# Comparison of Chemical Suppressants Under Different Atmospheric Temperatures for The Control of Fugitive Dust Emission on Mine Haul Roads

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## *ABSTRACT*

*Dust generated from haul roads poses a severe health and safety threat to mine sites. Traditionally, water has been applied on mine haul roads to control the dust. Although environmentally friendly, water lasts for a limited duration due to evaporation. Consequently, water has less longevity and requires consistent re-application, leading to an enormous waste of valuable water resources, especially in remote areas where most mine sites are located. One solution is to add chemical suppressant to water in mine sites. Despite many practical applications, there is a research gap for the effect of various atmosphere temperatures on the performance of chemical suppressants. The objective of this study is to investigate the role of different atmosphere temperature on the effectiveness of chemical suppressants to control mine haul road dust. In this study, water and selected chemical surfactants— salt, chloride free agents, polymers, and molasses—were tested experimentally for their dust retention efficiency under three different atmosphere temperatures within a time frame of 72 hours. Compared with water, salt solution, chloride free solution, polymer solution, and molasses solution achieved higher efficiencies than those of water. It is concluded that atmosphere temperatures play an important role in the effectiveness of chemical suppressants.*

## 1. Introduction

Road dust generated through truck hauling in the mining industry is a severe hazard to the health of workers and the maintenance of roads and vehicles. Road dust usually contains silica and other heavy metals that when inhaled can lead to diseases such as lung cancer, abnormal kidney function, and rheumatoid arthritis (Cecala et al., 2012). Accounting for about 78% to 97% of the total amount of dust emitted into the atmosphere in surface mining operations, road dust mainly consists of solid particulate matters having smaller particle diameters (i.e., 2 µm – 75 µm) (Foley et al., 1996; Kavouras et al., 2009; Thompson and Visser, 2007). Dust emissions from road surfaces lead to soil erosion, which has an adverse effect on vehicles' travel times (Thompson and Visser, 2007). Moreover, deteriorated mine roads increase drivers' whole-body vibration and affect the performance of haul trucks, the way operational service vehicles handle materials, and mine productivity. The moving parts of the haul trucks, such as bearings and engines, may also be affected by the emitted solid particles, creating downtime in operational scheduling and an increase in vehicular maintenance costs (Organiscak and Randolph Reed, 2004).

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A common road dust control method in the mining industry is to dampen the road with water (Kavouras et al., 2009; Thompson and Visser, 2007). Although environmentally friendly, this approach has a limited duration because water evaporates (Foley et al., 1996). As a result, water must be regularly reapplied, usually by frequent spraying, leading to a tremendous amount waste of valuable water resources, especially in remote areas, where most mine sites are located (Cecala et al., 2012; Kavouras et al., 2009; Thompson and Visser, 2007). In addition to water, using chemical surfactants to form a solution of chemical suppressants has been considered as a more effective method to control fugitive (DeLuca et al., 2012; FCM and NRC, 2005; Gillies et al., 1999). For example, some pilot studies have been done to determine how effective chemical suppressants are; they overviewed the duration and cost of using chemical suppressants on surface mine haul roads in some South African mines (Thompson and Visser, 2007).

A chemical suppressant as a control agent is formed by mixing water with an optimal volumetric concentration of surfactant (Samaha and Naggar, 1988). To date, the mining industry has used various chemical suppressants such as lignosulphonates products, salts, petroleum products, polymer emulsion products, and foaming agents to control fugitive dust on haul roads (Foley et al., 1996; Monjezi et al., 2009; Sanders et al., 2014; Shang et al., 2012). In general, previous research has shown that chemical suppressants provided better performance and greater longevity (Foley et al., 1996; Gillies et al., 1999; Kavouras et al., 2009; Thompson and Visser, 2007). Using chemical suppressants allows companies to generate higher revenues without having to increase their workforce (Cecala et al., 2012). However, atmospheric factors such temperature need to be considered when ensuring the efficacy of a chemical suppressant (Amponsah-Dacosta, 1997; Chiou and Tsai, 2001; Fitz and Bumiller, 2000). This is because temperature plays a critical role in the effectiveness of a chemical suppressant on mine haul roads (Chiou and Tsai, 2001), specifically on evaporation efficiency, which affects performance and longevity of the dust suppressants (Visser, 2013). For example, the effectiveness of different chemical suppressants was evaluated under hot atmospheric temperatures on unpaved roads in Chile, Australia, and the United States (Sanders et al., 2014; Valenzuela et al., 2014; Visser, 2013); however, these studies did not consider other atmospheric temperatures. So far, there is no guide for the comparative assessment analyses on dust control methods located in different climate zones. In particular, no research has been initiated on the evaluation of the effectiveness of chemical dust suppressants under different atmospheric temperatures.

In this research, four types of suppressants commonly used in the mining industry were chosen: a salt solution, chloride-free solution, polymer solution, and molasses solution. These suppressants were selected because unlike more traditional suppressant (i.e., water) have been used on a number of unpaved roads at different locations around the globe to achieve better results. For example, chloride salts, polymer emulsions, molasses, petroleum products and lignosulphonate products have been used on some unpaved roads in countries such as South Africa, Chile, India, and Sweden to achieve success in dust control (Edvardsson et al., 2011; Mishra and Jha, 2010; Thompson and Visser, 2007; Valenzuela et al., 2014). The first one is salt, which is cost effective, environmentally friendly, and easily accessible, and it works effectively in binding water molecules together to reduce the efficacy of evaporation under extreme weather conditions (i.e., dry and hot) (Amponsah-Dacosta, 1997; Cecala et al., 2012; Kavouras et al., 2009). Also, the chloride-free, polymer, and molasses solutions were selected because they perform efficiently and last longer as chemical suppressants in hot weather (Kavouras et al., 2009; Shang et al., 2012; Tran et al., 2008).

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

## 2. Experimental Details

### 2.1. Equipment and Materials

To mimic the hot season, a Despatch LLB series oven, model LBB1- 43A-1 with a maximum temperature of 204 $^{o}$C, was used. A room thermostat was used to control the room temperature of 15 $^{o}$C to represent the normal season. For the cold season, a heavy-duty freezer was used to maintain the temperature of -19 $^{o}$C. A blower with a full capacity speed of more than 80 km/h was set up as a source of wind to trigger dust generation for the experiment.

