WA School of Mines

Assessing the Effectiveness of Eco-friendly Dust Suppressants Used to Abate Dust Emission from Mine Haul Roads

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This thesis is presented for the Degree of

Master of Philosophy

Of

Curtin University

August 2018

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: XINGYUN GUO

Date: 09/08/2018

Dedication

This thesis is dedicated to my loving parents who have provided me with both emotional and financial support. With their support and guidance, I would not have been able to finish my study.

Statement of Contribution by Others

Principal Author	Candidate Contribution to the thesis	Overall (%)	Signature	Date
Xingyun Guo	Set research questions, developed methodology, developed experimental program, performed the experiments, conducted experimental analysis, and wrote manuscript.	85%	XINGYUN GUO	30/03/2019

Co-author Contribution

By signing the statement, the co-author certifies that:

The candidate's stated contribution is accurate as above.

Co-author	Contribution to the thesis	Signature	Date
Guang Xu	Supervised development of work and reviewed manuscript.	Guang Xu	30/03/2019

Acknowledgments

I would like to express my gratitude to my supervisor, Dr. Gaung Xu for providing me with the opportunity to study further. His guidance and knowledge helped me complete my study. I would also like to thank my co-supervisor, Dr. Apurna Ghosh for his help. My sincere thanks to Mr. Xuhan Ding for his help. He taught me a lot about experimental skills and research writing.

Produced during This Master Study

Manuscripts in preparation:

Guo XY, Xu G, Ding XH. Experimental and numerical study of effectiveness of xanthan gum used as an eco-friendly dust suppressant to abate haul road dust (**To be submitted**)

ABSTRACT

This thesis consists of two parts, literature review and experimental investigation. The first part of the thesis is a literature review of eco-friendly dust suppressant in dust control. Firstly, this part gives an introduction of haul road dust from two aspects, namely characteristics and environmental impacts of haul road dust. Secondly, the mechanisms and influencing factors of dust generation are investigated based on previous research. More importantly, several representative dust suppressants and commonly used evaluation methods are presented and discussed. Through the literature review, two eco-friendly dust suppressants, xanthan gum and lignosulfonate, are chosen in a further study.

The second part of the thesis is a laboratory-based study of the selected dust suppressants. This part includes two sets of experimental programs. The first experimental program is to evaluate the dust control effectiveness of xanthan gum via experimentations and numerical analysis. The infiltration depth test and moisture retention test are conducted to study the effect of xanthan gum on infiltration depth and moisture retention. The results show that there is a continuous decrease in the infiltration depth with increasing the xanthan gum concentration. However, with an increase in the concentration, the average moisture content firstly increases, then slightly decreases, and increases thereafter. Finally, the data from the experimentations is analysed in mathematical models. According to the numerical analysis, the greatest dust control effectiveness is achieved at a concentration of 2g/L. Another experimental program is to evaluate the dust control effectiveness of lignosulfonate via several experimental tests. The infiltration depth test, moisture retention test, zeta potential measurement are performed to investigate the effect of lignosulfonate on infiltration depth, moisture retention, and zeta potential, respectively. The results indicate that treatment of lignosulfonate leads to substantial changes in the above properties. Finally, the wind tunnel simulation test is conducted to directly assess the potential of dust generation (weight loss) from lignosulfonate-treated soil samples. According to the experimentations, the best dust control performance is achieved at a concentration of 80g/L. In addition, there is a strong correlation between the zeta potential and weight loss.

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Chapter 1 Introduction

1.1 Background

Dust generation from mine haul roads is a serious problem at surface mining operations. It brings surface mines and the surrounding environment many adverse impacts. In recent years, environmental concerns have led to a rise in the interest of eco-friendly dust suppressants used to mitigate the haul road dust. The dust suppressants are effective in reducing haul road dust emission without causing any detrimental impacts to the natural environment.

1.2 Objectives of research

The main objective of this study is to investigate the feasibility of using eco-friendly dust suppressants to address the problem of haul road dust. More specifically, two eco-friendly dust suppressants (xanthan gum and lignosulfonate) and several evaluation methods are chosen through literature review. The selected dust suppressants are investigated via two sets of experimental programs, with a view to studying the improvement of soil properties after being treated with them.

1.3 Organization of the thesis

The study presented in this thesis begins with **Chapter 1**, the Introduction to the research topic, followed by two main parts. The first part reviews the literature of eco-friendly dust suppressants in dust control (**Chapter 2**). The second part presents the laboratory study of two dust suppressants (xanthan gum and lignosulfonate) for haul road dust control and includes **Chapter 3** and **Chapter 4**.

Chapter 2 is a literature review of eco-friendly dust suppressants in dust control. Firstly, the characteristics and adverse impacts of haul road dust are introduced.

Secondly, based on previous research, the dust generation mechanisms and influencing factors are investigated. Lastly, the representative dust suppressants and commonly used evaluation methods for dust abatement effectiveness are discussed.

Chapter 3 presents an experimental and numerical study of using xanthan gum to enhance the soil properties and thus abate dust emissions from haul roads. The effect of xanthan gum on the infiltration depth and moisture retention is investigated. Based on the experimental programs (infiltration depth test and moisture retention test), a numerical analysis is done to evaluate the dust control effectiveness at various concentrations.

Chapter 4 presents an experimental study of using lignosulfonate to improve the soil properties and thus enhance the dust control performance. The effect of lignosulfonate on infiltration depth, moisture retention, and zeta potential is presented and discussed. Lastly, wind tunnel simulation test is conducted to study the relationship between the enhanced soil properties and erosion (wind and vehicular erosion) resistance. The dust control effectiveness was investigated via the above laboratory study.

Chapter 2 Research and application of environmental-friendly chemical dust suppressants to control airborne dust from haul roads: a review

2.1 Introduction

Mining is a one of primary industries in Australia, which contributes approximately 8% to gross domestic product (GDP) and 60% of exports (Giurco, Prior, Mudd, Mason, & Behrisch, 2010). Mining has made major contribution to Australian economy but has also brought environmental degradation in some areas. Recently the mining-related environmental impacts have received much attention. Airborne dust is regarded as a serious problem for surface mining operations. At surface mining operations, there is a great number of large-scale haul trucks used to transport mine and waste within a surface mine pit. In comparison to paved roads, surface layer material of haul roads is directly exposed and thus readily subjected to erosion induced by vehicular and wind action. As a result, the unpaved mine haul roads usually generate excessive amount of airborne dust during the transportation. The transportation on haul roads is a dominant source of airborne dust and it produces 70% to 90% of the total airborne dust within a surface mining site (Chaulya, 2004; Patra, Gautam, & Kumar, 2016; Reed & Organiscak, 2006; Thompson & Visser, 2007). Also, according to relevant studies, a dumper can produce as much as 0.25 – 0.70 kg of airborne dust per kilometre into the atmosphere (Singh, 1997).

The airborne haul road dust is one of primary environmental pollutants to surface mining sites and the surrounding environment. There have been extensive studies concerning the haul road dust. The dust has many adverse impacts on occupational safety, human health, and maintenance of mining equipment (Petavratzi, Kingman, & Lowndes, 2005; M. H. Ross & J. Murray, 2004; Thompson & Visser, 2007). Therefore, in response to these above impacts, to control the dust emission is of great importance. With a view to reducing the haul road dust, some different methods have been studies and adopted, such as restriction of speed of vehicles (Chaulya, 2004), prolonging intervals between adjacent haul trucks (Reed & Organiscak, 2006), physical cover of roads (Alzubaidi, 1999), and watering (Addo & Sanders, 1995; Han, 1992; Succarieh, 1992). Watering is usually more commonly used to abate the dust emissions at surface mining operations. This measure also can be categorized into two main types, namely non-chemical watering and watering with chemical dust suppressants. Non-chemical watering is usually used as a temporal method of reducing dust and it has a good dust-control performance for a relatively short time (Y.-M. Chang, Hwang, & Chou, 2003). However, due to several adverse factors, such as high evaporation rates and heavy vehicular erosion, water spraying without chemical normally requires a short interval between periodic re-applications. Moreover, watering process incurs an unduly fuel cost due to operation of graders and water carts. Therefore, this method is not cost-effective in reducing the dust emission, especially in water-shortage areas (Carter, 1995; Neuman, Boulton, & Sanderson, 2009).

Compared to non-chemical watering, application of chemical dust suppressants is more preferred due to its advantages, for example, good dust suppression performance, longer active time, high cost-effective, and more effective in semiarid and arid areas. This method is to enhance physical and chemical properties of surface layer of haul roads via spraying solutions of dust suppressants onto haul roads. Generally, the dust suppressants have a good water solubility at ambient temperature. Moreover, they have some favourable properties for reducing the dust emissions, such as moisture retention capacity, ability to induce cohesion, and hygroscopicity. Most importantly, due to environmental concerns, the suppressants should not be harmful to natural environmental. Therefore, this study has only focused on the environmental-friendly dust suppressants with relevant research on environmental effect. The dust suppressants are usually categorized into several types based on their chemical constituent, including chloride salt, organic non-bituminous binder, clay additives, bituminous binder, and biopolymer.

The airborne dust from haul roads is more common and detrimental to human health and surrounding environment compared to that from other unpaved roads. This is because operation of vehicles is more intensive and thus much more airborne dust is produced at surface mining operations. However, little research on the airborne haul road dust was found in literature review. Consequently, information about the airborne dust from haul roads is highly scarce. In particular, most of the information is only available from project reports of mining companies and documentation of local authorities, which is usually difficult to be accessed for scientific communities. Therefore, the objective of this study is to review the application of environmental-friendly chemical dust suppressants, discuss their dust generation and suppression mechanisms, characterize the haul road dust, investigate the adverse impacts of the dust, and study the evaluation methods of dust abatement effectiveness. Those suppressants that has potential environmental harm are excluded. In addition, dust suppressants used to other unpaved roads that has similar surface layer material to haul roads are also included in this study.

2.2 Characteristics and adverse impacts of haul road dust

2.2.1 Characteristics of haul road dust

In this current study, the airborne haul road dust refers to an aggregate of fine particles that is dislodged from surface layer of haul roads and remains suspended in the atmosphere for a period of time. Several characteristics of the haul road dust, including percent contribution, particle size, particle size distribution, and horizontal diffusion of the haul road dust are discussed in the following paragraphs.

The transportation of haul roads is a dominant source of airborne dust, which produces more airborne dust than other unit procedures (e.g. drilling, blasting, and overburden removal,) at surface mining operations. Previous research on percent contributions of airborne dust from different unit mining procedures has been conducted in typical surface coal mines of South Africa and India by Amponsah-Dacosta (Amponsah-Dacosta, 2015) and Mandal et al. (Mandal et al., 2012), respectively. The results obtained from the studies indicated that airborne dust generated from haul roads accounts for >80% of the total airborne dust emission in surface mining sites. In addition, they suggested that there was a slight variation in the percent contributions of other unit procedures considering different mining sites.

The particle size of the haul road dust is a primary parameter and physiological effects of the dust are largely affected by its particle size. In general, the particle size is described by its equivalent diameter. Aerodynamic diameter (a.d.), one of equivalent diameters, is based on aerodynamic behaviour of particles. This diameter is usually utilized to determine particle size (ISO 4225: 1994). It should be noted that all particle size shown in this thesis is described by aerodynamic diameter. Synthesis of available studies indicated that the physiological effects of the airborne dust are highly affected by its particle size. The dust with small particle size is more hazardous to health in humans (Kim, Kabir, & Kabir, 2015; Valavanidis, Fiotakis, & Vlachogianni, 2008). For example, most particulates with a particle size of >10μm (μm denotes micrometres, 10^{-6}m) are trapped by cilia and mucus and then lodged in trachea (Atkinson, Fuller, Anderson, Harrison, & Armstrong, 2010). Therefore, in general this fraction of the dust is not of concern for human health. On the contrary, the dust with a particle size of <10μm easily accesses respirable tracts and brings adverse health effect in humans. For example, particulates with a particle size of <1μm penetrates to alveoli and even cell tissue, which leads to a substantially increased incidence of respiratory diseases (Valavanidis et al., 2008).

Extensive relevant studies revealed that the haul road dust has a wide range of particle size distribution and the fraction with a particle size of >10μm is dominant compared to the other different-sized portion. In general, maximum size of airborne haul road dust is 500μm and minimum size of that is 0.5μm. This is because particles with a size of >500μm quickly deposits onto ground due to gravity settling. On the contrary, particulates with a size of <0.5μm tend to stick to surfaces of other larger particles (Kumar, Mulheron, & Som, 2012; Shao & Lu, 2000). The study of Reed et al. (Reed & Organiscak, 2006) investigated the particle size distribution of the airborne haul road dust. In Reed's study, cascade impactor sampler was used to collect data from two sampling locations alongside the investigated haul road. According to the results of this study, it can be found that 54.47% (mass fraction) of the dust consists of particulates with a particle size of 21.30-50.00μm, 19.01% of the dust has a particle size of 14.80-21.30μm, 12.02% of the dust has a particle size of 9.80-14.80μm and the rest of that has a particle size of <10μm. These results are similar to the results from the study of Organiscak et al. (Organiscak & Randolph Reed, 2004). The Organiscak's study showed that more >80% (mass fraction) of the haul road dust has a particle size of >10μm. In addition to the particle size distribution, the haul road dust is usually categorized into many types according to its particle size, such as total suspended particulates (TSP) (particle size <100μm), PM_{10} (particle size <10μm), and $PM_{2.5}$ (particle size <2.5μm) (EPA, 1996).

There is a continuous decrease in the concentration of the haul road dust with an increase of distance. Also, the concentration decreases to a minimum level (approximately approached background level) at a certain distance from the observed haul roads. The phenomenon, how the haul road dust disperses horizontally in the atmosphere, is referred as to the horizontal diffusion of the dust. Relevant research has been carried out to investigate this phenomenon. For example, Organiscak et al (Organiscak & Randolph Reed, 2004) performed two field surveys to study the horizontal dispersion in a coal mine site. In Organiscak's study, four different sampling locations were chosen in a direction perpendicular to the observed haul road (downwind). The results of the study showed that the concentration of the dust emission gradually decrease with increasing the distance and the measured concentration approached background level (0.05mg/m^3) at 30.5m from the observed road. These results are similar to the results from the study of Docx et al. (Docx et al., 2007), which indicated that the concentrations returned to background levels at 30m from the source. Furthermore, the value of measured concentrations likely has a substantial variation even in one sampling location. This is because the airborne dust disperses in the atmosphere not only in horizontal direction but in vertical direction. Dispersed particulates possibly escape dust samplers due to its vertical dispersion (Edvardsson & Magnusson, 2009).

2.2.2 Adverse impacts of haul road dust

There has extensive relevant research focused on the adverse impacts of the airborne haul road dust. The haul road dust has serious impacts on surface mining sites and the surrounding environment. In this thesis, these impacts are mainly focused on occupational safety, human health, and maintenance of mining equipment (Petavratzi et al., 2005).

The airborne haul road presents in working environment and exposes mining-related employees to excessively high concentration of airborne particulates that pose a severe health hazard. According to the study of The National Institute for Occupational Safety and Health (NIOSH), long-term exposure to this working environment has been found to be responsible for occupational respiratory disease in the mineworkers. The study of Kim et al. (Kim et al., 2015) also revealed that excessive airborne haul road dust increase the potential of health problems, such as lung cancer, silicosis, and chronic obstructive pulmonary disease. On the other hand, people living in surround community of mining sites possibly has same health hazard. For example, there is a high incidence of respiratory disease (i.e. tuberculosis and chronic bronchitis) in people who lived in the region near mining areas (M. H. Ross & J. Murray, 2004).

In addition to the occupational health problems, the haul road dust also poses a safety hazard to surface mining operations. The relevant studies of haul road dust revealed that it obscures the visibility of haul truck drivers and thus increases the possibility of traffic incident. In South Africa, about 75% of the surface mine accidents has been found to be associated with haul road transportation, and the excess airborne haul road dust was noted as a significant contributing factor of the incidents (Thompson & Visser, 2007).

The airborne haul road dust also brings an unduly high maintenance cost of mining-related equipment. At surface mining operations, the haul road dust penetrates into various parts of mining-related vehicles due to its excess penetrability. Since the particulates are abrasive, it greatly increases the wear of involved mechanical components, thereby reducing the service life of these components. As a result, the dust leads to an increase in the maintenance cost for mining companies (Addo & Sanders, 1995).

2.3 Generation mechanism and influencing factors of haul road dust

A discussion about the generation mechanism and influencing factors of haul road dust is given in this section. Also, based on these influencing factors, feasible approaches to controlling haul road dust are discussed.

2.3.1 Mechanism studies

The entrainment of haul road dust occurred when definite energy imparted to ground surfaces of haul roads. The energy induced separation forces and involved particles lost adhesion actions and were dislodged from the ground surfaces into the atmosphere in the form of airborne dust (Plinke, Maus, & Leith, 1992). More specifically, these separation forces must reach a certain minimum value. This value usually named as threshold that is sufficient to overcome the adhesive forces. Under the circumstances, the involved particles detached from soil aggregates and became available for suspension. The suspended particles were then transported by horizontal advection and turbulent diffusion (Braaten, Shaw, & Paw U, 1993; Chiou & Tsai, 2001; Hinds, 2012). The generation mechanism of the haul road dust is illustrated in Figure 2.1. Regarding the haul road dust, separation forces are usually provided by either wind action or vehicular action (e.g. torque of rotating wheels) (Succarieh, 1992). Previous research on dust generation indicated that there have many types of forces to function as adhesive forces between particles, such as van der Waals forces, electrostatic forces, and forces induced by surface tension of absorbed moisture in voids of granules. In terms of three forces, van der Waals forces, a long-range attractive force, are the most of importance in dust control, while electrostatic force is less importance of the other forces. There have many factors affect these forces and thus change the potential to generate dust, such as atmospheric temperature, particle size, and relative humidity (Hinds, 2012).

