road. It is very affordable as a dust suppressant on haul roads. However, it is only effective on fugitive dust for a shorter period when applied on road surfaces and therefore requires a consistent re-application. It becomes difficult to use in areas of water scarcity, hence an alternative means of chemical suppressant is recommended as replacement (Amponsah-Dacosta, 1997; DeLuca, Corr, Wallace, & Kanaroglou, 2012; Edvardsson et al., 2011; Foley, Cropley, & Giummarra, 1996; Gillies et al., 1999; Jones, 1996; NIOSH, 2013). In addition, the efficacy of a chemical suppressant is dependent on atmospheric temperature (Fitz & Bumiller, 2000; Foley et al., 1996; Monjezi, Shahriar, Dehghani, & Samimi Namin, 2009; NIOSH, 2013). Since mining companies are located all around the globe with different weather temperature, there is a need to evaluate the effectiveness of varying chemical suppressants at a different atmospheric temperature (i.e., hot, cold and normal temperature) to determine their performance and efficiency. However, past and current research focuses only on the influence of hot temperatures on the performance of chemical suppressants without considering other temperatures (i.e., cold and normal room temperatures). This research focuses on different atmospheric temperatures as control efficiency of a chemical dust suppressant on fugitive dust.

1.2 Research background

Road dust generated through truck hauling in the mining industry is a severe hazard to the health of workers (Alberta Government, 2008; NIOSH, 2013) and the maintenance of road and vehicles. Road dust usually contains silica and other heavy metals that when inhaled can lead to diseases such as lung cancer, abnormal kidney function, and rheumatoid arthritis (Alberta Government, 2008; Organiscak & Reed, 2004). Accounting for about 78% to 97% of the total amount of dust emitted into the atmosphere in surface mining operations, road dust mainly consists of solid particulate matters having smaller particles diameters (i.e., 2 μm – 75 μm) (Foley et al., 1996; Kavouras et al., 2009b; Thompson & Visser, 2007).

The emission of dust from road surface leads to soil erosion which has an adverse effect on the travel time of vehicles (Thompson & Visser, 2007). Moreover, deteriorated mine road affects haul trucks performance and operational service vehicles handling and conveying materials for in-pit regarding productivity, and increase the whole-body vibration of drivers. The moving parts of the haul trucks such as bearings and engines may also be affected by the emitted solid particles creating downtime in operational scheduling and an increase in vehicular maintenance cost (Organiscak & Reed, 2004).

A common road dust control method is to dampen the road with water in mining industries (Kavouras et al., 2009a; Thompson & Visser, 2007). Although environmentally friendly, this approach has a limited duration due to its associated deficiency of high evaporation efficiency (Foley et al., 1996). As a result, water spraying must frequently be reapplied, leading to a tremendous amount waste of valuable water resources, especially in remote areas where most mine sites are located (Kavouras et al., 2009a; NIOSH, 2013; Thompson & Visser, 2007). Improvement on the deficiency of water with chemical surfactants to form a solution of chemical suppressants has proven to be effective for the purpose of fugitive dust control (DeLuca et al., 2012; Foley et al., 1996; Gillies et al., 1999; Kavouras et al., 2009a; National Guide to Sustainable Municipal Infrastructure, 2005; NIOSH, 2013).

Past and current research works have proven the efficacy of chemical suppressants on fugitive dust emissions, assisting most mining industries during decision-making on dust control methods on mine haul roads (Kavouras et al., 2009a; National Guide to Sustainable Municipal Infrastructure, 2005; NIOSH, 2013; Reed & Organiscak, 2008; R. J. Thompson & Visser, 2007). For example, a number of chemical suppressants were assessed for their efficacy and cost efficiency on different surface mine haul roads in South Africa regarding their performance and duration (Thompson & Visser, 2007).

A chemical suppressant as a control agent is formed by mixing water with an optimal volumetric concentration of surfactant (Samaha & Naggar, 1988). So far, the mining industry has used various chemical suppressants such as lignosulphonates products, salts, petroleum products, polymers solution products, and foaming agents as a means for fugitive dust control on haul roads (Foley et al., 1996; Monjezi et al., 2009; Ruebel & Stuemke, 2004; Sanders, Quayenortey, & Jorgensen, 2014; Visser, 2013). In general, previous researchers show that chemical suppressants provide better performance and greater longevity (Foley et al., 1996; Gillies et al., 1999; Kavouras et al., 2009a; Thompson & Visser, 2007). Chemical suppressants contribute to higher revenue generation for industries without an additional workforce to the operational team (Cecala et al., 2012). Atmospheric factors such temperature needs to be considered when ensuring the efficacy of a chemical suppressant (Amponsah-Dacosta, 1997; Chiou & Tsai, 2001; Fitz & Bumiller, 2000; Foley et al., 1996; Monjezi et al., 2009; NIOSH, 2013).

The effectiveness of chemical suppressants is influenced by atmospheric temperature, which plays a critical role in the effectiveness of a chemical suppressant on mine haul roads (Chiou & Tsai, 2001; Foley et al., 1996; Thompson & Visser, 2007). Atmospheric temperature has an impact on the evaporation efficiency of a chemical suppressant contributing to better performance and longevity (Visser, 2013). For example, different chemical suppressants were evaluated on their efficiency under hot atmosphere temperature on unpaved roads in Chile, Colorado and some mines in Pilbara without taking into account other atmospheric temperatures (Sanders et al., 2014; Valenzuela et al., 2014; Visser, 2013). Evaluating the performance of different chemical suppressants at various temperatures can serve as a guide for the comparative assessment analyses on dust control methods for most mining industries located in non-hot climate zones. However, no research work has been initiated on the evaluation of the effectiveness of chemical dust suppressants at different temperatures.

In this research, four types of suppressants commonly used in the mining industry were chosen. For example, chloride salts, polymer solutions, molasses, petroleum products and lignosulphonate products have been used on a number of unpaved roads in countries like South Africa, Chile, India, and Sweden to achieve success in dust control (Edvardsson et al., 2011; Mishra & Jha, 2010; Thompson & Visser, 2007; Valenzuela et al., 2014). Among these chemical suppressants, four types are selected for this research—salt solution, chloride free solution, polymer solution, and molasses solution. Mining applications of these four suppressants can be referred to some extensive previous literature such as Edvardsson et al. (2011), Thompson & Visser (2007), Valenzuela et al. (2014), and Visser (2013). Salt is cost effective, environmentally friendly, and easily accessible, and it works effectively in binding water molecules together to reduce the efficacy of evaporation under extreme weather conditions (i.e., dry and hot) (Amponsah-Dacosta, 1997; Kavouras et al., 2009a; National Guide to Sustainable Municipal Infrastructure, 2005; NIOSH, 2013). Chloride free solution, polymer solution, and molasses solution were selected because these solutions perform efficiently and last longer as chemical suppressants under hot season (Kavouras et al., 2009a; Ruebel & Stuemke, 2004; Tran, Bo L; Bhattacharja, Sankar; Blubaugh, 2007). Consequently, the efficacy of each of the selected dust suppressant was tested under different weather season to determine the impact of different atmosphere temperatures.

1.3 Research scope

The investigation of the research has focused on the comparison of chemical suppressants under different atmosphere temperatures for the control of fugitive dust emission on mine haul roads. The evaluation of each selected chemical suppressant is described, taking into consideration their dust retention efficiency at different temperatures. Also, graphs are presented based on the dust retention efficiency for each chemical suppressant, which enables comparative analysis of the results. In combining the result of each dust palliative agent, a decision can be made by surface mining industries depending on their location on the most proficient chemical suppressant to be selected. The behavioral nature and the dust retention efficiency of each chemical suppressant under different atmospheric temperature have been studied and explored.

1.4 Research objective

The objective of this study is to examine the effects of selected chemical dust suppressants on fugitive dust emission on haul roads at three different atmosphere temperatures (i.e., 35, 15, and -19 ºC) mimicking hot, normal, and cold seasons. This research highlights the role of atmosphere temperature on the performance of four chemical dust suppressants commonly used in the mining industry. The research results will help curb haul road deterioration, maximize vehicular uptime, increase revenue generation, and assist in minimizing the threat fugitive dust to worker’s health and safety.

1.5 Research Methodology

The main aim of conducting this research is to improve the efficacy of chemical dust suppressants on fugitive dust with a focus on temperature as a control efficiency using different weather seasons. Temperature as a parameter is suitable for fugitive dust treatment because it exploits the performance of a chemical dust suppressant in different weather seasons, allowing comparative assessment analysis of different suppressants during decision-making by mining companies. The objective is to reduce the cost incurred by mining companies in the control of the amount of dust generated on mine haul roads, which will maximize expected Net Present Value (NPV). The following is a summary of the research tasks that must be completed to achieve the study's objectives:

- Propose, evaluate and analyze different chemical surfactants for the control of fugitive dust on unpaved haul roads.
- Prepare a solution of chemical suppressant by diluting a chemical surfactant with water.
- Evaluate the optimum volumetric concentration level of each chemical surfactant in a solution of chemical suppressant.
- Assess the control efficiency of each selected chemical dust suppressant by investigating the effectiveness at different atmospheric temperatures over a duration. Assess the results of different chemical dust suppressants at different atmospheric temperatures in terms of feasibility from a mining practice point of view by analyzing the dust retention efficiency.

- Weigh the impact of different atmospheric temperatures on chemical dust suppressants with regards to control effectiveness and cost effectiveness.

Mathematical equations were used to assess the dust retention efficiency of the chemical dust suppressants. The research focuses on different weather temperatures as a control efficiency to address the long-term performance dilemma of chemical dust suppressants.

1.6 Organization of Thesis

The outline of this thesis is presented in chapters. The main chapters of this thesis are Chapter 2 to Chapter 4, which elaborate on the dust retention efficiency of each of the selected chemical suppressants at different atmospheric temperatures. Chapter 2 focus on reviewing the work of previous researchers on the efficiency of dust suppressants on fugitive dust control. Moreover, Chapter 3 and Chapter 4 focus on the theoretical analysis of different chemical suppressants at different temperatures through their retention efficiency on fugitive dust. Each of the outlined chapters is summarized below.

Chapter 2**,** the literature review, elaborates on reviewing the previous research works of past researchers on different dust suppressants (i.e., water or chemical suppressant) that have been implemented by individuals and companies in controlling fugitive dust over the years. Moreover, the shortcoming of each of the researched work is evaluated and addressed. This chapter concludes the reason behind conducting the research for this thesis.

Chapter 3 emphasizes on the methodology used in evaluating the dust retention efficiency of each of the tested dust suppressants for this thesis at different atmospheric temperatures. A dosage of dust suppressant was applied on a soil sample, the sample was then placed under the atmosphere temperatures of 35 ºC (hot), 15 ºC (normal), and -19 ºC (cold), respectively, within a time frame of 72 hours. An experimental test on the sample was conducted by weighing the sample before and after an application of wind speed of 65 km/h, to assist in determining the percentage of loss material on each sample.

Chapter 4 presents the theoretical analysis of each of the tested dust suppressants at different atmospheric temperatures within a time frame of 72 hours. The results illustrated show the weight of material loss, the percentage of loss material, and dust retention efficiency of each of the selected dust suppressants. The weight of loss material was evaluated in determining the percentage of loss material and the associated dust retention efficiency per soil sample. It is found that atmospheric temperature does have an impact on the efficacy of dust suppressants on fugitive dust control. Moreover, some of the tested chemical suppressants perform better than others at different weather temperatures. Chemical suppressants as dust control agents have better efficacy in controlling fugitive dust on mine haul roads at different atmospheric temperatures compared to water.

Chapter 5, this chapter contains the thesis summary and conclusions on the research work and proposed some recommendations for future works.

CHAPTER 2
Literature Review

Chapter 2, the literature review, elaborates on reviewing the previous research works of past researchers on different dust suppressants (i.e., water or chemical suppressant) that have been implemented by individuals and companies in controlling fugitive dust over the years. Moreover, the shortcoming of each of the researched work is evaluated and addressed. This chapter concludes the reason behind conducting the research for this thesis.

2.1 Background

This chapter is concerned with a literature review on dust suppressants and its impact on the control of fugitive dust emissions on an unpaved haul road. This includes literature on different dust suppressants and the importance of atmospheric temperature on the efficiency of dust suppressants. First of all, evaluation of previous and recent developments in the dust palliative agents used for mining operations are also discussed. Next, environmental impacts associated with the use of dust suppressants are highlighted. After that, the impact of atmospheric weather temperature and wearing course materials on the efficiency of dust suppressants on an unpaved road surface are reviewed. Furthermore, this chapter identifies the shortcoming of previous and current research works and concludes with the reason for this research.

2.2 Fugitive dust emission control on an unpaved haul road

Measures in controlling the emission of fugitive dust on an unpaved haul road are categorized into three categories, namely, road surface improvement, source extent reduction and road surface treatment (Cowherd, Muleski, & Kinsey, 1988). The first two categories, road surface improvement and source extent reduction, provide mitigation actions on fugitive dust control rather than a preventive measure provided by road surface treatment. The third one, application of surface treatment on a road surface, ensures the retention of a desirable amount of moisture content within the wearing course material of the haul road. This is because the present of moisture content prevents the generation of fugitive dust from the road surface. Furthermore, road surface treatment can be classified into two subcategories: wet suppression (i.e., application of dust suppressant on the road surface) and chemical stabilization (i.e., improving the physical properties of the soil on the road surface) (Amponsah-Dacosta, 1997; Cowherd et al., 1988). According to previous research by Cowherd et al. (1988), road surface treatment such as the application of dust suppressant, in addition to selecting appropriate wearing course material for the road surface has proven to be the variable measure in controlling the emission of fugitive dust on an unpaved mine haul road.

2.3 Dust suppressant as fugitive dust control

Dust suppressant is a substance applied to a surface of aggregate materials to bind and prevent the emission of dust from the surface into the atmosphere NIOSH, 2013). Moreover, an addition of a dust suppressant on an unpaved haul road damps road surfaces by increasing the surface moisture content on the haul road. This process controls the total percentage of fine particles emitted from the road surface into the atmosphere as fugitive dust (Organiscak, Page, Cecala, & Kissell, 2003). The selection of appropriate dust suppressant for the control of fugitive dust on a surface is dependent on factors such as atmospheric weather conditions, the longevity of the suppressant when applied on the surface, cost efficiency, and the environmental concerns associated with the suppressant (Thompson & Visser, 2007). Dust suppressant can be grouped into two main types (i.e., biological and non-biological), which are introduced in the following section.

2.3.1 Biological dust suppressants

Biological dust suppressant (BDS) is an agent that depends on enzymes and bacteria reactions within soil microorganisms to prevent the emission of fugitive dust from an aggregate soil surface into the atmosphere (Meyer, Bang, Min, Stetler, 2011). Subsequently, many researchers have experimented with the use of bacteria in solving the problem of fugitive dust emission on an unpaved roads, construction sites, and open pit mining operations (Benini, Gessa, & Ciurli, 1996; Braissant, Cailleau, Dupraz, & Verrecchia, 2003; DeJong, Fritzges, & Nüsslein, 2006).

Bang et al. (2009), Bang, Frutiger, Nehl, & Comes (2009) and Meyer, Bang, Min, Stetler (2011), proposed the use of a bacteria called Sporosarcina pasteurii, which induces the precipitation of calcium carbonate into the atmosphere with the ability to suppress dust emissions. In their study, parameters such as humidity and temperature were modified to determine the effectiveness of Sporosarcina pasteurii.

2.3.2 Non-biological dust suppressant

Non-Biological dust suppressant (NDS) is classified as either water or chemical suppressant (NIOSH, 2013). NDS is an agent applied to a surface to prevent the emission of dust from the surface when disturbed either by natural or human-made activities into the atmosphere (NIOSH, 2013). This method is still widely used by most mining industries around the globe as a means of controlling the emission of fugitive dust in surface mining operations (Organiscak et al., 2003).

Many research works have been done in determining the effectiveness of NDS over time. Authors such as Sanders, Addo, Ariniello, & Heiden (1997) and Amponsah-Dacosta (1997) have done extensive research testing the efficacy of NDS to solve the problem of fugitive dust on unpaved haul roads. Sanders et al. (1997) evaluated the effectiveness of NDS on four different test sites on unpaved haul roads in Larimer County, Colorado for a duration of 4.5 months. One out of the four sites were used as control test site, where no dust suppressant was applied to the road surface. It was observed that after the duration of the experiment there was a 50% – 70% reduction in fugitive dust emission on the treated road surface compared to the untreated road surface. The result concluded that dust suppressant can control the emission of dust but its efficiency varies widely over a duration. Amponsah-Dacosta (1997) also tested the use different dust suppressants on unpaved haul roads in New Vaal Colliery opencast mines, Johannesburg, South Africa. The research work showed the importance of dust suppressant on fugitive dust control on mine haul road compared to other control measures. The drawback in the implementation of the technique of dust suppressants on fugitive dust is the non-consideration of the atmospheric weather temperature on the effectiveness of each control agent applied.

2.3.3 Water

Water is considered as a category of NDS and it has been used over the years as the traditional method for fugitive dust control on unpaved haul roads (Amponsah-Dacosta, 1997). Water truck controlled by an operator is used in applying water on unpaved haul roads through the process of spraying. Water application is the easiest mode of dust control on haul roads because no road preparation is required before usage (NIOSH, 2013). Application of water to the road surface increases the moisture content of the road's wearing course materials (USEPA, 1998a). An increase in moisture content binds both fine and coarse particles of the road surface materials together preventing the suspension of particles into the atmosphere as dust. The control efficiency of water as a treatment for dust control is dependent on the application rate of water, the time between application, traffic volume on the applied road, and the meteorological condition during the period of application (NIOSH, 2013; USEPA, 1998a).

Many researchers and organizations have conducted a series of research on the effectiveness of water treatment on dust control. A study by the United States Department of the Interior, Bureau of Mines on the efficacy of water treatment showed an application of water on an unpaved haul road at an interval of an hour produces a control efficiency of 40% of the total percentage of particles suspended from the road surface. However, when the rate of application was reduced to every 30 minutes, there was an increase of 55% in the control efficiency of the total percentage of particles suspended (Rosbury & Zimmer, 1983). The experimented result shows how the interval between the time of application affects the effectiveness of water treatment. The limitations of this measure of dust control include the following aspects: (i) consistent re-application to achieve a substantial control efficiency for dust control leading to a tremendous amount of wasting valuable water resource; (ii) higher depreciation of control efficiency with time; (iii) high capital and operating cost of equipment used for the application on road surface. A research was done in South Africa on a number of unpaved mine haul roads in Mpumalanga Highveld Coalfields on water treatment as dust control. The haul trucks that used the haul road during the experiment were of 730/CAT 789 model and were travelling at a speed of 40 km/h. Figure 2.1 shows the dust reading of the dust meter attached along the road over time modified after Thompson & Visser (2007).