As shown in Fig 1, a portion of 35 kg of soil sample was received from a local unpaved construction site in the City of Edmonton. Some of the characteristics of the soil sample are similar to characteristics of chernozemic soil found in the City of Fort McMurray, where most haul roads are constructed for oil sands mining (Crown and Twardy, 1975; SCWG, 1998). The soil sample used for the experiment had particle sizes ranging from 0.850 mm to 0.063 mm, which falls within the specification standard for haul road construction in both Edmonton and Fort McMurray (AASHTO, 1993). Hence, the collected soil could be used to construct a mine haul road similar to one in Fort McMurray. In designing a haul road on a mine site, a mining company takes into consideration the wheel load of the haul truck and the particle size distribution of the soil before deciding what type of soil will be added to the wearing course materials (Cecala et al., 2012; Thompson and Visser, 2007).

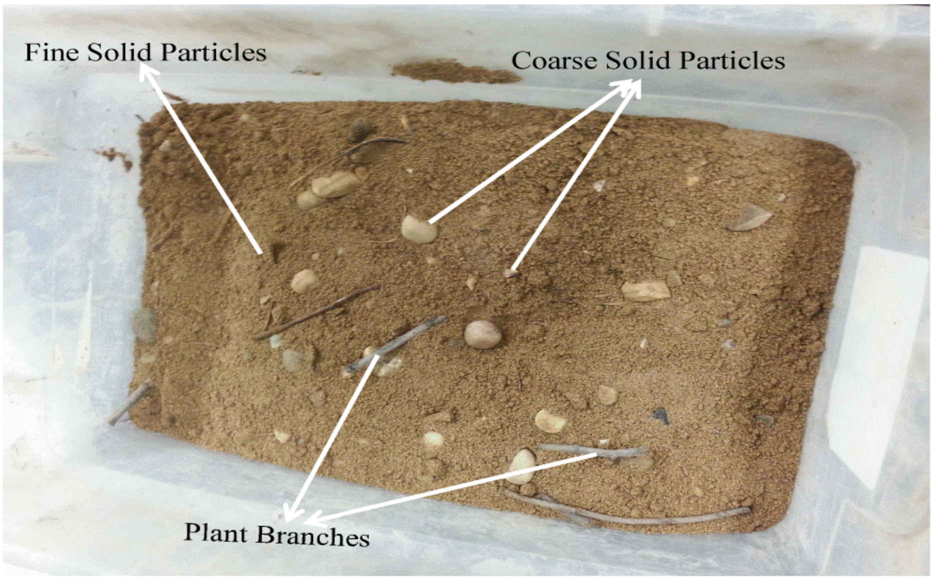

Fig 1. A photo of a fraction of the received soil sample

According to the typical design standard for the mine haul road, the particle size distribution of the used soil sample, as shown in Fig 2, falls within the design limit (AASHTO, 1993; Cecala et al., 2012), which makes the sample appropriate for a haul road design.

Fig 2 illustrates the particle size distribution of the soil sample used for the experiment. $D_{10}$, $D_{30}$, and $D_{60}$ represent the diameter of the soil particles corresponding to the total percentage of a sample of 10%, 30%, and 60%, respectively, on the plotted particle size distribution curve. The coefficient of curvature ($C_C$) and the coefficient of uniformity ($C_U$) are calculated from $D_{10}$, $D_{30}$, and $D_{60}$ (ASTM, 2011).

According to ASTM D2487-11 (ASTM, 2011), the coefficient curvature and coefficient of uniformity are calculated using Equations 1 and 2 to determine the classification category of the soil (ASTM, 2011).

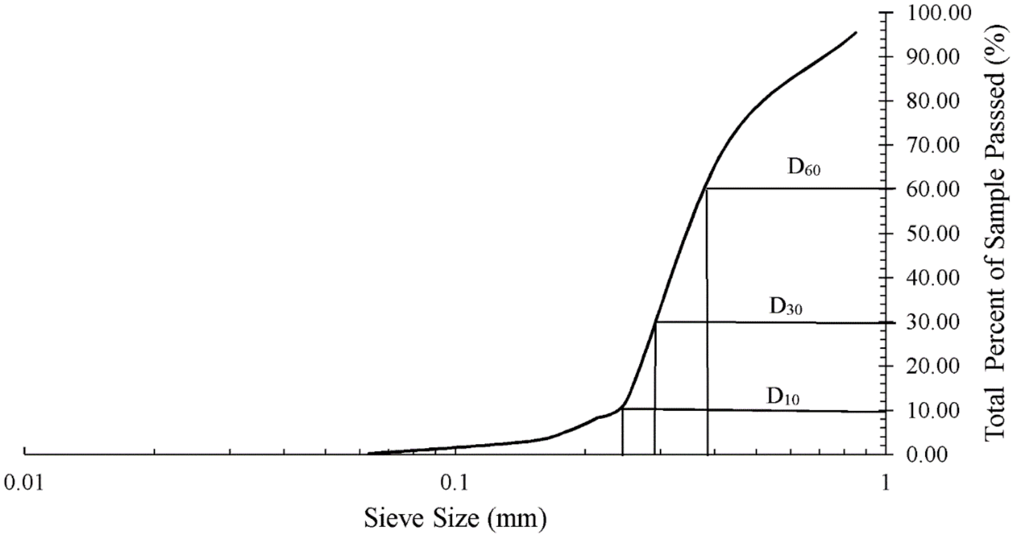

Fig 2. Particle size distribution of the soil sample

$$C_C = \frac{(D_{30})^2}{(D_{10} * D_{60})} \quad (1)$$

$$C_U = \frac{D_{60}}{D_{10}} \quad (2)$$

According to Fig 2, the CC and CU are 0.86 and 1.56, respectively. The result shows CU < 6 and CC < 1 with more than 50% of the soil sample retained on the sieve mesh with an opening of 75 µm. According to ASTM D2487-11, with these parameters, the soil sample is classified as a poorly graded sand with silt which falls within the mine haul roads design guidelines (ASTM, 2011; Tannant and Regensburg, 2001). The grading distribution of the collected soil sample for the research conforms to the typical surface layer particle size distribution for a mine haul road, which ranges from 25 mm to 0.074 mm (Tannant and Regensburg, 2001).