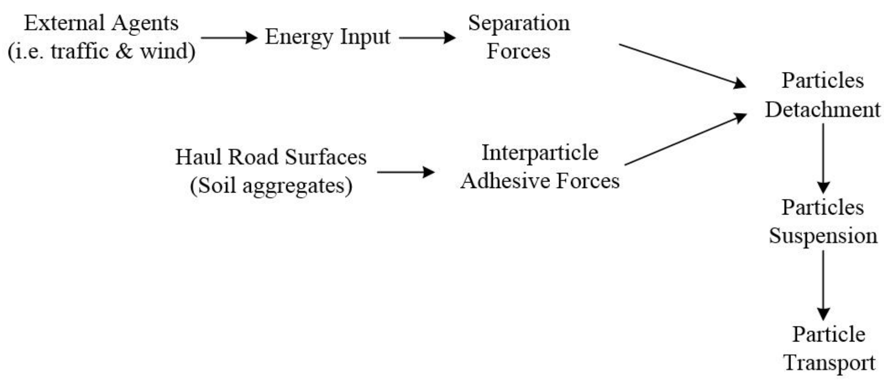

Figure 2.1 Dust generation mechanism

2.3.2 Influencing factors

Extensive research has been focused on influencing factors of haul road dust. There are many factors that affect the dust generated from haul roads. For example, Denby et al. (B. Denby et al., 2013) conducted studies on moisture content of surface material. In Denby’s study, it can be observed that there is a strong relationship between the moisture content and dust emission. The studies of Edvardsson (Edvardsson, 2009) and Edvardsson et al. (Edvardsson & Magnusson, 2009) revealed that there is a continuous increase in dust concentration with increasing vehicle speed. Ding et al. (Ding, Xu, Kizil, Zhou, & Guo, 2018) carried out a study on mechanical properties and dust emission. In Ding’s study, a linear correlation between the properties and dust emission has been established via experimental investigation. The similar research on mechanical properties and dust generation has been done by Chen et al.(Chen, Ding, Ramey, Lee, & Zhang, 2015). These influencing factors can be categorized into three major groups as follows:

(1) Factors specific to the roads, such as mechanical properties, compaction degree, particle size distribution, moisture content of surface material of haul roads;

(2) Factors specific to the geographical area, such as atmospheric temperature, humidity, and evaporation;

(3) Factors related to vehicular action on the roads, such as vehicle speed, vehicle weight, and tyre properties.

Based on the above-mentioned the generation mechanism and influencing factors, some dust control methods can be used with a view to address the problems of haul road dust. A possible approach to abate haul road dust emission can be achieved via either changing the factors of the road surface material (1) or changing the factors related to vehicular action (3). To change the factors related to vehicular action (e.g. vehicle speed, vehicle weight, and tyre properties) is usually not feasible at surface mining operations. Therefore, the only viable option is to change some factors of the road surface material, such as optimization of mechanical properties (e.g. unconfined compression strength), chemical properties (e.g. moisture retention), fine content, particle size distribution, and compaction of exposed ground surfaces. Since most of mine haul road are not designed, to optimize the physico-chemical properties via spraying solutions of chemical dust suppressants is more preferred than the others. Therefore, this thesis was only focused on the chemical dust suppressants.

2.4 Evaluation methods

Given the serious impacts of haul road dust, some methods can be used in order to evaluate effectiveness of dust suppressants for haul road dust abatement. Several commonly used evaluation methods, including infiltration depth test, moisture retention test, mechanical test, wind tunnel test, and microstructural analysis, are discussed in this section. The evaluation methods and their objectives are illustrated in Figure 2.2.

It should be noted that there are two common ways of sample preparation for evaluating the dust suppressants, sprayed-on and mixed-in. Although the dust suppressants are usually used via spraying onto surface layer of haul roads, this thesis is not only limited to review the evaluation methods that prepare samples by using the sprayed-on way. To review the evaluation methods that prepare samples by using the mixed-in way is imperative with a view to better understanding the dust suppressants. Moreover, this thesis mainly focused on laboratory studies and a few field investigations were given briefly.

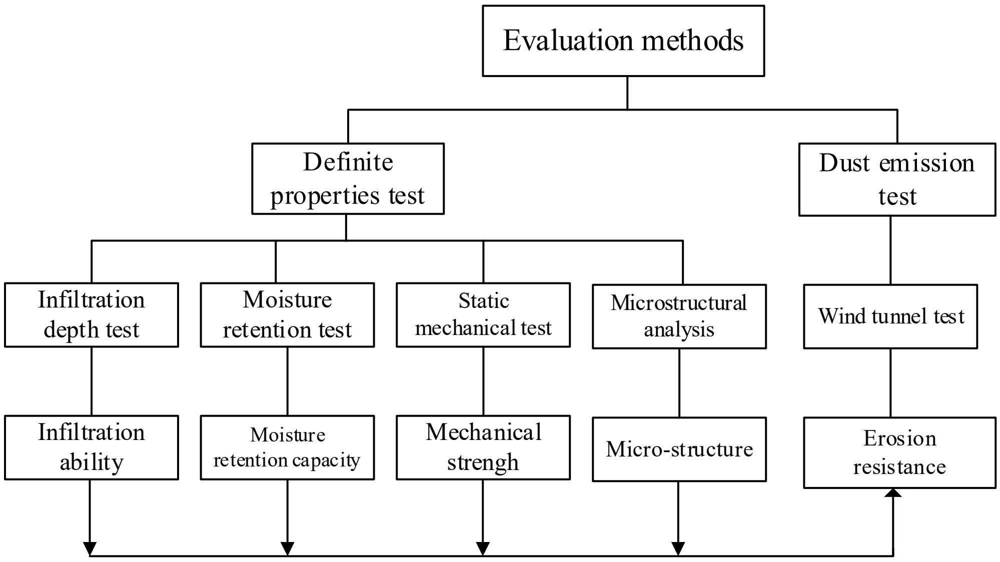

Figure 2.2 Evaluation methods and their objectives

2.4.1 Infiltration depth test

Infiltration depth test is to evaluate effectiveness of dust suppressants via measuring their infiltration depth into soil samples. Previous studies of dust abatement revealed that infiltration depth of a dust suppressant into soil samples is a critical factor in achieving effective dust abatement. For example, the study of Bolander et al. (Bolander & Yamada, 1999) showed that greater infiltration depth results in better dust abatement performance. This is because sufficient infiltration depth is capable of preventing leaching and inducing more cohesion. Also, they suggested that the infiltration depth of a dust suppressant should be >10mm for road dust suppression. The study of Foley et al. (Foley, Cropley, & Giummarra, 1996) indicated that an increase of infiltration depth brings about a reduction in road dust emission. Since an increase in infiltration depth, more soil particles were wetted by the dust suppressant and then aggregated into larger groups, thereby reducing potential to be dislodged from ground surfaces. Based on the above findings, it is imperative to investigate the infiltration depth for the evaluation of dust suppressants.

Infiltration depth test is directly to measure the infiltration depth of a dust suppressant. In general, the dust suppressant is used in a form of aqueous solution. Two commonly used methods are utilized to measure the infiltration depth. One is to measure the infiltration depth on dehydration condition and the other is to measure on non-dehydration condition. More specifically, the former method is to measure the depth of crust layer formed after dehydration. The other method is to directly measure the depth of wetted layer after spraying of the dust suppressant. Both of these two methods are easy to be performed. In addition, during sample preparation, a definite compaction should be achieved to study road dust abatement. Chen et al. (Chen et al., 2015) performed infiltration depth tests by using the non-dehydration method. In Chen's study, dry granular material (silty sand) and xanthan gum were chosen to investigate a relationship between infiltration depth and concentration. It has been found that the infiltration depth decreases with an increase in the concentration. Also, the results of the infiltration depth tests were used in numerical simulations to study correlation between surface strength and dust resistance. Ding et al. (Ding et al., 2018) performed infiltration depth tests by using the dehydration method. In Ding's study, SP sand and two lignosulfonates were selected to investigate a relationship between the infiltration depth and the concentration of two lignosulfonates. According to the results of this study, the infiltration depth was significantly affected by the concentrations. In addition, the results of infiltration depth tests were used to study concentration effects on crust densities.

2.4.2 Moisture retention test

Moisture retention test is to evaluate effectiveness of dust suppressants via studying moisture retention of dust suppressant-treated samples. Results obtained in previous research (Fitz & Bumiller, 2000; X. Wang et al., 2015) indicated that high moisture content in soil is particularly favourable to dust abatement from it. In general, moisture exists in soil in a form of thin film. The thickness of the films increases with an increase in an amount of moisture existing in soil. The film which bridges two neighbouring grains of soil is effective in aggregating the soil grains, thereby reducing their potential to be dislodged from soil. Even when the thickness of the film is reduced by desiccation processes, the bound soil grains were not immediately separated. Therefore, to reduce moisture loss in soil is of critical importance with a view to abating dust generation.

Moisture retention capacity is a fundamental property in soil. This property retards processes of desiccation (moisture loss) from the soil. However, soil desiccation rate is not desirable under natural conditions. Recently relevant studies have been conducted to treat soil with some dust suppressants and thus improve its moisture retention capacity. According to Bae et al. (Bae, Inyang, Galvão, & Mbamalu, 2006), even a small improvement of the capacity resulted in a notable decrease in dust generation. Therefore, to study moisture retention capacity is imperative for the evaluation of dust suppressants. Given this purpose, some methods have been employed. In this thesis, moisture retention test refers to one type of experimental program for evaluating this capacity. This test is used to assess the moisture retention of samples. In general, the samples with lower desiccation rate has better moisture retention capacity. During the test processes, weight loss of tested samples was recorded and used to investigate the moisture retention (Santoni, Tingle, & Webster, 2002; Yang, Wang, Fang, & Tan, 2007). For example, Bae et al. (Bae et al., 2006) conducted moisture retention tests to investigated the improvement of moisture retention after being treated with a neutral polymer (PEO). The study by Bae et al. (Bae et al., 2006) indicated that the PEO treatment is effective in enhancing the moisture retention. They also suggested that the enhancement leads to a substantial reduction in dust generation and the PEO-treated (optimal concentration) sample produced less dust emission than that only treated with water by 27.8%. More recently, Inyang et al. (Inyang, Bae, Lee, & Park, 2012) performed moisture retention tests to study the enhancement of moisture retention after treatments of sodium carboxymethyl cellulose (CMC). The study of Inyang et al. (Inyang et al., 2012) showed that with increasing CMC concentrations the moisture retention of kaolinite firstly decreases and slightly increases and the optimal concentration is 1g/L for enhancing the moisture retention. In addition, there is a strong correlation between moisture retention and dust control efficacy (Inyang et al., 2012).

On the other hand, moisture retention capacity of treated samples possibly changes after a number of wet-dry cycles. Chen et al. (Chen, Lee, & Zhang, 2014) carried out a test to study durability of moisture retention for selected biopolymers. According to Chen's study, there was a slight change in the moisture retention and the biopolymers were still effective after five dry-wet cycles. This result is similar to the result obtained from the study by Ayeldeen et al. (M. Ayeldeen, Negm, El Sawwaf, & Gädda, 2018).

2.4.3 Mechanical test

Mechanical test is to evaluate effectiveness of dust suppressants via studying their strength behaviour. Strength behaviour is one of macro-behaviours of soil and significant factor of dust abatement. With addition of dust suppressants, some adhesion were induced, such as ionic bonds, covalent bonds, and van der Waals forces (Khatami

& O'Kelly, 2012). These active bonds bridged neighbouring soil grains in treated soil, thereby binding the grains to some aggregations. Through this process, the treated soil gained more strength in a macroscopic scale. The strength behaviour can be investigated via mechanical tests (M. K. Ayeldeen, Negm, & El Sawwaf, 2016). Given the evaluation of dust suppressant, there have three common used mechanical tests to study the improvement of strength behaviour after being treated with dust suppressants, including penetration resistance test, shear strength test, and unconfined compressive strength (UCS) test. The penetration resistance test is to determine penetration resistance of crusted surface layers, which directly reflects resistance against external erosion actions of the layers (e.g. wind and vehicular action). The resistance is usually measured by using different relevant testing equipment, such as micro-penetrometer, flat-ended cylindrical penetrometer, and modified tri-axial equipment (Chen et al., 2015; Ding et al., 2018; Maleki, Ebrahimi, Asadzadeh, & Tabrizi, 2016). It has been considered as a promising tool of the evaluation of dust suppressant used to control dust emission. The shear strength test is to determine shear strength by using direct shear equipment or tri-axial equipment. The unconfined compressive strength test is performed by using either uniaxial or tri-axial equipment. In addition, for the shear strength test and UCS test, selections of loading rate and confining pressure are crucial to capture failure characteristics during test processes.

Results obtained from previous research indicated that there has a strong correlation between the structure strength and dust control effectiveness. The study by Chen et al. (Chen et al., 2014) indicated that there exists a strong linear relation between penetration resistance and dust emissions. A relationship between these two factors has been established, $W_L=3\times10^{11} (F_p)^{-4.576}$. Herein, W_L is weight loss of treated samples and F_p is maximum penetration force. More recently, the study by Ding et al.

(Ding et al., 2018) correlated strength behaviour of treated samples to dust control performance. According to Ding et al (Ding et al., 2018), two linear relationship have been established, $W_L=1.333\times10^4(F_p)^{-3.52}$ and $W_L=8.535\times10^{-2}(q_u)^{-8.878}$. Herein, W_L is weight loss of treated samples, F_p is average penetration force, and q_u is unconfined compressive strength.

Mechanical test is a good indicator for dust suppressing performance and it has been investigated for decades. This study focused on other innovative evaluation methods and mechanical test will not be performed.

2.4.4 Wind tunnel test

Wind tunnel test is a commonly used method to directly evaluate the dust suppression effectiveness via measuring dust emission from treated soil samples. Compared to the other evaluation methods, this method is more direct to evaluate potential to generate dust. It is usually used accompanying those definite property studies (e.g. infiltration depth test, moisture retention test, and mechanical test). Unlike definite property studies, wind tunnel test is not focused on definite properties of dust suppressants instead of their dust abatement performance.

Extensive relevant research has been carried out for this purpose. Wind tunnel test is generally categorized into two types, including a wind tunnel system with a trafficked section and a wind tunnel system without a trafficked section. The former test system usually focused on wind erosion, while the other system focused on vehicular erosion. For example, Ayeldeen et al. (M. Ayeldeen et al., 2018) performed a wind tunnel test to study the efficacy of biopolymers in wind erosion suppression. In Ayeldeen's study, four biopolymers were chosen, and mass loss of treated samples was used as a dust suppression index. According to this study, it has been observed that the selected biopolymers have remarkable effect on dust abatement performance.

In addition, Epps et al. (Epps & Ehsan, 2002) used a wind tunnel system (length × width × height=450×75×100mm) with trafficked section to investigate dust control performance of two dust suppressants under vehicular action. In Epps's study, average erosion depth was measured from 15 sampling locations and results were reported as erosion index. According to Epps (Epps & Ehsan, 2002), the dust suppressants significantly reduced vehicular erosion and suppressed dust emission from the samples.

2.4.5 Microstructural analysis

Microstructural analysis is to investigate micro-structure of a mixture of soil and dust suppressants by using microscope. Scanning electron microscope (SEM) is one of common way to conduct microstructural analysis. It is achieved by using electron microscope that produces images of a sample surface with a focused beam of electrons. SEM has been utilized extensively to analyse micro-structure of a soil/dust suppressant mixture. Through microstructural analysis, a real geometry and texture of the mixture can be seen clearly. This is usually used as an auxiliary tool of dust suppressant evaluation. More specifically, by analysing the SEM images, physico-chemical reactions between the soil and dust suppressant were determined. For example, the study by Ivanov et al. (Ivanov & Chu, 2008) reported that the formation of cross-linking interpenetrating networks leads to an increase in strength within the biopolymer-treated soil. The cross-linking interpenetrating networks can be captured via SEM. Therefore, SEM analysis can be used to assess strength improvement of the soil after being treated with dust suppressants, and thus to evaluate their effectiveness of dust control. Massive research on the evaluation of dust suppressants has been conducted by SEM analysis. For example, the study by Ayeldeen et al. (M. K. Ayeldeen et al., 2016) investigated physical characteristics of biopolymer (xanthan gum and guar gum)/soil mixture via SEM analysis. From SEM images of soil/dust suppressant mixtures at various curing time, it can be seen that the biopolymer was transferred from gel state to glassy state with time, which directly reflects a change in strength of the mixture. In Ayeldeen's study, the samples for SEM analysis were prepared in a same way of mechanical tests. Chen et al. (Chen et al., 2014) investigated mixtures of biopolymer and soil via SEM analysis and evaluated dust control effectiveness of the biopolymer. From SEM images of tested samples, it can be observed that the samples treated with biopolymer have a denser structure than those treated with water, which is closely related to strength improvement of the samples. In Chen's investigation, the sample for SEM analysis were prepared in a same way of wind tunnel tests.