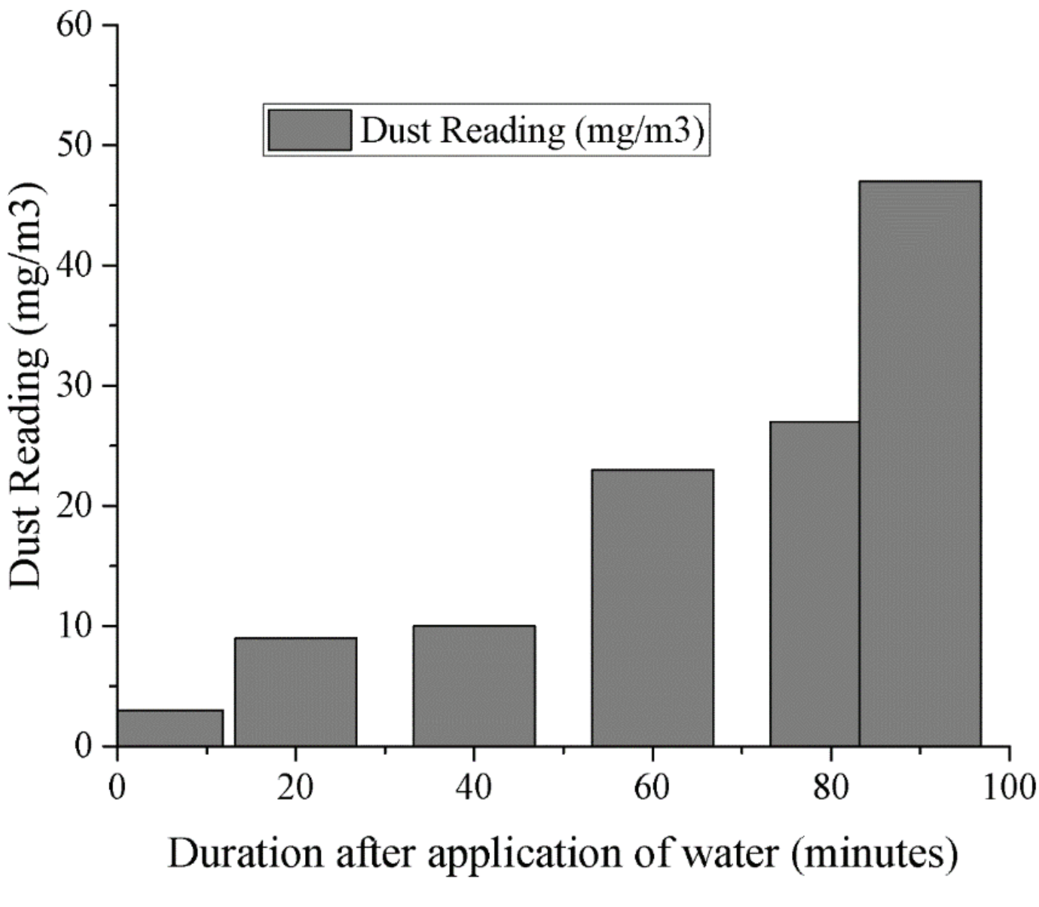

Figure 2.1. The effectiveness of water treatment as dust control on mine haul road modified after Thompson (2007)

It was observed that at the initial stage of water application the dust reading was minimal but starts to increase with time. This incremental trend in the dust reading showed water as a dust control performs less effectively with time (Thompson & Visser, 2007). It was found that the reason behind this deficiency of water was due to its widely spaced of molecules (DeLuca et al., 2012; Foley et al., 1996). Widely spaced molecules contribute to higher surface tension, which lowers the retention of moisture content within the soil. Lower moisture content retention affects the control efficiency of water as a dust control measure (DeLuca et al., 2012; Foley et al., 1996). Some of the shortfalls of most of the past research works were that factors such meteorological conditions that affects the control efficiency of water as a treatment on dust control were not considered.

2.3.4 Chemical Suppressants

Many research works have been done in finding a solution to the deficiency of water as a dust suppressant over the years. A practical addition of chemical surfactants such as polymer solutions, lignosulphonate, salt, foam, and petroleum products to water have been experimented and proposed by different researchers as a means of improving the drawback of water treatment (Cowherd et al., 1988; Organiscak et al., 2003; Reed & Organiscak, 2008). The chemical surfactant is added to water to form a solution of chemical suppressant (NIOSH, 2013). According to some previous research conducted by Amponsah-Dacosta (1997), Cowherd et al. (1988), Foley et al., (1996), Gillies et al. (1999), Organiscak et al. (2003), Reed & Organiscak (2008) and Thompson & Visser (2007), chemical surfactant in water increases the adhesive and reduces the cohesiveness between the water molecules making it spread easily when applied as a dust control treatment on a road surface. A study by (Midwest Research Institute (Kansas City Mo.), 1981), showed a 32 – 52% reduction in application time when surfactants are added to water for dust treatments on roads. The addition of surfactant reduces the surface tension of the solution (i.e., chemical suppressant), which assist in binding together loose wearing course materials on a road surface by retaining moisture content and preventing the emission of fugitive dust into the atmosphere. Chemical suppressant can be applied on an unpaved haul road in two ways (i.e., spray-on application and mix-in application) (Thompson & Visser, 2007). Spray-on application is where a spraying truck is used in sprinkling chemical suppressant on a road surface. Mix-in application is when a chemical suppressant is added to wearing course materials of a road surface using graders with scarifying blades and compactors through the process of mixing (Thompson & Visser, 2007). The control efficiency of a chemical suppressant is dependent on factors such as dilution rate, application rate, the time interval between application, traffic volume, road and vehicle characteristics (Cowherd et al., 1988; USEPA, 1998b). The variation in the control efficiency factors affects the performance of each chemical suppressant applied on a road surface.

Authors and environmental organizations such as (Midwest Research Institute (Kansas City Mo.), 1981; NIOSH, 2013; Olson & Veith, 1987; Rosbury & Zimmer, 1983; Thompson & Visser, 2007), have done extensive research on the control efficiency of different chemical suppressants. Salt-based control agents such as Magnesium Chloride ($MgCl_2$) and Calcium Chloride ($CaCl_2$) were added to water and tested on some unpaved haul roads as dust treatment. After 22 days of application of $MgCl_2$ solution on the road surface under hot climate, a control efficiency of 95% was achieved. However, when $CaCl_2$ was applied for a duration of 2 weeks a control efficiency of 82% was achieved, which later declined to 14% after 7 weeks of application (NIOSH, 2013; Rosbury & Zimmer, 1983). According to a previous research conducted by NIOSH (2013), petroleum solutions were examined as a dust suppressant on both access and haul road. After 6 months of application on the access road, a control efficiency of 100% was achieved. Moreover, a dust free efficiency was also achieved on the haul road after 3 to 4 weeks of application.

However, a previous research conducted by Olson & Veith (1987), showed a control efficiency of up to 70% for the application of petroleum solutions on unpaved haul roads after 21 days. A research conducted by (Rosbury & Zimmer, 1983), on polymer solutions as a dust control agent on unpaved public roads showed a control efficiency of 74 – 81% after 4 weeks of application and declined to 3 – 14% after 5 weeks. Another study by Gillies et al. (1999), on polymer solutions on unpaved mine haul roads showed a control efficiency of 94 – 100% after one week of application and reduced to 37 – 65% after 11 months. In addition, the use of adhesives as a chemical suppressant have become one of the dominant products for dust control on unpaved roads. Lignin sulfonate, as a type of adhesive, has been shown to be effective on dust emissions. Researchers such as (Midwest Research Institute (Kansas City Mo.), 1981; Rosbury & Zimmer, 1983), have conducted an extensive practical evaluation on the efficiency of lignin sulfonate on a number of unpaved haul roads. (Midwest Research Institute (Kansas City Mo.), 1981), observed that after an application of lignin sulfonate solution on some mine access roads showed 100% control efficiency for a duration of 6 months – 2 years. Moreover, on mine haul roads, a dust free environment was observed for a duration of 3 – 4 weeks after the application. Another study conducted by Rosbury & Zimmer (1983), concluded that a control efficiency of 50 – 63% was achieved for an application of lignin sulfonate solution on mine haul roads after a duration of 4 weeks. Some of the benefits attributed to the use of lignin sulfonate as a dust treatment method includes reduced road and vehicle maintenance cost, increased equipment utilization, steady production and productivity rates, and contributed to incident-free working environment (Foley et al., 1996; Midwest Research Institute (Kansas City Mo.), 1981; Rosbury & Zimmer, 1983; Thompson & Visser, 2007).

The performance evaluation of different chemical suppressants on unpaved dirt roads plays a vital role in decision-making on comparative assessment analysis on the selection process on a dust control method. Selection matrices such as heavy traffic, ramp roads, long and short term efficiency, have been evaluated by researchers such as (Jones, 1999; Thompson & Visser, 2007), on a number of dust suppressants. Chemical suppressants such as hygroscopic salt, lignosulfonate, petroleum, polymer and tar solutions were tested using these selection matrices. It was observed by (Jones, 1999; Thompson & Visser, 2007), that on road of high traffic volume, hygroscopic salt, petroleum, polymer and tar solutions perform better than lignosulfonates and other wetting agents, and on ramp roads petroleum, polymer and tar solutions were effective than the other tested chemical suppressants. In addition, for long-term efficiency lignosulfonate, polymer and tar solutions performed better but for a short-term duration, hygroscopic salt, lignosulfonate, and petroleum solution were the most efficient. However, less information was provided on the environmental factors such as different atmospheric temperatures to enable an assessment of the practicality of the solutions from mining operation point of view.

2.4 Effects of atmospheric temperatures on dust suppressants

Environmental conditions such as temperature affect the efficiency and longevity of a dust suppressant. Temperature plays a critical role in the effectiveness of a chemical suppressant on mine haul roads, specifically on evaporation efficiency, which affects performance and longevity of dust suppressants (Chiou & Tsai, 2001; Foley et al., 1996; Thompson & Visser, 2007; Visser, 2013). One of the main problem associated with the use of the traditional method of applying water on unpaved roads is that discovered by other researchers was water lasts for a limited duration due to evaporation (Edvardsson et al., 2011; Jones, 1996; Reed & Organiscak, 2008). As a result, water has less longevity and requires consistent re-application, leading to an enormous waste of valuable water resources, especially in remote areas where most mine sites are located (NIOSH, 2013).

The addition of chemical surfactant to water was introduced by other researchers, to control the rate of evaporation and increase the longevity of chemical suppressants when applied as dust treatment agent (Reed & Organiscak, 2008). In addition, studies by researchers and environmental agencies such as (Foley et al., 1996; Gillies et al., 1999; NIOSH, 2013; Sanders et al., 1997, 2014), show that some chemical dust suppressants perform better than other in terms of longevity and one of the dominant reason for this shortfall is the higher evaporation rate of moisture within the soil. Temperature has an impact on evaporation rate of moisture within a soil (Durre, Wallace, & Lettenmaier, 2000), making it important to be considered on the control efficiencies of different chemical dust suppressants.

Thompson & Visser (2007) experimented the importance of water vapour as an environmental condition on a number of dust suppressants such as hygroscopic and deliquescent chloride. According to Thompson and Visser, hygroscopic and deliquescent chloride as chemical dust suppressants performs better by attracting water vapour from the atmosphere to keep the applied surface moist. The surface moisture content of an unpaved haul road is increased by the addition of a dust suppressant, this mechanism keeps the soil wet and prevents the emission of fine soil particles into the atmosphere (Organiscak et al., 2003). It was observed after the evaluation that hygroscopic chloride as a chemical dust suppressant performs less effective when the relative atmospheric humidity gets below 70% and deliquescent chloride also becomes ineffective as a control agent at a relative humidity of 50 – 63% (Thompson & Visser, 2007).

Temperature as an environmental condition has a greater influence on the amount of moisture and relative humidity that will be present in the atmosphere (Durre et al., 2000; Manabe, 1969; Zhang, Wang, & Wu, 2009). The outcome of the study showed the importance of temperature on the effectiveness of different dust suppressants. However, there is a lack of consideration of different atmospheric temperatures on the effectiveness of chemical dust suppressants in most research works. Atmospheric temperatures as a parameter on the control efficiency of chemical dust suppressants will assist mining companies on comparative assessment analysis on dust treatment methods. This research will introduce different atmospheric temperatures (i.e., cold, normal, and hot temperatures) as a factor of the efficacy of a chemical dust suppressant.

2.5 Summary and Conclusions

A review of the relevant literature for this research has been done. In a dust control treatment on an unpaved haul road, an omission of atmospheric temperatures as a control efficiency of a chemical suppressant can have a profound impact on mine safety, economics, and productivity. Over the last 30 years, continuous attempts have been made to address the importance of different control efficiency that affects the performance of chemical dust suppressants.

This has resulted in numerous research works some of which have been outlined in this thesis. As a result of the research works of others, many types of control efficiencies have experimented on several chemical dust suppressants. A summary includes: (i) dilution rate; (ii) application rate; (iii) time between application; (iv) traffic volume; (v) road characteristics; and (vi) vehicle characteristics.

However, most of the literature have a less tended focus on the role of atmospheric temperatures as a control efficiency on the effectiveness of a chemical dust suppressant. Evaluating the performance of different chemical suppressants at various temperatures can serve as a guide for the comparative assessment analyses on dust control methods for most mining industries located in different climate zones. This research will introduce different atmospheric temperatures as a parameter for the efficacy of different chemical dust suppressants which will enhance the application and selection of dust treatment methods on mine haul roads.

CHAPTER 3
Research Methodology *

Chapter 3 emphasizes on the methodology used in evaluating the dust retention efficiency of each of the tested dust suppressants for this thesis at different atmospheric temperatures.

*A section of this Chapter has been prepared and submitted as a journal manuscript: Omane, D., Liu, W. V., Pourrahimian. Y. (2017) Comparison of chemical suppressants under different atmosphere temperatures for the control of fugitive dust emission on mine haul roads. *International Journal of Mining, Reclamation and Environment*

3.1 Introduction

The main motivation for conducting this research is to understand the efficacy of chemical suppressants as dust treatment methods on fugitive dust by evaluating the effect of different atmospheric temperatures as a control efficiency. The first part of this study involved a literature survey on fugitive dust as a problem on unpaved haul roads, the negativities associated with the problem, and the use of dust suppressants as a means of control of the menace. Subsequently, three sets of dust suppressants are mostly considered (i.e., water, enzymes, and chemical suppressants). A dust treatment method of chemical suppressant was selected and evaluated for this study. The research focuses on the improvement and analysis of chemical suppressants as dust control measures by evaluating different atmospheric temperatures as control efficiency parameter. Figure 3.1 shows a summary of the research methodology.

3.1 Experimental Details

This section explains the specifics of the method of investigation on the effect of different temperatures as a control parameter on the effectiveness of chemical dust suppressants for the research work in terms of observation and measurement.

3.1.1 Equipment and Materials

To mimic the hot season, a Despatch LLB series oven, model LBB1- 43A-1 with a maximum temperature of 204 ºC, was used. A room thermostat was used to control the room temperature of 15 ºC to represent the normal season.

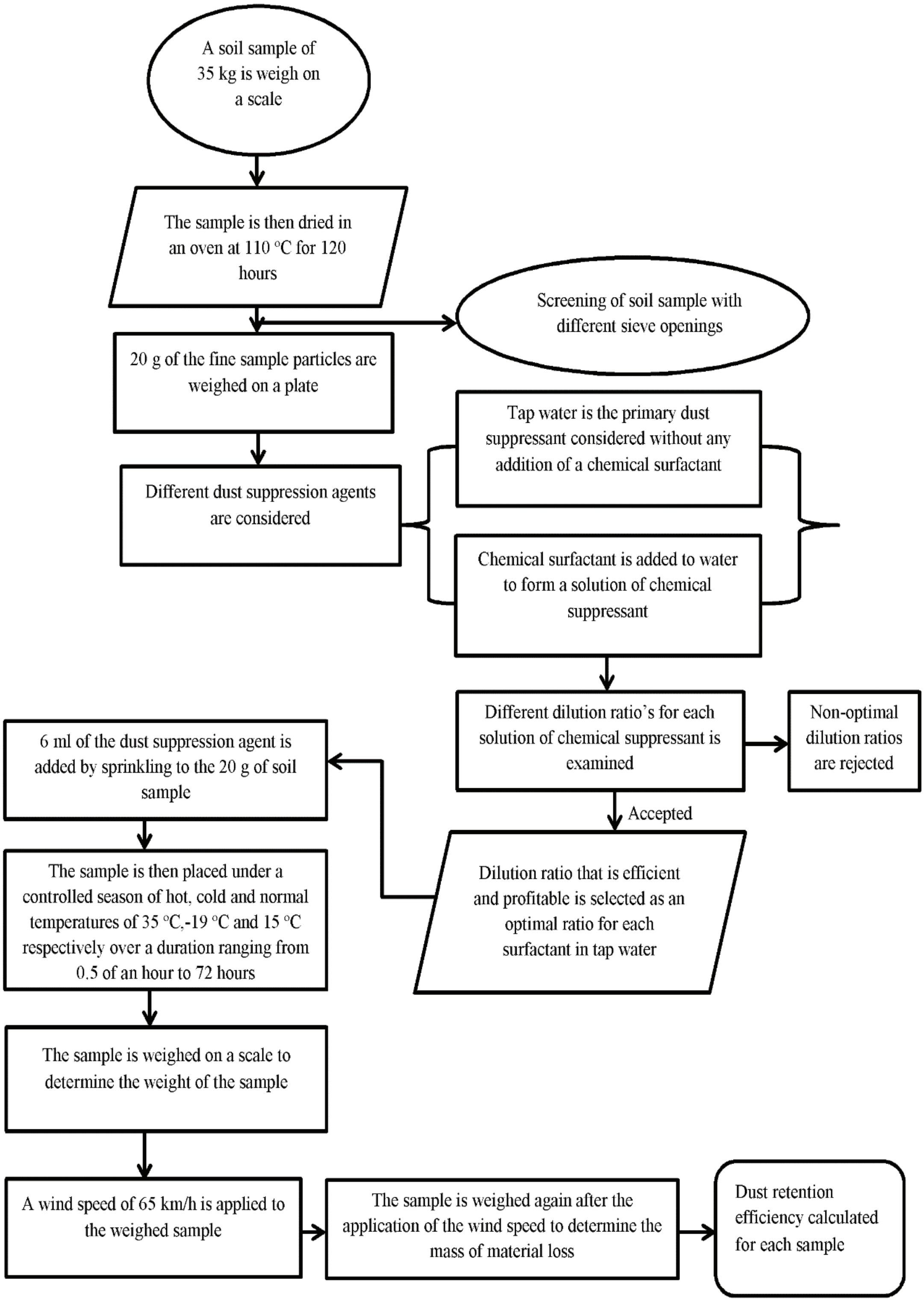

Figure 3.1. Summary of research methodology

For the cold season, a heavy-duty freezer was used to maintain the temperature of -19 ºC. A blower with a full capacity speed of more than 80 km/h was set up as a source of wind to trigger dust generation for the experiment.

As shown in Figure 3.2, a portion of 35 kg of soil sample was received from a local unpaved construction site in the City of Edmonton.