### 2.2. Dust Suppressants

Water and four different selected chemical suppressants were examined as dust suppression agents for the study. These suppressants fall into the general categories of a salt, chloride-free agent, polymer, and molasses. Fig 3 shows the different dust suppressants tested during the experiment.

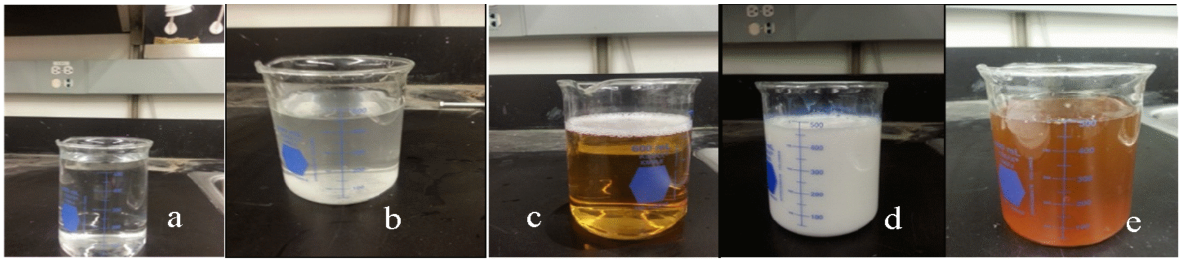

Fig 3. Dust suppression agents tested for the study: (a) Water, (b) Salt solution, (c) Chloride-free solution, (d) Polymer solution, (e) Molasses solution

Fig 3(a) shows water used as the control sample. The water used for this test is from the City of Edmonton (Canada) supplied by EPCOR Canada. The water was composed of a total chlorine level of 1.96 mg/L, total hardness of 181 mg/L as $CaCO_3$, and a total organic carbon content of 1.9 mg/L (EPCOR, 2016). Also, a composition of sodium concentration of 16.0 mg/L, a pH value of 7.7, and 0.70 mg/L of fluoride was dissolved in the water with no bacteriological data (EPCOR, 2016). Fig 3(b) shows the salt solution, which is an iodized table salt with a content composition of 570 mg and an iodide that is 70% soluble in water with a specific gravity of 2.16. Fig 3(c) shows the chloride-free solution as a non-flammable yellowish liquid with a mild odour. This chloride-free agent has a specific gravity of 1.3 and a boiling and freezing point of 100$^o$C and 0$^o$C, respectively. The pH value is in the 8-9 range. Fig 3(d) shows the polymer solution as a non-flammable white liquid with a mild odour, with a boiling and freezing point of 100 $^o$C and 0 $^o$C, respectively. This polymer-agent has a pH value of 8-9 and a specific gravity of 1.0. Fig 3(e) shows the molasses solution consisting of natural molasses, pure vegetable glycerin, and a pure food-grade citric acid with no additives. In addition, the molasses solution contains preservatives with 11g of sugar, 14g of total carbohydrate, and 1g of protein per 350 g of pure molasses.

### 2.3. Experimental Parameters

Different parameters were used for this investigation. The parameters are described in Table 1.

Table 1. Parameters and their descriptions used for the experimental work

| Parameters | Description |
|---|---|
| $D_{10}, D_{30}, \& D_{60}$ | Diameter of soil sample at 10%, 30%, and 60% on particle size distribution curve |
| $C_C \& C_U$ | Co-efficient Curvature and Coefficient of Uniformity of the soil sample |
| $\omega_C$ | Weight of the container (g) |
| $\omega_D$ | Weight of the dried soil sample and container (g) |
| $\omega_m$ | Weight of the moist soil sample and container (g) |
| $v$ | Volumetric dilution for surfactants (%) |
| $\omega_p$ | Weight of the plate (g) |
| $\omega_1$ | Weight of the sample before blowing (g) |
| $\omega_2$ | Weight of the sample after blowing (g) |
| $\Delta\omega$ | Weight of the sample loss (g) |
| $r$ | Dust retention efficiency (%) |
| $R$ | Average dust retention efficiency (%) |
| $M_S$ | Moisture content of the soil sample (%) |

The sample of the soil was placed in an oven at a temperature of 110 $^o$C for 120 hours to dry out all the moisture content as per ASTM standard. The temperature selection and method of calculation for drying out the moisture content in the soil sample $(M_S)$ in Equation 3 are according to the ASTM D2216-10 standard [31].

$$M_S = \frac{\omega_m(g) - \omega_D(g)}{\omega_D(g) - \omega_C(g)} * 100 \tag{3}$$

The particle size distribution of the soil sample was investigated using sieve analysis. A sieve mesh with openings ranging from 0.850 mm to 0.063 mm was used.

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

### 2.4. Experimental Methodology

A general experimental procedure was followed for all the tested chemical dust suppressants under each considered temperature season for the experiment. Fig 4 is a schematic diagram showing the testing principle, and Fig 5 shows the actual experimental set-up. The set-up comprises an air blower, a measuring tape ruler, a steel tripod stand, and a flat plate. The soil sample was measured on the plate before a dosage of chemical suppressant was applied. Then, the sample was placed on the tripod stand before the wind effect was applied from the blower. The sample was then weighed again to determine how much weight was lost from the sample material. Before testing the four chemical dust suppressants, a series of base control tests were performed to determine the effects of wind speed and temperatures on a soil sample. No dust suppressants were used in those tests. The wind speed for the base control tests was 65 km/h, and it was applied for 10 seconds.

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

Water was used in the control group. Four typical chemical surfactants were selected to form a solution of chemical suppressants to be examined for the experiment. In the test, using a sprinkler, 6 mL of water or a chemical suppressant was sprayed onto 20 g of soil sample on a plate. Then the sample was placed at a controlled temperature for a specified duration (i.e., 30 minutes, one hour, two hours, three hours, five hours, 24 hours, 48 hours, and 72 hours).