2.4.6 Zeta potential measurement

Zeta potential is a fundamental parameter in chemical and metallurgic engineering and it has potential to be utilized in the study of dust suppression performance. Zeta potential represents the electrical potential which developed at interfacial region between solid and liquid. It is a good indicator which directly reflects the potential to aggregate particles. It can be measured by several methods and zeta potential analyser is highly prevalent for zeta potential measurement. Although zeta potential has been extensively investigated in chemical and metallurgical engineering, no research that introduced zeta potential to study dust suppression was found in literature review. Previous studies reveal that soil particle aggregation is a positive factor in dust abatement (Bae et al., 2006). And zeta potential is a good indicator for particulate aggregation. Therefore, in this study, zeta potential measurement was selected and to investigate the potential of being utilized in dust control after treatment of eco-friendly dust suppressants. However, this method has its limitations. For instance, it is viable only when solution of dust suppressants has a mass of free electric charge.

2.4.7 Other evaluation methods

Apart from the above-mentioned evaluation methods, there have several other laboratory methods also used to evaluate the effectiveness of dust suppressants in dust control. For example, Edvardsson (Edvardsson, 2010) and Edvardsson et al. (Edvardsson & Magnusson, 2011) performed leaching tests to investigate leaching effects on dust suppressant concentration. On the other hands, some field investigations have been performed to evaluate the dust abatement effectiveness in dust control (Edvardsson & Magnusson, 2009; Karin Edvardsson, 2008; Rushing, Harrison, Tingle, Mason, & McCaffrey, 2006). In addition, some representative studies that focused on commonly used evaluation methods were summarized in Table 2.1.

Table 2.1 Summary of representative studies on the evaluation methods

Study	Dust suppressant	Application concentration	Soil	Evaluation method
(Bae et al., 2006)	PEO polymer	0.05, 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, and 1% (Wt. %)	Clay soil Specific gravity=1.7	Moisture retention test
(Sharma, Phanikumar, & Rao, 2008)	Calcium chloride and lime	0.5, 1, 1.5, and 2% (w/w)	USCS Classification: CH; OMC=24%; MDD=1.63g/cm^3	Unconfined compressive strength (UCS) California bearing ratio (CBR)
(Das, Mahamaya, Panda, & Swain, 2015)	Xanthan gum (XG) Guar gum (GG)	XG: 1, 2, and 3% GG: 0.5, 1, and 2% (Wt. %)	USCS Classification: SM Specific gravity=2.21	UCS Modified proctor compaction test
(Khatami & O'Kelly, 2012)	Agar Modified starches	0.3 to 1.2% (w/w)	Sandy soil; Specific gravity=2.66;	UCS Unconsolidated-undrained tri-axial compression test

(I. Chang & Cho)	Agar gum Gellan gum Xanthan gum	1-5%. Interval: 1% (w/w)	USCS Classification: SP	Direct shear test Scanning electron microscope (SEM)
(M. K. Ayeldeen et al., 2016)	Xanthan gum Guar gum Starpol 136	0.25, 0.5, 1, and 2% (Wt. %)	USCS Classification: SP (Gs=2.70); USCS Classification: CH (Gs=2.73)	Modified proctor compaction test Direct shear test UCS Falling head permeability test
(Santoni et al., 2002)	Lignosulfonates (LS) Polymers (PL) Enzymes (EZ)	LS: 2.9, 5, AND 8%; PL:0.1 to 5%; EZ: 0.1 and 0.2%. (w/w)	Silty sand USCS Classification: SM	UCS
(I. Chang, Im, Prasidhi, & Cho, 2015)	Xanthan gum	1% (w/w)	USCS classification SP SP-SM, and CL	SEM, UCS, and Long-term durability test
(Chen, Ding, Ramey, Lee, & Zhang, 2016)	Xanthan gum	0.3, 0.5, and 0.8% (Wt. %)	USCS Classification: SM	Infiltration depth test Penetration resistance test
(Chen, Zhang, & Budhu, 2013)	Xanthan gum Guar gum	XG: 1, 2, and 3% GG: 0.5, 1, and 2% (Wt. %)	USCS Classification: SM	Penetration resistance test SEM
(Chen et al., 2014)	Xanthan gum Guar gum	0.6, 1, and 1.6% (Wt. %)	USCS Classification: SM	Moisture retention test Wind tunnel test SEM

2.5 Eco-friendly dust suppressants

Chemical dust suppressants, also named soil stabilizers or dust palliatives, have been studied in recent decades, and they have been used in many fields, such as unpaved road maintenance, interim airfield construction, mine ecological reclamation, dust control in soil sands region, and soil desertification prevention (Army & Force, 2005; I. Chang, Prasidhi, Im, Shin, & Cho, 2015; Mulholland, 1972; Succarieh, 1992; X. Wang et al., 2015; Xu, Ding, Kuruppu, Zhou, & Biswas, 2017). In previous studies, they were classified into various categories (Alzubaidi, 1999; Amato, Querol, Johansson, Nagl, & Alastuey, 2010). In this thesis, the dust suppressants were categorized according to their chemical constituents and physical properties: water and surfactant, chloride salt (i.e. calcium chloride and magnesium chloride), clay additive (i.e. enzyme), polymer (i.e. lignosulfonate), and biopolymer. Moreover, they were used to abate dust emission through various dust suppression mechanisms. For instance, chloride salt was used to control dust emission by increasing moisture content within treated soil. Lignosulfonate was usually used to induce more bonds and increase strength behaviour with soil matrix, thereby reducing potential to generate dust from treated soil. On the other hand, their dust control performance generally affected by several factors, such as fine content, plasticity index, environmental conditions (Epps & Ehsan, 2002; Lindh, 1981). In other words, dust suppressants attain desirable dust suppression effectiveness only when they are used in proper context. Dust abatement mechanisms and proper soil parameters were summarized in Table 2.2.

Table 2.2 Representative dust suppressants and their dust abatement mechanisms

Dust suppressant	Mechanism	Other Attributes	Optimal Soil Parameters	
			Fine content (%)	Plasticity Index
Water	Capillary tension	Readily available		
Surfactant	Capillary tension			
Chloride salt	Ambient moisture absorption	Moisture absorption depends on ambient conditions (e.g. atmospheric temperature & humidity)	10-20	>8
Lignosulfonate	Cement/moisture retention	Most effective in dry conditions	20-30	>8
Polymers	Cement/moisture retention	Bio-degradation, eco-friendly	5-20	<3

It has been reviewed that there are >60 kinds of chemical dust suppressants used to address the problems of dust emission (Birst & Hough, 1999). The investigation showed that chloride salt was the most commonly suppressant and it approximately accounted for 64% of the dust suppressants in total (shown in Figure 2.3). This result is in accordance with the study by Han (Han, 1992), which reported that the estimated usage of inorganic chemicals (mainly refers to chloride salt) make up 75-80% of all dust suppressants.

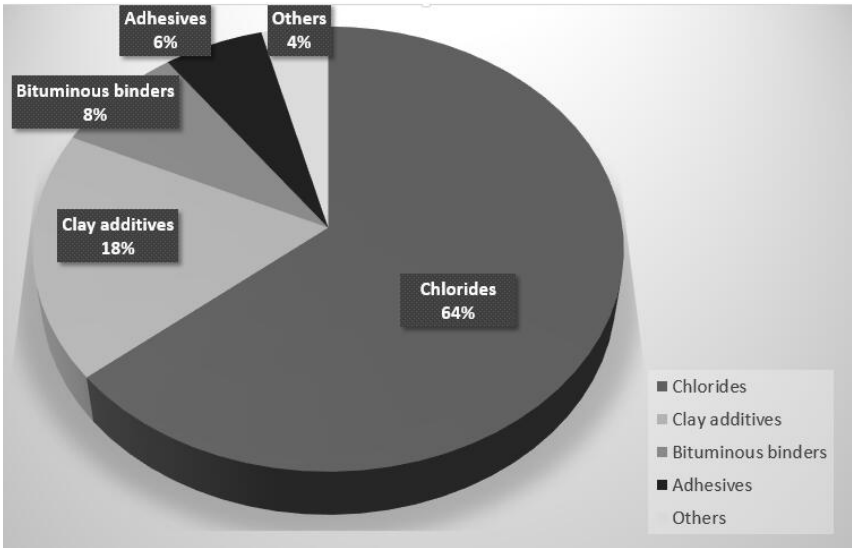

Figure 2.3 Percentage contribution of different dust suppressants (Birst & Hough, 1999)

As discussed above, the categories of dust suppressants include water and surfactant, chloride salt, clay additive, organic non-bituminous binder, and biopolymer. A discussion about their basic description, favourable properties of dust control, or limitations were given in detail.

2.5.1 Water and surfactant

Water spraying has been regards as the easiest way to temporarily control dust emission by improving moisture content within soil. Previous studies showed that higher moisture content is a favourable to reduce dust generation from soil (B. Denby et al., 2013; B. R. Denby et al., 2013). Moisture in soil usually exists in a form of films. After water spraying, the films form onto soil grain surfaces. Since the formation of films, the grains tend to contact under adhesive forces and the involved grains are aggregated into aggregations due to surface tension. This keeps the soil grains bound within ground surfaces, thereby preventing them from dislodging from the surfaces into the atmosphere in a form of road dust (Alzubaidi, 1999; Epps & Ehsan, 2002). In addition to the aggregation, water spraying makes the soil grains heavier, which results in a reduction potential to be dislodged from ground surfaces by wind and vehicular action (Chen et al., 2014). These two actions induced by water spraying suppress dust emissions for a short period of time. The active life time of water spraying in dust control largely depends on local traffic conditions and environmental conditions (e.g. wind speed, atmospheric humidity and temperature). In general, the active life time ranges from 30 minutes to several hours (Alzubaidi, 1999). Relatively frequent reapplication required a continued operating of water carts, which leads to an unduly high operation cost. Moreover, watering gives rise to several detrimental side-effect, such as erosion, slipperiness, and adhesion of mud to wheels. Considering these factors, periodical water spraying is not a cost-effective alternative for dust abatement for a long-term benefits, especially in water-shortage areas (Neuman et al., 2009; Thompson & Visser, 2007).

Surfactant, also named surface active agent, is an organic compound that effectively reduces surface tension of water molecules to air. Due to this property, it is usually added into detergent as a dispersing agent (Furse, 2010; Rosen & Kunjappu, 2012). In terms of dust control, it has potential to be used as a dust suppressant. In general, it can be categorized into two types according to its electrical property in aqueous solution, anionic and cationic surfactant. A reduction in the surface tension leads to higher infiltration depth into soil. Therefore, it is usually added into solutions of other dust suppressants with a view to achieving better dust abatement performance (Foley et al., 1996). Liquid transportation is subjected to the surface tension that regarded as a negative factor to wet more grains in soil. By addition of surfactants, liquid penetrates more easily, resulting in an increase in moisture available in soil. Consequently, a greater number of soil grains are wetted, which brings better dust suppression performance (Tannant & Regensburg, 2010; Thompson & Visser, 2007). The study of Wu (Wu, 2000) indicated that the penetration effect of $CaCl_2$ aqueous solution improved by 27-47% after the addition of surfactants. Due to the improvement, the dust suppressant is more effective in dust abatement performance.

2.5.2 Chloride salt

Calcium Chloride

The study of chloride salt used to control dust started in the 1930s (Harkins & Gilbert, 1926). It is a significant inorganic compound with very good solubility in polar solvents. Calcium chloride, a typical chloride salt, is commonly used for road dust control. It is a crystalline salt with good solubility in water at atmospheric temperature. It is achieved through either by-product of synthetic processes or deposits of natural brine. It is available in several different forms, including colourless liquid, white flakes, and white pellets (Kirchner & Gall, 1991).

In previous studies, hygroscopic and deliquescent have been considered as two important properties of chloride salt. The purpose of dust control is achieved by these two properties (Bolander & Yamada, 1999). Since the hygroscopic and deliquescent, $CaCl_2$ has a strong attraction for atmospheric moisture and thus absorb moisture from the atmosphere. This process leads to an increase in moisture content within soil. The absorbed moisture wets a greater number of soil grains, which not only makes the grains heavier but gains more inter-particle cohesion through capillary tension in soil. Therefore, the contributory properties have notable effects on dust abatement effectiveness (Chen et al., 2014). In addition to these properties, calcium chloride has other beneficial properties in dust control. For example, due to the presence of calcium chloride, surface tension of water molecules increased significantly. This property brings a substantial increase in inter-particle adhesive forces in soil and thus improve dust abatement performance (Alzubaidi, 1999; Harkins & Gilbert, 1926). Moreover, vapour pressure of aqueous solutions reduced after addition of calcium chloride. High vapour pressure brings the aqueous solutions greater potential to lose moisture. Therefore, this characteristic is also effective in reducing dust generation (Conde, 2004). Additionally, there have a mass of cations (calcium ions) in calcium chloride solution. These cations are capable of flocculating anions through electrostatic forces. For example, the calcium ions flocculates clay particles (negatively charged) within soil. Consequently, the flocculation leads to more aggregations in soil and thus reduces the potential of dust generation (Sharma et al., 2008). On the contrary, calcium chloride has some drawbacks when used as dust suppressants. Its main disadvantages include corrosive action, slipperiness, and the loss of effectiveness arising from leaching and crystallization. Its corrosion action causes serious damages to mining-related vehicles or other mining equipment when used control haul road dust. In addition, the application of calcium chloride possibly results in a lack of skid resistance on treated road surfaces, particularly on wet conditions. Therefore, this possess a safety hazard to haul road transportation at surface mining operations (Han, 1992; Rushing & Tingle). Under a poor drainage condition, calcium chloride is prone to leach out (downward transportation) in occurrence of rainfall (Rushing & Tingle). This leads to a reduction in calcium chloride concentration within treated road surface material. Furthermore, calcium chloride rises to road surfaces on dry conditions and crystallize due to upward capillary action (Succarieh, 1992). Consequently, this fraction of crystallized calcium chloride loses its effectiveness in dust control.

The dust control effectiveness of calcium chloride is affected ambient condition and its physico-chemical properties. For example, calcium chloride is sensitive to ambient conditions (e.g. atmospheric temperature and humidity). At a temperature of

25°C, it absorbs moisture from the atmosphere when humidity exceeds 29%. Also, the moisture absorption increases with a higher atmospheric humidity (Epps & Ehsan, 2002; Han, 1992). Therefore, the ambient conditions reduce the potential to be used in semi-arid or arid areas. In these areas, to achieve a desirable dust control performance, it is imperative to periodically recharge water into calcium chloride-treated road surface material (Thompson & Visser, 2007). On the other hand, better penetration ability brings calcium chloride greater dust suppression effectiveness. Infiltration depth is a good indicator of penetration ability. Previous research indicated that infiltration depth largely depends on its application concentration and soil properties (i.e. particle size distribution and fine content) (Quirk & Schofield, 1955; Sharma et al., 2008; Wu, 2000).

Magnesium Chloride

Magnesium chloride, a colourless crystalline salt, has also been commonly used as a dust suppressant in road dust control. In general, it has similar physico-chemical properties with calcium chloride. For instance, both magnesium chloride and calcium chloride have a very good solubility in water or other polar solvents. The purpose of dust abatement is achieved by their beneficial properties (deliquescent and hygroscopic). Both of them improve the dust control effectiveness by greater surface tension of water molecules and lower vapour pressure (Alzubaidi, 1999; Epps & Ehsan, 2002). In addition, they have positive-charged ions in their aqueous solution and these ions are effective in reducing repulsion between neighbouring soil grains (Epps & Ehsan, 2002).

On the other hand, there are several differences between these two chloride salts. Although both of them have a good H_2O solubility, the solubility of magnesium chloride is greater than that of calcium chloride. This is because H_2O solubility decreases with increasing ionic radius (radius of Mg^{2+}:0.78unit, radius of Ca^{2+}:1.06unit). This difference brings magnesium a high potential to leach (Epps & Ehsan, 2002; Rushing & Tingle). In terms of surface tension enhancement, magnesium chloride is more effective in increasing the tension compared to calcium chloride. Greater surface tension is a negative factor of penetration ability. Therefore, calcium chloride has greater infiltration depth into soil. Conversely, greater surface tension is beneficial to develop inter-particle adhesive forces. Thus, magnesium chloride gains more adhesive forces and has a stronger strength behaviour (Epps & Ehsan, 2002; Han, 1992).

2.5.3 Polymer

Lignosulfonates

Lignosulfonate, also named lignin sulfonate or sulphite lignin, is a polyelectrolyte polymer that has a good water solubility. There has a mass of anions in its aqueous solution. It is a principal industrial lignin, which is achieved as a by-product through chemical pulping processes. Wood is principal raw material of wood pulp production. In general, lignin accounts for 15-25% of dry weight in wood. It is a principle component of cell wall. Also, in the presence of lignin, other components (e.g. cellulose and hemicellulose) are adhered together. During the pulping process, the lignin existing in wood become water-soluble through sulfonation. Due to the dissolution of the lignin, original cell structure is destroyed, and cellulose fibres separate from sulphite lignin (lignosulfonate). Consequently, the lignosulfonate is achieved by different methods (e.g. Howard process) from sulfonation solutions. In addition, since different pulping methods utilized during the pulping process, several different types of lignosulfonates are achieved, such as calcium lignosulfonate, magnesium lignosulfonate, and ammonium lignosulfonate (Alzubaidi, 1999; Dong, Wang, & Zhao, 2008; Gargulak, Lebo, & McNally, 2001).

