Journal of Air Pollution and Health (Winter 2026); 11(1): 25-44

Original Article

Available online at http://japh.tums.ac.ir

Utilizing sugar beet molasses for stabilization and dust suppression of mine haul road soil: A case study of Abyek Cement Mine

Mahdi Salehabadi[1], Farhang Sereshki[1], Mir Hossein Shahami[2], Mohammad Karamoozian[1], Ali Mirzaghorbanali[3], Hossein Khakshour[1,*]

[1] Faculty of Mining, Petroleum and Geophysics Engineering, Shahrood University of Technology, Shahrood, Iran
[2] Mining Engineering, Rock Mechanics, Iran Minerals Production and Supply Company (IMPASCO), Tehran, Iran
[3] Geotechnical Engineering, School of Engineering, University of Southern Queensland, Toowoomba, Queensland, Australia

ARTICLE INFORMATION

Article Chronology:
Received 28 February 2025
Revised 15 February 2026
Accepted 03 March 2026
Published 29 March 2026

Keywords:
Haul roads dust; Dust suppression; Molasses; Sugar beet; Atterberg limits tets

CORRESPONDING AUTHOR:
hossainkhakshour@gmail.com
Tel: (+98 23) 32392204
Fax: (+98 23) 32392204

ABSTRACT

Introduction: Haul roads are one of the main sources of dust in mines. Dust pollution not only causes lung diseases, but also reduces the useful vision of machine drivers, slows down trucks, and interferes with transportation operations. On the other hand, machines' operation in dust increases their depreciation and fuel consumption. The popular spraying method is used in mines to overcome this problem. To suppress dust on mining roads, water and oil mulch are commonly used. The first method requires a large amount of water, and the second method has undesirable environmental effects. Therefore, an appropriate alternative method should be found. According to the results, the proposed method may be effective in dust suppression. This process causes both environmental and operational difficulties, including high water consumption, inefficiency in hot and dry areas, and costly water supply in many regions, not to mention its cultural value, soil liquefaction, traffic by the irrigation process, imposing repairing and maintaining costs for sprinklers and ramps, etc.

Materials and methods: Soil stabilization is a technique that enhances the engineering and mechanical characteristics of soil, such as its strength, stiffness, formation, and loading capacity using technology and proper materials. The present research aimed at finding out how the physical and strength properties could be improved with the addition of optimum ratios of sugar beet molasses to the ramp soils to make the unpaved roads within the Abyek cement mine region stronger and more durable.

Results: As analytical tests for soils containing additives with specified weight percentages, Atterberg limits, compaction, Unconfined Compressive Strength (UCS), and direct shear tests were conducted. The incorporation of sugar beet molasses into both soils resulted in an 11.6% reduction in Optimum Moisture Content (OMC) and increased the Maximum Dry Density (MDD) to 1.955 g/cm³ for AB01 soil and 1.942 g/cm³ for AB02 soil.

Conclusion: The optimal result was obtained from direct shear and unconfined compressive tests by adding 2% molasses for AB02 soil and 1% molasses for AB01 soil.

Please cite this article as: Salehabadi M, Sereshki F, Shahami MH, Karamoozian M, Mirzaghorbanali A, Khakshour H. Utilizing sugar beet molasses for stabilization and dust suppression of mine haul road soil: A case study of Abyek Cement Mine. Journal of Air Pollution and Health. 2026;11(1): 25-44.
Doi: https://doi.org/10.18502/japh.v11i1.21268