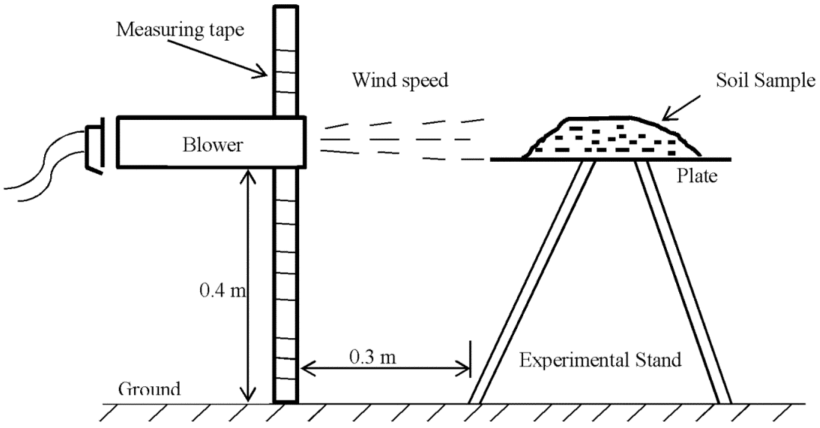

Fig 4. A representation of the experimental procedure

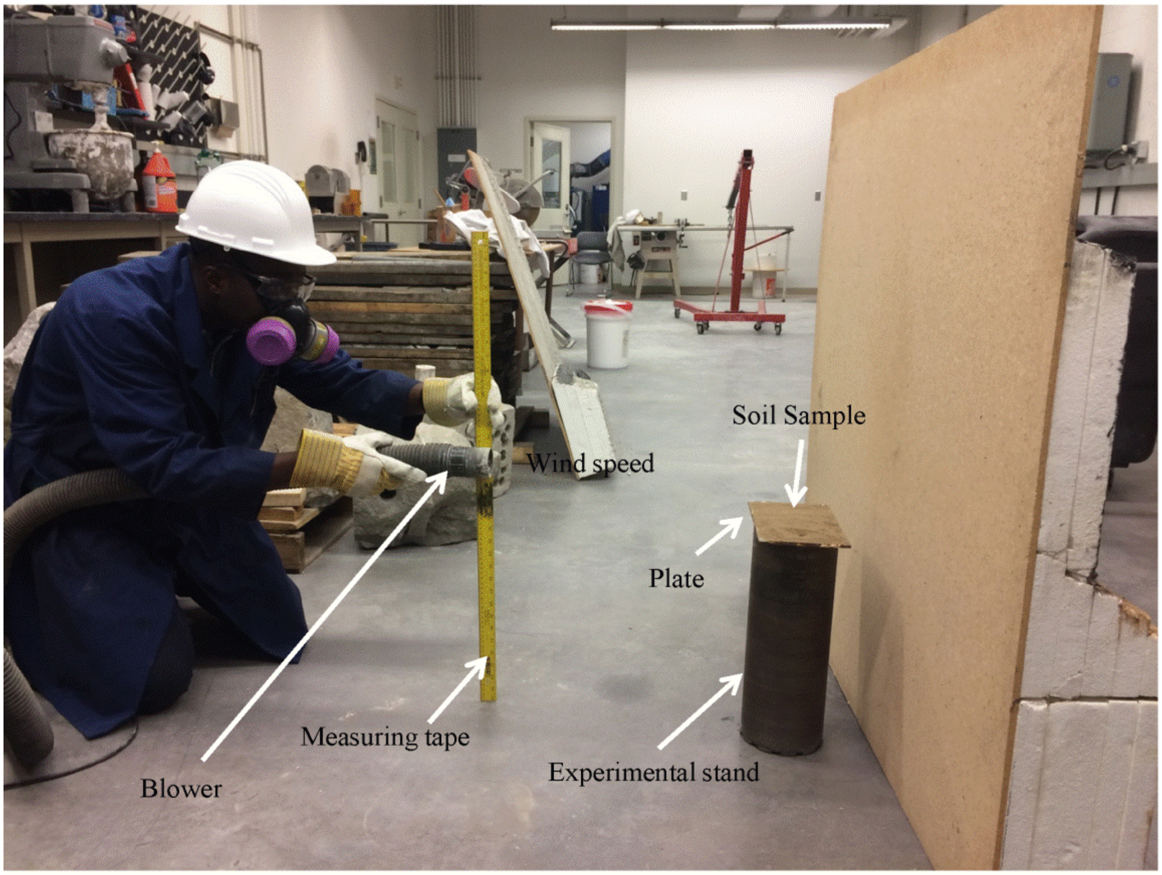

Fig 5. Experimental set-up in the laboratory

After reaching the required time for the sample to be in the oven, the sample was weighed on a scale as $\omega_1$ (g). A wind speed of 65 km/h was applied to the sample for 10 seconds because this duration was used for the base control test. The soil sample was weighed again as $\omega_2$ (g). The weight loss $(\Delta\omega)$ of the soil sample was determined by the difference between the two measured weights. Each test was repeated three times to improve accuracy. The weight loss helps ascertain the mass of sample loss of the material; this serves as a contributing factor when calculating the sample's dust retention efficiency.

### 2.5. Calculation Method

Equation 4 calculates the weight loss of the sample material ($\Delta\omega$) before and after the application of a wind speed of 65 km/h:

$$\Delta\omega(g) = \omega_1(g) - \omega_2(g) \tag{4}$$

The weight loss contributes to the calculation of the sample's dust retention efficiency. Equation 5 calculates the dust retention efficiency $(r)$ of a chemical dust suppressant:

$$r(\%) = 1 - \frac{\Delta\omega}{(\omega_1 - \omega_p)} \tag{5}$$

Three series of dust retention efficiency were conducted for each sample, and the average of the series was taken. Equation 6 calculates the average dust retention efficiency ($R$) of the soil sample for the series:

$$R(\%) = \frac{r_1 + r_2 + r_3}{3} \tag{6}$$

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

## 3. Results and Discussion

### 3.1. Effect of the volumetric dilution concentration on dust retention efficiency

Table 2 shows the statistical result of each chemical surfactant under different volumetric dilution concentrations in water under room temperature in the laboratory. Three series of data were collected for each dilution concentration. The tested volumetric concentration of the dilution of salt ranged was 1.5%, 1.6%, 1.7%, 1.8%, and 2.0%.