In response to environmental concerns, its significance has been rising in recent years. For instance, lignosulfonate has been extensively studied and used to control dust emission as an eco-friendly dust suppressant (Gargulak et al., 2001). It is a natural binder and thus has the potential to work as a dust suppressant in dust control. By adding lignosulfonate into soil, soil grains are cemented together within the mixture of soil/lignosulfonate. Although these cemented grains are still prone to breakdown due to external actions (wind and vehicular erosion), they have more potential to resist the actions compared to uncemented ones. Therefore, the lignosulfonate-treated soil is less potential to generate dust from ground surfaces (Lohnes & Coree, 2002). Moreover, a crust is formed onto surface layers after dehydration of lignosulfonate. The crust has a strong structure strength and thus is effective in resisting external erosion (Dong et al., 2008). Apart from the cementation, lignosulfonate also has other beneficial properties of dust control. For example, it has potential to be used as a clay dispersant. The addition of lignosulfonate leads to an increase in clay density under a same compaction condition, thereby reducing void volume in soil and increasing its structure strength (Foley et al., 1996; Han, 1992; Lohnes & Coree, 2002). It is known from the previous studies that lignosulfonate has a good biodegradation and no environmental impacts (Dong et al., 2008; Gargulak et al., 2001).

Conversely, there have several factors that adversely affect its dust control effectiveness. For example, lignosulfonate has good solubility in water. In the presence of rainfall, it tends to leach away from ground surfaces. Consequently, its concentration significantly reduced within surface layer, which leads to a reduction in dust abatement effectiveness (Thompson & Visser, 2007). In addition, the application of lignosulfonate brings road surfaces an increase in slipperiness, thereby possessing a serious safety hazard to transportation. Moreover, lignosulfonates is corrosive to some metal and their alloys (e.g. aluminium) (Han, 1992).

2.5.4 Biopolymer

Xanthan gum and Guar gum

Biopolymer is a particular polymer that is achieved through microbial activities. It usually contains a mass of monomeric units and these units bond together through covalence bonds. Biopolymer is commonly classified into three main types according to the monomeric unit of biopolymer structure, namely polynucleotides, polypeptides, and polysaccharides. Polysaccharides are effective in improving soil physico-chemical properties, and thus have the potential to be used in dust abatement. In recent years, polysaccharides have been extensively studied with a view to controlling dust emission (Chen et al., 2014; Das et al., 2015). Xanthan gum and guar gum are commonly used polysaccharides in dust control. They have very good bio-degradation and thus they are used to abate dust emission without environmental impacts.

Xanthan gum, an anionic polysaccharide, has a long-chain polymeric structure. The linear polymeric structure consists of a mass of saccharide units. In addition, it has a very good solubility in water at atmospheric temperature. It is commercially available in a form of off-white powder. It is widely used in food additive, oil recovery, and agriculture products for several beneficial properties, such as remarkable thickening, moisture retention property, and good stability to acid and salt (Rosalam & England, 2006; Z. Wang, Wu, Zhu, & Zhan, 2017). Moreover, it is particular effective in increasing viscosity in aqueous solutions (Rosalam & England, 2006). The study by Chen et al (Chen et al., 2014) suggested that xanthan gum has a number of hydroxyl groups that create hydrogen bonds with soil/xanthan gum mixture.

Consequently, the mixture gains more cohesion and thus its structure strength substantially improved. For example, the study by Karimi (Karimi, 1999) revealed that shear strength of Bonnie silt increases by 30% after being treated with xanthan gum solution at a concentration of 2%. On the other hand, xanthan gum has a good stability over a wide range of PH and temperature (Kavazanjian Jr, Iglesias, & Karatas, 2009).

Guar gum, a galactomannan polysaccharide, is achieved from ground endosperm of guar beans. Since both of guar gum and xanthan gum have a linear polymeric structure, they usually have several similar properties. For instance, both of them have a good water solubility and adhesion. Moreover, their viscosity of aqueous solutions increases with higher application concentrations. This also leads to a reduction in infiltration depth (Chen et al., 2015). On the other hand, guar gum has a good compatibility with salts (Q. Wang, Ellis, & Ross-Murphy, 2000). Therefore, mixing with salts (i.e. chloride salts) appears to be feasible when guar gum is used in dust control. The study by Etemadi et al. (Etemadi, Petrisor, Kim, Wan, & Yen, 2003) indicated that the treatment of guar gum significantly improves some soil properties, such as reducing hydraulic permeability, increasing shear strength, and inducing metal uptake potential.

2.5.5 Clay additive

Enzymes

Enzyme, a complex protein-based compound, has been commonly used in road dust control. It is a crop-plant derivation and achieved as a by-product from fermentation processes. In general, enzyme contains a protein chain with metal ions and it has a molecular weight of 35,000 (Scholen, 1995). It usually works as an organic catalyst that speeds up a chemical reaction without its consumption (Velasquez, Marasteanu, & Hozalski, 2006).

In general, when mixed with soil, enzyme functions in several ways for dust control. According to Scholen (Scholen, 1995), when enzyme is used to treat soil materials, it assists with alignment of clay particles, which prevents the clay from expanding in the presence of water. Consequently, the enzyme-treated soil attains greater density. An increase in the density results in a reduction of dust emissions. This is because the denser road surface material generally has little void volume. The reduction in void volume results in greater inter-particle friction. As a result, more energy input is necessary to break original structure. Consequently, the enzyme-treated soil has less potential to dislodge soil particle into the atmosphere (Foley et al., 1996). In addition, the study by Velasquez et al. (Velasquez et al., 2006) indicated that enzyme is more capable of reducing surface tension than a normal surfactant (sodium dodecyl sulfate). This property is beneficial to reach more densely compacted. The similar result is obtained from the study of Marasteanu et al. (Marasteanu, Hozalski, Clyne, & Velasquez, 2005). Moreover, the addition of enzyme leads to an improvement of bonding capacity. For instance, there have a mass of ionic bonds within enzyme-treated soil. These bonds result in an improvement of structure strength in soil. Therefore, the treated soil has more potential to resist external erosion (wind and vehicular action) and reduce dust generation from it (Marasteanu et al., 2005). On the other hand, enzyme effectively achieves the purpose of dust control in the soil that has a wide range of fine content. The study by Marasteanu et al. (Marasteanu et al., 2005) showed that enzyme is effective for the soil with a fine content of 8-11%. Also, the study by Birst et al. (Birst & Hough, 1999) indicated that enzyme is effective for the soil that has a fine content of 18-30%.

2.6 Summary and comments

The airborne haul road dust is a major constituent of airborne dust at surface mining operations, which accounts for 70-90% of total airborne dust emissions considering various mining sites. The airborne haul road dust has a wide range of particle size distribution, which largely depends on the size distribution of road surface materials. In addition, the haul road dust has serious impacts on surface mining sites and the surrounding environment, such as occupational safety and health and maintenance of mining equipment.

The dust produced when the separation forces reach a certain minimum value (threshold value) that is sufficient to overcome the adhesive forces between soil grains. Moreover, the previous research on road dust generation indicated that there have three categories of influencing factors affect the dust generation, including factors specific to roads, factors specific to geographical area, and factors related to vehicular action on the roads.

In order to minimize the impacts of the dust, a variety of chemical dust suppressants have been studied and used. Due to environmental concerns, the dust suppressants should not be harmful to the environment. Several common types of eco-friendly dust suppressants, chloride salt, polymer, biopolymer, and clay additive, were reviewed in this thesis. They are effective in reducing dust emission without causing any detrimental impacts to the natural environment.

The physico-chemical properties of soil were improved after being treated with the dust suppressants, thereby enhancing the dust abatement effectiveness. According to the improvement of physico-chemical properties, some methods can be used to evaluate the effectiveness of the dust suppressants, such as infiltration depth test, moisture retention test, mechanical test, wind tunnel test, and microstructural analysis.

In addition, the effectiveness of the dust suppressants affected by several factors, such as soil properties and environmental conditions. Therefore, to attain a desirable dust control performance, the dust suppressant should be used in a proper context.

Compared to other dust suppressants, calcium lignosulfonate and xanthan gum have more potential to be used to abate dust emission from haul roads. For instance, they are more effective in controlling dust emission, especially in arid or semi-arid areas. Both calcium lignosulfonate and xanthan gum can form a thin crust on treated road surfaces, which leads to a substantial improvement of dust control effectiveness. More importantly, they have excellent bio-degradation, which gives rise to least impact to the environment. However, as emerging dust suppressants, they have been less investigated in previous studies and they need to be more extensively studied. For instance, less research that focused on long-term soil desiccation has been found in literature review. The soil desiccation is significant for dust emission from haul roads. Also, no research was done to study physic-chemical property by zeta potential analyser. In this study, these two dust suppressants were selected and evaluated as more eco-friendly alternative to address the problem of haul road dust.

Chapter 3 Experimental and numerical study of effectiveness of xanthan gum used to abate airborne haul road dust

3.1 Introduction

Airborne dust is one of the primary sources for environmental pollution. In surface mining, a great deal of airborne dust is produced from haul roads during transportation of mine product and waste. In previous studies, a dumper can produce 0.25–0.70kg of airborne dust per kilometre (Singh, 1997). The airborne haul road dust (AHD) is a dominant portion of airborne dust in surface mining, which represents more than 80% of the total airborne dust generation (Amponsah-Dacosta, 2015; Mandal et al., 2012). The AHD has a number of serious impacts on worker's health and safety. Relevant studies showed that the dust has potential to increase the possibility of traffic incident by obstructing the visibility of drivers in surface mining (Thompson & Visser, 2007). In addition, long-term exposure to heavy airborne dust causes occupational respiratory diseases within mineworkers (M. Ross & J. Murray, 2004).

Previous studies revealed that the generation of AHD is systematically affected by many factors, such as atmospheric temperature, atmospheric humidity, fine content, moisture content, wind velocity, and vehicular action (Ding et al., 2018; Edvardsson & Magnusson, 2009; Omane, Liu, & Pourrahimian, 2018). Also, Thenoux el al. (Thenoux, Bellolio, & Halles, 2007) categorized these factors into three main groups, namely factors specific to the road (e.g. moisture content, fine content, and compaction), factors specific to the geographical area (e.g. atmospheric temperature, humidity, and evaporation), and factors specific to external actions (e.g. vehicular action and wind action).

To abate AHD emission, the only option of dust suppression is to optimize road surface material (e.g. moisture content, fine content, and particle size distribution). Generally, most haul road surfaces are not designed, namely without optimization of fine content and particle size distribution in practice. Therefore, the more viable method is to control moisture content of road surface material via water spraying or chemical-based solution spraying. Water spraying is commonly used to mitigate AHD emission as a temporal method (Y.-M. Chang et al., 2003). However, due to high evaporation rates this normally required more frequent re-spraying, which is less cost-effective, especially in water-shortage areas (Carter, 1995; Neuman et al., 2009). Thus, chemical-based solution spraying is more preferred for its longer effective time. Chemical-based dust suppressants have been investigated to abate airborne dust emission for decades (Addo & Sanders, 1995; Sanders & Addo, 2000). In response to environmental concerns, the research interest of biological materials has been raised in recent years. Many "greener" and environmentally-friendly materials have been investigated to replace the traditional suppressants.

This chapter aims to conduct a laboratory-based study on the effectiveness of xanthan gum used to abate AHD emission. Two main properties of xanthan gum, infiltration ability and moisture retention capacity, are investigated experimentally. Treatment of xanthan gum leads to substantial changes in infiltration depth or moisture retention. After that, the results from the experimentations were analysed via a mathematical model which produces an estimation of dust emission rates. Finally, an optimal concentration of xanthan gum was determined to achieve a desirable dust suppression performance.

3.2 Materials and methods

3.2.1 Source and characteristics of soil

Grain size and main minerals of the studied soil are significant factors, which largely affect dust suppression performance. Previous studies have been shown that a dust suppressant generally provides various suppressing performance under different soil conditions. Therefore, to better determine the dust suppressant effectiveness and provide accurate experimental data for future researchers, soil characterization was performed before experimental programs.

Soil was sampled from a local mining site in Kalgoorlie, Western Australia, Australia. Its natural moisture content ranges from 7.4 to 9.2%, which was tested by using oven dry method. Particle size distribution analysis was done. Figure 3.1 indicated the particle size distribution of the tested soil. Over 50% of coarse fraction passes No. 4 sieve. The coefficient of uniformity (C_u) is more than 6.0 and the coefficient of curvature (C_C) is more than 1.0 and less than 3.0. This soil is classified as well-graded sand (SW). In addition, the soil was characterized by X-ray diffraction (XRD) measurements and the X-ray diffraction pattern was shown in Figure 3.2. The main minerals present in the soil are quartz (SiO_2), kaolinite ($Al_2Si_2O_5(OH)_4$), and global Amorphous, accounting for 45.5%, 39.8%, and 14.7%, respectively.

In order to determine the fundamental properties of the selected soil, all relevant tests were performed according the following testing standards:

- Soil moisture content tests (AS 1289.2.1-Method 2.1.1)
- Particle size distribution (AS 1289.3.6.1)
- Classification of soils (ASTM 2487-17-Unified Soil Classification System)

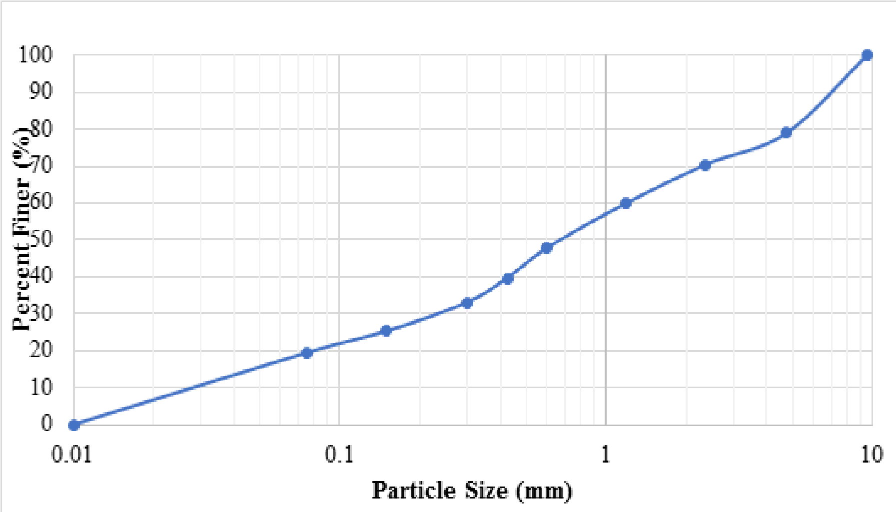

Figure 3.1 Particle size distribution curve of tested soil

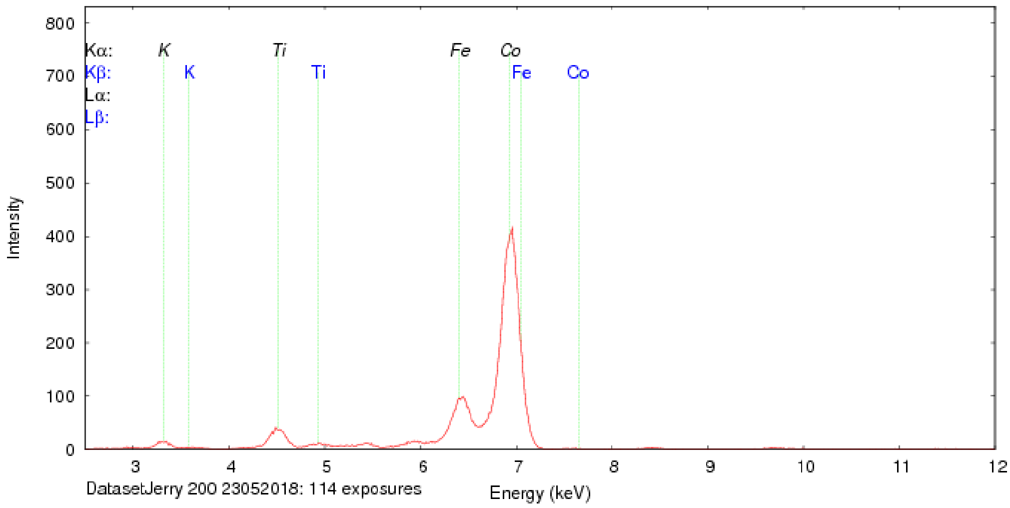

Figure 3.2 X-ray diffraction pattern

3.2.2 Polymer selection and aqueous solution preparation

Xanthan gum (XG), a natural microbial polysaccharide, has been studied as an environmentally-friendly dust suppressant. It is produced from glucose by microbial process and its molecular weight ranges from $2x10^6$ to $20x10^6$ Da (Palaniraj & Jayaraman, 2011). Figure 3.3 shows the structure unit of xanthan gum. It is commonly used in food industry, oil recovery, and agriculture products for its remarkable thickening, moisture retention property, and good stability to acid and salt (Rosalam & England, 2006; Z. Wang et al., 2017). In addition, it has good solubility in water and its aqueous solution at low concentrations has high viscosity yield (600-2,000 ppm) (Rosalam & England, 2006). Xanthan gum is commercially available. Also, it can form a thin crust on treated road surfaces after soil desiccation, which gives rise to less potential to be break due to wind and traffic action. Thus, the formation leads to a substantial improvement of dust suppression performance. More importantly, it has excellent bio-degradation, which has least impact to the environment compared to other types of dust suppressants. Therefore, it has more potential to be used to control haul road dust. In this study, it was purchased in the form of beige powder from Sigma-Aldrich Corporation, Australia.