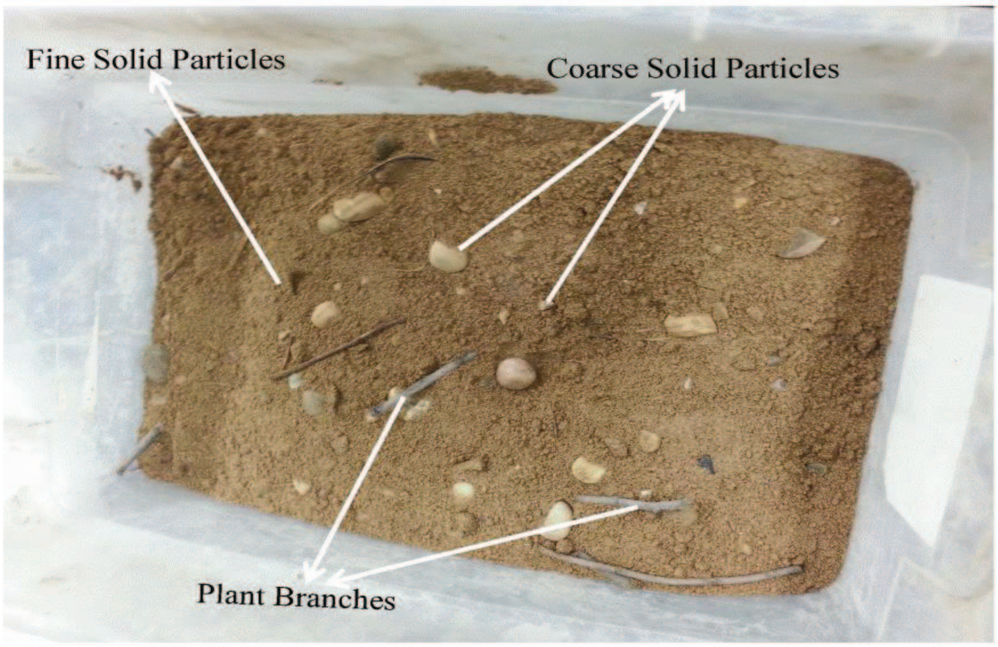

Figure 3.2. A photo of a fraction of the received soil sample

Some of the characteristics of the soil sample are similar to characteristics of chernozemic soil found in the City of Fort McMurray, where most haul roads are constructed for mining purposes (Crown & Twarty, 1970; Soil Classification Working Group, 1998). The soil sample used for the experiment had particle sizes ranging from 0.850 mm to 0.063 mm, which falls within the specification standard for haul road construction in both Edmonton and Fort McMurray (AASHTO, 1993a). Hence, the collected soil could be used to construct a mine haul road similar to one in Fort McMurray. In designing a haul road on a mine site, a mining company takes into consideration the wheel load of the haul truck and the particle size distribution of the soil before deciding what type of soil will be added to the wearing course materials (NIOSH, 2013; Thompson & Visser, 2007). According to the typical design standard for the mine haul road, the particle size distribution of the used soil sample, as shown in Figure 3.3, falls within the design limit (AASHTO, 1993b; NIOSH, 2013), which makes the sample appropriate for a haul road design.

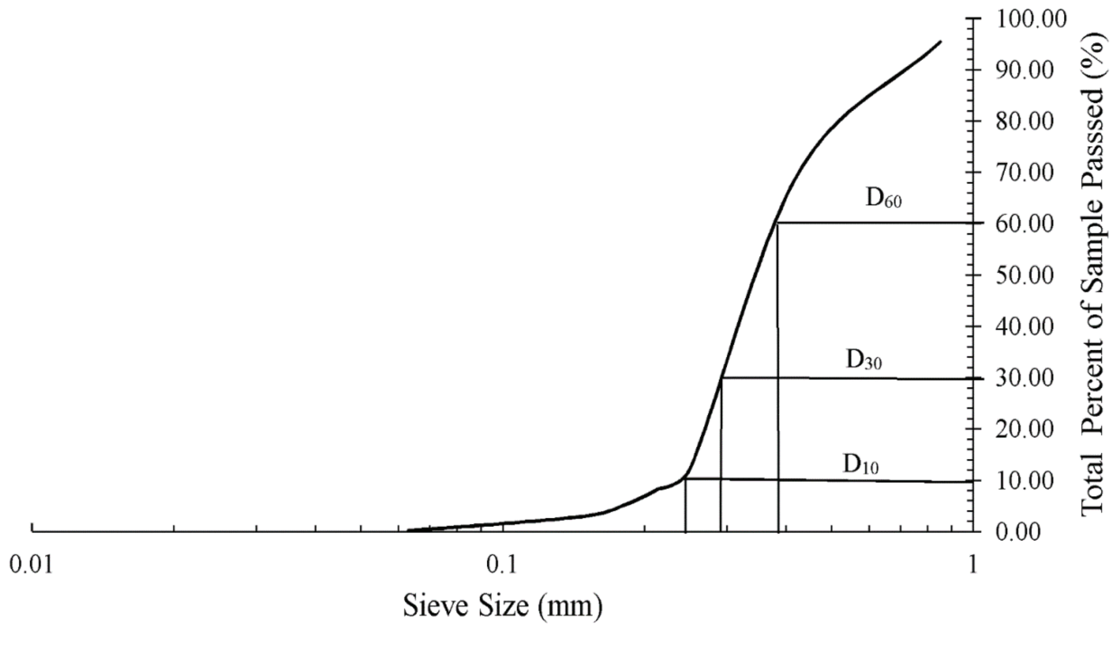

Figure 3.3. Particle size distribution of the soil sample

Table 3.1 represents the total percentage of a soil sample that passed through a sieve number in order to determine the particle size distribution analysis of the used soil sample for the experiment.

Table 3.1. Percentage of soil sample that passed through each sieve number

Sieve #	Sieve Size (mm)	Mass retained on sieve (g)	Cumulative mass retained (g)	Total percent (%) of sample passed
20.00	0.85	45.4	953.1	95.45
40.00	0.425	254.1	699	70.01
60.00	0.25	575.6	123.4	12.36
70.00	0.212	41.6	81.8	8.19
80.00	0.18	31.1	50.7	5.08
100.00	0.15	20.4	30.3	3.03
200.00	0.075	23.2	7.1	0.71
230.00	0.063	4.8	2.3	0.23
Pan		2.3	0	0.00
Total		998.5		

Figure 3.3 illustrates the particle size distribution of the soil sample used for the experiment. D_{10}, D_{30}, and D_{60} represent the diameter of the soil particles corresponding to the total percentage of a sample of 10%, 30%, and 60%, respectively, on the plotted particle size distribution curve. The coefficient of curvature (C_C) and the coefficient of uniformity (C_U) are calculated from D_{10}, D_{30}, and D_{60} (Astm & International, 2006). According to ASTM D2487-11 (Astm & International, 2006), the coefficient curvature and coefficient of uniformity are

calculated using Equations 3.1 and 3.2 to determine the classification category of the soil (Astm & International, 2006).

$$C_C = \frac{(D_{30})^2}{(D_{10} * D_{60})} \tag{3.1}$$

$$C_U = \frac{D_{60}}{D_{10}} \tag{3.2}$$

According to Figure 3.3, the C_C and C_U are 0.86 and 1.56, respectively. The result shows $C_U < 6$ and $C_C < 1$ with more than 50% of the soil sample retained on the sieve mesh with an opening of 75 µm. According to ASTM D2487-11, with these parameters, the soil sample is classified as a poorly graded sand with silt which falls within the standard of mine haul roads design guidelines (Astm & International, 2006; NIOSH, 2013). The grading distribution of the collected soil sample for the research conforms to the typical surface layer particle size distribution for a mine haul road, which ranges from 25 mm to 0.074 mm (AASHTO, 1993a; D. Tannant & Regensburg, 2010).

3.1.2 Dust Suppressants

Water and four different selected chemical suppressants were examined as dust suppression agents for the study. These suppressants fall into the general categories of a salt, chloride-free agent, polymer, and molasses. Figure 3.4 shows the different dust suppressants tested during the experiment.

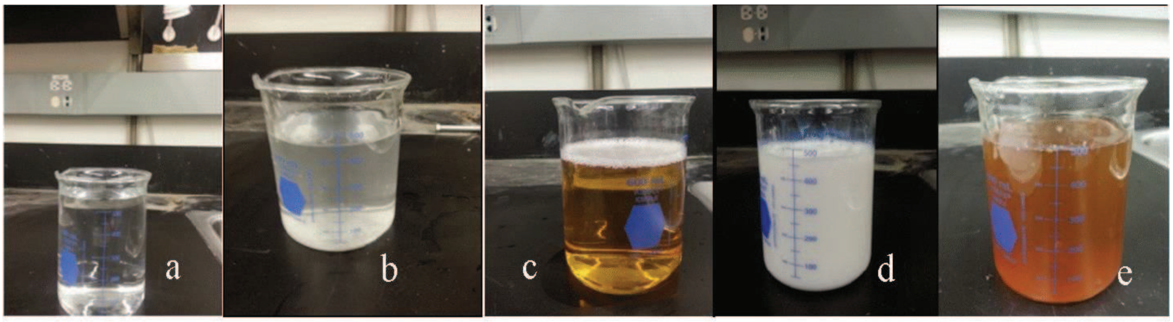

Figure 3.4. Dust suppression agents tested for the study: (a) Water, (b) Salt solution, (c) Chloride-free solution, (d) Polymer solution, (e) Molasses solution

Figure 3.4a shows water used as the control sample. The water used for this experiment is from the City of Edmonton (Canada) supplied by EPCOR Canada. The water was composed of a total chlorine level of 1.96 mg/L, total hardness of 181 mg/L as $CaCO_3$, and a total organic carbon content of 1.9 mg/L (Epcor Canada, 2016). Also, a composition of sodium concentration of 16.0 mg/L, a PH value of 7.7, and 0.70 mg/L of fluoride was dissolved in the water with no bacteriological data (Epcor Canada, 2016). Figure 3.4b shows the salt solution, which is an iodized table salt with a content composition of 570 mg and an iodide that is 70% soluble in water with a specific gravity of 2.16. Figure 3.4c shows the chloride-free solution as a non-flammable yellowish liquid with a mild odour. This chloride-free agent has a specific gravity of 1.3 and a boiling and freezing point of 100ºC and 0ºC, respectively. The pH value is in the 8-9 range. Figure 3.4d shows the polymer solution as a non-flammable white liquid with a mild odour, with a boiling and freezing point of 100 ºC and 0 ºC, respectively. This polymer-agent has a pH value of 8-9 and a specific gravity of 1.0. Figure 3.4e shows the molasses solution consisting of natural molasses, pure vegetable glycerin, and a pure food-grade citric acid with no additives. In addition, the molasses solution contains preservatives with 11g of sugar, 14g of total carbohydrate, and 1g of protein per 350 g of pure molasses.

3.1.3 Experimental Parameters

Different parameters were used for this investigation. The parameters are described in Table 3.2.

The sample of the soil was placed in an oven at a temperature of 110 ºC for 120 hours to dry out all the moisture content as per ASTM standard. The temperature selection and method of calculation for drying out the moisture content in the soil sample$\left(M_S\right)$ in Equation 3.3 are according to the ASTM D2216-10 standard ("Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass," 2010).

$$M_S = \frac{\omega_m(g) - \omega_D(g)}{\omega_D(g) - \omega_C(g)} * 100 \tag{3.3}$$

The particle size distribution of the soil sample was investigated using sieve analysis. A sieve mesh with openings ranging from 0.850 mm to 0.063 mm was used. The experimental weather temperatures selected were based on the average quarterly statistical temperature data for the City of Edmonton between 2011 and 2016 and were provided by Environment and Climate Canada.

Table 3.2. Parameters and their descriptions used for the experimental work

Parameters	Description
D_{10}, D_{30}, & D_{60}	Diameter of soil sample at 10%, 30%, and 60% on particle size distribution curve (mm)
C_C & C_U	Co-efficient Curvature and Coefficient of Uniformity of the soil sample
ω_C	Weight of the container (g)
ω_D	Weight of the dried soil sample and container (g)
ω_m	Weight of the moist soil sample and container (g)
v	Volumetric dilution for surfactants (%)
ω_p	Weight of the plate (g)
ω_1	Weight of the sample before blowing (g)
ω_2	Weight of the sample after blowing (g)
$\Delta\omega$	Weight of the sample loss (g)
r	Dust retention efficiency (%)
R	Average dust retention efficiency (%)
M_S	Moisture content of the soil sample (%)

These temperatures were similar to those in the City of Fort McMurray (Environment and Climate Change Canada, 2016). To mimic different weather temperatures, an average controlled temperature was selected for the hot, cold, and normal seasons. A wind speed of 65 km/h was set as the base velocity for the experiment to help determine how efficiently the dust suppression agents could control fugitive dust under extreme wind conditions. This speed was the highest quarterly wind speed in Fort McMurray during 2011-2016 according to Environment and Climate Change Canada.

3.1.4 Experimental Methodology

A general experimental procedure was followed for all the tested chemical dust suppressants under each considered temperature season for the experiment. Figure 3.5 is a schematic diagram showing the testing principle.

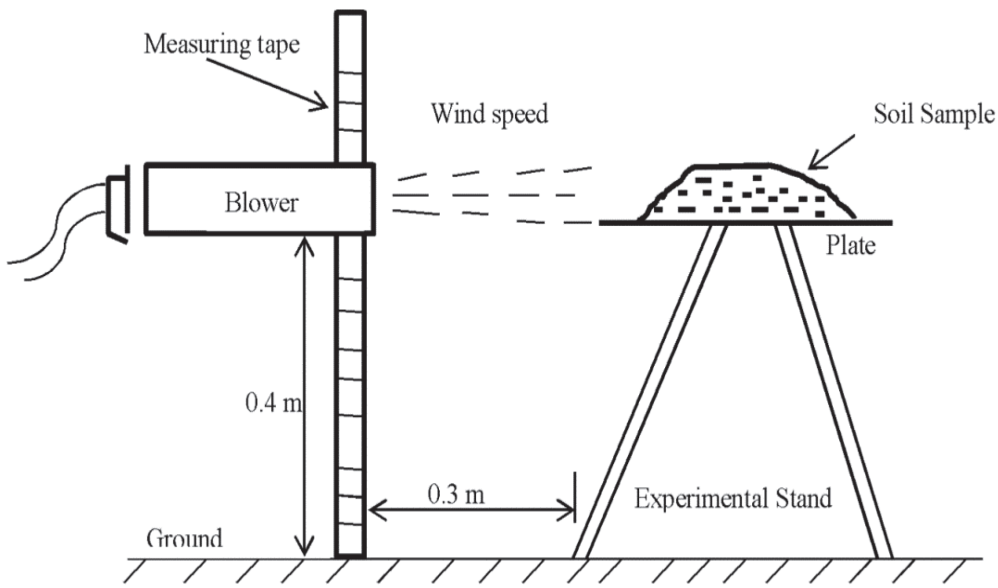

Figure 3.5. A representation of the experimental procedure

Figure 3.6 shows the actual experimental set-up. The set-up comprises an air blower, a measuring tape ruler, a steel tripod stand, and a flat plate. The soil sample was measured on the plate before a dosage of chemical suppressant was applied.

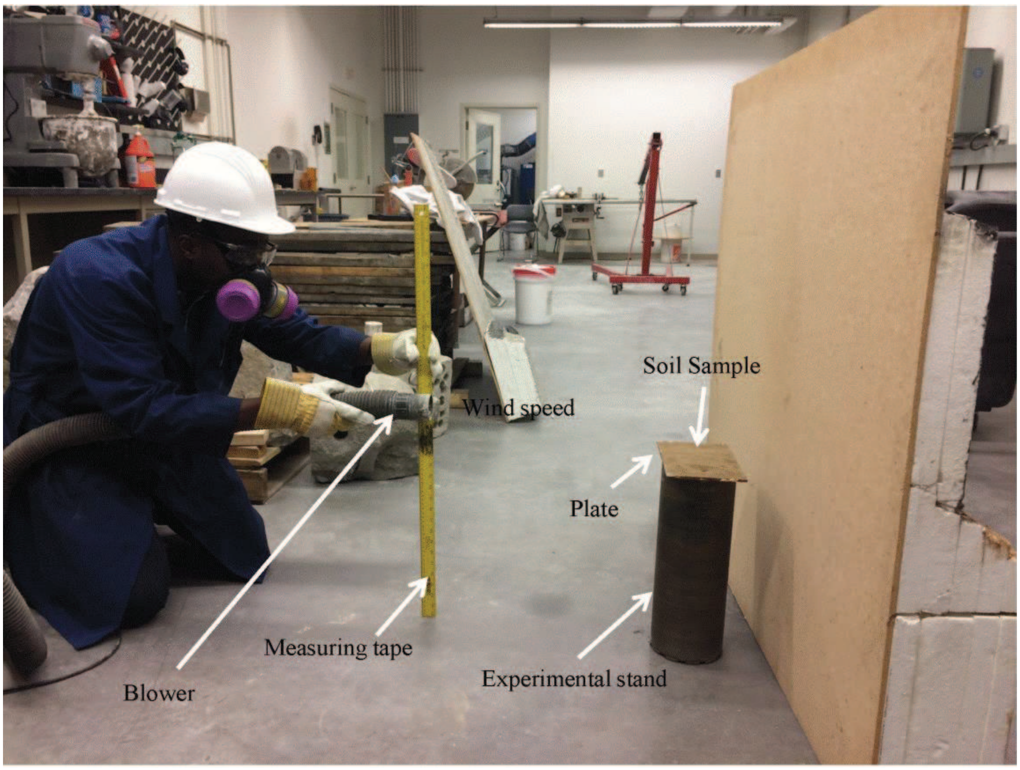

Figure 3.6. Experimental set-up in the laboratory

Then, the sample was placed on the tripod stand before the wind effect was applied from the blower. The sample was then weighed again to determine how much weight was lost from the sample material. Before testing the four chemical dust suppressants, a series of base control tests was performed to determine the effects of wind speed and temperatures on a soil sample. No dust suppressants were used in those tests. The wind speed for the base control tests was 65 km/h, and it was applied for 10 seconds.

Then a series of dosage calibrations (i.e., 1 mL- 8 mL) was tried to determine the required amount of chemical suppressant to be applied on the soil sample to avoid under- or over-usage of the solution. After the calibration, a dosage of 6 mL was selected as the required amount to be applied to 20 g of the soil sample. Chepil (Chepil, 1959) found that there is a constant lift-to-drag ratio on elements of roughness between 0.16 and 5.08 cm for any fluid drag velocity (i.e., wind speed). After several trials, a depth of one cm was selected as the thickness of the soil sample on the plate. A stipulated time ranging from 30 minutes to 72 hours was selected as the test period for the soil sample, to assist in determining the efficiency of each dust suppressant at different temperatures.

Water was used in the control group. Four typical chemical surfactants were selected to form a solution of chemical suppressants to be examined for the experiment. In the test, using a sprinkler, 6 mL of water or a chemical suppressant was sprayed onto 20 g of soil sample on a plate. Then the sample was placed at a controlled temperature for a specified duration (i.e., 30 minutes, one hour, two hours, three hours, five hours, 24 hours, 48 hours, and 72 hours). After reaching the required time for the sample to be in the oven, the sample was weighed on a scale as ω_1 (g). A wind speed of 65 km/h was applied to the sample for 10 seconds because this duration was used for the base control test. The soil sample was weighed again as ω_2 (g). The weight loss $(\Delta\omega)$ of the soil sample was determined by the difference between the two measured weights. Each test was repeated three times to improve accuracy. The weight loss helps ascertain the mass of sample loss of the material; this serves as a contributing factor when calculating the sample's dust retention efficiency.