Table 2. Dust retention efficiencies versus volumetric concentrations under normal temperature

| Solution type | Average volumetric concentration (%) | Average dust retention efficiency (%) |
|---|---|---|
| Salt | 1.5% | 97.12% ± 0.51% |
| Salt | 1.6% | 98.25% ± 0.05% |
| Salt | 1.7% | 99.54% ± 0.10% |
| Salt | 1.8% | 99.54% ± 0.67% |
| Salt | 2.0% | 99.55% ± 0.18% |
| Chloride-free agent | 2.0% | 97.12% ± 2.48% |
| Chloride-free agent | 3.0% | 97.21% ± 2.01% |
| Chloride-free agent | 5.0% | 99.22% ± 0.82% |
| Chloride-free agent | 8.0% | 99.22% ± 0.47% |
| Chloride-free agent | 10.0% | 99.22% ± 0.57% |
| Polymer | 2% | 99.04% ± 0.52% |
| Polymer | 3% | 99.33% ± 0.70% |
| Polymer | 5% | 99.69% ± 0.04% |
| Polymer | 8% | 99.69% ± 0.11% |
| Polymer | 10% | 99.70% ± 0.08% |
| Molasses | 2% | 99.73% ± 0.02% |
| Molasses | 3% | 99.85% ± 0.09% |
| Molasses | 5% | 99.95% ± 0.02% |
| Molasses | 8% | 99.95% ± 0.03% |
| Molasses | 10% | 99.95% ± 0.03% |

Table 2 also shows different dosages of volumetric concentrations of salt as a chemical surfactant in water. Salt as a chemical surfactant showed a retention efficiency of 97.12% at a dosage of 1.5%. However, the retention efficiency started to increase with time when more concentrated amounts of salt were added to the dosage. A retention efficiency of 99.54% was achieved with a 1.7% dosage and remained constant up until 2.0%. The constantly increasing trend shows that salt performs more effectively over time until the optimum dosage is achieved. A dosage of 1.7% was observed as an optimum volumetric concentration of dilution for the salt solution because beyond this dosage adding a diluted concentration had no impact on the solution's retention efficiency. At a 1.7% optimum value, high-efficiency retention was achieved with less salt. The tested dosage for the chloride-free agent, polymer, and molasses was 2%, 3%, 5%, 8%, and 10%. The volumetric concentration of the chloride-free agent, polymer, and molasses as chemical surfactants in water is shown in Table 2. Retention efficiencies of 97.14%, 99.04%, and 99.73% were achieved at a dosage of 2% for the chloride-free agent, polymer, and molasses, respectively. However, the retention efficiencies started to increase with time when more dosages of concentration were added. Retention efficiencies of 99.22%, 99.69%, and 99.95% were achieved at 5% dilution concentration for the chloride-free agent, polymer, and molasses, respectively. Each retention efficiency remained constant from the 5% dosage to the 10%. The constantly increasing trend shows that the chloride-free agent, polymer, and molasses perform better with time until the optimum dosage is achieved. A volumetric concentration of 5% was observed to be the appropriate dosage for the chloride-free solution, polymer, and molasses solution because after this concentration no added dosage affected the retention efficiency.

Researchers including Samaha and Nagger (1988) and Hancock et al. (1997) also tested different volumetric dilution concentrations until they found the optimum dilution concentration. For example, Samaha and Nagger (1988) used a liquid-by-liquid interaction between chemical surfactants and water to achieve the optimum concentration of a solution. After attaining the optimum dosage, the surface tension of the solution became constant even when they added more surfactant. Samaha and Nagger's objective was to control the concentration of chemical surfactants dispersed in water to avoid overusing of material. The results of Table 2 show the importance of dosage concentration in mixing a solution of chemical suppressant.

### 3.2. The performance of water under different temperatures

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

Fig 6 shows the impact of cold temperatures on water: there is a crusty formation of ice on the surface of the soil sample. This explains why, in the Arctic, brine needs to be sprayed on haul roads to combat freezing (BIMC, 2014; Mikkelsen, 1998; Mitchell et al., 2004; Stotterud and Magne Reitan, 1993). For example, brine was used in combating icy roads in Norway, Denmark, Canada, and the United States to increase vehicle efficiency and reduce road maintenance (BIMC, 2014; Mikkelsen, 1998; Mitchell et al., 2004; Stotterud and Magne Reitan, 1993). Fig 6 shows water at cold temperature forms a crusty slippery surface on the soil sample, which prevents the soil particles from escaping into the atmosphere to form fugitive dust. However, slippery road surfaces can lead to vehicular accidents and an extension in vehicular travel time (Mitchell et al., 2004).

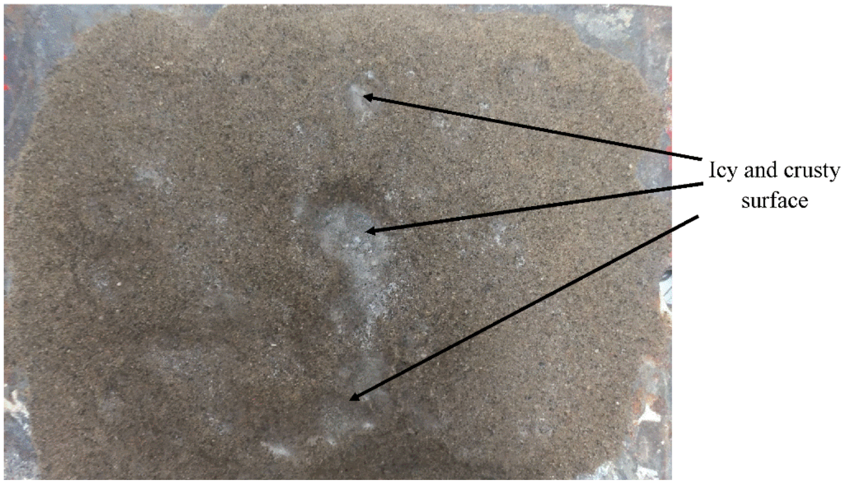

Fig 6. Icy crusty surface formed on the sample with water as a dust suppressant at cold temperatures

Fig 7(a) displays the performance of water as a dust suppressant at different temperatures (i.e., hot, cold, and normal temperatures) for a duration of 30 minutes to 72 hours. Tests were run for 30 minutes, one hour, two hours, three hours, five hours, 24 hours, 48 hours, and 72 hours to help determine the role that time plays in the potency of dust suppression at different temperatures. The corresponding dust retention efficiency associated with each time duration was recorded and plotted.