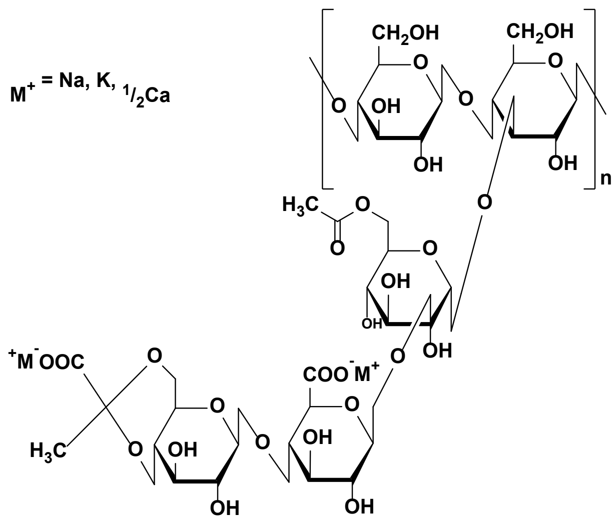

Figure 3.3 Molecular structure of xanthan gum (Garcıa-Ochoa, Santos, Casas, & Gomez, 2000)

The XG solutions were prepared using a volumetric flask. First, a precisely weighed XG powder was added to the beaker containing an appropriate amount of deionized (DI) water. To prevent clumping, the XG powder was slowly added into beaker and the beaker was placed onto a magnetic stirrer plate (rotate speed: 30 rpm). Next, the solution was transferred to the volumetric flask. Finally, the stopper-sealed flask was shaken to achieve a homogeneous solution.

3.2.3 Infiltration depth test

Infiltration depth directly reflects the infiltration ability of the XG aqueous solution in soil samples. Relevant studies suggested that infiltration depth is one of the main parameters that affects the effectiveness of a dust suppressant in dust control. Sufficient infiltration depth has more potential to resist erosion of surface materials (e.g. traffic and wind action), prevent leaching, and induce cohesion between soil particles (Bolander & Yamada, 1999; Copeland, Eisele, Chesney, & Kawatra, 2008). Also, they suggested an infiltration depth should reach 10-20mm with a view to control road dust.

The samples for infiltration depth tests were prepared by using a 70×94×135-mm (internal diameter × external diameter × height) steel cylinder mould. The laboratory study of Eisazadeh et al. (Eisazadeh, Kassim, & Nur, 2012) revealed that oven drying can significantly change the compaction properties of the tested soil. In order to prevent this effect, the soil was air-dried under ambient conditions. First, air-dried soil was mixed with DI water to reach 12% moisture content. After that, the mixture was then compacted into the mould. During the compaction, a 2.5kg top-load was slight applied onto the top of the specimen and a vibration table was employed for uniform compaction degree. Finally, the resulting cylindrical samples were extruded from the mould with care. Each sample contained 300g of wet soils with 50mm height approximately.

During the test process, the prepared samples were cured under ambient conditions for 7 days. After that, the XG solution was evenly sprayed onto the top surface of the sample at various concentrations. Then, the sample was cut vertical into two even pieces, which is shown in Figure 3.4 (a). The infiltration depth was measured from its section, which is illustrated in Figure 3.4 (b). In this study, the concentration of XG solution was selected from 2 to 8g/L at 2g/L interval. Untreated samples (deionized water) was also tested as a control. Three replicates were prepared for each concentration.

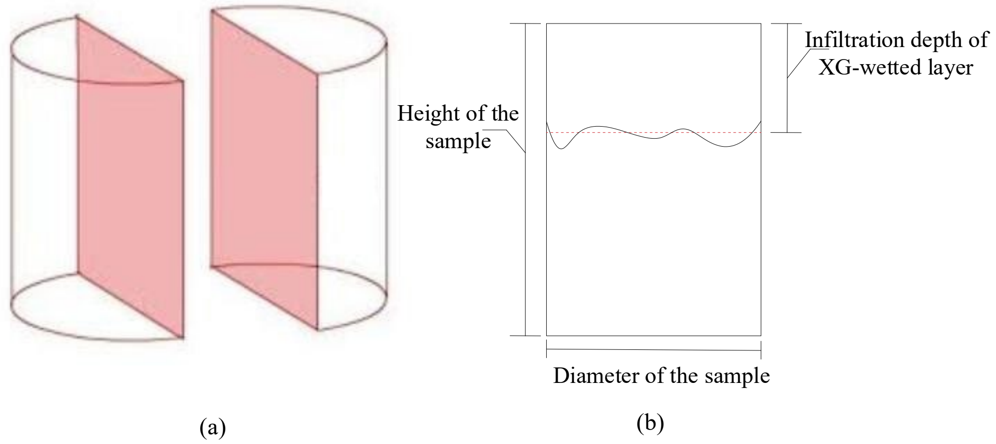

Figure 3.4 Schematic diagram of infiltration depth tests

3.2.4 Moisture retention test

Moisture content capacity is one of the most fundamental properties of soils. The moisture retention test reflects the improvement of moisture retention capacity of soil samples after being treated with xanthan gum. Previous studies of dust control indicate that dust generation is closely related to moisture retention capacity. Better moisture retention capacity results in a reduction in the moisture loss rate of soil, thereby reducing the potential to generate dust (Bae et al., 2006; Chen et al., 2014; Xu et al., 2017). In this study, the moisture content curve of treated sample was determined from the experimentation. According to the curve, the average moisture content was calculated by calculus.

The samples of moisture retention tests were prepared by using a 22×145-mm (internal diameter × height) glass tube. First, soil was mixed with XG solution before putting into the tube. The mixture was transferred into the tube and the tube was sealed immediately using cling wrap. After that, the samples were left to hydrate for 24 hours under ambient temperature and humidity. Then, the tubes were unwrapped and weighed using an analytical balance. Finally, the prepared samples were waited and tested in an incubator which was set at temperature of 20℃ and 40% relative humidity. The weight of the samples was measured at 24-hour intervals for 900h. In this study, the concentration of XG solution was selected from 2 to 8% at 2% interval. Untreated samples (deionized water) was also tested as a control. Three replicates were prepared for each concentration.

3.3 Results and discussions

The results of infiltration depth tests are shown in Figure 3.5. It is observed that there is a continuous decrease in the infiltration depth with increasing the XG concentration. The reason for this trend is possible the changes in viscosity with increasing XG concentration (Xue & Sethi, 2012). According to the results, with increase of XG concentration from 0 to 8g/L the average infiltration depth decreases from 20.86 to 11.74mm. The result is similar to the result from the study of Chen et al. (Chen et al., 2015) on silty sand stabilization by using xanthan gum. In their study the same trend has been revealed. In addition, the infiltration depth in this study is slight smaller than that in the study conducted by Chen et al. (Chen et al., 2015). There are two possible reasons for this discrepancy. One reason is the treated soil in these two studies have different particle size distributions. The other reason is the compaction degree of the prepared samples are different. In this study, a 2.5kg top-load and a vibration table were employed to achieve a desirable compaction. In Chen's study, there is no compaction process during the sample preparation. The statistical data of infiltration depth tests was summarized in Table 3.1.

Table 3.1 N total, mean, and standard deviation (SD) of measured infiltration depth for various concentrations

Concentration (g/L)	N total	Mean	Standard deviation (SD)
0	3	20.86	1.1179
2	3	18.46	0.9361
4	3	15.31	1.2115
6	3	13.86	1.3372
8	3	11.74	0.8031

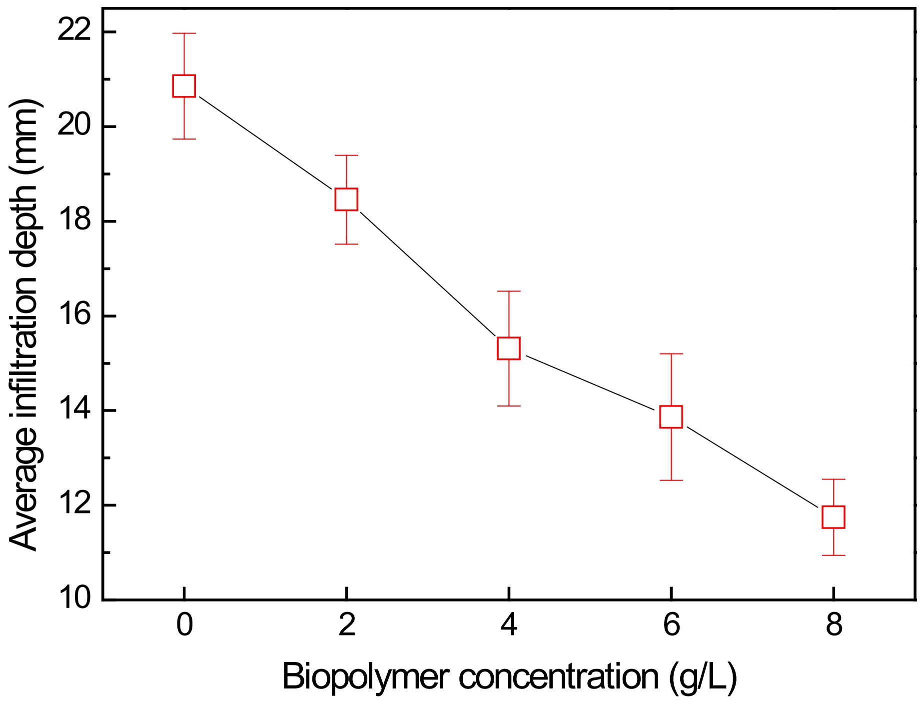

Figure 3.5 Infiltration depth test results

The plots of moisture content versus time are shown in Figure 3.7 for various XG aqueous concentrations. The results reveal that XG-treated soil samples lost moisture exponentially. Figure 3.6 represents the moisture loss pattern during a desiccation (moisture loss) period. Where m' represents average moisture content during soil desiccation; m_{ti} represents the moisture content at t_i time (initial time); and m_{tf} represents the moisture content at t_f time (final time). According to the pattern, fitting equations were determined from the plots by data fitting and the natural logarithm ($\ln(Q_t)$) of moisture quantity (Q) and time (t) were summarized in Table 3.2. The lowest slope of the linear equations is -0.0013g/h obtained at a XG concentration of 6g/L and the highest slope is -0.0017g/h. The slope of DI water is -0.0024g/h. It is found that the XG-treated samples lose moisture more slowly than DI-treated samples (control) and the DI-treated sample lose more moisture than the 8g/L-treated sample by 58.3% per hour. This result imply that moisture retention capacity of XG-treated samples has been significantly enhanced and the XG concentration of 8 g/L shows the best moisture retention capacity in this observation. In addition, it is observed that the rate constants of XG-treated samples firstly slight increase and then decrease with increasing XG concentrations. The findings are similar to the study of Inyang et al. (Inyang et al., 2012). In Inyang's study, the Kaolinite was selected to be treated with sodium carboxymethyl cellulose (CMC) and same trend has been revealed. However, the moisture loss in unit time of Inyang's study is more than that of current observation. The differences in test conditions and materials possibly result in the discrepancy.

Table 3.2 The linear equations of cumulative moisture loss (ln (Qt)) and rate constants

XG concentration (g/L)	**Linear equation**	**R^2**	**Rate constant** (g/h)
DI water	$\ln(Qt) = -0.0024t + 4.2641$	0.9920	0.0024
2	$\ln(Qt) = -0.0016t + 4.5097$	0.9918	0.0016
4	$\ln(Qt) = -0.0017t + 4.4973$	0.9988	0.0017
6	$\ln(Qt) = -0.0013t + 4.4237$	0.9925	0.0013
8	$\ln(Qt) = -0.0010t + 4.3494$	0.9841	0.0010

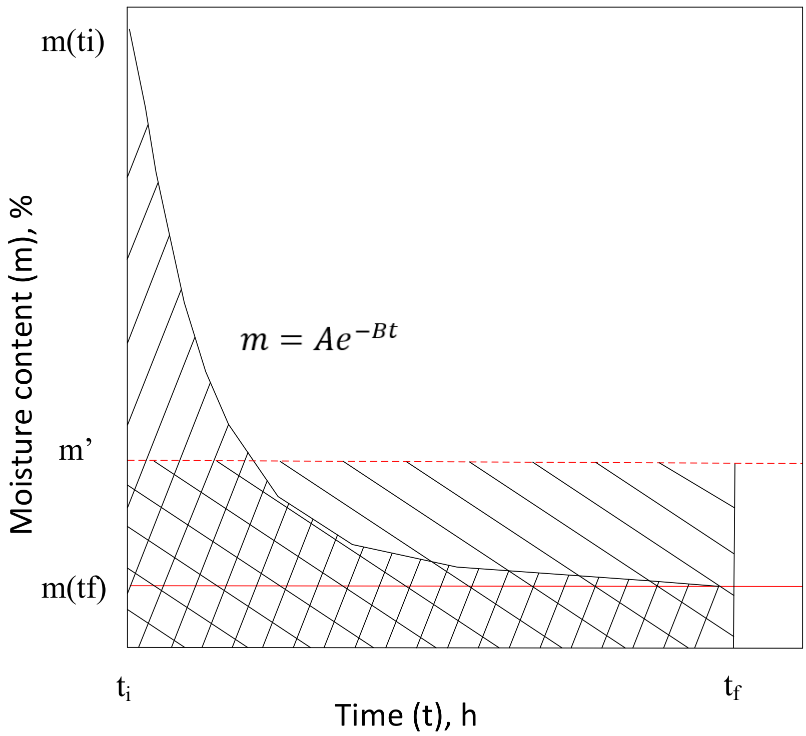

Figure 3.6 Schematic illustration of moisture loss during soil desiccation

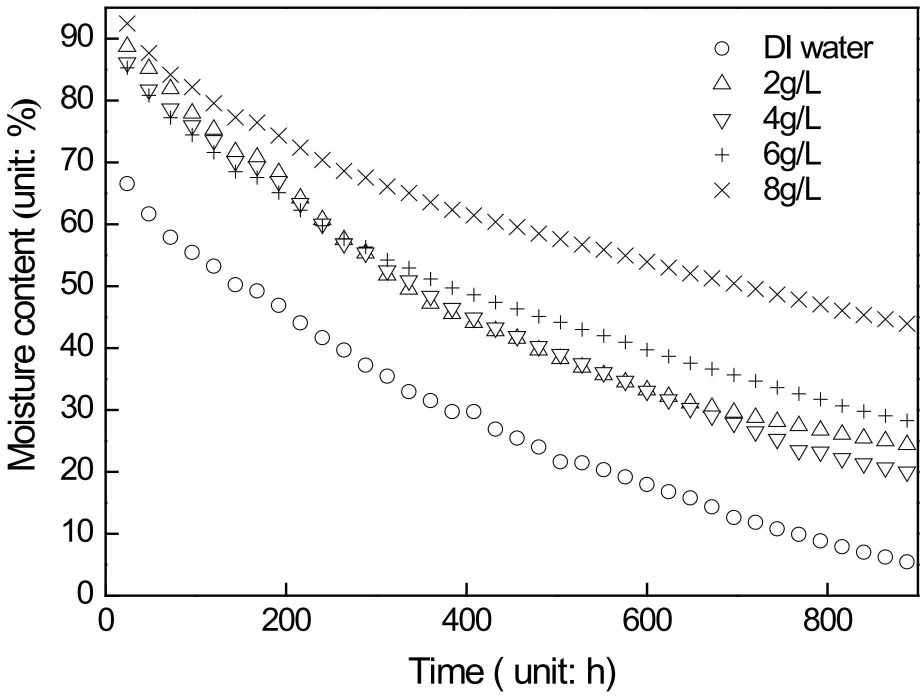

Figure 3.7 Moisture content curves for various concentrations during a desiccation period of 900h

3.4 Numerical analysis

Previous studies show that greater moisture retention capacity and infiltration ability are favourable in dust abatement. The experimental study indicates that the moisture retention capacity of the samples was significantly enhanced with increasing XG concentrations. On the contrary, the infiltration ability was diminished with an increase in the concentrations. Therefore, simply based on the results, it is impossible to directly evaluate the dust control effectiveness of xanthan gum. This study provides an innovative methodology which systematically correlates the results of the experimentations to dust emission rate via numerical analysis.

3.4.1 Mathematical models

In this study, two main properties of xanthan gum, infiltration ability and moisture retention capacity, were investigated through the corresponding experimental programs. The mathematical model (1) (Chakraborty et al., 2002) was selected and modified into model (2). The results of the experimentation were put into the modified model and then the estimation of dust emission was computed from this model. Finally, the estimations were used to evaluate the effectiveness of xanthan gum used to abate dust emission.

$$E = [\{(100 - m)(m)^{-1}\}^{0.8}\{(s)(100 - s)\}]^{0.1}u^{0.3}\{2663 + 0.1(v + fc)\}10^{-6} \quad (1)$$

$$E' = \mathrm{K}[\{(100 - m')(m')^{-1}\}^{0.8}\{(s)(100 - s)^{-1}\}]^{0.1}u^{0.3}\{2663 + 0.1(v + fc)\}10^{-6} \quad (2)$$

Where *E'* is the dust emission rate (g/s), *s* is silt content (%), *u* is wind speed (m/s), *f* is frequency (no. of holes d^{-1}), *v* is average vehicle speed (m/s), *c* is capacity of haul trucks, *K* is the amendable constant, and *m'* is average moisture content.

3.4.2 Dust emission rates

The parameters of the modified mathematical model were determined as follows. Silt content was 22%, obtained from particle size distribution curve of studied soil. The value of frequency was 11, obtained from the study of Chakraborty et al. (Chakraborty et al., 2002). According to field data and project reports, 10km/h (2.78m/s), 32km/h (8.94m/s), and 270t were chosen as wind speed, average vehicle speed, and capacity of haul trucks, respectively. Only the amendable constant (*K*) and average moisture content (*m'*) were calculated. The *K* was summarized in Table 3.3. The *m'* and calculated dust emission rates were summarized in Table 3.4 for each concentration.