3.1.5 Calculation Method

Equation 3.4 calculates the weight loss of the sample material ($\Delta\omega$) before and after the application of a wind speed of 65 km/h:

$$\Delta\omega(g) = \omega_1(g) - \omega_2(g) \tag{3.4}$$

The weight loss contributes to the calculation of the sample's dust retention efficiency. Equation 3.5 calculates the dust retention efficiency (r) of a chemical dust suppressant:

$$r(\%) = 1 - \frac{\Delta\omega}{(\omega_1 - \omega_p)} \tag{3.5}$$

Three series of dust retention efficiency were conducted for each sample, and the average of the series was taken. Equation 3.6 calculates the average dust retention efficiency (R_1) of the soil sample for the series:

$$R_1(\%) = \frac{r_1 + r_2 + r_3}{3} \tag{3.6}$$

Where r_1, r_2 and r_3 are the dust retention efficiencies for each of the sets of the soil sample.

CHAPTER 4
Results and Discussion *

Chapter 4 discusses the theoretical analysis of each of the tested dust suppressants at different atmospheric temperatures within a time frame of 72 hours. This includes the weight of material loss, the percentage of loss material, and dust retention efficiency of each of the selected dust suppressants. The percentage of loss material was evaluated and the associated dust retention efficiency per soil sample was generated.

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* The content of this Chapter has been prepared and submitted as a journal manuscript: Omane, D., Liu, W. V., Pourrahimian. Y. (2017) Comparison of chemical suppressants under different atmosphere temperatures for the control of fugitive dust emission on mine haul roads. *International Journal of Mining, Reclamation and Environment*

4.1 Introduction

This chapter will include discussions about the volumetric concentration of dilution of the chemical suppressants and the results in terms of dust retention efficiency from the obtained experimental dataset. In order to achieve the proposed objective of this research, a set of data was collected using the principle of weight loss. The percentage of weight loss of the material for an application of a chemical suppressant was used as the determinant for evaluating the dust retention efficiency of the soil sample. A number of dataset were collected for the retention efficiency. The results of the dataset were then analyzed and discussed.

4.2 Experimental dataset

A series of results were collected during the experiment in determining the concentration of dilution of the chemical suppressants in water. Table 4.1 to Table 4.24 show the three-series test and the summary results of the volumetric concentration of the selected chemical suppressants.

Table 4.1. Three series test result of 1.5% volumetric concentration of salt solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
1.5%	96.84%	
1.5%	97.70%	97.12% ± 0.51%
1.5%	96.81%	

Table 4.2. Three series test result of 1.6% volumetric concentration of salt solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
1.6%	98.30%	
1.6%	98.20%	98.25% ± 0.05%
1.6%	98.25%	

Table 4.3. Three series test result of 1.7% volumetric concentration of salt solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
1.7%	99.65%	
1.7%	99.45%	99.54% ± 0.10%
1.7%	99.53%	

Table 4.4. Three series test result of 1.8% volumetric concentration of salt solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
1.8%	98.76%	
1.8%	99.91%	99.54% ± 0.67%
1.8%	99.94%	

Table 4.5. Three series test result of 2.0% volumetric concentration of salt solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
2.0%	99.76%	
2.0%	99.45%	99.55% ± 0.18%
2.0%	99.45%	

Table 4.6. Summary results of the volumetric concentration of salt solution

Average volumetric concentration for salt solution (%)	Average dust retention efficiency (%)
1.5%	97.12% ± 0.51%
1.6%	98.25% ± 0.05%
1.7%	99.54% ± 0.10%
1.8%	99.54% ± 0.67%
2.0%	99.55% ± 0.18%

Table 4.7. Three series test result of 2.0% volumetric concentration of chloride-free solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
2.0%	94.34%	
2.0%	97.92%	97.12% ± 2.48%
2.0%	99.11%	

Table 4.8. Three series test result of 3.0% volumetric concentration of chloride-free solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
3.0%	99.32%	
3.0%	97.01%	97.21% ± 2.01%
3.0%	95.31%	

Table 4.9. Three series test result of 5.0% volumetric concentration of chloride-free solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
5.0%	99.76%	
5.0%	98.27%	99.22% ± 0.82%
5.0%	99.62%	

Table 4.10. Three series test result of 8.0% volumetric concentration of chloride-free solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
8.0%	98.85%	
8.0%	99.05%	99.22% ± 0.47%
8.0%	99.75%	

Table 4.11. Three series test result of 10.0% volumetric concentration of chloride-free solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
10.0%	98.56%	
10.0%	99.47%	99.22% ± 0.57%
10.0%	99.62%	

Table 4.12. Summary results of the volumetric concentration of chloride-free agent in water

Average volumetric concentration for chloride-free solution (%)	Average dust retention efficiency (%)
2.0%	97.12% ± 2.48%
3.0%	97.21% ± 2.01%
5.0%	99.22% ± 0.82%
8.0%	99.22% ± 0.47%
10.0%	99.22% ± 0.57%

Table 4.13. Three series test result of 2.0% volumetric concentration of polymer solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
2.0%	98.48%	
2.0%	99.12%	99.04% ± 0.52%
2.0%	99.52%	

Table 4.14. Three series test result of 3.0% volumetric concentration of polymer solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
3.0%	99.77%	
3.0%	99.70%	99.33% ± 0.70%
3.0%	98.53%	

Table 4.15. Three series test result of 5.0% volumetric concentration of polymer solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
5.0%	99.70%	
5.0%	99.65%	99.69% ± 0.04%
5.0%	99.72%	

Table 4.16. Three series test result of 8.0% volumetric concentration of polymer solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
8.0%	99.60%	
8.0%	99.65%	99.69% ± 0.11%
8.0%	99.81%	

Table 4.17. Three series test result of 10.0% volumetric concentration of polymer solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
10.0%	99.72%	
10.0%	99.76%	99.70% ± 0.08%
10.0%	99.61%	

Table 4.18. Summary results of the volumetric concentration of polymer in water

Average volumetric concentration for polymer solution (%)	Average dust retention efficiency (%)
2%	99.04% ± 0.52%
3%	99.33% ± 0.70%
5%	99.69% ± 0.04%
8%	99.69% ± 0.11%
10%	99.70% ± 0.08%

Table 4.19. Three series test result of 2.0% volumetric concentration of molasses solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
2.0%	99.72%	
2.0%	99.75%	99.73% ± 0.02%
2.0%	99.73%	

Table 4.20. Three series test result of 3.0% volumetric concentration of molasses solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
3.0%	99.93%	
3.0%	99.88%	99.85% ± 0.09%
3.0%	99.75%	

Table 4.21. Three series test result of 5.0% volumetric concentration of molasses solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
5.0%	99.97%	
5.0%	99.95%	99.95% ± 0.02%
5.0%	99.94%	

Table 4.22. Three series test result of 8.0% volumetric concentration of molasses solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
8.0%	99.94%	
8.0%	99.93%	99.95% ± 0.03%
8.0%	99.98%	

Table 4.23. Three series test result of 10.0% volumetric concentration of molasses solution

Volumetric concentration	Dust retention efficiency	Average dust retention efficiency
10.0%	99.98%	
10.0%	99.95%	99.95% ± 0.03%
10.0%	99.93%	

Table 4.24. Summary results of the volumetric concentration of molasses in water

Average volumetric concentration for molasses solution	Average dust retention efficiency (%)
2%	99.73% ± 0.02%
3%	99.85% ± 0.09%
5%	99.95% ± 0.02%
8%	99.95% ± 0.03%
10%	99.95% ± 0.03%

For each chemical mix in 500 mL of water, an average dust retention efficiency was recorded. The results obtained showed 1.5% dilution efficiency for salt and 5% for the other chemical suppressants as the most desirable. A base control test of no application of dust suppressant was performed to determine the effects of wind speed and temperatures on a soil sample as shown in Table 4.25 and Figure 4.1.

Table 4.25. Average dust retention efficiency using no dust suppressant

Time (Hours)	Dust retention efficiency (%)*
0.5	46.47
1	46.47
2	46.47
3	46.47
5	46.47
24	46.47
48	46.47
72	46.47

* The test was only conducted once because of the availability of experimental materials.

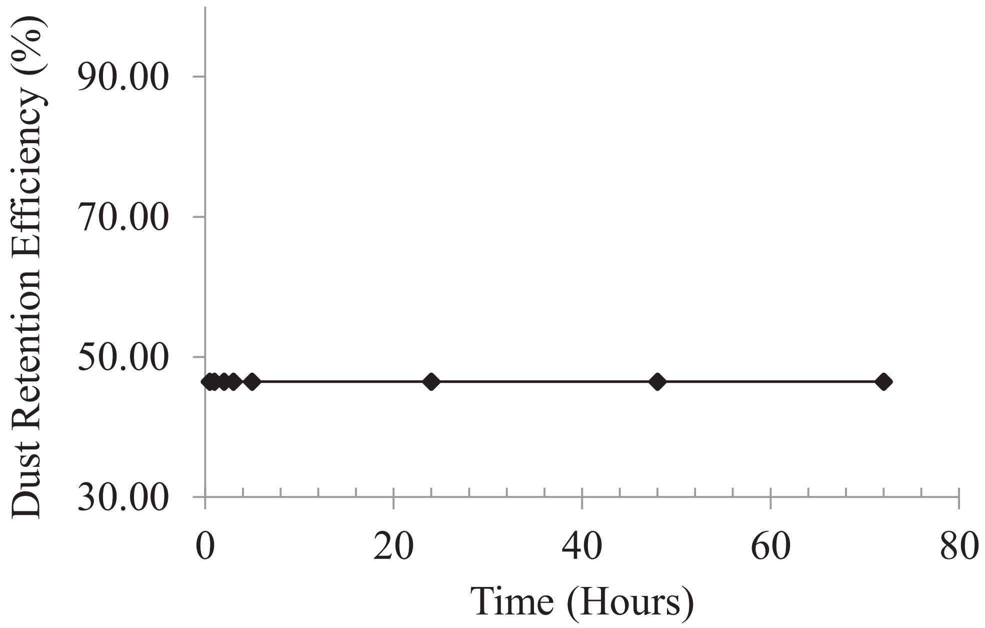

Figure 4.1. Effect of no dust suppressant on soil sample

The retention efficiency of all the selected dust suppressants under different atmospheric temperatures is presented from Table 4.26 to Table 4.30. The outcome shows the impact of temperature on all the suppression agents.

Table 4.26. Summary results of retention efficiency using tap water as the dust suppressant under hot, cold, and normal room temperatures

Time (Hours)	Tap Water (%) H	Tap Water (%) R	Tap Water (%) C
0.5	98.38% ± 2.06%	99.40% ± 5.6%	99.81% ± 0.02%
1	90.00% ± 2.04%	96.80% ± 5.2%	99.81% ± 0.01%
2	82.02% ± 2.05%	94.11% ± 5.3%	99.90% ± 0.01%
3	70.36% ± 2.03%	91.81% ± 5.7%	99.90% ± 0.02%
5	51.42% ± 2.05%	90.42% ± 5.1%	99.91% ± 0.03%
24	49.30% ± 2.04%	83.23% ± 5.7%	99.91% ± 0.02%
48	48.68% ± 2.03%	66.68% ± 5.4%	99.92% ± 0.02%
72	48.67% ± 2.05%	54.67% ± 5.0%	99.92% ± 0.04%

Table 4.27. Summary results of retention efficiency using salt solution as the dust suppressant under hot, cold, and normal room temperatures

Time (Hours)	Salt Solution (%) H	Salt Solution (%) R	Salt Solution (%) C
0.5	99.45% ± 1.05%	99.80% ± 1.85%	99.81% ± 0.02%
1	99.23% ± 1.10%	99.70% ± 1.65%	99.82% ± 0.01%
2	98.53% ± 1.00%	99.40% ± 1.80%	99.90% ± 0.02%
3	96.87% ± 1.21%	97.91% ± 1.76%	99.90% ± 0.02%
5	94.31% ± 0.97%	95.11% ± 1.78%	99.91% ± 0.01%
24	91.27% ± 1.08%	93.82% ± 1.86%	99.92% ± 0.03%
48	88.32% ± 1.04%	90.32% ± 1.90%	99.92% ± 0.02%
72	85.85% ± 1.11%	87.21% ± 1.82%	99.93% ± 0.03%

Table 4.28. Summary results of retention efficiency using chloride-free solution as the dust suppressant under hot, cold, and normal room temperatures

Time (Hours)	Chloride-free Solution (%) H	Chloride-free Solution (%) R	Chloride-free Solution (%) C
0.5	99.30% ± 0.36%	99.70% ± 0.98%	99.83% ± 0.01%
1	99.33% ± 0.32%	99.72% ± 0.95%	99.84% ± 0.02%
2	99.47% ± 0.37%	99.82% ± 1.00%	99.91% ± 0.02%
3	99.82% ± 0.31%	99.85% ± 0.93%	99.91% ± 0.02%
5	99.68% ± 0.32%	99.73% ± 0.96%	99.92% ± 0.01%
24	98.57% ± 0.29%	99.07% ± 0.90%	99.93% ± 0.03%
48	93.45% ± 0.41%	94.27% ± 0.89%	99.93% ± 0.01%
72	90.15% ± 0.42%	93.20% ± 0.99%	99.93% ± 0.02%

Table 4.29. Summary results of retention efficiency using polymer solution as the dust suppressant under hot, cold, and normal room temperatures

Time (Hours)	Polymer Solution (%) H	Polymer Solution (%) R	Polymer Solution (%) C
0.5	99.83% ± 0.01%	99.87% ± 0.02%	99.88% ± 0.03%
1	99.84% ± 0.02%	99.91% ± 0.01%	99.92% ± 0.01%
2	99.87% ± 0.01%	99.92% ± 0.01%	99.93% ± 0.01%
3	99.89% ± 0.01%	99.92% ± 0.01%	99.94% ± 0.02%
5	99.85% ± 0.02%	99.92% ± 0.02%	99.94% ± 0.01%
24	99.83% ± 0.02%	99.92% ± 0.03%	99.94% ± 0.02%
48	99.80% ± 0.01%	99.90% ± 0.03%	99.94% ± 0.03%
72	99.78% ± 0.01%	99.89% ± 0.01%	99.94% ± 0.02%

Table 4.30. Summary results of retention efficiency using molasses solution as the dust suppressant under hot, cold, and normal room temperatures

Time (Hours)	Molasses Solution (%) H	Molasses Solution (%) R	Molasses Solution (%) C
0.5	99.93% ± 0.01%	99.97% ± 0.02%	99.98% ± 0.01%
1	99.94% ± 0.01%	99.98% ± 0.01%	99.99% ± 0.02%
2	99.95% ± 0.02%	99.98% ± 0.01%	99.99% ± 0.02%
3	99.97% ± 0.01%	99.98% ± 0.01%	99.99% ± 0.01%
5	99.97% ± 0.02%	99.99% ± 0.02%	99.99% ± 0.01%
24	99.98% ± 0.01%	99.99% ± 0.02%	99.99% ± 0.02%
48	99.98% ± 0.01%	99.99% ± 0.01%	99.99% ± 0.01%
72	99.98% ± 0.01%	99.99% ± 0.02%	99.99% ± 0.01%

Table 4.31 to Table 4.34 show a summary of comparison of the results of different dust retention efficiencies for all the tested suppressants under different weather temperature (i.e., hot, cold, and normal room temperature).

Table 4.31. Comparison of the results of different retention efficiencies using all the selected suppressants as dust suppression agents under hot temperature

Time (Hours)	Tap Water (%) H	Salt Solution (%) H	Chloride Free Solution (%) H	Polymer Solution (%) H	Molasses Solution (%) H
0.5	98.38% ± 2.06%	99.45% ± 1.05%	99.30% ± 0.36%	99.83% ± 0.01%	99.93% ± 0.01%
1	90.00% ± 2.04%	99.23% ± 1.10%	99.33% ± 0.32%	99.84% ± 0.02%	99.94% ± 0.01%
2	82.02% ± 2.05%	98.53% ± 1.00%	99.47% ± 0.37%	99.87% ± 0.01%	99.95% ± 0.02%
3	70.36% ± 2.03%	96.87% ± 1.21%	99.82% ± 0.31%	99.89% ± 0.01%	99.97% ± 0.01%
5	51.42% ± 2.05%	94.31% ± 0.97%	99.68% ± 0.32%	99.85% ± 0.02%	99.97% ± 0.02%
24	49.30% ± 2.04%	91.27% ± 1.08%	98.57% ± 0.29%	99.83% ± 0.02%	99.98% ± 0.01%
48	48.68% ± 2.03%	88.32% ± 1.04%	93.45% ± 0.41%	99.80% ± 0.01%	99.98% ± 0.01%
72	48.67% ± 2.05%	85.85% ± 1.11%	90.15% ± 0.42%	99.78% ± 0.01%	99.98% ± 0.01%

Table 4.32. Comparison of the results of different retention efficiencies using all the selected suppressants as dust suppression agents under normal room temperature

Time (Hours)	Tap Water (%) R	Salt Solution (%) R	Chloride Free Solution (%) R	Polymer Solution (%) R	Molasses Solution (%) R
0.5	99.40% ± 5.6%	99.80% ± 1.85%	99.70% ± 0.98%	99.87% ± 0.02%	99.97% ± 0.02%
1	96.80% ± 5.2%	99.70% ± 1.65%	99.72% ± 0.95%	99.91% ± 0.01%	99.98% ± 0.01%
2	94.11% ± 5.3%	99.40% ± 1.80%	99.82% ± 1.00%	99.92% ± 0.01%	99.98% ± 0.01%
3	91.81% ± 5.7%	97.91% ± 1.76%	99.85% ± 0.93%	99.92% ± 0.01%	99.98% ± 0.01%
5	90.42% ± 5.1%	95.11% ± 1.78%	99.73% ± 0.96%	99.92% ± 0.02%	99.99% ± 0.02%
24	83.23% ± 5.7%	93.82% ± 1.86%	99.07% ± 0.90%	99.92% ± 0.03%	99.99% ± 0.02%
48	66.68% ± 5.4%	90.32% ± 1.90%	94.27% ± 0.89%	99.90% ± 0.03%	99.99% ± 0.01%
72	54.67% ± 5.0%	87.21% ± 1.82%	93.20% ± 0.99%	99.89% ± 0.01%	99.99% ± 0.02%

Table 4.33. Comparison of the results of different retention efficiencies using all the selected suppressants as dust suppression agents under cold temperature