Introduction

One of the environmental pollutants is dust. In open-pit mines, trucks are used to transport ore and waste materials. Dust is a general term used to describe fine particles or airborne solid particles in a size range of about 0.5 to 100 µm and more. Mineral dust is produced by an extensive range of processes such as blasting and drilling, loading, transporting minerals, and primary crushing of minerals for processing. Moving high-tonnage trucks on roads has been generally proven to be challenging for the environment. Prolonged exposure to dust can cause health issues such as silicosis, lung cancer, pneumoconiosis, tuberculosis, emphysema, chronic bronchitis, and Chronic Obstructive Pulmonary Disease (COPD). Quartz particles can also lead to chronic kidney diseases, monoclonal gammopathy, amyloidosis, Sjogren's syndrome, rheumatoid arthritis, systemic sclerosis (scleroderma),sarcoidosis and lupus (systemic lupus erythematosus). As the amount of dust increases, so does the risk of explosion. Dust accumulation can reduce visibility for operators and exacerbate wear on machinery's moving parts, leading to quicker equipment failure and aging. It also increases cleaning costs, as regular maintenance is necessary to control dust buildup. These harmful impacts of workplace dust may translate into financial losses for mining firms through legal sanctions, health-related claims, and decreased production and efficiency. The health issues arising from silica-related diseases can significantly lower the quality of life for workers and their families. The research results of the United States Environmental Protection Agency (EPA) on open-pit roads revealed that haul trucks produce the highest amount of dust with a particle size of less than 10 µm in open-pit mines (approximately 78% to 97% of the emitted dust particles by haul trucks) [1, 2]. Researchers conducted researched on open-pit coal mines in South Africa and showed that 93.3% of total dust emissions on roads were by haul trucks [3]. The amount of emitted dust by various types of equipment in open-pit mines (along with fire dust) showed that haul road dust (91%) has the first rank as a dust production source in open-pit mines [4]. There are generally three mechanisms for vehicle movement that change particles to volatile dust including mechanical shear, shear stress caused by turbulence, and saltation [5]. Other researchers found that vehicle speed and weight had a higher effect on dust production. They demonstrated that the other two mechanisms (turbulence and saltation) may have a greater effect on the amount of dust produced by the moving vehicle [6].

The most frequently utilized method for reducing dust on haul roads involves watering the roads. This method has a simple mechanism and is the simplest method for dust control. However, using water in hard conditions such as arid mountainous areas is costly and inefficient. In one of the mines in Iran, for an extraction of 300,000 tons in 24 h, the amount of water used for dust suppression was 1,700,000 liters, indicating that 5.6 liters of water were consumed per ton of extracted material. On the other hand, daily water use imposes excessive water consumption and is a one-way partial solution with an efficiency of over 40% and a high evaporation rate of nearly 30 min [1]. The U.S. EPA found that using 0.13 gal/yd^2 of water on haul roads controlled total suspended particles (TSP) with 95% efficiency for 0.5 h, while applying 0.46 gal/yd^2 achieved 74% efficiency over 3-4 h [7].

In general, haul road dust can be controlled by three main methods. The first method is road construction and proper maintenance. The second method is using dust palliatives, and the third method is soil stabilization [8]. The first step to prevent dust from spreading on haul roads is to pay attention to the design and construction of the road. Although proper road construction has high initial costs, it reduces other costs such as road maintenance, increased tire lifespan, and dust control on the road [1].

Dust palliatives refer to substances or chemicals applied to surfaces to mitigate dust generation. Dust palliatives or chemical soil stabilizers are used to remove particulate material in many places. Selecting the best dust palliative optimizes the costs, protects the environment, and improves personnel's health [9]. Soil stabilization is defined as the modification of the physical, strength, and engineering properties of soil to supply a series of pre-determined goals. The most important goals of soil stabilization include modifying soft and low-strength soils, reducing dust, increasing soil load-bearing resistance, preventing soil erosion, reducing the thickness of pavement layers, and forming base and substrate layers with more load-bearing capacity. Since natural soils rarely have essential engineering properties to build a road, adding additives to the soil to improve unpaved roads' strength properties has changed to the common construction technic for unpaved roads called soil stabilization. Soil stabilization was employed using chemical technology, and sugar beet molasses was used as a chemical additive to suppress dust.

In 2024, researchers introduced a bio-based dust suppressant using urease-induced carbonate precipitation technology. They reported mass loss rates of 0.24 $g/m^2/min$ for wind erosion and 156.51 $g/m^2/min$ for rain erosion, demonstrating resistance to these forces. Relative to pure urease treatment, erosion resistance from windincreased by 90%, while rain erosion resistance showed a 25.53% improvement. According to the study, the distribution of calcium carbonate was uneven and closely related to the hardness, penetration resistance, and thickness of the crusts. This can be explained by the macromolecular organic components in raw urease, which facilitate the creation of a spatial network, act as bonding agents, and offer nucleation sites for urease-induced calcium carbonate production. This promotes calcium carbonate deposition and aggregation, thereby enhancing the crust's strength [10].

In 2023, many researchers carried out field experiments to evaluate the use of three biopolymers Corn Starch (CS), Xanthan Gum (XG), and Faba Bean Protein Concentrate (FBPC) as effective dust suppressants. Their results indicated that all three biopolymers were effective at reducing Dust emissions for as long as 8 days post-application, with the treatments showing greater durability under dry conditions. They suggested that biopolymers could be a promising short-term solution for dust control in barren, mineral-rich soils, Offering a natural substitute for conventional dust suppressants like chloride salts or petroleum-based products [11].