Table 3.3 Corresponding K values of various concentrations

Concentration (g/L)	**K value**
0 (DI water)	$92.2\% = (1 - \frac{20.86 - 11.74}{11.74 * 10}) * 100\%$
2	$94.3\% = (1 - \frac{18.46 - 11.74}{11.74 * 10}) * 100\%$
4	$96.7\% = (1 - \frac{15.31 - 11.74}{11.74 * 10}) * 100\%$
6	$98.2\% = (1 - \frac{13.86 - 11.74}{11.74 * 10}) * 100\%$
8	100% (Reference value)

Table 3.4 Average moisture content and its corresponding emission rate for various concentrations

Concentration (g/L)	**Average moisture content** (%)	**Amendable constant (k)** (%)	**Emission rate** (g/h)
0 (DI water)	29.12	92.2	12.63
2	48.17	94.3	11.58
4	45.97	96.7	12.10
6	49.16	98.2	12.43
8	62.78	100	12.24

The average moisture content and the dust emission rate are presented in Figure 3.8. The highest value of average moisture content is 62.78 obtained at a concentration of 8g/L, which is more than twice of that treated with DI water. In addition, it can be seen that the highest emission rate (12.63g/h) is obtained at a concentration of 0g/L and the lowest (11.58g/h) is obtained at the concentration of 2g/L. It can be inferred that xanthan gum has potential to enhance the moisture retention capacity in soil samples and thus effectively suppress dust emission from mine haul roads. Also, the sample treated with 2g/L XG aqueous solution can reduce dust emission by 8% compared with that treated with DI water. In this observation, the optimal application concentration is 2g/L.

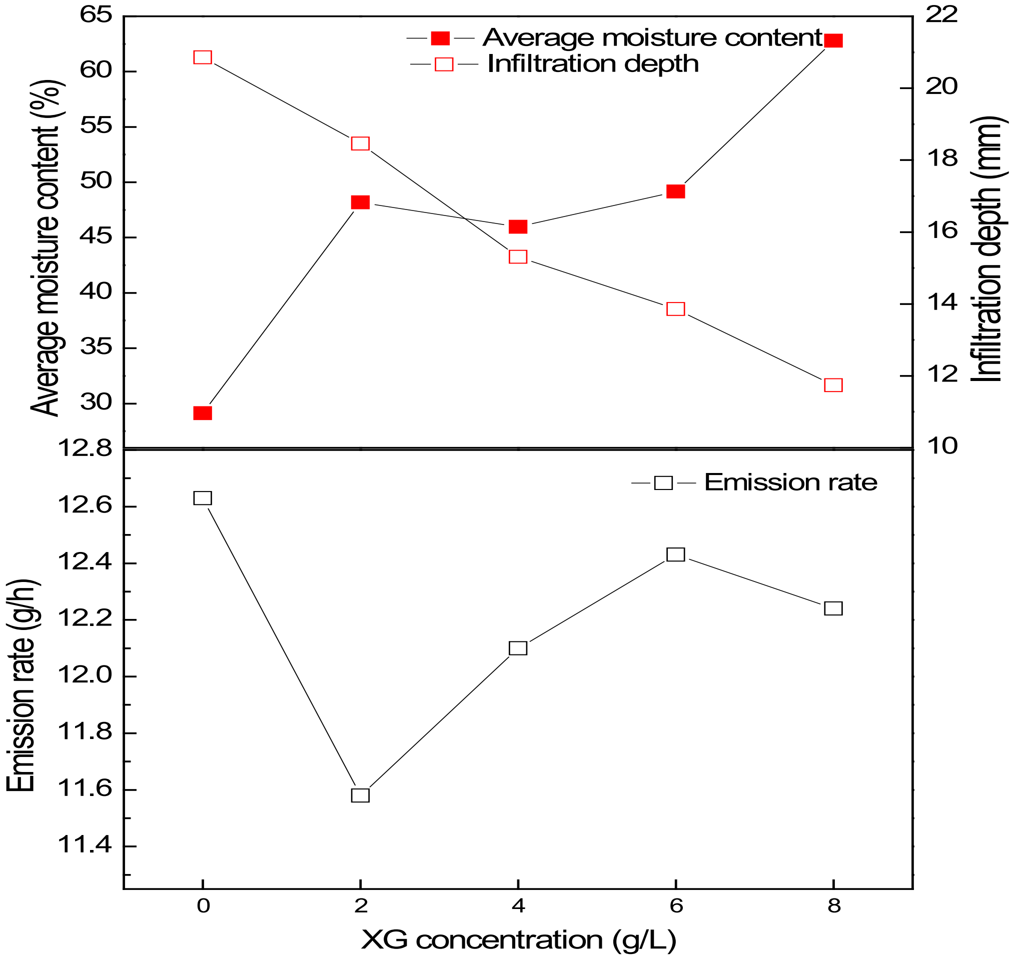

Figure 3.8 Average moisture content, infiltration depth, and emission rate for various concentrations

Chapter 4 Laboratory study on effectiveness of calcium lignosulfonate for haul road dust abatement

4.1 Introduction

Airborne haul road dust, which gives rise to environmental degradation, accounts for more than 80% of the total quantity of dust generation at surface mines. Also, it has many adverse impacts on worker's health and safety at surface mining operation.

Previous studies indicate that many factors affect the dust generation, such as soil moisture, infiltration depth into the soil, atmospheric temperature, moisture content of road surface material, and soil strength (Bae et al., 2006; Copeland et al., 2008; Khatami & O'Kelly, 2012; Omane, Liu, & Pourrahimian, 2017). Chemical methods, using chemical dust suppressants, were commonly studied to control dust emission by modifying the moisture content of road surface material. Therefore, the modification of road surface material after the treatment of dust suppressant is a good indicator for evaluating the effectiveness of the suppressants. Dust suppressants have been widely study to abate dust for decades (Addo & Sanders, 1995; Sanders & Addo, 2000). However, most of them were focused on the improvement of physical properties (e.g. static and dynamic mechanical properties) after being treated with the dust suppressants.

This chapter aims to experimentally study on changes in soil properties after being treated with calcium lignosulfonate via moisture retention test and zeta potential measurement. Moisture retention test and zeta potential measurement are to evaluate, respectively, the improvement of moisture retention and changes in zeta potential. In addition, infiltration depth test was performed to measure the infiltration depth of calcium lignosulfonate aqueous solution into soil samples. Finally, wind tunnel simulation test was conducted to evaluate the potential to generate dust for calcium lignosulfonate at various concentrations.

4.2 Materials and methods

4.2.1 Source and basic properties of soil

The soil studied in this chapter is same with chapter 3.

4.2.2 Polymer selection and aqueous solution preparation

Lignosulfonate, a polymeric compound, is also named lignin sulfonate or sulphite lignin. It is one of the primary by-products of chemical paper-making industry (Gargulak et al., 2001). Its molar mass ranges from 4,600 to 398,00g and molecular weight ranges from 800 to 100,000 (Lemes, Soto-Oviedo, Innocentini Mei, & Durán, 2005). Figure 4.1 shows the structure of calcium lignosulfonate. In addition, it has good solubility in water but do not dissolve in organic solvents. Several diffident types of lignosulfonates, such as calcium lignosulfonate, sodium lignosulfonate, and ammonium lignosulfonate, can be obtained due to various pulping methods utilized during the process of paper manufacturing (Dong et al., 2008). Lignosulfonate, as nature polymeric compound, has excellent bio-degradation, which has more environmental benefits. Also, its solution has a mass of free charge. It is feasible to perform zeta potential measurement and evaluate its dust suppression effectiveness in an innovative way. Previous studies reveal that there is no substantial variation between calcium lignosulfonate and sodium lignosulfonate when they are used to control dust emission (Ding et al., 2018). Calcium lignosulfonate (Ca-LS) is commonly used among those lignosulfonates. Also, its moisture retention capacity is slightly better than other two lignosulfonates. Therefore, calcium lignosulfonate was selected in this study.

Calcium lignosulfonate (Ca-LS) was selected in the current study for its non-toxic, environmentally friendly, and commercially available. It was obtained from Sigma-Aldrich chemicals company. Table 4.1 summarized detailed information about Ca-LS used in this study.

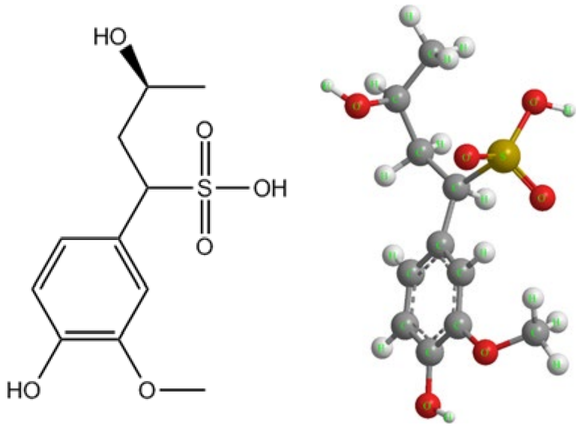

Figure 4.1 2-D & 3-D unit structure of lignosulfonate

Table 4.1 Detailed information of calcium lignosulfonate

Designation	Calcium lignosulfonate (Ca-LS)
Appearance	Yellow powder
Average Mn/Mw	2,500/18,000
Composition	Ca, 5 wt.%
pH	4.0-7.0 at 100g/L
Water solubility	Soluble
Decomposition temperature	130 °C

The Ca-LS aqueous solutions were prepared using a volumetric flask. First, a precisely weighed Ca-LS powder was slowly added to the beaker containing an appropriate amount of deionized (DI) water. After the complete dissolution, the solution was transferred to the volumetric flask with care. Finally, the stopper-sealed flask was shaken to achieve a homogeneous solution. In order to prevent clumping, a magnetic stirrer plate was used, and its rotate speed was set at 30rpm.

4.2.3 Infiltration depth test

This test is to measure infiltration depth of Ca-LS aqueous solution into soil samples. The infiltration depth is a positive factor to abate dust emission. Previous studies suggested that infiltration depth is one of the primary parameters that affects the effectiveness of dust suppressants used to abate dust emission. Greater infiltration depth is more effective in resisting erosion by external action (e.g. traffic and wind), preventing leaching, and inducing more cohesion between soil particles (Bolander & Yamada, 1999; Copeland et al., 2008). Also, they suggested infiltration depth should be more than 10mm for road dust abatement.

The soil samples for this test were prepared by using a 70×94×135-mm (internal diameter × external diameter × height) steel cylinder mould. Relevant studies revealed that oven drying can substantially change the compaction properties of tested soil (Eisazadeh et al., 2012). In order to prevent this effect, the soil was air-dried under ambient conditions in the current study. During the preparation of samples, air-dried soil was mixed with DI water to reach 12% moisture content. Then, the mixture was compacted into the steel mould. To achieve uniform compaction degree, a steel top-load and a vibration table were employed. Finally, the resulting cylindrical samples were extruded from the mould. Each sample approximately has a density of 1.56g/cm^3 before curing.

Before testing processes, the prepared samples were cured under ambient conditions for 7 days. After that, a sprayer was used to evenly spray Ca-LS aqueous solution onto the top surface of the sample at an application rate of 2L/m^2 for each concentration. Then, the sample was cut vertical into two halves shown in Figure 3.4 (a). The infiltration depth was measured based on its section illustrated in Figure 3.4 (b). In this test, the concentration of Ca-LS solution was selected from 20 to 80g/L at 20g/L interval. Untreated samples (deionized water) was also tested as a control. Three replicates were prepared for each concentration.

4.2.4 Moisture retention test

Moisture retention capacity, ability to retard desiccation (moisture loss) process, is one of the most basic properties of soils. Better moisture retention capacity keeps more moisture within soils. Moisture retention tests were to evaluate enhancement of moisture retention capacity of soil samples after being treated with Ca-LS. Previous experimental investigations of dust generation show that high moisture retention is positive factor to abate dust emission (Bae et al., 2006; Chen et al., 2014; Xu et al., 2017). Better moisture retention capacity leads to a lower moisture loss rate of soil, thereby keeping more liquid with soils and reducing dust generation. Moisture content curve (moisture content versus time) of treated sample was determined from the experimentation at various Ca-LS concentrations. Based on the curve, the average moisture content was calculated by calculus and used to reflect the moisture retention capacity for each Ca-LS concentration.

Soil samples for this test were prepared by using a 22×145-mm (internal diameter × height) glass tube. First, air-dried soil was mixed with Ca-LS aqueous solution. After that, the mixed soil was put into the tube and the tube was sealed immediately. Next, the samples were left to hydrate for 24 hours under ambient temperature and humidity. After the hydration, the tubes were weighed without wrap by using an analytical balance. In this test, all prepared samples were placed into an incubator (20℃ and 40% relative humidity). The samples were weighed at 24-hour intervals and the duration of this test was 900h. The Ca-LS concentration was chosen from 2 to 8% at 2% interval. Untreated samples (deionized water) was also tested as a control. Three replicates were prepared for each concentration.

4.2.5 Zeta potential measurement

Zeta potential measurement was performed as one of experimental program to evaluate the effectiveness of Ca-LS used in dust control. The objectives of this test were: (i) to determine the zeta potential of tested soil sample in the presence of Ca-LS aqueous solution at various concentrations, and (ii) to compare the obtained results with that obtained from control group (DI-water treated samples). The zeta potential measurement was performed by using a dedicated zeta potential analyser (Zetasizer Nano Z) under ambient conditions. The instrument enables all statistical results to be obtained from tested soil samples. Three replicates were prepared for each concentration.

4.2.6 Wind tunnel simulation test

Wind tunnel simulation test was conducted in a trafficked wind tunnel system which consists of a suction type wind tunnel (length × width × height=200×50×40cm) with a cyclone dust collector and a trafficked section. The wind tunnel testing system is illustrated in Figure 4.2. The trafficked section consists of a wooden track, a wooden tray, and a model vehicle. Both the track and the tray have same height. The cyclone dust collector (model: G0638) can provide a uniform wind velocity during testing procedure.

Figure 4.2 Wind tunnel testing system

Soil sample for this test was prepared using a wooden tray (length × width × height=58×40×5cm). Relevant studies revealed that oven drying can substantially change the compaction properties of tested soil (Eisazadeh et al., 2012). In order to prevent this effect, the tested soil was air-dried under ambient conditions. First, air-dried soil was mixed with DI water to reach a moisture content of 12%. After that, the mixture was compacted into the wooden tray. During the compaction, a 3-kg steel roller was applied onto the top of the specimen for a desirable compaction degree (1.2g/cm^3). Then, the prepared sample was cured under atmospheric temperature and humidity for 7 days. Finally, Ca-LS aqueous solution was evenly sprayed onto the sample surface at an application rate of 2L/m^2, with various concentrations of 20, 40, 60, and 80g/L. Untreated samples (deionized water) was also tested as a control. Three replicates were prepared for each concentration. During the test process, wind velocity was set at 5.5m/s (19.8km/h) in the wind tunnel system. Dust produced by wind and traffic erosion was sucked through the dust collector. After each test, the tested sample was weighed and recorded. The weight loss of the tested sample was used to evaluate the potential to generate dust after being treated with Ca-LS aqueous solution.

4.3 Results and discussions

The infiltration depth of Ca-LS aqueous solutions into samples is not even. Such phenomenon is similar to the results of Chen et al (Chen et al., 2015). The primary cause of this result is the heterogeneity of tested soil in this observation. Table 4.2 summarizes the statistical data of the infiltration depth test results for various concentrations. According to the results, the difference in the infiltration depth between DI- and Ca-LS-treated samples are not notable. Therefore, it can be found that Ca-LS treatment does not significant affect the infiltration depth into the sample at an application rate of $2L/m^2$. In addition, it can be observed that the infiltration depth of various Ca-LS concentrations reaches more than 10mm, which potentially provide a desirable dust suppression performance in practice.

Table 4.2 Infiltration depth test results

Ca-LS concentration (g/L)	Infiltration depth (mm)				
	Sample 1	Sample 2	Sample 3	Mean	Standard Deviation (SD)
0 (DI water)	20.08	19.27	17.23	18.86	1.4686
20	20.17	18.27	19.31	19.25	0.9514
40	16.23	17.60	19.74	17.86	1.7690
60	19.94	18.33	17.82	18.70	1.1065
80	17.16	19.97	19.16	16.67	1.4464

The plots of moisture content versus time are shown in Figure 4.3 for each Ca-LS concentration. The results reveal that the soil sample lost liquid at an exponential rate with testing time. The desiccation process follows an exponential pattern and the moisture loss pattern was shown in Figure 3.6. Fitting equations of moisture retention were determined from the plots by data fitting. The fitted natural logarithm (ln (Q_t)) of moisture quantity (Q) and time (t) were summarized in Table 4.3. According to the results, it is observed that there is a continuous decrease in rate constant (moisture loss rates) with increasing the Ca-LS concentration. The lowest slope of the linear equations is -0.0008g/h which is obtained at a Ca-LS concentration of 80g/L. On the contrary, the highest slope is -0.0015 which is obtained at a Ca-LS concentration of 20g/L. In addition, that of DI-water treated sample is -0.0024g/h. It was found that the Ca-LS treated sample lose liquid more slowly than DI-treated sample by 66.7% per hour. This imply that moisture retention capacity of Ca-LS treated samples has been significantly enhanced and 80g/L Ca-LS concentration shows the best moisture retention capacity in this observation. These results are similar to the results of the study of Ding et al. (Ding et al., 2018). In Ding's study, a poorly graded sand (SP) was tested after being treated with calcium lignosulfonate in dust control. The same trend has been revealed in both Ding's study and current research.