Time (Hours)	Tap Water (%) C	Salt Solution (%) C	Chloride Free Solution (%) C	Polymer Solution (%) C	Molasses Solution (%) C
0.5	99.81% ± 0.02%	99.81% ± 0.02%	99.83% ± 0.01%	99.88% ± 0.03%	99.98% ± 0.01%
1	99.81% ± 0.01%	99.82% ± 0.01%	99.84% ± 0.02%	99.92% ± 0.01%	99.99% ± 0.02%
2	99.90% ± 0.01%	99.90% ± 0.02%	99.91% ± 0.02%	99.93% ± 0.01%	99.99% ± 0.02%
3	99.90% ± 0.02%	99.90% ± 0.02%	99.91% ± 0.02%	99.94% ± 0.02%	99.99% ± 0.01%
5	99.91% ± 0.03%	99.91% ± 0.01%	99.92% ± 0.01%	99.94% ± 0.01%	99.99% ± 0.01%
24	99.91% ± 0.02%	99.92% ± 0.03%	99.93% ± 0.03%	99.94% ± 0.02%	99.99% ± 0.02%
48	99.92% ± 0.02%	99.92% ± 0.02%	99.93% ± 0.01%	99.94% ± 0.03%	99.99% ± 0.01%
72	99.92% ± 0.04%	99.93% ± 0.03%	99.93% ± 0.02%	99.94% ± 0.02%	99.99% ± 0.01%

Table 4.34. Summary results of retention efficiency of all the tested dust suppressants under hot, cold, and normal room temperatures

Time (hours)	Tap Water (%) H	Tap Water (%) R	Tap Water (%) C	Salt Solution (%) H	Salt Solution (%) R	Salt Solution (%) C	Chloride Free Solution (%) H	Chloride Free Solution (%) R	Chloride Free Solution (%) C	Polymer Solution (%) H	Polymer Solution (%) R	Polymer Solution (%) C	Molasses Solution (%) H	Molasses Solution (%) R	Molasses Solution (%) C
0.5	98.38% ± 2.06%	99.40 % ± 5.6%	99.81 % ± 0.02%	99.45% ± 1.05%	99.80% ± 1.85%	99.81% ± 0.02%	99.30% ± 0.36%	99.70% ± 0.98%	99.83% ± 0.01%	99.83% ± 0.01%	99.87% ± 0.02%	99.88% ± 0.03%	99.93% ± 0.01%	99.97% ± 0.02%	99.98% ± 0.01%
1	90.00% ± 2.04%	96.80 % ± 5.2%	99.81 % ± 0.01%	99.23% ± 1.10%	99.70% ± 1.65%	99.82% ± 0.01%	99.33% ± 0.32%	99.72% ± 0.95%	99.84% ± 0.02%	99.84% ± 0.02%	99.91% ± 0.01%	99.92% ± 0.01%	99.94% ± 0.01%	99.98% ± 0.01%	99.99% ± 0.02%
2	82.02% ± 2.05%	94.11 % ± 5.3%	99.90 % ± 0.01%	98.53% ± 1.00%	99.40% ± 1.80%	99.90% ± 0.02%	99.47% ± 0.37%	99.82% ± 1.00%	99.91% ± 0.02%	99.87% ± 0.01%	99.92% ± 0.01%	99.93% ± 0.01%	99.95% ± 0.02%	99.98% ± 0.01%	99.99% ± 0.02%
3	70.36% ± 2.03%	91.81 % ± 5.7%	99.90 % ± 0.02%	96.87% ± 1.21%	97.91% ± 1.76%	99.90% ± 0.02%	99.82% ± 0.31%	99.85% ± 0.93%	99.91% ± 0.02%	99.89% ± 0.01%	99.92% ± 0.01%	99.94% ± 0.02%	99.97% ± 0.01%	99.98% ± 0.01%	99.99% ± 0.01%
5	51.42% ± 2.05%	90.42 % ± 5.1%	99.91 % ± 0.03%	94.31% ± 0.97%	95.11% ± 1.78%	99.91% ± 0.01%	99.68% ± 0.32%	99.73% ± 0.96%	99.92% ± 0.01%	99.85% ± 0.02%	99.92% ± 0.02%	99.94% ± 0.01%	99.97% ± 0.02%	99.99% ± 0.02%	99.99% ± 0.01%
24	49.30% ± 2.04%	83.23 % ± 5.7%	99.91 % ± 0.02%	91.27% ± 1.08%	93.82% ± 1.86%	99.92% ± 0.03%	98.57% ± 0.29%	99.07% ± 0.90%	99.93% ± 0.03%	99.83% ± 0.02%	99.92% ± 0.03%	99.94% ± 0.02%	99.98% ± 0.01%	99.99% ± 0.02%	99.99% ± 0.02%
48	48.68% ± 2.03%	66.68 % ± 5.4%	99.92 % ± 0.02%	88.32% ± 1.04%	90.32% ± 1.90%	99.92% ± 0.02%	93.45% ± 0.41%	94.27% ± 0.89%	99.93% ± 0.01%	99.80% ± 0.01%	99.90% ± 0.03%	99.94% ± 0.03%	99.98% ± 0.01%	99.99% ± 0.01%	99.99% ± 0.01%
72	48.67% ± 2.05%	54.67 % ± 5.0%	99.92 % ± 0.04%	85.85% ± 1.11%	87.21% ± 1.82%	99.93% ± 0.03%	90.15% ± 0.42%	93.20% ± 0.99%	99.93% ± 0.02%	99.78% ± 0.01%	99.89% ± 0.01%	99.94% ± 0.02%	99.98% ± 0.01%	99.99% ± 0.02%	99.99% ± 0.01%

The generated outcome shows the impact of temperatures of the effectiveness of a dust suppressant. The size of a soil particle has an impact on the total amount of dust generation into the atmosphere. Smaller particle sizes generate more dust compared to larger particles as shown in Table 4.35.

Table 4.35. Potential impact of soil particle sizes and the total fraction of fugitive dust generated on field

d (mm)	V_d (m/s)	ε (%)	T (%)
0.850	4.13	11	34
0.450	2.13	20	59
0.250	1.14	31	94

Where T is the total fraction of dust generated from the mining activities, ε is mass fraction of dust that escapes the pit, d is diameter of the soil particles, and V_d, settling velocity of the emitted particles

4.3 Effect of the volumetric dilution concentration on dust retention efficiency

Figure 4.2 to Figure 4.5 show the result of each chemical surfactant under various volumetric dilution concentrations under room temperature in the laboratory. The tested volumetric concentration of the dilution of salt ranged was 1.5%, 1.6%, 1.7%, 1.8%, and 2.0%. Figure 4.2 shows different dosages of volumetric concentrations of salt as a chemical surfactant in water. Salt as a chemical surfactant showed a retention efficiency of 97.12% at a dosage of 1.5%. However, the retention efficiency started to increase with time when more concentrated amounts of salt were added to the dosage. A retention efficiency of 99.54% was achieved with a 1.7% dosage and remained constant up until 2.0%. The constantly increasing trend shows that salt performs more effectively over time until the optimum dosage is achieved.

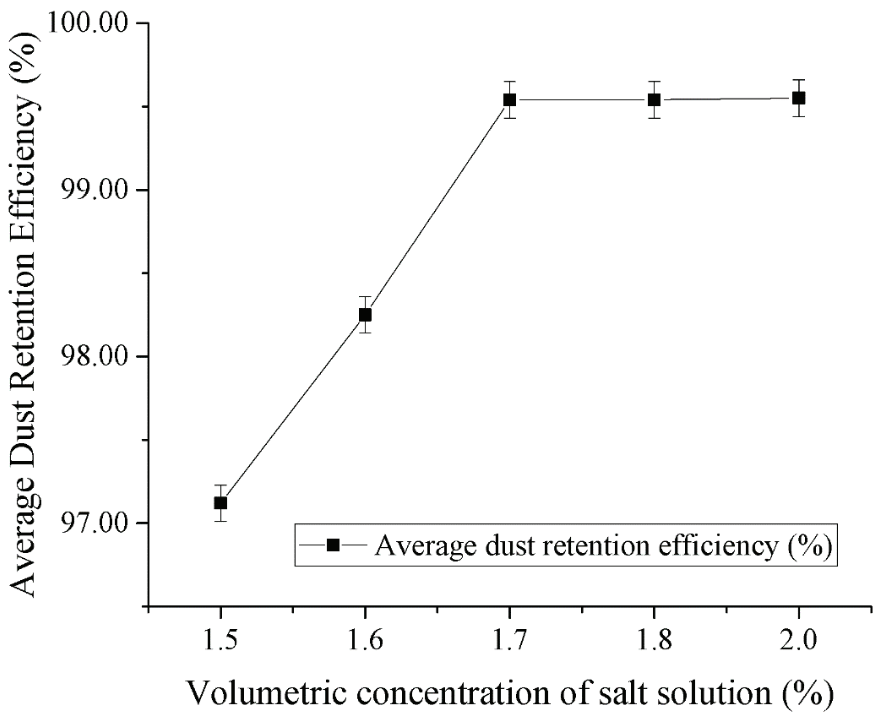

Figure 4.2. The relationship between the salt solution and dust retention efficiency

A dosage of 1.7% was observed as an optimum volumetric concentration of dilution for the salt solution because beyond this dosage adding a diluted concentration had no impact on the solution's retention efficiency. At a 1.7% optimum value, high-efficiency retention was achieved with less salt. The tested dosage for the chloride-free agent, polymer, and molasses was 2%, 3%, 5%, 8%, and 10%. The volumetric concentration of the chloride-free agent, polymer, and molasses as chemical surfactants in water is shown in Figure 4.2 to Figure 4.5.

Each figure presents the retention efficiencies of each chemical surfactant at a different concentration dosage.

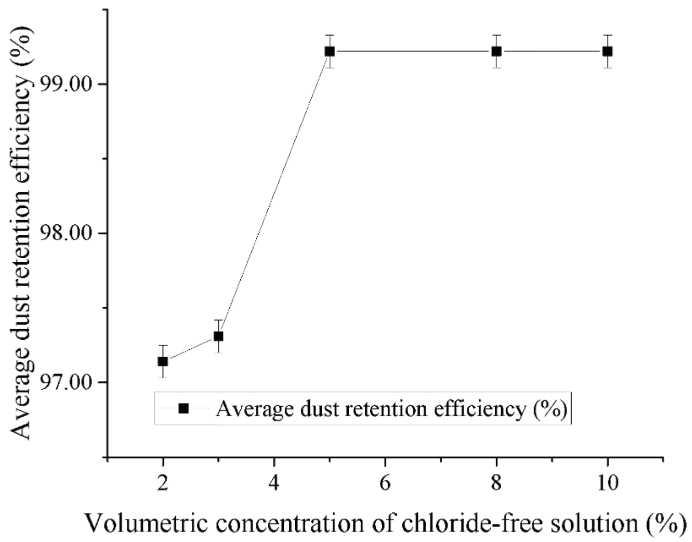

Figure 4.3. The relationship between the chloride-free solution and dust retention efficiency

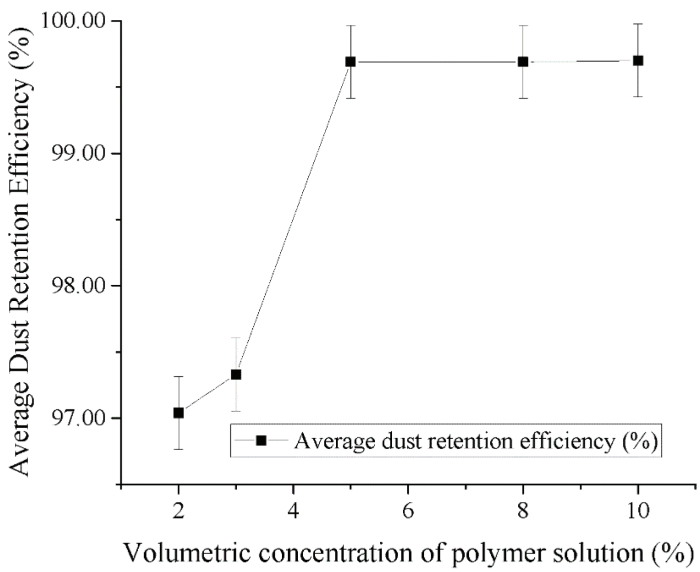

Figure 4.4. The relationship between the polymer solution and dust retention efficiency

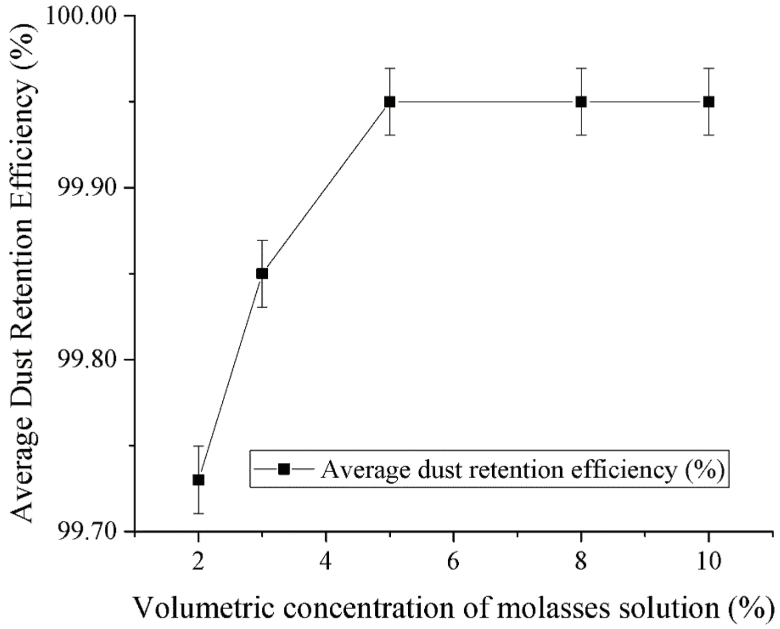

Figure 4.5. The relationship between the molasses solution and dust retention efficiency

Retention efficiencies of 97.14%, 99.04%, and 99.73% were achieved at a dosage of 2% for the chloride-free agent, polymer, and molasses, respectively. However, the retention efficiencies started to increase with time when more dosages of concentration were added. Retention efficiencies of 99.22%, 99.69%, and 99.95% were achieved at 5% dilution concentration for the chloride-free agent, polymer, and molasses, respectively. Each retention efficiency remained constant from the 5% dosage to the 10%. The constantly increasing trend shows that the chloride-free agent, polymer, and molasses perform better with time until the optimum dosage is achieved. A volumetric concentration of 5% was observed to be the appropriate dosage for the chloride-free solution, polymer, and molasses solution because after this concentration no added dosage affected the retention efficiency.

A previous study by Ruebel & Stuemke (2004), Samaha & Naggar (1988), and Hancock, York, & Rowe (1997), also tested different volumetric dilution concentrations until they found the optimum dilution concentration. For example, Samaha & Naggar (1988) used a liquid-by-liquid interaction between chemical surfactants and water to achieve the optimum concentration of a solution.

After attaining the optimum dosage, the surface tension of the solution became constant even when they added more surfactant. Samaha and Nagger's objective was to control the concentration of chemical surfactants dispersed in water to avoid over-using of material (Hancock et al., 1997; Ruebel & Stuemke, 2004; Samaha & Naggar, 1988). The results of Figure 4.2 to Figure 4.5, show the importance of dosage concentration in mixing a solution of chemical suppressant.

4.4 The performance of water under different temperatures

When no dust suppressant was applied to the soil sample, the entire sample was blown away at a wind speed of 65 km/h after 10 seconds. The soil sample that had no dust suppressant applied on it had a retention efficiency of 0% at a wind speed of 65 km/h from 30 minutes to 72 hours at different temperatures.

Figure 4.6 displays the performance of water as a dust suppressant at different temperatures (i.e., hot, cold, and normal temperatures) for a duration of 30 minutes to 72 hours. Tests were run for 30 minutes, one hour, two hours, three hours, five hours, 24 hours, 48 hours, and 72 hours to help determine the role that time plays in the potency of dust suppression at different temperatures. The corresponding dust retention efficiency associated with each time duration was recorded and plotted. The figure presents the retention efficiencies of water varying with time at hot, cold, and normal temperatures. Water as a dust suppressant in the hot season showed a retention efficiency of 82.02% during the first two hours. However, the retention efficiency started to decrease with time, with a retention efficiency of less than 50% at the end of the 72 hours. The reduction trend shows that water performs less effectively over time as a dust suppression agent in the hot season. Using water at normal room temperatures as a dust suppressant works effectively on dust retention at the preliminary stages, but efficiency decreases as time passes. Other researchers, including Thompson and Visser, also found that water is deficient in this regard; they discovered that instead of cohering to one another, the molecules in the water spread out over time, leading to a higher surface tension (Thompson & Visser, 2007).

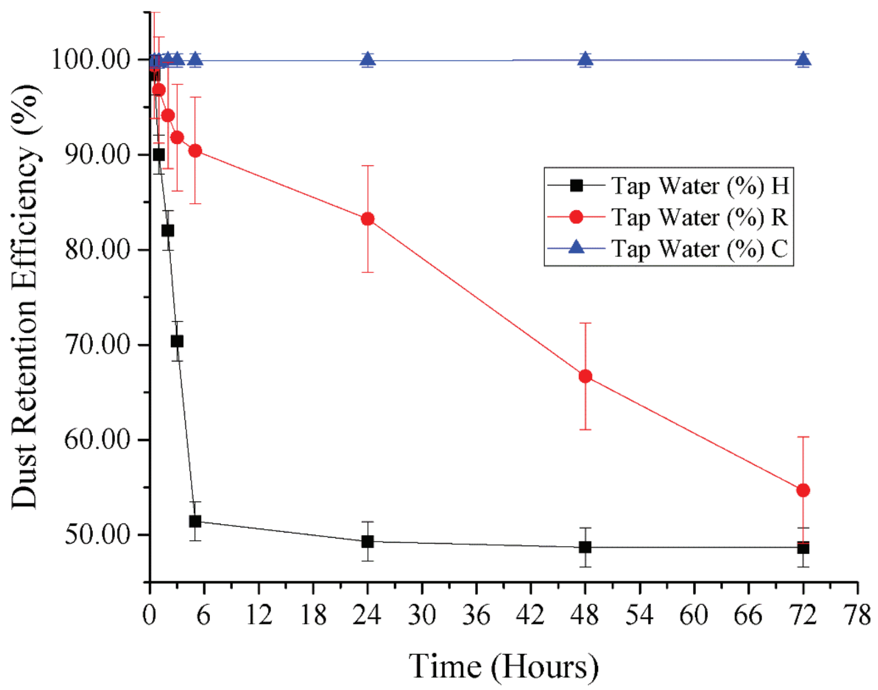

Figure 4.6. Effect of water as a dust suppressant for all temperature ranges

Consequently, there is greater evaporation rate, causing water to be less effective as a suppressant at hot and normal temperatures. However, at cold temperatures, dust retention efficiency is high and consistent with time.

Figure 4.7 shows the impact of cold temperatures on water: there is a crusty formation of ice on the surface of the soil sample. This explains why, in the Arctic, brine needs to be sprayed on haul roads to combat freezing (Baffinland Iron Mines Corporation, 2014; Mikkelsen, 1998; Mitchell, Hunt, & Richardson, 2004; Stotterud & Reitan, 1993). For example, brine was used in combating icy roads in Norway, Denmark, Canada, and the United States to increase vehicle efficiency and reduce road maintenance (Baffinland Iron Mines Corporation, 2014; Mikkelsen, 1998; Mitchell et al., 2004; Stotterud & Reitan, 1993).