Fig 7(a) presents the retention efficiencies of water varying with time at hot, cold, and normal temperatures. Water as a dust suppressant in the hot season showed a retention efficiency of 82.02% during the first two hours. However, the retention efficiency started to decrease with time, with a retention efficiency of less than 50% at the end of the 72 hours. The reduction trend shows that water performs less effectively over time as a dust suppression agent in the hot season. Using water at normal room temperatures as a dust suppressant works effectively on dust retention at the preliminary stages, but efficiency decreases as time passes. Other researchers, including Thompson and Visser (2007), also found that water is deficient in this regard; they discovered that instead of cohering to one another, the molecules in the water spread out over time, leading to a higher surface tension. Consequently, there is greater evaporation rate, causing water to be less effective as a suppressant at hot and normal temperatures. However, at cold temperatures, dust retention efficiency is high and consistent with time.

### 3.3. Comparison of dust suppressants under different temperatures

Fig 7(b), (c), (d), and (e) show the average dust retention efficiencies for the chemical suppressants—salt, chloride-free, polymer, and molasses solutions—tested for 30 minutes to 72 hours under all temperature ranges.

Fig 7(b) shows the dust retention efficiency of the salt solution with time under all temperature ranges. Each point marked on the chart represents the retention efficiency of dust on the tested soil sample at different temperatures. In hot temperatures, the salt solution acted effectively when it was first applied as a dust suppressant on the soil sample. Five hours after being applied, it had achieved a retention efficiency of 94.31%. This dust retention decreased steadily up until the third day (after 72 hours) when its effectiveness reached 85.85%. The reduction trend shows that the salt solution performs less effectively over time in hot temperatures. At normal temperatures, for the first five hours, the salt solution held the soil sample together from the moment it was applied, by preventing the fugitive dust from escaping into the atmosphere. The dust retention achieved an efficiency of 95.11%. The longer the suppression agents were exposed to normal temperatures, the less efficient the solution was at dust retention; efficiencies decreased to 87.21% after 72 hours of exposure. However, in cold temperatures, the dust retention was consistent: it was 99.81% after 30 minutes of exposure and 99.93% after 72 hours. Note that mines in Canada's northern territories apply brine to control haul road dust. For example, the Mary River Iron Project in Nunavut uses brine as the sole chemical suppressant for dust control on all their project roads (BIMC, 2014). The efficacy of salt in a solution of water as a dust suppressant was also found in other literature showing that the addition of salt introduces cohesiveness between the water molecules (Cecala et al., 2012). Higher cohesiveness within a solution contributes to the solution's ability to resist atmospheric temperature and lower the evaporation rate (Thompson and Visser, 2007). The result showed in Fig 7(b) supports the claim by the study of former researcher's such as NIOSH, on the efficacy of salt solution as a dust control agent.

Fig 7(c) illustrates the how the chloride-free solution acts as a dust suppression agent on the soil sample at different temperatures. It shows the dust retention efficiency of the chloride-free solution experiment per duration for each temperature. The solution under a hot temperature showed a retention efficiency of 99.30% during the first 30 minutes of exposure. However, the retention efficiency started to decrease with time to 90.15% after 72 hours. The reduction trend shows that the chloride-free solution performed less effectively over time in a hot temperature. At a normal temperature, at the initial stage of application, the chloride-free solution worked effectively on dust retention but became less effective over time. Fig 7(c) shows how effectively the chloride-free solution works, by binding together all the particles in the soil to avoid the generation of dust. The chloride-free solution has a high dust retention efficiency compared to the water and salt solution at different temperatures.

Fig 7(d) presents the effect of the polymer solution as a dust suppressant at all temperature ranges. After 30 minutes in the hot temperature, a retention efficiency of 99.83 % was achieved, but it decreased to 99.78% after 72 hours. Although there is a reduction, the result shows the efficacy of the polymer solution at a hot temperature. At normal and cold temperatures, the polymer solution shows consistently high (above 99.87%) dust retention efficiencies. Other researchers, such as Watson et al. (2000), have reported similar findings, that the adhesiveness between the molecular structure of the polymer solution is higher, with a smaller surface tension contributing to its lower evaporation rate. Polymer emulsion is a popular chemical suppressant for road haul dust control (Goma and Mwale, 2016; Thompson and Visser, 2007) in humid subtropical climates, such as Zambia and South Africa. Among the mines that use this method is The Highveld Coalfields Mine in South Africa's Mpumalanga Province (Thompson and Visser, 2007). Fig 7(d) shows that the polymer solution is more efficient than water, the salt solution, and the chloride-free solution at controlling dust on the soil sample at different temperatures.

Fig 7(e) shows the outcome of dust retention efficiency with time when a solution of molasses is used as a dust suppression agent to control fugitive dust emissions on a soil sample at different temperatures. At a hot temperature, after 30 minutes of exposure to the molasses solution, a dust retention efficiency of 99.93% is achieved. By the end of 72 hours, the retention efficiency had increased to 99.98%. The increasing trend shows that the molasses solution is highly effective over time in the hot temperatures. At normal room and cold temperatures, the molasses solution became even more effective as time passed. Thompson and Visser (2007), Watson et al. (2000), and NIOSH (Cecala et al., 2012) also found that molasses is effective at suppressing dust: the adhesiveness between the molecular structure of the molasses solution are closer together than most chemical dust suppressants, thus contributing to smaller surface tension and less evaporation rate. However, the molasses solution is efficient regardless of the temperature. This explains why some cities located in tropical, semi-arid climates use molasses as a chemical suppressant to control dust on haul roads. For example, the city of Maharashtra in India used molasses as a dust control method on their roads after an experimental research, which proved molasses to be an effective chemical dust suppressant. Fig 7(e) shows the effectiveness of molasses as a chemical suppressant at different temperatures compared to water, and to salt, chloride-free, and polymer solutions.