Sanders et al. assessed the relative effects of three main dust palliatives, namely magnesium chloride, calcium chloride, and lignosulfonate. All three reduced fugitive dust on unpaved roads by 50% to 70%, and the sections tested with dust palliatives reduced dust emissions by approximately 40% to 60% compared to other sections [12].

Many researchers investigated dust palliatives in open-pit mines using YCH dust palliatives. Testing this palliative on mining roads and daily measurement of particle size showed that the dust concentration was 4.9 mg/m3, and this palliative was effective in reducing dust by 98.4%. Furthermore, it reduces water consumption by 98% and costs by 31% compared to water spraying [13]. Other researchers studied dust suppressant treatments and stated that the purpose of treatment is to add additives to the soil. These additives are chemical products or organic compounds the change geotechnical properties of soil and control the emission of particulate materials. This treatment is also called soil stabilization when the additives in soil are mixed by a enough-thick layer (by mechanical equipment). The described methods are comparable when assessing wind erosion and unpaved roads as yield evaluation of different types of particulate materials' suppressant using objective data [9].

Barnes et al. studied dust management on unpaved roads and airport runways and found that fugitive dust originating from vehicle traffic on unpaved roads and airport runways can have a significant effect on safety, health, and quality of life. Therefore, dust production can be managed by reducing the speed of automobiles on roads and correct usage of dust palliatives as the made shear force in the interface of road surface and automobile tires makes dust. The results showed that selecting a dust palliative depends on the granulation, traffic volume, weather conditions, and location [5].

Many researchers studied the effectiveness of using dust suppressors. The results of their research show a cost saving of 30% using lignin sulfonate for dust control [14]. Other researcherscompared dust palliatives under different temperatures to control dust diffusion on mining roads. The research involved testing four types of dust palliatives commonly used in mining: Salt-based solution, polymer solution,non-chlorine solution and molasses-based treatment. The goal was to determine their impact on dust emissions from mining roads across three distinct atmospheric temperatures, simulating cold, normal, and hot seasons. The study found that salt, chloride-free, and polymer solutions were more effective than water. Additionally, the atmospheric temperature was shown to be a key factor influencing the efficiency of the palliatives [15].

Other researchers evaluated unpaved roads using a dust palliative based on polymer. A co-polymer palliative with four concentrations of 1, 2 3, and 5 wt% was used for dust emission. The test results showed that 5% of the copolymer sample manifested better yield to reduce dust with 1, 2, and 3% of copolymer samples. In addition, electron microscopy imaging showed that higher concentration rates of co-polymer palliative caused thin layers to increase adhesion and bonding of the specimens, which reduced dust production on unpaved roads and mineral roads [16].

Many researchers studied chemical techniques for dust control in open-pit mines. Using dust palliatives is a practical solution to suppress and reduce dust in open mine haul roads [17].

Cecala et al. discuss the control of road dust caused by mineral transport in a book entitled "dust control in mines and processing plants". This book mainly addresses the issue of controlling road dust.This book describes the types of required dust palliatives such as water, salts, adhesives, surfactants, nano clays, and equipment needed to use palliatives [1].

Mechanism of dust production in the haul roads

Dust production from unpaved roads can originate from multiple sources. The mechanical loss of the surface of unpaved roads produces dust. In addition, the shear force created at the interface between the vehicle tire and aggregates brings about dust when vehicles cross the road surface. The weight of the vehicle also crushes particles, as a mill, when the aggregates are placed on tires. The repetition of crushing breaks down the particles produces dust and places fine soil particles on the surface of unpaved roads. Airborne dust from other sources such as farms or other dust roads, etc. can be placed on the road. Finally, the dust adhered to the automobile and its tires entering the road is another probable source of dust. These processes are depicted in Fig. 1 This dust is available from various sources to change into airborne dust and fugitive dust [5].