Figure 4.7 shows water at cold temperature forms a crusty slippery surface on the soil sample, which prevents the soil particles from escaping into the atmosphere to form fugitive dust. However, slippery road surfaces can lead to vehicular accidents and an extension in vehicular travel time (Mitchell et al., 2004).

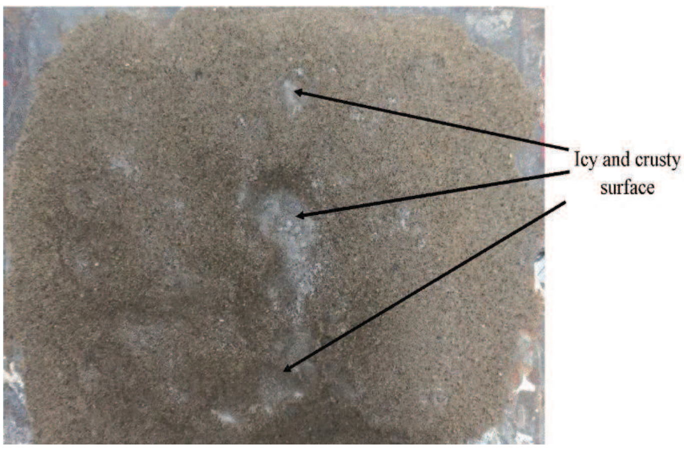

Figure 4.7. Icy crusty surface formed on the sample with water as a dust suppressant at cold temperatures

4.5 Comparison of dust suppressants under different temperatures

Figure 4.8 to Figure 4.11 show the average dust retention efficiencies for the chemical suppressants—salt, chloride-free, polymer, and molasses solutions—tested for 30 minutes to 72 hours under all temperature ranges. Figure 4.8 shows the dust retention efficiency of the salt solution with time under all temperature ranges. Each point marked on the chart represents the retention efficiency of dust on the tested soil sample at different temperatures. In hot temperatures, the salt solution acted effectively when it was first applied as a dust suppressant on the soil sample. Five hours after being applied, it had achieved a retention efficiency of 94.31%. This dust retention decreased steadily up until the third day (after 72 hours) when its effectiveness reached 85.85%.

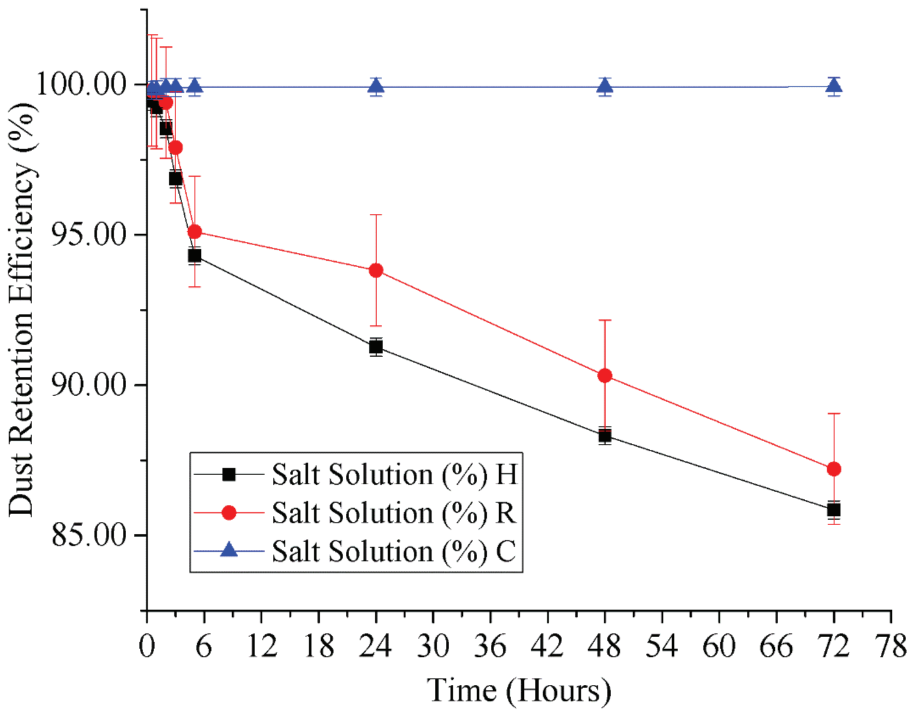

Figure 4.8. Effect of salt solution as a dust suppressant under all temperature ranges

The reduction trend shows that the salt solution performs less effectively over time in hot temperatures. At normal temperatures, for the first five hours, the salt solution held the soil sample together from the moment it was applied, by preventing the fugitive dust from escaping into the atmosphere. The dust retention achieved an efficiency of 95.11%. The longer the suppression agents were exposed to normal temperatures, the less efficient the solution was at dust retention; efficiencies decreased to 87.21% after 72 hours of exposure. However, in cold temperatures, the dust retention was consistent: it was 99.81% after 30 minutes of exposure and 99.93% after 72 hours.

Note that mines in Canada's northern territories apply brine to control haul road dust. For example, the Mary River Iron Project in Nunavut uses brine as the sole chemical suppressant for dust control on all their project roads (Baffinland Iron Mines Corporation, 2014). The efficacy of salt in a solution of water as a dust suppressant was also found in other literature showing that the addition of salt introduces cohesiveness between the water molecules (NIOSH, 2013; Thompson & Visser, 2007). Higher cohesiveness within a solution contributes to the solution’s ability to resist atmospheric temperature and lower the evaporation rate (NIOSH, 2013; Thompson & Visser, 2007). The result showed in Figure 4.8 supports the claim by the study of former researcher’s such as NIOSH, on the efficacy of salt solution as a dust control agent. Figure 4.9 illustrates the how the chloride-free solution acts as a dust suppression agent on the soil sample at different temperatures.

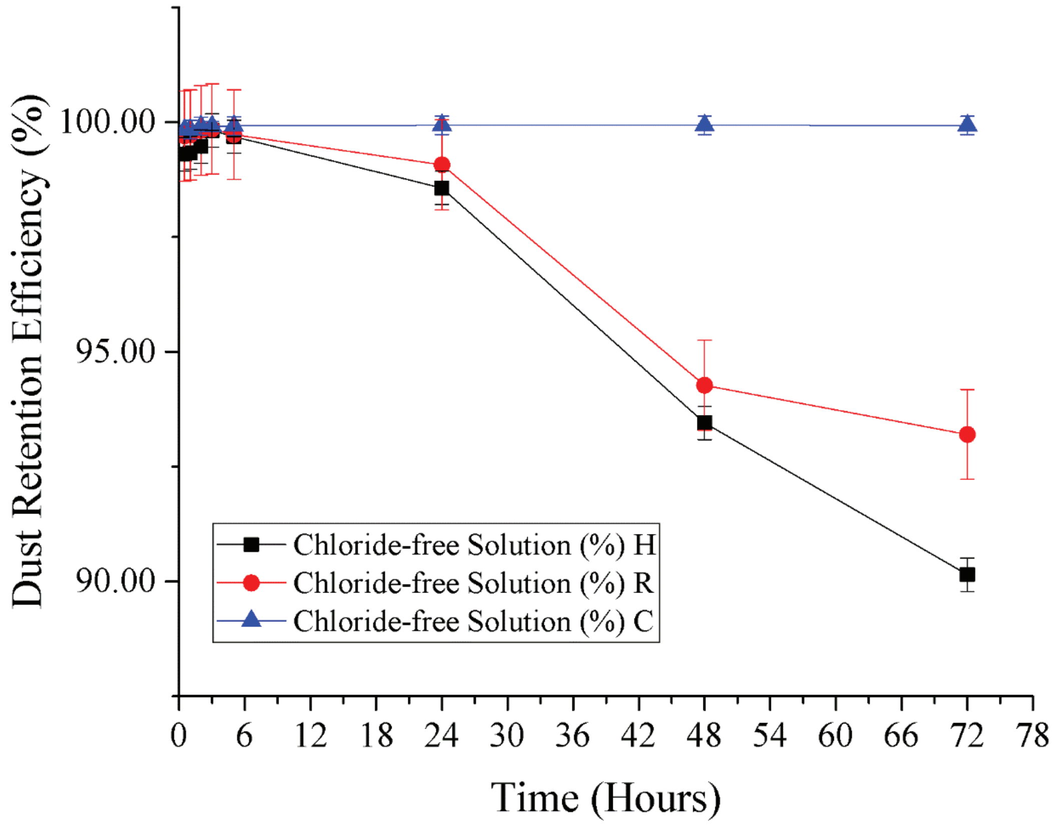

Figure 4.9. Effect of chloride-free solution as a dust suppressant under all temperature ranges

It shows the dust retention efficiency of the chloride-free solution experiment per duration for each temperature. The solution under a hot temperature showed a retention efficiency of 99.30% during the first 30 minutes of exposure. However, the retention efficiency started to decrease with time to 90.15% after 72 hours. The reduction trend shows that the chloride-free solution performed less effectively over time in a hot temperature. At a normal temperature, at the initial stage of application, the chloride-free solution worked effectively on dust retention but became less effective over time. Figure 4.9 shows how effectively the chloride-free solution works, by binding together all the particles in the soil to avoid the generation of dust. The chloride-free solution has a high dust retention efficiency compared to the water and salt solution at different temperatures. Figure 4.10 presents the effect of the polymer solution as a dust suppressant at all temperature ranges. After 30 minutes in the hot temperature, a retention efficiency of 99.83 % was achieved, but it decreased to 99.78% after 72 hours. Although there is a reduction, the result shows the efficacy of the polymer solution at a hot temperature. At normal and cold temperatures, the polymer solution shows consistently high (above 99.87%) dust retention efficiencies. Other researchers, such as Watson et al. (Watson, Chow, & Pace, 2000), have reported similar findings, that the adhesiveness between the molecular structure of the polymer solution is higher, with a smaller surface tension contributing to its lower evaporation rate.

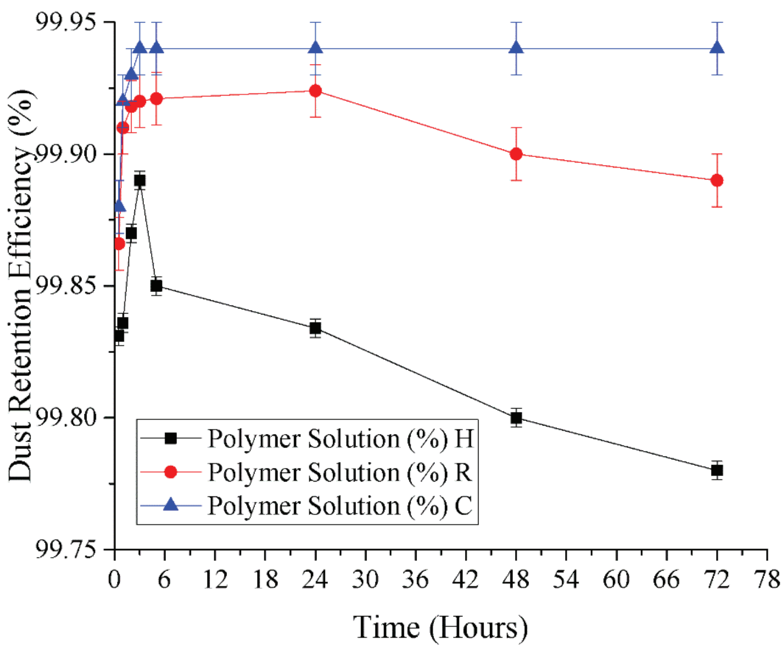

Figure 4.10. Effect of polymer solution as a dust suppression agent under all temperature ranges

Polymer solution is a popular chemical suppressant for road haul dust control (Goma & Mwale, 2016; Thompson & Visser, 2007) in humid subtropical climates, such as Zambia and South Africa. Among the mines that use this method is The Highveld Coalfields Mine in South Africa's Mpumalanga Province (Thompson & Visser, 2007). Figure 4.10 shows that the polymer solution is more efficient than water, the salt solution, and the chloride-free solution at controlling dust on the soil sample at different temperatures.

Figure 4.11 shows the variation of dust retention efficiency with time when a solution of molasses is used as a dust suppression agent to control fugitive dust emissions on a soil sample at different temperatures. At a hot temperature, after 30 minutes of exposure to the molasses solution, a dust retention efficiency of 99.93% is achieved. By the end of 72 hours, the retention efficiency had increased to 99.98%. The increasing trend shows that the molasses solution is highly effective over time in the hot temperatures. At normal room and cold temperatures, the molasses solution became even second effectiveas time passed. A number of previous research conducted by Thompson & Visser (2007), Watson et al. (2000), and NIOSH (2013), also found that molasses is effective at suppressing dust: the adhesiveness between the molecular structure of the molasses solution are closer together than most chemical dust suppressants, thus contributing to smaller surface tension and less evaporation rate. However, the molasses solution is efficient regardless of the temperature. This explains why some cities located in tropical, semi-arid climates use molasses as a chemical suppressant to control dust on haul roads (Shirsavkar & Koranne, 2010). For example, the city of Maharashtra in India used molasses as a dust control method on their roads after an experimental research, which proved molasses to be an effective chemical dust suppressant (Shirsavkar & Koranne, 2010). Figure 4.11 shows the effectiveness of molasses as a chemical suppressant at different temperatures compared to water, and to salt, chloride-free, and polymer solutions.

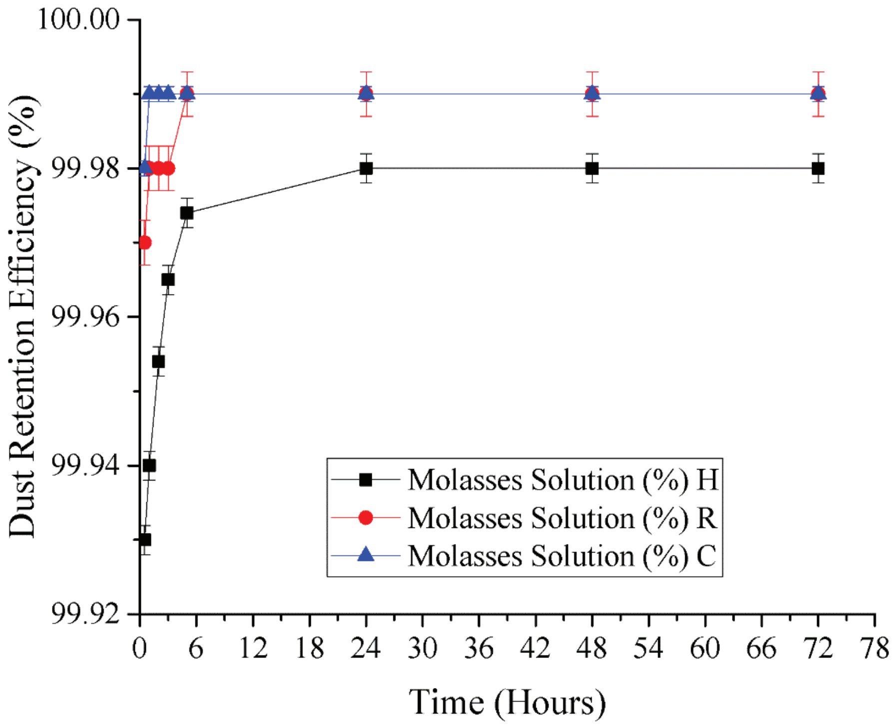

Figure 4.11. Effect of molasses solution as a dust suppression agent under all temperature ranges

4.6 Comparison of dust suppressants at a hot temperature

Figure 4.12 shows the effectiveness of all the tested dust suppressants at a hot temperature. Water was the first dust suppressant examined under a hot temperature. At the initial stage of application, water was highly efficient, but as time progressed the dust retention decreased. As the water was exposed to heat, it quickly evaporated. Higher surface tension lowers the ability of the solution to hold particulates together (Kavouras et al., 2009a; Thompson & Visser, 2007).

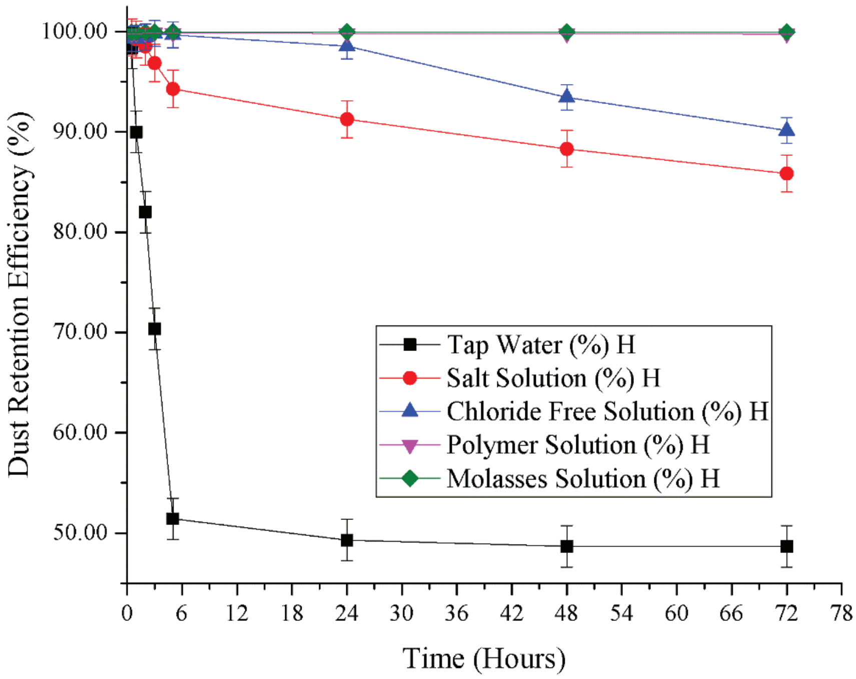

Figure 4.12. Effect of all the tested dust suppressants at a hot temperature

These characteristics of water make it less effective, hence the need to introduce chemicals as dust suppression agents. Figure 4.12 shows that adding chemical suppressants improves dust retention efficiency over time. The salt solution made the water a second effectivesuppressant, and the chloride-free solution also enhanced the efficiency.

4.7 Comparison of dust suppressants under a normal temperature

Figure 4.13 shows the effect of all the tested dust suppressants over time at room temperature.