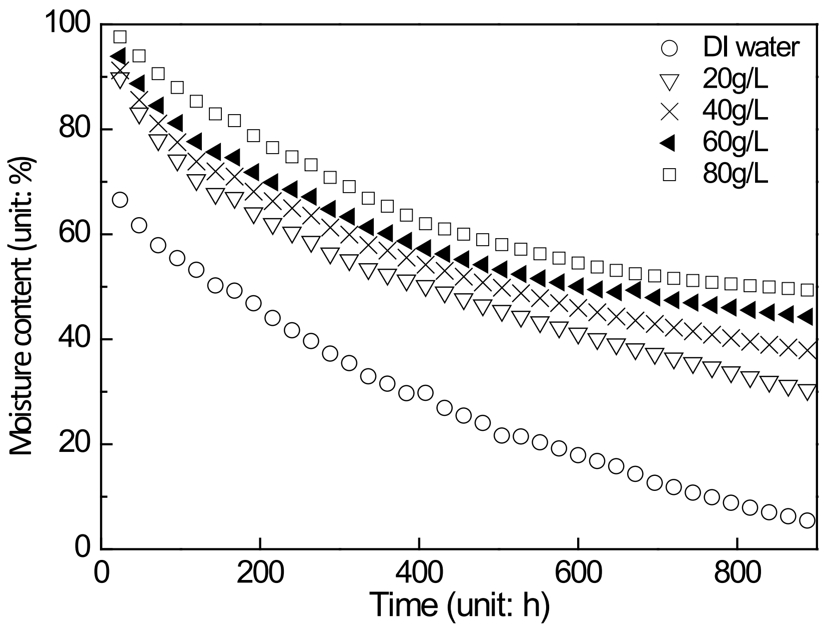

Figure 4.3 Relationship between liquid content retained in the soil amended with Ca-LS at various concentrations during a desiccation period of 900h

Table 4.3 The linear equation of cumulative liquid loss (ln (Qt)) of Ca-LS-amended samples against time (t) and rate constants

Ca-LS Concentration (g/L)	Linear equation	R^2	Rate constant (g/h)	Average moisture content (%)
0 (DI water)	$\ln(Qt) = -0.0024t + 4.2641$	0.9920	0.0024	29.12
20	$\ln(Qt) = -0.0012t + 4.4230$	0.9794	0.0012	50.97
40	$\ln(Qt) = -0.0010t + 4.4428$	0.9730	0.0010	56.06
60	$\ln(Qt) = -0.0009t + 4.4652$	0.9521	0.0009	59.59
80	$\ln(Qt) = -0.0008t + 4.5367$	0.9582	0.0008	65.27

Figure 4.4 demonstrates the relationship between zeta potential and Ca-LS concentration and the experimental data was summarized in Table 4.4. It is observed that there is a continuous decrease in the value of zeta potential with increase of concentration of Ca-LS solution. With increase of Ca-LS concentration from 20 to 80g/L the corresponding zeta potential decreases from -22.1 to -15.7mV. In addition, the control (DI water) has a zeta potential of -24.8. These results imply the value of zeta potential decreases in the presence of Ca-LS in this observation. In addition,

according to Figure 4.5, there is a correlational relationship between zeta potential and average moisture content. Based on this result, it can be inferred that zeta potential was affected after the addition of Ca-LS into soil samples, and thus the moisture retention capacity was changed. Repelling forces between soil particles increase with higher electrical potential, thereby retarding aggregation of the particles. As a result, pore size tends to expand, and more space provided to transfer liquid in the soil.

Table 4.4 Statistical data of zeta potential measurements

Ca-LS concentration (g/L)	Zeta potential (mV)				
	Sample 1	Sample 2	Sample 3	Mean	Standard Deviation (SD)
0 (DI water)	-25.6	-24.7	-24.2	24.8	0.7095
20	-22.5	-23.1	-20.8	22.1	1.1930
40	-20.2	-19.7	-21.0	20.3	0.6557
60	-18.5	-19.3	-18.9	18.9	0.4000
80	-16.6	-15.4	-15.1	15.7	0.7937

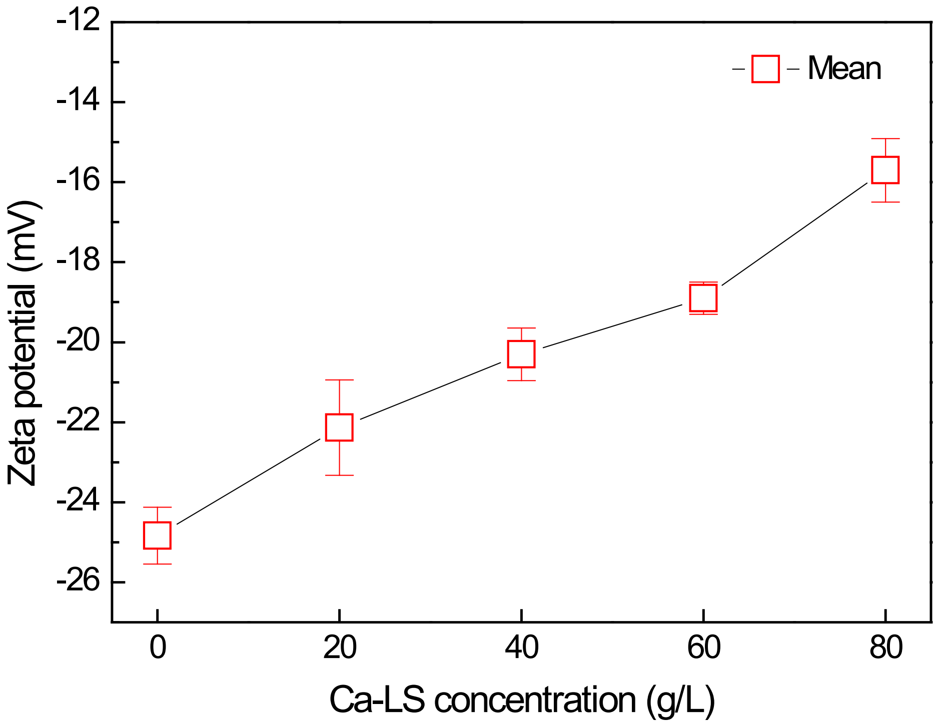

Figure 4.4 Zeta potential measurement result for various concentrations

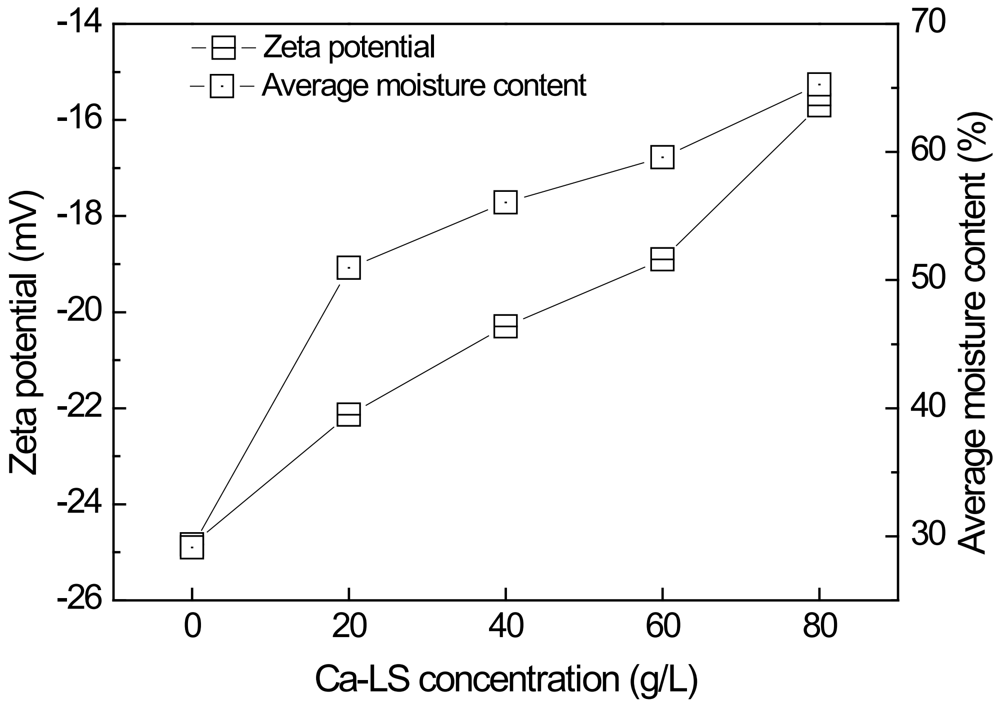

Figure 4.5 Relationship between average moisture content and zeta potential

Figure 4.6 shows the weight loss versus application concentration of Ca-LS solution during wind tunnel testing. It can be seen that there is a continuous decrease with increasing the Ca-LS concentration. With increase of Ca-LS application concentration from 20 to 80g/L the corresponding weight loss decreases from 184.5 to 102.5g. The sample treated with DI water lost 199.5g after the wind tunnel test. This implies the dust suppression performance has been improved with the increasing the Ca-LS concentration. Also, compared to the result from control group, the Ca-LS can effectively abate dust emission in this observation. The best dust suppression effectiveness (48%) can be obtained at a Ca-LS concentration of 80g/L. Moreover, Table 4.5 summarizes the statistical data of the wind tunnel test.

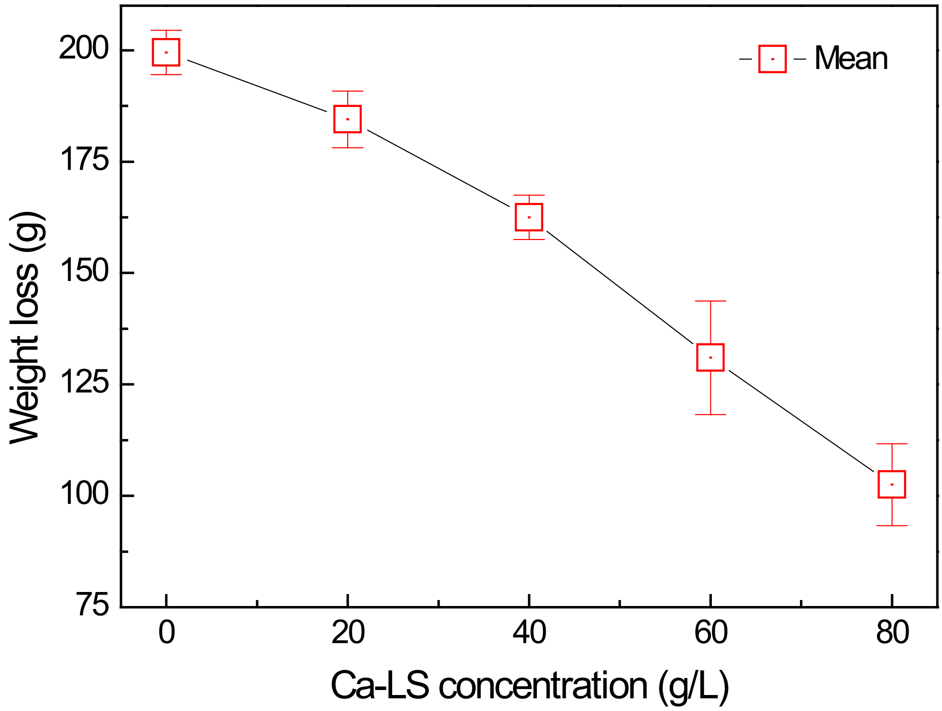

Figure 4.6 Wind tunnel simulation test result for various concentrations

Table 4.5 Statistical data of wind tunnel simulation test

Ca-LS concentration (g/L)	Wind tunnel simulation test		
	Mean	Standard deviation (SD)	Relative efficiencies (%)
0	199.5	4.9498	Reference
20	184.5	6.3640	-7.5
40	162.5	4.9498	-18.5
60	131.0	12.7279	-34.0
80	102.5	9.1924	-48.6

Chapter 5 Conclusions and recommendations

5.1 Summary

This study assessed the effectiveness of two eco-friendly dust suppressants, xanthan gum and calcium lignosulfonate, for airborne dust suppression on haul roads. The evaluation was completed by experimental and mathematical analysis to investigate the effectiveness of the selected suppressants under the studied soil conditions. This included characterizing soil conditions, infiltration depth test, moisture retention test, zeta potential measurement, and wind tunnel simulation test. This study provides a comprehensive assessment of the effectiveness of the suppressants. Both selected suppressants were effective in dust suppression for the same studied conditions. However, there is no significant difference of dust suppressing performance in this study. Also, the optimal application concentrations were determined for xanthan gum and calcium lignosulfonate. Compared to the performance of two dust suppressants, calcium lignosulfonate with selected application concentrations was preferable for the studied soil conditions.

It is recommended that economic analysis of the two dust suppressants be performed. This can be accomplished by collecting data from chemical vendors and calculating preliminary cost in unit area. This will be helpful to determine which one is preferable.

5.2 Conclusions and recommendations

5.2.1 Study 1: Xanthan gum

This study reveals that the infiltration ability and moisture retention capacity show approximately contrary trends with increasing XG concentration. The infiltration ability was investigated via infiltration depth test. There is a continuous decrease in the infiltration depth with higher XG concentration. The moisture retention capacity was studied via moisture retention test. The moisture retention capacity firstly slight diminishes and then substantially improves with increasing the XG concentration. Both the infiltration ability and the moisture retention capacity are two positive factors to abate dust emissions. In this study, the results of the experimentations were put into a mathematical model and the optimal XG concentration was finally determined via this model. The samples produce less dust emission after being treated with XG and a concentration of 2g/L provides the best dust suppression performance in this observation. Compared with control (DI water), the potential to produce dust emission decreases by 8.3%. However, the improvement is not notable when the XG concentration ranges from 4 to 8g/L. Although the original mathematical model has good accuracy, the its accuracy after the modification has not been studied. Therefore, further work should be done to validate the results from the numerically investigation. In this study, all the experimental tests were performed under ambient temperature. Dust suppression performance may be sensitive to temperature. Hence, it is recommended that ambient temperature should be evaluated.

5.2.2 Study 2: calcium lignosulfonate

The main objective of this research was to experimentally investigate the effectiveness of calcium lignosulfonate in haul road dust control. The following findings can be found based on the laboratory experimentations:

Ca-LS treatment did not lead to notable changes in the infiltration depth. The infiltration depths of various Ca-LS concentration were large enough to achieve a desirable dust suppression performance in this observation. Regarding the infiltration depth, there was a slight difference between the Ca-LS-treated samples and DI-treated samples.

The soil samples treated with Ca-LS show better moisture retention capacity than the samples treated with DI water, and the improvement is greater with increasing Ca-LS concentration. Ca-LS at a concentration of 80g/L has the best moisture retention capacity in this observation, and the enhancement was up to 66.7% compared with control group.

Zeta potential was significantly affected by the concentration of Ca-LS aqueous solution, and there is a continuous decrease in the value of zeta potential with higher Ca-LS concentrations. In addition, there is a correlational relationship between zeta potential and average moisture content.

The soil samples treated with Ca-LS show better dust suppression performance than the samples treated with DI water, and there is a continue decrease in the potential to generate dust from the treated samples with increasing Ca-LS concentration. In addition, the samples treated with 80g/L Ca-LS produced 102.5g dust, which decreased up to 48.6% compared with the samples treated with DI water.

Further studies should be conducted on the effectiveness of calcium lignosulfonate used to abate dust emission from mine haul roads at field conditions.

References

Addo, J. Q., & Sanders, T. G. (1995). *Effectiveness and environmental impact of road dust suppressants*. Retrieved from

Alzubaidi, H. (1999). Operation and maintenance of gravel roads: a literature study.

Amato, F., Querol, X., Johansson, C., Nagl, C., & Alastuey, A. (2010). A review on the effectiveness of street sweeping, washing and dust suppressants as urban PM control methods. *Science of the total environment, 408*(16), 3070-3084.

Amponsah-Dacosta, F. (2015). *Cost-effective strategies for dust control in an opencast coal mine.*

Army, U., & Force, U. A. (2005). Dust control for roads, airfields, and adjacent areas. *Honolulu: University Press of the Pacific, 48*.

Atkinson, R. W., Fuller, G. W., Anderson, H. R., Harrison, R. M., & Armstrong, B. (2010). Urban ambient particle metrics and health: a time-series analysis. *Epidemiology, 21*(4), 501-511.

Ayeldeen, M., Negm, A., El Sawwaf, M., & Gädda, T. (2018). Laboratory study of using biopolymer to reduce wind erosion. *International Journal of Geotechnical Engineering, 12*(3), 228-240.

Ayeldeen, M. K., Negm, A. M., & El Sawwaf, M. A. (2016). Evaluating the physical characteristics of biopolymer/soil mixtures. *Arabian Journal of Geosciences, 9*(5), 371.

Bae, S., Inyang, H. I., Galvão, T. D. B., & Mbamalu, G. E. (2006). Soil desiccation rate integration into empirical dust emission models for polymer suppressant evaluation. *Journal of hazardous materials, 132*(1), 111-117.

Birst, S., & Hough, J. A. (1999). *Chemical additive usage on unpaved roads in the mountain plains states*. Retrieved from

Bolander, P., & Yamada, A. (1999). *Dust palliative selection and application guide*. Retrieved from

Braaten, D. A., Shaw, R. H., & Paw U, K. T. (1993). Boundary-layer flow structures associated with particle reentrainment. *Boundary-Layer Meteorology, 65*(3), 255-272.