### 3.4. Comparison of dust suppressants at a hot temperature

Fig 7(f) shows the effectiveness of all the tested dust suppressants at a hot temperature. Water was the first dust suppressant examined under a hot temperature. At the initial stage of application, water was highly efficient, but as time progressed the dust retention decreased. As the water was exposed to heat, it quickly evaporated.

Higher surface tension lowers the ability of the solution to hold particulates together (Kavouras et al., 2009). These characteristics of water make it less effective, hence the need to introduce chemicals as dust suppression agents. Fig 7(f) shows that adding chemical suppressants improves dust retention efficiency over time. The salt solution made the water a more effective suppressant, and the chloride-free solution also enhanced the efficiency.

### 3.5. Comparison of dust suppressants under a normal temperature

Fig 7(g) shows the effect of all the tested dust suppressants over time at room temperature. Of all the tested dust suppressants, water was the least efficient at dust retention over time: the other chemical suppressants tested were better able than water to control the dust.

Many authors (Amponsah-Dacosta, 1997; DeLuca et al., 2012; Foley et al., 1996; Gillies et al., 1999) (Jones, 1996; Kavouras et al., 2009; Plush et al., 2011; Reed and Organiscak, 2008) found that water was less effective than chemical suppressants at controlling dust. They all concluded that water is composed of molecules that are widely spaced from each other, causing a higher evaporation rate when applied as a dust suppressant. In addition, they explained that introducing a chemical suppressant in place of water works effectively because it solves the deficiency of water. Moreover, the closer the distance between molecules in a solution, the lower the surface tension of the solution, leading to a decreased in evaporation rate of the solution when applied as a dust suppressant (Jones, 1996; Plush et al., 2011; Reed and Organiscak, 2008). Fig 7(g) shows the effectiveness of the chemical suppressants compared to water at a normal temperature, consistent with findings from previous research.

### 3.6. Comparison of dust suppressants in a cold temperature

Fig 7(h) shows the effect of all the selected dust suppressants in cold temperatures over time. As a dust suppressant in cold temperatures, water presented a dust retention efficiency of 99.81% after 30 minutes and increased to 99.92% at the end of 72 hours. This incremental trend shows that over time, water performs more effectively a dust suppressant in cold temperatures. In cold temperature, an icy structure is formed on the soil sample when water is applied with time as shown in Fig 6, which prevents the escape of the soil particles into the atmosphere. This decreases the surface tension of water and reduces the rate of evaporation. The outcome of this result with water as the dust suppressant at cold temperature refutes the claim by former researchers, such as Thompson and Visser (2007) and Reed and Organiscak (2008), showing that the efficiency of water decreases with time.

All the selected chemical suppressants (i.e., salt, chloride-free, polymer, and molasses solutions) showed dust retention efficiencies of 99.81%, 99.83%, 99.88%, and 99.98%, respectively, after 30 minutes of exposure to cold temperatures and efficiencies of 99.93%, 99.93%, 99.94%, and 99.99%, respectively, after 72 hours. The incremental trend is evidence that the chemical suppressants are effective in the cold. This explains why most mining and road construction companies use chemical suppressants instead of water to control dust on haul roads (Amponsah-Dacosta, 1997; Cowherd et al., 1988). For example, Gilles et al. (1999) used different chemical suppressants for dust control on unpaved public roads in Merced County, California. Amponsah-Dacosta (1997) used chemical suppressants such as calcium chloride and polymerized bitumen to control dust on most surface mine haul roads in South Africa.

Fig 7(h) confirms previous research claims (Jones, 1996; Plush et al., 2011; Reed and Organiscak, 2008). At a cold temperature, it was observed that a crusty icy surface formed on the soil sample after water and the chloride-free and polymer solutions were applied over time.

### 3.7. Comparison of dust suppressants under all temperatures

A summary of the effect of all the tested dust suppressants at hot, cold, and normal temperatures over time is shown in Table 3. The data shows the importance of temperature on the effectiveness of chemical suppressants over time on fugitive dust.

The best solutions for dust control are those that can withstand external environmental factors such as extreme temperatures and wind speed, contributing to a good retention of moisture content on the surface of application. The ability to withstand external environmental factors makes chemical suppressants more effective than water, which requires constant reapplication to be efficient at dust control in hot and normal temperatures