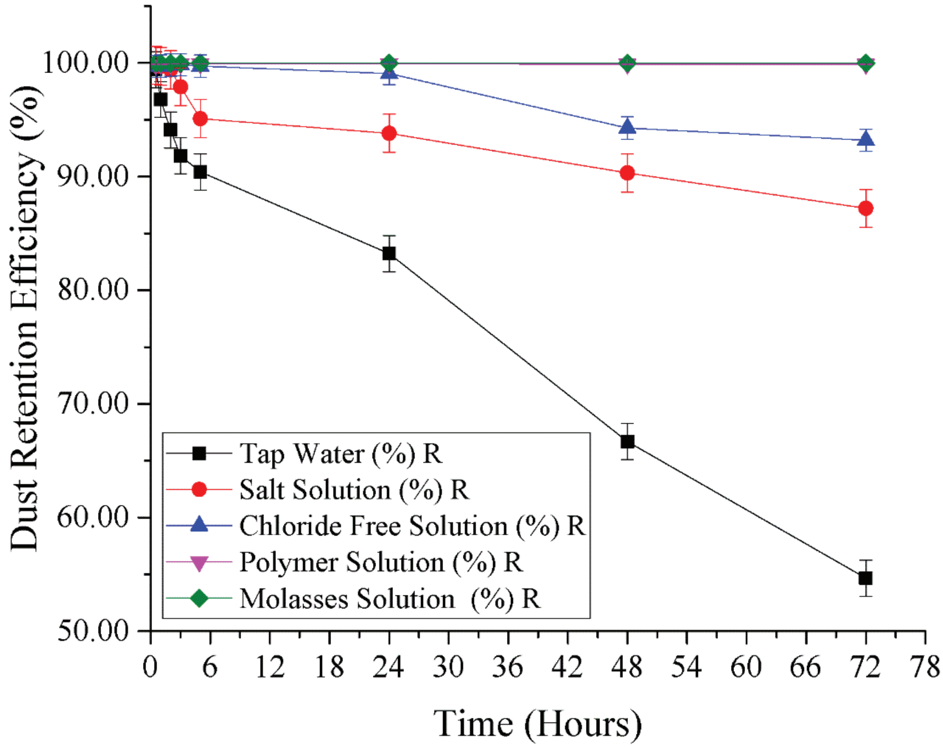

Figure 4.13. Effect of all the tested dust suppressants at a normal temperature

Of all the tested dust suppressants, water was the least efficient at dust retention over time: the other chemical suppressants tested were better able than water to control the dust. Authors such as Amponsah-Dacosta (1997), DeLuca et al. (2012), Foley et al. (1996), Gillies et al. (1999), Jones (1996), Kavouras et al. (2009a), Plush, Ren, Cram, & Aziz (2011), and Reed & Organiscak (2008), also found that water was less effective than chemical suppressants at controlling dust. They all concluded that water is composed of molecules that are widely spaced from each other, causing a higher evaporation rate when applied as a dust suppressant. In addition, they explained that introducing a chemical suppressant in place of water works effectively because it solves the deficiency of water (Amponsah-Dacosta, 1997; DeLuca et al., 2012; Foley et al., 1996; Gillies et al., 1999; Jones, 1996; Kavouras et al., 2009a; Plush et al., 2011; Reed & Organiscak, 2008). Moreover, the closer the distance between molecules in a solution, the lower the surface tension of the solution, leading to a decreased in evaporation rate of the solution when applied as a dust suppressant (Amponsah-Dacosta, 1997; DeLuca et al., 2012; Foley et al., 1996; Gillies et al., 1999; Jones, 1996; Kavouras et al., 2009a; Plush et al., 2011; William Randolph Reed & Organiscak, 2008). Figure 4.13 shows the effectiveness of the chemical suppressants compared to water at a normal temperature, consistent with findings from previous research.

4.8 Comparison of dust suppressants in a cold temperature

Figure 4.14 shows the effect of all the selected dust suppressants in cold temperatures over time. As a dust suppressant in cold temperatures, water presented a dust retention efficiency of 99.81% after 30 minutes and increased to 99.92% at the end of 72 hours. This incremental trend shows that over time, water performs more effectively a dust suppressant in cold temperatures. In cold temperature, an icy structure is formed on the soil sample when water is applied with time as shown in Figure 4.7, which prevents the escape of the soil particles into the atmosphere.

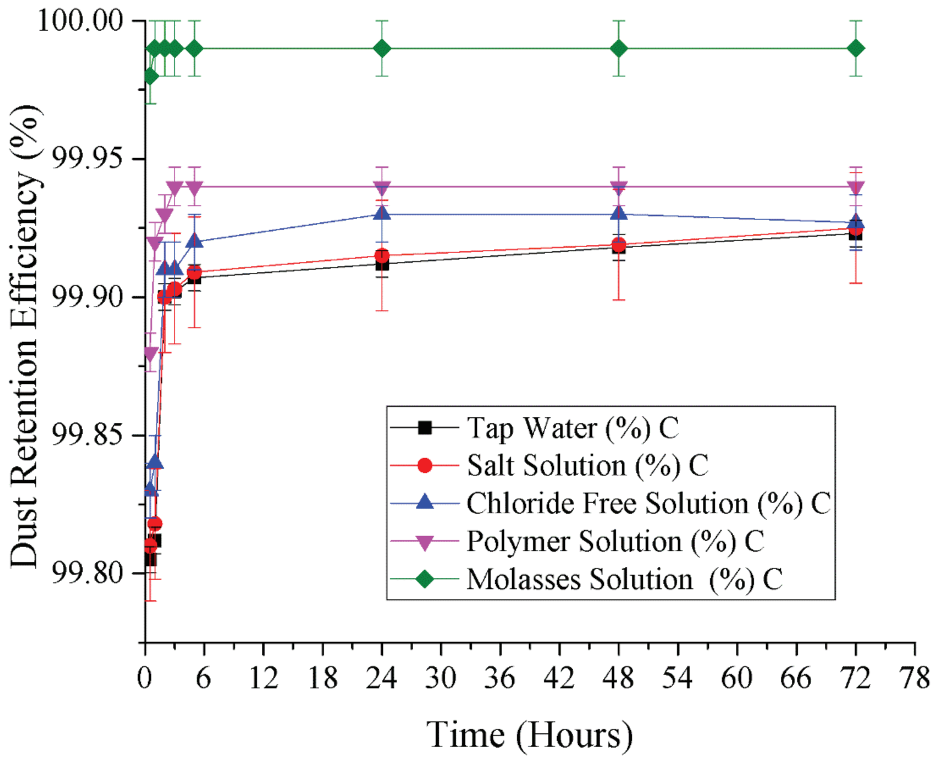

Figure 4.14. Effect of all the tested dust suppressants in the cold season

This decreases the surface tension of water and reduces the rate of evaporation. The outcome of this result with water as the dust suppressant at cold temperature refutes the claim by former researchers, such as Foley et al.,(1996); Reed & Organiscak (2008); and Thompson & Visser (2007), showing that the efficiency of water decreases with time.

All the selected chemical suppressants (i.e., salt, chloride-free, polymer, and molasses solutions) showed dust retention efficiencies of 99.81%, 99.83%, 99.88%, and 99.98%, respectively, after 30 minutes of exposure to cold temperatures and efficiencies of 99.93%, 99.93%, 99.94%, and 99.99%, respectively, after 72 hours. The incremental trend is evidence that the chemical suppressants are effective in the cold. This explains why most mining and road construction companies use chemical suppressants instead of water to control dust on haul roads (Amponsah-Dacosta, 1997; Cowherd et al., 1988; NIOSH, 2013). For example, Gillies et al.(1999), used different chemical suppressants for dust control on unpaved public roads in Merced County, California. Amponsah-Dacosta (1997), used chemical suppressants such as calcium chloride and polymerized bitumen to control dust on most surface mine haul roads in South Africa. Figure 4.14 confirms previous research claims Amponsah-Dacosta (1997); DeLuca et al.(2012); Foley et al.(1996); Gillies et al.(1999); Jones (1996); Kavouras et al.(2009a); Plush et al.(2011); and Reed & Organiscak (2008). At a cold temperature, it was observed that a crusty icy surface formed on the soil sample after water and the chloride-free and polymer solutions were applied over time, as shown in Figure 4.7. No crusty ice surface formed when the salt and molasses solutions were used.

4.9 Comparison of dust suppressants under all temperatures

Figure 4.15 and Figure 4.16 show the summarized results of the effect of all the tested dust suppressants at hot, cold, and normal temperatures over time. The data indicates that chemical suppressants are more efficient dust suppression agents than water at controlling the emission of fugitive dust on soil samples over time. No two chemical suppressants displayed the same percentage of dust retention efficiency; some are more efficient than others. The best solutions for dust control are those that can withstand external environmental factors such as extreme temperatures and wind speed, contributing to a good retention of moisture content on the surface of application.

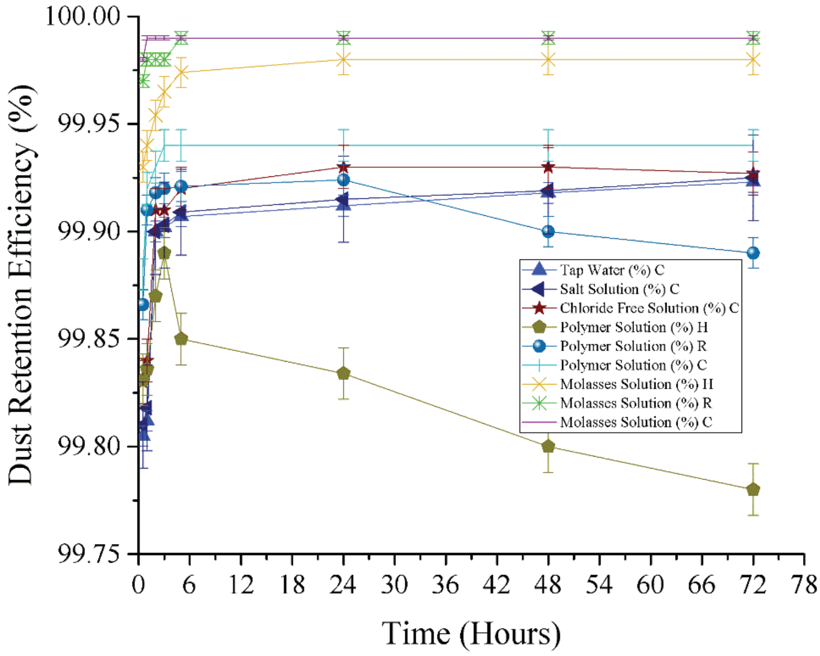

Figure 4.15. An enlarged section of Figure 4.16 showing dust retention efficiencies ranging from 99.75% to 100%

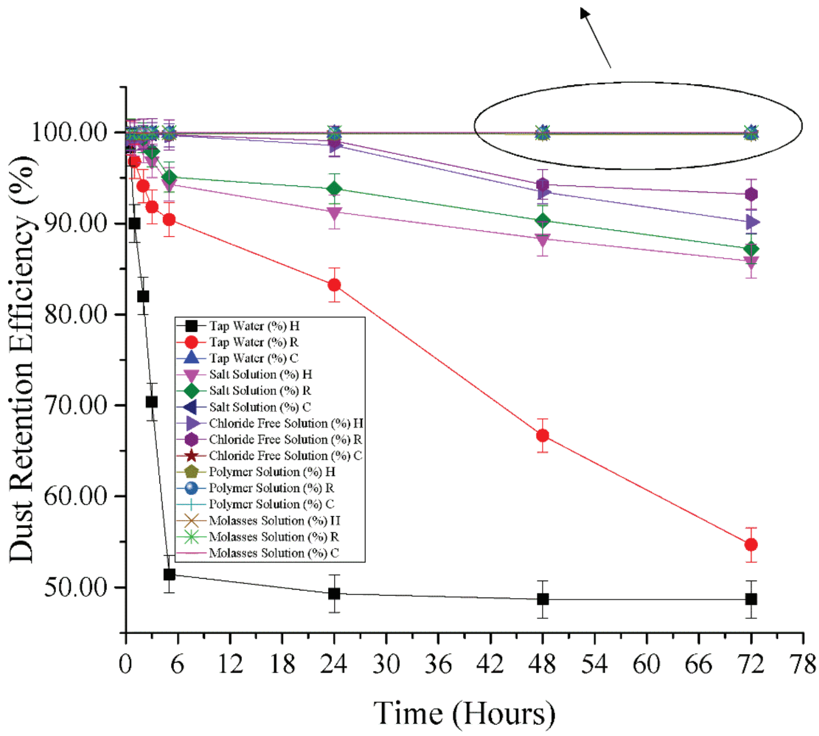

Figure 4.16. Effect of all the tested dust suppressants for all seasons

The ability to withstand external environmental factors makes chemical suppressants second effectivethan water, which requires constant re-application to be efficient at dust control in hot and normal temperatures.

4.10 Theoretical Extension of the Research Work

An economic analysis of all the tested dust suppressants in terms of ranking, environmental impact, application frequency, and the price is shown in Table 4.36. The effectiveness of each of the tested dust suppressant at different weather seasons and their corresponding environmental impact in this research have been ranked rated from 1-5. The following gives more details on the ranking.

Number 1 represents the most effective dust suppressant under a certain weather season and is most favorable to the environment followed by 2 which is effective as a dust suppressant and favorable to the environment. Then 3 is third effective as a dust suppressant and fairly favorable to the environment; 4 is less effective as a dust suppressant and less favorable to the environment; 5 is the least effective as a dust suppressant and least favorable to the environment. The most effective dust suppressant has a higher potency of preventing a greater emission of dust into the atmosphere followed by more effective, third effective, less effective, and least effective dust suppressants. Molasses had a ranking number of 1 for hot, cold and normal room temperatures because, during the experiment at temperatures of 35 ^{o}C, -19 ^{o}C, and 15 ^{o}C which was set to mimic atmospheric temperature condition, molasses was the most effective solution among all the tested dust suppressants in terms of dust retention efficiency. In addition, at cold temperature, no crusty icy formation was formed on the soil surface. Polymer solution had 2 for the hot season, 2 for normal room temperature and 3 for cold season. This is because at hot and normal temperatures the results of the experiment showed the tested polymer solution as the second most effective dust suppressant. However, at the cold season, although polymer solution is effective, it forms a crusty icy surface, potentially hindering normal traffic. Hence, the rating of polymer solution drops to number 3. The chloride-free agent was rated 3 for the hot season, and3 for normal room season because the outcome of the test results evaluated chloride-free agent as the third most effective solution among all the tested dust suppressants in terms of retention efficiency. However, in cold season the chloride-free agent solution is less effective than polymer solution. Furthermore, chloride-free agent forms an icy crusty surface on the soil sample at the cold season, thereby having the rating to “4”.

The evaluated test results of the experiment showed salt solution as the fourth most effective tested dust suppressant under hot and normal room temperature in terms of the percentage of fine soil particles retained on the sample; hence, the ranking number goes to 4. However, in cold season, salt solution performs effectively on dust retention and prevents the formation icy slippery crusty surface on the soil sample, making it the second most effective tested dust suppressant at the cold season. Tap water was rated as “5” because the outcome of the experimental work showed tap water as the least effective dust suppressant among all the five tested dust suppressants on the control of fugitive dust. The frequency of application of the tested dust suppressants over a period of 72 hours was based on the observation during the experimental research work in the laboratory. The cost per liter of the tested dust suppressants was deduce based on a telephone quote on the 17th of January, 2017 from the management of a dust control company in Alberta, Canada.

Environmental impact of a dust suppressant after application on a soil sample plays a critical role in the selection of an appropriate solution for the control of fugitive dust into the atmosphere (NIOSH, 2013; William Randolph Reed & Organiscak, 2008; Sanders et al., 1997; R. J. Thompson & Visser, 2007). According to NIOSH (2013) and Thompson & Visser (2007), water is the most environmentally friendly dust suppressant on the globe. That is, water has no environmental related problems after application as a dust control agent on a soil sample. Therefore, a ranking number of "1" was selected for water under environmental impact.

The environmental impact of molasses solution as a dust suppressant for this research was "2" because a number of research works have been done on the environmental impact of molasses over time. For instance, Gopal & Kammen (2009) and Smith (2003) have done extensive research testing on the environmental impact of molasses to the environment. The outcome of their work stated that molasses is a chloride-free agent that is friendly to the ground and surface water bodies when running off from road surfaces. In addition, molasses is non-corrosive and very soluble in water; hence, it does not lead to oxidation and rusting.

The environmental ranking number of “3” was selected for chloride- free agent base on the research work conducted by a number of researchers (Foley et al., 1996; Kavouras et al., 2009a; Sanders et al., 1997; Smith, 2003; R. Thompson, 2011). The chloride-free agent is environmentally friendly to plants, water bodies, living organisms due to the absence of chlorine. However, the result of this research shows the crusty ice formed on the applied soil surface when the chloride-free agent is applied, leading to road deterioration and soil erosion. Authors such as Amponsah-Dacosta (1997), Foley et al. (1996), Thompson & Visser (2007), Valenzuela et al. (2014) and Smith (2003) have conducted environmental impact assessments on polymer solutions as dust suppressants, concluding that the impact of chloride-free agent is uncertain to the environment depending on the chemical composition. Also, chloride-free agent may lead to soil erosion when applied in cold season. Consequently, chloride- free was assigned a “4” as the ranking number for environmental impact.

It is known that salt solution has been widely used in mine sites to control dust. Nevertheless, the use of salt solution as a dust suppressant generates a secondary negative impact on the environment (Amponsah-Dacosta, 1997; Gillies et al., 1999; Kavouras et al., 2009a; Smith, 2003; Stotterud & Reitan, 1993). According to NIOSH, (2013) and Thompson & Visser (2007), the salt solution contains chlorine that tends to leache off from a soil surface into surrounding water bodies or a vegetation, killing fishes and plants and causing disrupt in the ecosystem. In addition, salt, when mixed with water and oxygen, can cause oxidation, leading to rusting on the vehicles (i.e., mining haul trucks) causing downtime in operational truck scheduling and an increase in vehicular maintenance cost leading to a loss in NPV. (NIOSH, 2013). Based on the findings of past researchers the ranking number of environmental impact for a salt solution was “5”.

In conclusion, Table 4.36 gives a summary of the research work, which allows mining companies to conduct a preliminary comparative assessment during decision-making on different dust control methods.

Furthermore, a statistical data regressional analysis test was used to generate a preliminary formula for the assessment on the ranking orders of all the tested dust suppressants from Table 4.36. This preliminary formula is based on the parameters used for the research work and more work is to validate the formula. Note that this this is only a preliminary approach extending the work theoretically, more investigations need to be done to further validate these formulae.

$$\text{Overall Ranking (Hot Temperature)} = -0.57336 + 1.039594F - 0.06463(F)^2 + 0.019717(EI)^2 + 0.010603(Ct)^2$$

$$\text{Overall Ranking (Normal Temperature)} = -1.73456 + 2.412352F - 0.28361(F)^2 + 0.017938(EI)^2 + 0.010899(Ct)^2$$

$$\text{Overall Ranking (Cold Temperature)} = 5.955556 + 25.21481(EI) - 9.1963(Ct) + 4.05926(EI)^2 + 0.514815(Ct)^2$$

where F is the application frequency of the dust suppressant, EI is environmental impact of dust suppressant, and Ct is cost of the dust suppressant.

Table 4.36. Economic analysis of the tested dust suppressants in terms of ranking, environmental impact, application frequency, and price

Dust suppressants	Overall season ranking					Application frequency of suppressant over 72-hour period		
	Hot season	Normal season	Cold season	Cost /liter (CND $)	Environmental Impact	Hot season	Cold season	Normal season
Water	5	5	5	15	1	twelve	once	six
Salt solution	4	4	2	4	5	six	once	four
Chloride-free solution	3	3	4	9	3	three	once	two
Polymer solution	2	2	3	11	4	once	once	once
Molasses solution	1	1	1	7	2	once	once	once

Where 1 to 5 shows the ranking of the tested dust suppressants, with 1 as the most effective dust suppressant, 2 is second effective dust suppressant, 3 is third effective dust suppressant, 4 is fourth effective dust suppressant, and 5 is least effective dust suppressant.