Carter, R. A. (1995). Knocking down dust. *Rock Prod, 98*(5), 8.

Chakraborty, M., Ahmad, M., Singh, R., Pal, D., Bandopadhyay, C., & Chaulya, S. (2002). Determination of the emission rate from various opencast mining operations. *Environmental Modelling & Software, 17*(5), 467-480.

Chang, I., & Cho, G.-C. Shear strength behavior and parameters of microbial gellan gum-treated soils: from sand to clay. *Acta Geotechnica*, 1-15.

Chang, I., Im, J., Prasidhi, A. K., & Cho, G.-C. (2015). Effects of Xanthan gum biopolymer on soil strengthening. *Construction and Building Materials, 74*, 65-72.

Chang, I., Prasidhi, A. K., Im, J., Shin, H.-D., & Cho, G.-C. (2015). Soil treatment using microbial biopolymers for anti-desertification purposes. *Geoderma, 253*, 39-47.

Chang, Y.-M., Hwang, J.-S., & Chou, C.-M. (2003). Study on short-term prevention efficiencies of chemical binders to reduce fugitive dust. *Environmental engineering science, 20*(4), 265-280.

Chaulya, S. (2004). Assessment and management of air quality for an opencast coal mining area. *Journal of environmental management, 70*(1), 1-14.

Chen, R., Ding, X., Ramey, D., Lee, I., & Zhang, L. (2015). Experimental and numerical investigation into surface strength of mine tailings after biopolymer stabilization. *Acta Geotechnica*, 1-11.

Chen, R., Ding, X., Ramey, D., Lee, I., & Zhang, L. (2016). Experimental and numerical investigation into surface strength of mine tailings after biopolymer stabilization. *Acta Geotechnica, 11*(5), 1075-1085.

Chen, R., Lee, I., & Zhang, L. (2014). Biopolymer stabilization of mine tailings for dust control. *Journal of Geotechnical and Geoenvironmental Engineering, 141*(2), 04014100.

Chen, R., Zhang, L., & Budhu, M. (2013). Biopolymer stabilization of mine tailings. *Journal of Geotechnical and Geoenvironmental Engineering, 139*(10), 1802-1807.

Chiou, S.-F., & Tsai, C.-J. (2001). Measurement of emission factor of road dust in a wind tunnel. *Powder technology, 118*(1), 10-15.

Conde, M. R. (2004). Properties of aqueous solutions of lithium and calcium chlorides: formulations for use in air conditioning equipment design. *International Journal of Thermal Sciences, 43*(4), 367-382.

Copeland, C., Eisele, T., Chesney, D., & Kawatra, S. K. (2008). Factors influencing dust suppressant effectiveness. *Minerals and Metallurgical Processing, 25*(4).

Das, S. K., Mahamaya, M., Panda, I., & Swain, K. (2015). Stabilization of Pond Ash using Biopolymer. *Procedia Earth and Planetary Science, 11*, 254-259.

Denby, B., Sundvor, I., Johansson, C., Pirjola, L., Ketzel, M., Norman, M., . . . Omstedt, G. (2013). A coupled road dust and surface moisture model to predict non-exhaust road traffic induced particle emissions (NORTRIP). Part 1: Road dust loading and suspension modelling. *Atmospheric Environment, 77*, 283-300.

Denby, B. R., Sundvor, I., Johansson, C., Pirjola, L., Ketzel, M., Norman, M., . . . Kauhaniemi, M. (2013). A coupled road dust and surface moisture model to predict non-exhaust road traffic induced particle emissions (NORTRIP). Part 2: Surface moisture and salt impact modelling. *Atmospheric Environment, 81*, 485-503.

Ding, X., Xu, G., Kizil, M., Zhou, W., & Guo, X. (2018). Lignosulfonate Treating Bauxite Residue Dust Pollution: Enhancement of Mechanical Properties and Wind Erosion Behavior. *Water, Air, & Soil Pollution, 229*(7), 214.

Docx, J., Kingman, S., Lester, E., Lowndes, I., Silvester, S., & Wu, T. (2007). An investigation into unpaved road emissions from a UK surface limestone quarry using cylindrical adhesive pad collectors and image analysis. *International Journal of Mining, Reclamation and Environment, 21*(2), 126-143.

Dong, Z., Wang, L., & Zhao, S. (2008). A potential compound for sand fixation synthesized from the effluent of pulp and paper mills. *Journal of arid environments, 72*(7), 1388-1393.

Edvardsson, K. (2009). Gravel roads and dust suppression. *Road Materials and Pavement Design, 10*(3), 439-469.

Edvardsson, K. (2010). Evaluation of dust suppressants for gravel roads: Methods development and efficiency studies.

Edvardsson, K., & Magnusson, R. (2009). Monitoring of dust emission on gravel roads: Development of a mobile methodology and examination of horizontal diffusion. *Atmospheric Environment, 43*(4), 889-896.

Edvardsson, K., & Magnusson, R. (2011). Impact of fine materials content on the transport of dust suppressants in gravel road wearing courses. *Journal of materials in civil engineering, 23*(8), 1163-1170.

Eisazadeh, A., Kassim, K. A., & Nur, H. (2012). Stabilization of tropical kaolin soil with phosphoric acid and lime. *Natural hazards, 61*(3), 931-942.

EPA. (1996). *Air Quality Criteria for Particulate Matter*. National Center for Environmental Assessment.

Epps, A., & Ehsan, M. (2002). Laboratory study of dust palliative effectiveness. *Journal of materials in civil engineering, 14*(5), 427-435.

Etemadi, O., Petrisor, I. G., Kim, D., Wan, M.-W., & Yen, T. F. (2003). Stabilization of metals in subsurface by biopolymers: Laboratory drainage flow studies. *Soil and Sediment Contamination, 12*(5), 647-661.

Fitz, D. R., & Bumiller, K. (2000). Evaluation of watering to control dust in high winds. *Journal of the Air & Waste Management Association, 50*(4), 570-577.

Foley, G., Cropley, S., & Giummarra, G. (1996). Road dust control techniques: evaluation of chemical dust suppressants' performance.

Furse, S. (2010). Bubbles, Bubbles, Everywhere, But Not a Drop to Drink. *The lipid cronicles*.

Garcıa-Ochoa, F., Santos, V., Casas, J., & Gomez, E. (2000). Xanthan gum: production, recovery, and properties. *Biotechnology advances, 18*(7), 549-579.

Gargulak, J. D., Lebo, S. E., & McNally, T. J. (2001). Lignin. *Kirk-Othmer encyclopedia of chemical technology*.

Giurco, D., Prior, T., Mudd, G. M., Mason, L., & Behrisch, J. (2010). *Peak minerals in Australia: A review of changing impacts and benefits*: Institute for Sustainable Futures, UTS & Department of Civil Engineering, Monash University.

Han, C. (1992). *Dust Control on Unpaved Roads*: Minnesota Department of Transportation.

Harkins, W. D., & Gilbert, E. (1926). The structure of films of water on salt solutions. II. The surface tension of calcium chloride solutions at 25. *Journal of the American Chemical Society, 48*(3), 604-607.

Hinds, W. C. (2012). *Aerosol technology: properties, behavior, and measurement of airborne particles*: John Wiley & Sons.

Inyang, H. I., Bae, S., Lee, J.-Y., & Park, K. J. (2012). Desiccation of contaminant barrier materials amended with aqueous carboxymethyl cellulose solution. *Journal of Material Cycles and Waste Management, 14*(1), 19-26.

Ivanov, V., & Chu, J. (2008). Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil in situ. *Reviews in Environmental Science and Bio/Technology, 7*(2), 139-153.

Karimi, S. (1999). A study of geotechnical applications of biopolymer treated soils with an emphasis on silt.

Karin Edvardsson, R. M. (2008). monitor of dust emission on gravel roads:development of a mobile methodology and examination of horizontal diffusion. *Atmospheric Environment, 43*(4), 889-896.

Kavazanjian Jr, E., Iglesias, E., & Karatas, I. (2009). *Biopolymer soil stabilization for wind erosion control.* Paper presented at the Proc. 17th Int. Conf. Soil Mech. Geotech. Engng, Alexandria.

Khatami, H. R., & O'Kelly, B. C. (2012). Improving mechanical properties of sand using biopolymers. *Journal of Geotechnical and Geoenvironmental Engineering, 139*(8), 1402-1406.

Kim, K.-H., Kabir, E., & Kabir, S. (2015). A review on the human health impact of airborne particulate matter. *Environment international, 74*, 136-143.

Kirchner, H., & Gall, J. A. (1991). Liquid calcium chloride for dust control and base stabilization of unpaved road systems. *Transportation Research Record, 1291*, 173-178.

Kumar, P., Mulheron, M., & Som, C. (2012). Release of ultrafine particles from three simulated building processes. *Journal of Nanoparticle Research, 14*(4), 771.

Lemes, A., Soto-Oviedo, M., Innocentini Mei, L., & Durán, N. (2005). *Processing, chemical structure and morphology of poly (hydroxybutyrate-co-valerate)/lignosulfonate composites.* Paper presented at the Proceedings of the 2nd mercosur congress on chemical engineering, 4th mercosur congress on process systems engineering, Enpromer. Enpromer, Rio de Janeiro, Brazil.

Lindh, E. (1981). *DUST-BINDING OF GRAVEL ROADS. A LITERATURE STUDY* (0347-6049). Retrieved from

Lohnes, R. A., & Coree, B. (2002). *Determination and evaluation of alternate methods for managing and controlling highway-related dust*. Retrieved from

Maleki, M., Ebrahimi, S., Asadzadeh, F., & Tabrizi, M. E. (2016). Performance of microbial-induced carbonate precipitation on wind erosion control of sandy soil. *International journal of environmental science and technology, 13*(3), 937-944.

Mandal, K., Kumar, A., Tripathi, N., Singh, R., Chaulya, S., Mishra, P., & Bandyopadhyay, L. (2012). Characterization of different road dusts in opencast coal mining areas of India. *Environmental Monitoring and Assessment, 184*(6), 3427-3441.

Marasteanu, M. O., Hozalski, R. M., Clyne, T. R., & Velasquez, R. (2005). Preliminary laboratory investigation of enzyme solutions as a soil stabilizer.

Mulholland, R. (1972). *Evaluation of selected dust palliatives on secondary highways*. Retrieved from

Neuman, C. M., Boulton, J. W., & Sanderson, S. (2009). Wind tunnel simulation of environmental controls on fugitive dust emissions from mine tailings. *Atmospheric Environment, 43*(3), 520-529.

Omane, D., Liu, W., & Pourrahimian, Y. (2017). Comparison of chemical suppressants under different atmospheric temperatures for the control of fugitive dust emission on mine hauls roads. *Atmospheric Pollution Research*.

Omane, D., Liu, W., & Pourrahimian, Y. (2018). Comparison of chemical suppressants under different atmospheric temperatures for the control of fugitive dust emission on mine hauls roads. *Atmospheric Pollution Research, 9*(3), 561-568.

Organiscak, J. A., & Randolph Reed, W. (2004). Characteristics of fugitive dust generated from unpaved mine haulage roads. *International journal of surface mining, reclamation and environment, 18*(4), 236-252.

Palaniraj, A., & Jayaraman, V. (2011). Production, recovery and applications of xanthan gum by Xanthomonas campestris. *Journal of Food Engineering, 106*(1), 1-12.

Patra, A. K., Gautam, S., & Kumar, P. (2016). Emissions and human health impact of particulate matter from surface mining operation—A review. *Environmental Technology & Innovation, 5*, 233-249.

Petavratzi, E., Kingman, S., & Lowndes, I. (2005). Particulates from mining operations: A review of sources, effects and regulations. *Minerals Engineering, 18*(12), 1183-1199.

Plinke, M. A., Maus, R., & Leith, D. (1992). Experimental examination of factors that affect dust generation by using Heubach and MRI testers. *The American Industrial Hygiene Association Journal, 53*(5), 325-330.

Quirk, J., & Schofield, R. (1955). The effect of electrolyte concentration on soil permeability. *European Journal of Soil Science, 6*(2), 163-178.

Reed, W., & Organiscak, J. (2006). Evaluation of dust exposure to truck drivers following the lead haul truck. *TRANSACTIONS-SOCIETY FOR MINING METALLURGY AND EXPLORATION INCORPORATED, 318*, 147.

Rosalam, S., & England, R. (2006). Review of xanthan gum production from unmodified starches by Xanthomonas comprestris sp. *Enzyme and Microbial Technology, 39*(2), 197-207.

Rosen, M. J., & Kunjappu, J. T. (2012). *Surfactants and interfacial phenomena*: John Wiley & Sons.

Ross, M., & Murray, J. (2004). Occupational respiratory disease in mining. *Occupational Medicine, 54*(5), 304-310.

Ross, M. H., & Murray, J. (2004). Occupational respiratory disease in mining. *Occupational Medicine, 54*(5), 304-310. doi:10.1093/occmed/kqh073

Rushing, J. F., Harrison, A., Tingle, J. S., Mason, Q., & McCaffrey, T. (2006). Evaluation of dust palliatives for unpaved roads in arid climates. *Journal of performance of constructed facilities, 20*(3), 281-286.

Rushing, J. F., & Tingle, J. S. Comprehensive Field Studies to Address Performance of Chemical Dust Palliatives.

Sanders, T. G., & Addo, J. Q. (2000). Experimental road dust measurement device. *Journal of Transportation Engineering, 126*(6), 530-535.

Santoni, R., Tingle, J., & Webster, S. (2002). Stabilization of silty sand with nontraditional additives. *Transportation Research Record: Journal of the Transportation Research Board*(1787), 61-70.

Scholen, D. E. (1995). *Stabilizer mechanisms in nonstandard stabilizers.* Paper presented at the Transportation research board conference proceedings.

Shao, Y., & Lu, H. (2000). A simple expression for wind erosion threshold friction velocity. *Journal of Geophysical Research: Atmospheres, 105*(D17), 22437-22443.

Sharma, R. S., Phanikumar, B., & Rao, B. V. (2008). Engineering behavior of a remolded expansive clay blended with lime, calcium chloride, and rice-husk ash. *Journal of materials in civil engineering, 20*(8), 509-515.

Singh, T. N. (1997). *Geo-environment of Indian Coalfields*: Sharda Prakashan.

Succarieh, M. (1992). *Control of dust emissions from unpaved roads*. Retrieved from

Tannant, D., & Regensburg, B. (2010). Guidelines for mine haul road design.

Thenoux, G., Bellolio, J., & Halles, F. (2007). Development of a methodology for measurement of vehicle dust generation on unpaved roads. *Transportation Research Record: Journal of the Transportation Research Board*(1989), 299-304.

Thompson, R., & Visser, A. (2007). Selection, performance and economic evaluation of dust palliatives on surface mine haul roads. *JOURNAL-SOUTH AFRICAN INSTITUTE OF MINING AND METALLURGY, 107*(7), 435.

Valavanidis, A., Fiotakis, K., & Vlachogianni, T. (2008). Airborne particulate matter and human health: toxicological assessment and importance of size and composition of particles for oxidative damage and carcinogenic mechanisms. *Journal of Environmental Science and Health, Part C, 26*(4), 339-362.

Velasquez, R., Marasteanu, M. O., & Hozalski, R. (2006). Investigation of the effectiveness and mechanisms of enzyme products for subgrade stabilization. *International Journal of Pavement Engineering, 7*(3), 213-220.

Wang, Q., Ellis, P., & Ross-Murphy, S. (2000). The stability of guar gum in an aqueous system under acidic conditions. *Food hydrocolloids, 14*(2), 129-134.

Wang, X., Chow, J. C., Kohl, S. D., Yatavelli, L. N. R., Percy, K. E., Legge, A. H., & Watson, J. G. (2015). Wind erosion potential for fugitive dust sources in the Athabasca Oil Sands Region. *Aeolian Research, 18*, 121-134.

Wang, Z., Wu, J., Zhu, L., & Zhan, X. (2017). Characterization of xanthan gum produced from glycerol by a mutant strain Xanthomonas campestris CCTCC M2015714. *Carbohydrate polymers, 157*, 521-526.

Wu, C. (2000). Development of an in situ soil binding agent. *Waste Management, 20*(7), 527-535.

Xu, G., Ding, X., Kuruppu, M., Zhou, W., & Biswas, W. (2017). Research and application of non-traditional chemical stabilizers on bauxite residue (red sand) dust control, a review. *Science of the total environment*.

Xue, D., & Sethi, R. (2012). Viscoelastic gels of guar and xanthan gum mixtures provide long-term stabilization of iron micro-and nanoparticles. *Journal of Nanoparticle Research, 14*(11), 1239.

Yang, J., Wang, F., Fang, L., & Tan, T. (2007). Synthesis, characterization and application of a novel chemical sand-fixing agent-poly (aspartic acid) and its composites. *Environmental Pollution, 149*(1), 125-130.

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Appendix

Statement of Contribution by Others

Principal Author	Candidate Contribution to the thesis	Overall (%)	Signature	Date
Xingyun Guo	Set research questions, developed methodology, developed experimental program, performed the experiments, conducted experimental analysis, and wrote manuscript.	85%	XINGYUN GUO	30/03/2019

Co-author Contribution

By signing the statement, the co-author certifies that:

The candidate's stated contribution is accurate as above.

Co-author	Contribution to the thesis	Signature	Date
Guang Xu	Supervised development of work and reviewed manuscript.		30/03/2019