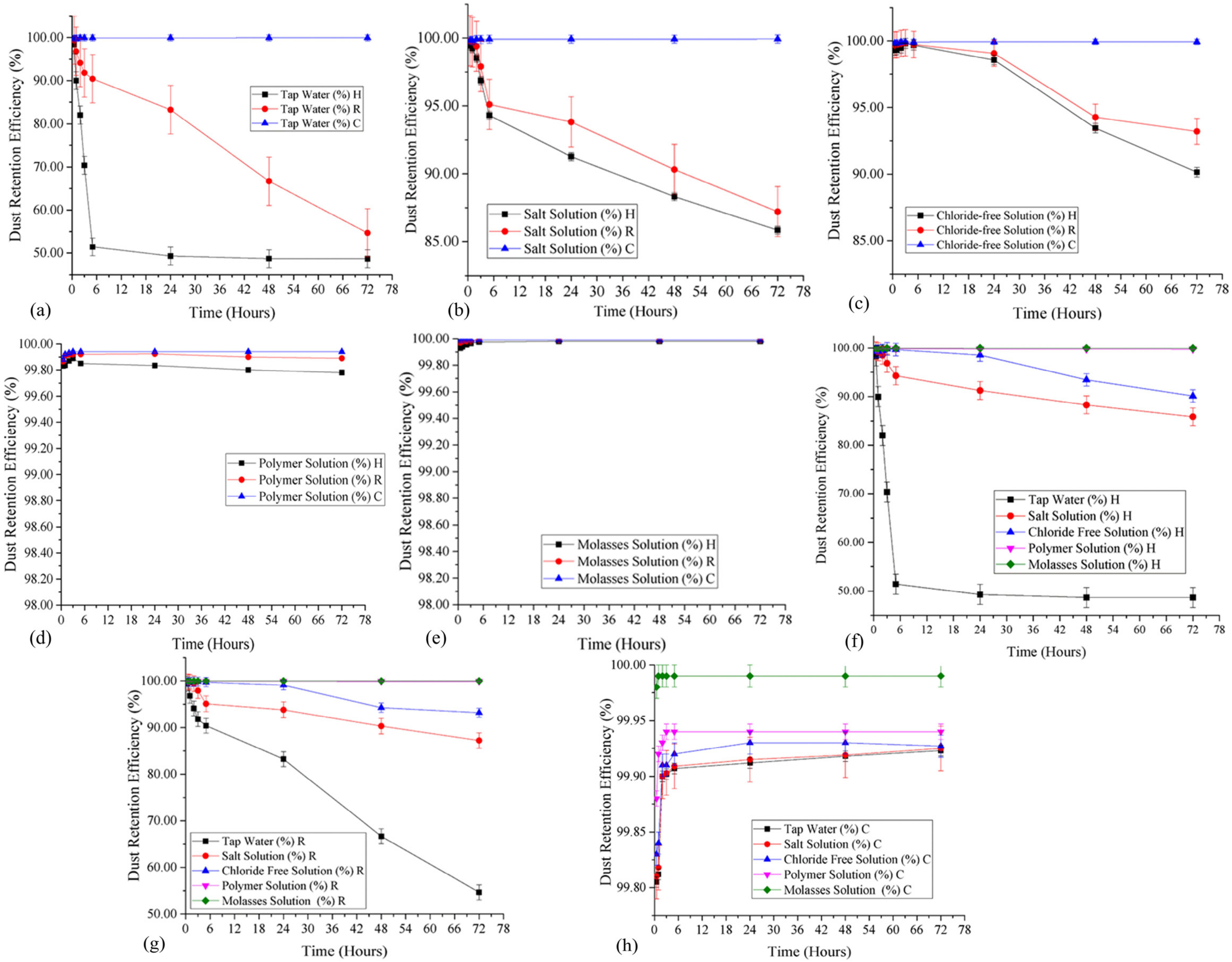

Fig 7. (a) Effect of water as a dust suppressant for all temperature ranges; (b) Effect of salt solution as a dust suppressant under all temperature ranges; (c) Effect of chloride-free solution as a dust suppressant under all temperature ranges; (d) Effect of polymer solution as a dust suppression agent under all temperature ranges; (e) Effect of molasses solution as a dust suppression agent under all temperature ranges; (f) Effect of all the tested dust suppressants at a hot temperature; (g) Effect of all the tested dust suppressants at a normal temperature; (h) Effect of all the tested dust suppressants in the cold season

Table 3. Summary of retention efficiency of all the tested dust suppressants under hot, cold, and normal room temperatures

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

## 4. Conclusion

This paper presents the effects of different temperature conditions on suppression agents for the control of fugitive dust emissions. The conclusive findings are enumerated as follows:

- There is an optimum volumetric concentration level of chemical surfactant in a solution. This optimum concentration plays an important role in the effectiveness of a chemical dust suppressant. An increase above the optimum concentration level will have little or no impact on a chemical dust suppressant's efficiency. In short, increasing the concentration over the optimum level incurs more cost and time, which can be avoided.
- Water performs differently depending on the environmental temperatures. In experiments with cold temperatures, at the initial application of water on the soil sample after 30 minutes, a dust retention efficiency of 99.81% was achieved, which gradually increased to 99.92% after 72 hours of exposure. Under hot and normal temperatures, a dust retention efficiency of 98.38% and 99.40%, respectively, was achieved after 30 minutes of application on the soil sample but the efficiency diminished over time to 48.67% and 54.57%, respectively, after 72 hours. This problem of diminished efficiency in dust retention under the hot and normal temperatures means that water has to be constantly reapplied to the soil sample to prevent fugitive dust emissions.
- The salt solution as a dust suppressant worked effectively in controlling the emission of dust from the soil samples. After 30 minutes of applying the salt solution suppressant to the soil samples in both hot and normal temperatures, dust retention efficiencies of 99.45% and 99.80%, respectively, were achieved. These efficiencies decreased with time to 88.85% and 87.21% after 72 hours of exposure to hot and normal temperatures, respectively. In cold temperatures, a dust retention efficiency of 99.81% was achieved during the initial 30 minutes of application to the soil sample, but efficiency gradually increased to 99.93% after 72 hours of exposure. Also, salt combined with water proved to be more effective at dust retention than water alone.
- After 30 minutes of exposure to hot, normal, and cold temperatures, the dust retention efficiencies of the chloride-free solution were 99.30%, 99.70%, and 99.93%, respectively. The effectiveness of the chloride-free solution decreased with time to 90.15%, 93.20%, and 99.93%, respectively, after 72 hours of exposure to different temperatures. This outcome shows that the chloride-free solution has a better capacity than the water-and-salt solution to control the emission of fugitive dust into the atmosphere.
- After 30 minutes of exposure to hot, normal and cold temperatures, the polymer solution demonstrated dust retention efficiencies of 99.83%, 99.87%, and 99.88%, respectively. After 72 hours, there was a reduction in the efficiencies to 99.78%, 99.89%, and 99.94%, respectively. This stable performance showed that the polymer solution is an effective dust suppressant. Unlike water and the salt and chloride-free solutions, the polymer solution's retention efficiency is not affected by temperature.
- The molasses solution showed dust retention efficiencies of 99.93%, 99.97%, and 99.98% after 30 minutes of exposure to hot, normal and cold temperatures. After 72 hours of exposure, there were efficiencies of 99.98%, 99.99%, and 99.99%, respectively, showing that the molasses solution is an effective dust suppression agent compared to the other tested agents. As with the polymer solution, the molasses solution's retention efficiency is not affected by atmosphere temperature
- A crusty, slippery surface formed on the soil sample under the cold temperature when water, the chloride-free solution, and the polymer solution were applied as dust suppression agents. No crusty, slippery surface formed when the salt and molasses solutions were used at a cold temperature.

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