In addition, a theoretical extension of the laboratory work was presented to explain a real case scenario on an actual surface mining site with similar soil type and wind speed as the considered parameters for the experiment. The experimental laboratory results were scaled up to a model of a surface mining operation. An empirical formulation proposed by the United States Environmental Protection Agency (USEPA) (Arpacıoğlu & Er, 2003) was used for the experiment as shown in Equation 3.7. This equation estimates the total fraction of fugitive dust that can be generated during mining operations provided that the particle sizes of the available soil sample and the average velocity of the surrounding wind be known (Arpacıoğlu & Er, 2003). Determining the estimated total fraction of generated dust will assist in decision-making when selecting an appropriate chemical dust suppressant for the area of operation.

$$\varepsilon = \frac{1}{1+\dfrac{V_d}{a*W_V}} \tag{3.7}$$

Where ε is the mass fraction of dust that escapes an open pit (%), V_d is settling deposition velocity of the emitted soil particles (m/s), a is proportional constant (0.029), and W_V is wind velocity (m/s).

The diameter of the particles associated with the soil sample is shown in Table 3.1. The total percentage of the sample that passes through each sieve size is represented. Using Table 3.1, it is possible to obtain the correlation between the sieve size and the total percentage of the sample retained on each sieve. Due to the high proportion of particles less than 0.150 mm, a smaller percentage of that sample was able to pass through the 0.150 mm sieve with a total passage percentage of 3.03.

This is evidence of the advantage of using graded sand with silt for this research, as displayed in Figure 3.2. On a large-scale surface mining operation, the diameter of the soil particles emitted from the haul road contributes to the amount of fugitive dust generated. Figure 4.17 shows a schematic diagram of the principles behind the theoretical extension of the research work on the field. The settling deposition velocity of the emitted solid particulate matter is calculated using Stokes law (Reed, 2005). One-third of the mass fraction that escapes the open pit constitutes the total fraction of dust generated from the mining activities (Reed, 2005). Of the total amount of dust, 78% - 97% is generated during hauling operations in the pit (Cole & Zapert, 1995; NIOSH, 2013; Reed, 2005).

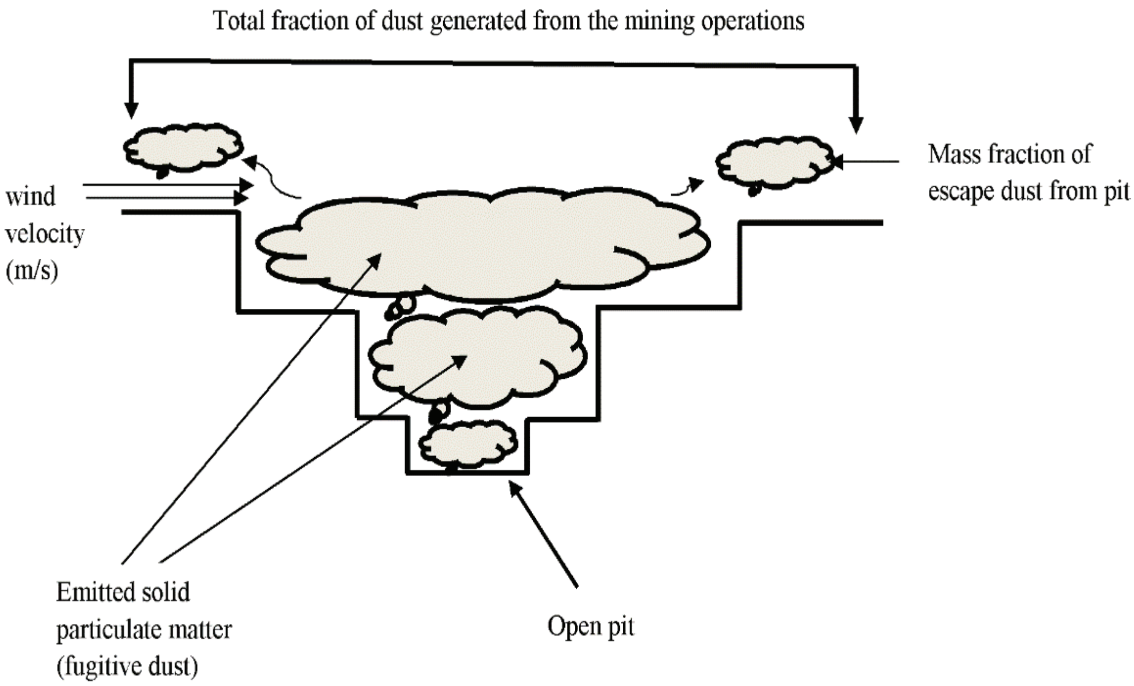

Figure 4.17. A schematic diagram representing the potential impact of fugitive dust on a mining field

Therefore, it is necessary to control the emissions of fugitive dust in mining operations, to achieve a highly productive output in a safe and risk-free environment. Table 4.35 shows the relationship between the soil particle sizes and the total fraction of fugitive dust generated in a surface mining operation on the field. This information will be useful when selecting the appropriate dust suppressant to control fugitive dust.

The variation of diameters of soil particles with their corresponding settling deposition velocities is shown in Figure 4.18. Each mark on the graph shows the settling deposition velocity per particle size. At particle diameter sizes of 0.250 mm, 0.450 mm, and 0.850 mm, corresponding settling deposition velocities of 1.14 m/s, 2.13 m/s, and 4.13 m/s, respectively, were achieved.

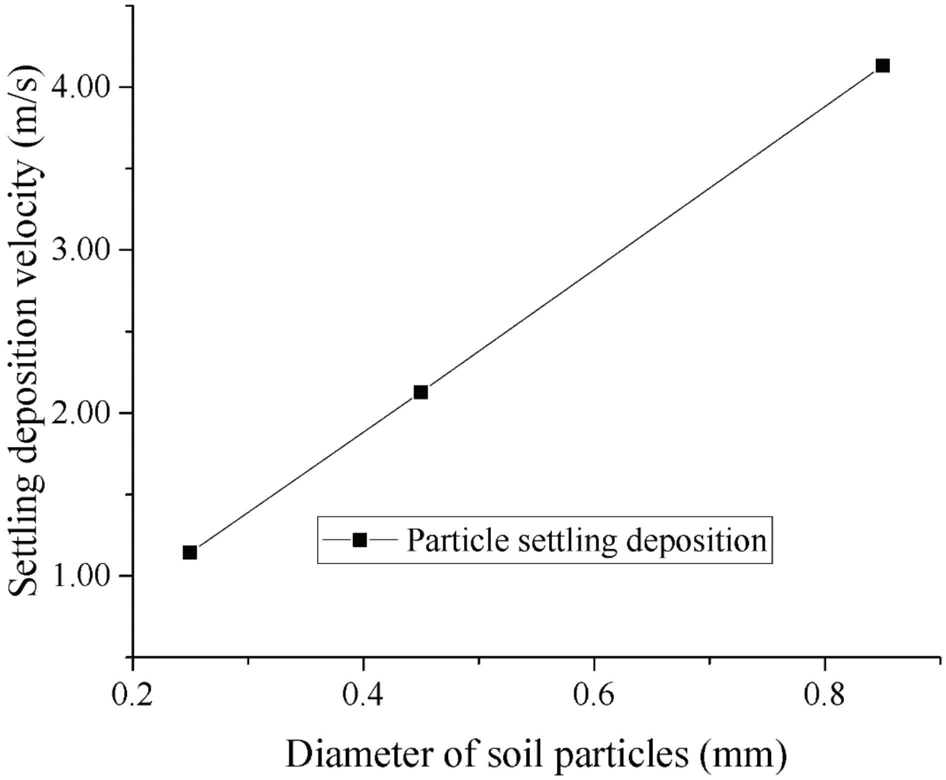

Figure 4.18. The relationship between the diameter of soil particles and their settling deposition velocity

The result shows that the larger the soil particle size with greater the deposition speed settling the particle. Figure 4.19 demonstrates the relationship between the settling deposition velocity of soil particles and the total fraction of fugitive dust generated from the surface mining activities. At particle sizes of 0.250 mm, 0.450 mm, and 0.850 mm, a corresponding total fraction of the fugitive dust of 0.94, 0.59, and 0.34, respectively, was achieved. The results explain a relationship: it has been observed that as the particle size decreases, the total fraction of fugitive dust generated increases at a lower settling particle deposition velocity.

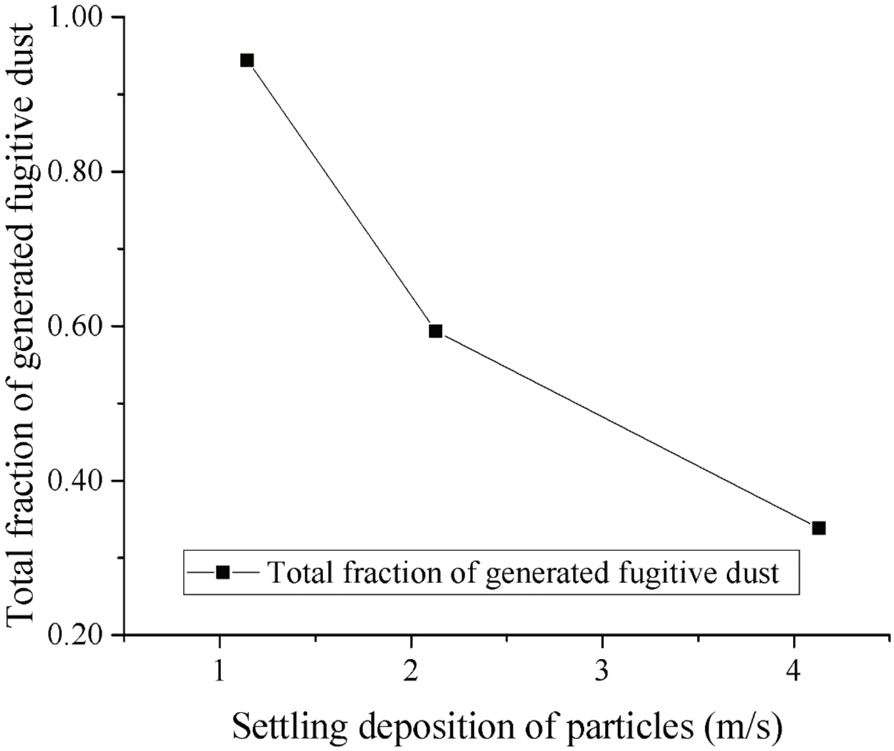

Figure 4.19. The relationship between the diameter of soil particles and their total fraction of fugitive dust generated from the mining activities

CHAPTER 5
Summary, Conclusions and Recommendations *

Chapter 5 contains the summary of the thesis and concluding remarks. The relevance, contribution, and recommendations for the future work of this research are also highlighted.

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*The content of this Chapter has been prepared and submitted as a journal manuscript: Omane, D., Liu, W. V., Pourrahimian. Y. (2017) Comparison of chemical suppressants under different atmosphere temperatures for the control of fugitive dust emission on mine haul roads. *International Journal of Mining, Reclamation and Environment*

5.1 Summary of Research

Chemical dust suppressant is continually coming to the forefront as one of the important measures in controlling the emission of fugitive dust in surface mining operations. As the mining industry faces turmoil in commodity prices, industries are making effort to reduce their cost of expenditure to maximize NPV. Efforts have been made over the years to address the effectiveness of chemical dust suppressants. In summary, the major bottlenecks using chemical dust suppressants are: a) inability to integrate the parameter of different atmospheric temperatures as a control efficiency of chemical dust suppressants; b) limitations of low longevity of some chemical dust suppressants when applied as dust control agents on unpaved haul roads; and c) deficiency of less efficacy of some chemical dust suppressants on fugitive dust over time. These deficiencies can cause a mining company to incur more cost on purchasing chemical dust suppressants, in addition maximizing road and vehicle maintenance cost resulting in loss of profitability. Hence, the objective of this research is to implement and use the mathematical principle of weight loss to test soil sample with different chemical suppressants, to assist in solving the limitations of using dust control agents on unpaved haul roads. The principle of material weight loss is implemented in this research to determine the dust retention efficiency of each of the selected dust suppressants under different weather temperatures (i.e., hot, cold, and normal room temperature). The research focuses on the objective of evaluating the role of atmospheric temperatures on the performance of chemical dust suppressants as a control efficiency on an unpaved road.

5.2 Conclusions

In pursuing this research, the literature review conducted established the limitations in the knowledge of different atmospheric temperatures as a control efficiency on dust suppressants. The literature review shows that there has not been any attempt to integrate atmospheric temperatures as a parameter on the effectiveness of chemical suppressants on fugitive dust emission in mining operations. This research, therefore, initiated an effort to employ a mathematical equation in the form of a percentage of weight loss to provide an understanding on different weather temperatures on the efficacy of chemical suppressants on fugitive dust control. The research objectives outlined in Chapter 1 have been achieved within the research scope. The following conclusive findings were enumerated from the application of the mathematical equation for integrating different atmospheric temperatures as a control efficiency:

1. There is an optimum volumetric concentration level of chemical surfactant in a solution. This optimum concentration plays an important role in the effectiveness of a chemical dust suppressant. An increase above the optimum concentration level will have little or no impact on a chemical dust suppressant’s efficiency. In short, increasing the concentration over the optimum level incurs more cost and time, which can be avoided.
2. Water performs differently depending on the environmental temperatures. In experiments with cold temperatures, at the initial application of water on the soil sample after 30 minutes, a dust retention efficiency of 99.81% was achieved, which gradually increased to 99.92% after 72 hours of

exposure. Under hot and normal temperatures, a dust retention efficiency of 98.38% and 99.40%, respectively, was achieved after 30 minutes of application on the soil sample but the efficiency diminished over time to 48.67% and 54.57%, respectively, after 72 hours. This problem of diminished efficiency in dust retention under the hot and normal temperatures means that water must be constantly re-applied to the soil sample to prevent fugitive dust emissions.

3. The salt solution as a dust suppressant worked effectively in controlling the emission of dust from the soil samples. After 30 minutes of applying the salt solution suppressant to the soil samples in both hot and normal temperatures, dust retention efficiencies of 99.45% and 99.80%, respectively, were achieved. These efficiencies decreased with time to 88.85% and 87.21% after 72 hours of exposure to hot and normal temperatures, respectively. In cold temperatures, a dust retention efficiency of 99.81% was achieved during the initial 30 minutes of application to the soil sample, but efficiency gradually increased to 99.93% after 72 hours of exposure. Also, salt combined with water proved to be second effectiveat dust retention than water alone.
4. After 30 minutes of exposure to hot, normal, and cold temperatures, the dust retention efficiencies of the chloride-free solution were 99.30%, 99.70%, and 99.93%, respectively. The effectiveness of the chloride-free solution decreased with time to 90.15%, 93.20%, and 99.93%, respectively, after 72 hours of exposure to different temperatures. This

outcome shows that the chloride-free solution has a better capacity than the water-and-salt solution to control the emission of fugitive dust into the atmosphere.

5. After 30 minutes of exposure to hot, normal and cold temperatures, the polymer solution demonstrated dust retention efficiencies of 99.83%, 99.87%, and 99.88%, respectively. After 72 hours, there was a reduction in the efficiencies to 99.78%, 99.89%, and 99.94%, respectively. This stable performance showed that the polymer solution is an effective dust suppressant. Unlike water and the salt and chloride-free solutions, the polymer solution's retention efficiency is not affected by temperature.
6. The molasses solution showed dust retention efficiencies of 99.93%, 99.97%, and 99.98% after 30 minutes of exposure to hot, normal and cold temperatures. After 72 hours of exposure, there were efficiencies of 99.98%, 99.99%, and 99.99%, respectively, showing that the molasses solution is an effective dust suppression agent compared to the other tested agents. As with the polymer solution, the molasses solution's retention efficiency is not affected by atmosphere temperature.
7. A crusty, slippery surface formed on the soil sample under the cold temperature when water, the chloride-free solution, and the polymer solution were applied as dust suppression agents. No crusty, slippery surface formed when the salt and molasses solutions were used at a cold temperature.

8. Each result shows that time played a role in the effectiveness of a chemical dust suppressant. The outcomes for each selected chemical dust suppressant depended on the length of exposure at various temperatures.

The combined result for all the tested suppressants proves the importance of chemical suppressants, rather than water, to control fugitive dust. Moreover, each chemical suppressant has a different level of efficiency. Their use should be dependent on factors such as temperature and specific suppression properties. For instance, polymer and molasses solutions have proven to work independently of the environmental temperature. Chemical suppressants reduce the need for the consistent re-application of an agent on an unpaved haul road at different temperatures and therefore it is cost efficient for mining companies to use regardless of the location of the mining operation as a dust control measure. However, environmental regulations differ from province to province, and country to country; the selection of a dust suppression agent must fit within the acceptable guidelines of the area of operation.

5.3 Contributions of the Research

This research has used a mathematical equation based on the principle of material weight loss for determining dust retention efficiency of different dust suppressants. The major contributions of this research are as follows:

1. This is the first effort in integrating different atmospheric temperatures as a parameter for evaluating the performance of dust suppressants using the principle of material weight loss. This research contributes significantly to the body knowledge on dust control methods in surface mining operations.

2. The control efficiency of different atmospheric temperatures provides comparative assessment analysis during decision-making for surface mining industries towards the selection of dust suppressants for dust control, depending on the weather temperature of the area of location.

3. Atmospheric temperatures as a control efficiency provide the platform of change in the effectiveness and duration of chemical suppressants on dust emissions in surface mining operations, with the objective of addressing the long-term performance dilemma of chemical dust suppressants, maximizing NPV, and minimizing road and vehicle maintenance cost.

4. The principle of considering different atmospheric temperatures as a tool for analyzing the performance of chemical dust suppressants provide a new direction for advancement in the commercial dust control software packages.

5.4 Recommendations for Future Research

Notwithstanding the use of atmospheric temperatures as control efficiency developed in this thesis has provided innovative ways of analyzing the performance of dust suppressants, there is still the need for continued investigation into using dust suppressants for curbing fugitive dust in the mining and mineral industry. The following recommendations could improve and add to the body of knowledge in this research area:

1. This research considered atmospheric temperatures as the performance environmental condition, there are other environmental conditions that can

be investigated. Future research will need to consider different environmental conditions and establish the relationship between the effect on chemical dust suppressants.

2. In addition to the use of atmospheric temperatures as a control efficiency in this research, four different chemical suppressants were evaluated in this research, however, there are other chemical suppressants that can be considered. Future research will need to assess diverse types of chemical suppressants and determine the effect under an environmental condition in terms of dust retention efficiency.

3. The time evaluation of this research was done under a short duration. However, for future research, an extended duration should be applied to be able to establish a greater correlation between the dust retention efficiency of each chemical suppressant and the corresponding time of exposure to an atmospheric temperature.

4. The mineralogy of the fine materials and water used for research experiment should be considered for future work to establish their impact on the retention efficiency of dust.

5. Future research work should explore the relationship between pile mass retention and air quality to the environment in terms of part per million (ppm).

6. This research assumed all the applied dust suppressants evaporates at an equal frequency indicating the negligence of the solution evaporation on the results. Future research will need to consider the impact of the solution applied on the soil sample in terms of evaporation rate.

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