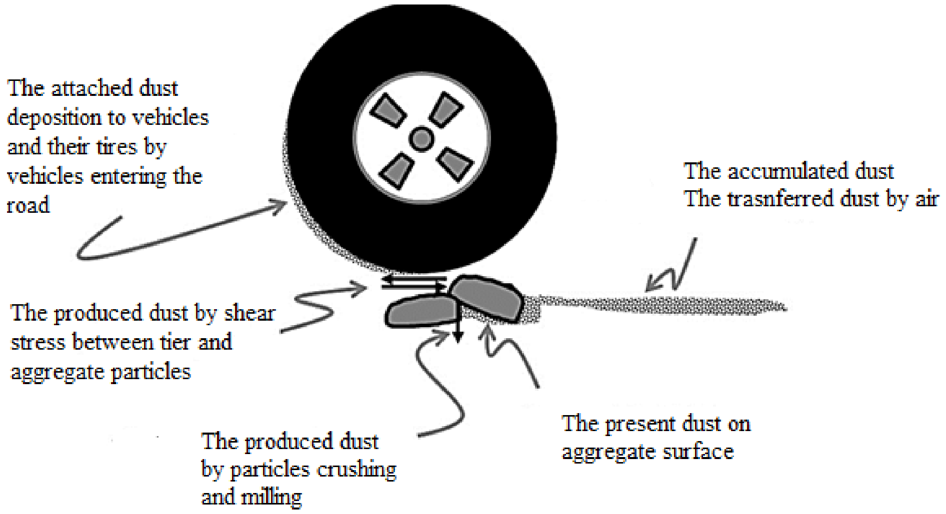

Fig. 1. Dust sources in the soil and mine roads[5]

Fig. 2. The used molasses in the research

Investigation of sugar beet molasses yield in improving soil strength properties additives

Molasses are concentrated, dark, and sticky extracts and a by-product in the process of preparing sugar from sugar beet or sugarcane a concentrated brown juice remains after extracting the sugar crystal from sugarcane and sugar beet extract. The produced molasses in sugar factories include cane sugar molasses and beet sugar molasses. The additive used in this research is sugar beet molasses. The used molasses is shown in Fig. 2 with a specific weight of 1.4 g/cm^3, and its color is blackish-brown with a specific odor.

The physical and chemical properties of sugar beet molasses are provided in Table 1.

Table 1. The chemical and physical characteristics of sugar beet molasses

Physical and chemical properties	Sugar beet molasses
Color	Blackish brown
Appearance	Milky
Specific weight	1.4 g/cm^3
Brix	85%
Weight percentage of sugar (sucrose)	46 %
Percentage by weight of minerals	12 %
Percentage of water	16.5 %
Percentage by weight of crude protein	10%

Fig. 3. The region map road access ramp, and soil mine ramp

Materials and methods

Soil samples were taken from Qazvin Province, Abyek City, Abyek Cement Mine, Main Road Access Ramp, and Soil Mine Ramp which are known as AB01 and AB02. Abyek is located at 4.36° latitude north and 45.50° east. Abyek Cement Complex is located 80 km west of the Tehran- Qazvin High-Way on the southern slope of Pirali Mountain. Its medium latitude is about 1300 m of sea level and has a relatively cold winter and moderate summer.
The region map is shown in Fig. 3.

The geotechnical properties of both soil types are shown in Table 2.

Table 2. Soil properties of AB01 and AB02 from a geotechnical perspective

No.	Tests	AB 01 soil	AB 02 soil
1	USCS Soil Classification	GC	GP-GC
2	Grain Size Distribution (%)		
	Gravel content% (25 to 4.75 mm)	71.09	61.96
	Sand content% (4.75 to 0.075 mm)	28.75	26.59
	Silt and clay content% (less than 0.075 mm)	0.15	11.45
3	Atterberg limit test (Soil passing through sieve number 40)		
	Liquid limit (%)	33.02	37.46
	Plastic limit (%)	20.47	20.77
	Plasticity index (%)	12.55	16.69
4	Standard compaction test (soil passing through sieve number 4		
	Maximum Dry Density (MDD) $^{gr}/_{cm^3}$	1.927	1.902
	Optimum Moisture Content (OMC) (%)	13	13.70
5	Direct shear (Soil passing through sieve number 4)		
	C: cohesion (Kpa)	49.79	57.82
	Ø: angle of friction (°)	21.33	27.27
6	unconfined compressive strength UCS (Kpa) (Soil passing through sieve number 4)	203.3	271.066

Fig. 4 presents the grain size distribution results from sieve analysis and hydrometer tests for both soil types.

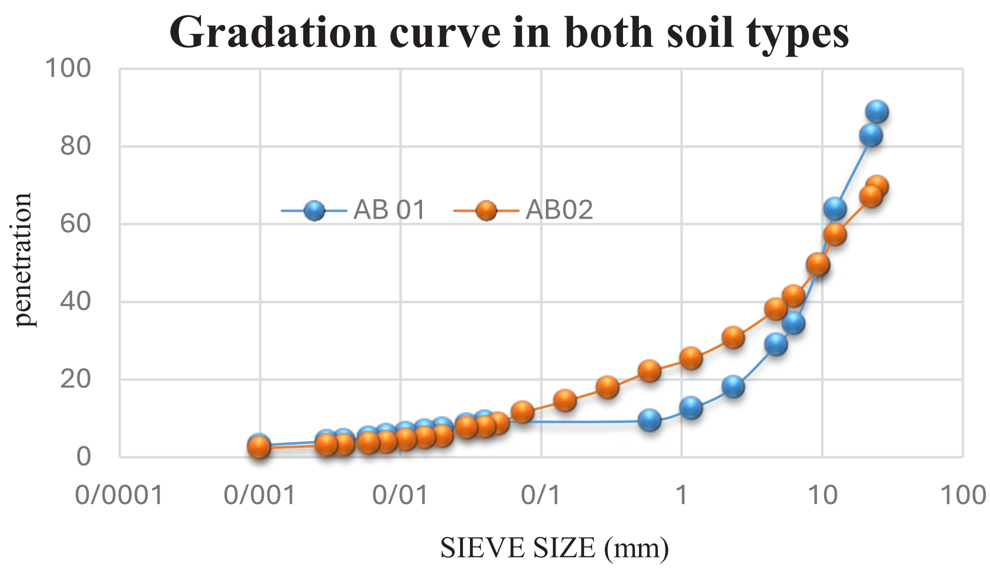

Fig. 4. Gradation curve for soil types AB01 and AB02

Preparation method and sample test

Various additives including cement or chemicals have been used to improve the soil. Additives used in the past are still used today including cement, bitumen, lime, ash, etc. The effect of adding sugar beet molasses on soil resistance behavior was investigated with a certain percentage of molasses on the sample weight.

Laboratory tests

Soil samples from two haul roads of Abyek Cement Mine (AB01 and AB02) were mixed with 1%, 2%, 3%, and 5% by weight ratios of sugar beet molasses To enhance the soil's mechanical and strength characteristics. Since the shear force at the interface between the tires of heavy types of machinery and aggregates creates more dust, strength tests such as compaction tests, Tests for direct shear and unconfined compressive strength were carried out on soil samples and molasses mixtures, with molasses content specified by weight percentages.

Compaction test

The standard Proctor test, based on ASTM D 698, was used to assess the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of soil samples, both without molasses and with molasses concentrations of 1, 2, 3, and 5 wt% for each soil type [18]. A compaction test was performed in this research by Standard proctor compaction method and with a small mold to examine soils that have passed the grade 4 sieve. According to Fig. 5, the first 2 kg of soil with initial moisture and sugar beet molasses was mixed with the mentioned percentages in the mold in three layers, and each layer received 25 hits. Then the mold was weighed with the soil. The weight of soil was calculated after determining the mold weight. In addition, the specific wet weight of the soil was obtained after determining the mold volume and soil weight. Then moisture was added to the soil again and the experiment was repeated.

Fig. 5. Compaction test

Investigation of molasses in soil compaction improverment

The standard compaction test findings for untreated soils and those treated with molasses at dosages of 1%, 2%, 3%, and 5% by weight are reported in Tables 3 and 4. The corresponding changes in optimum moisture content and maximum dry density appear in Figs. 6 and 7. It is observed that treating soils with molasses slightly increases the maximum dry density and marginally decreases the optimum moisture content. Figs. 6 and 7 demonstrate that the application of molasses raises the maximum dry density while lowering the optimum moisture content in both soils. The decrease in moisture uptake is a result of molasses-induced soil aggregation and agglomeration, which enhance coarse aggregate formation and lower the clay colloidal content. According to Tables 3 and 4, adding molasses resulted in a slight enhancement of the maximum dry density, increasing from 1.927 g/cm^3 to 1.955 g/cm^3 for ab01 soil and from 1.902 g/cm^3 to 1.942 g/cm^3 for ab02 soil. Molasses' adhesive properties are likely responsible for the observed increase, as they cause soil particles to bind together, enhancing the maximum dry density.

The standard compaction test findings for untreated soils and those treated with molasses at dosages of 1%, 2%, 3%, and 5% by weight are reported in Tables 3 and 4. The corresponding changes in optimum moisture content and maximum dry density appear in Figs. 6 and 7. It is observed that treating soils with molasses slightly increases the maximum dry density and marginally decreases the optimum moisture content. Figs. 6 and 7 demonstrate that the application of molasses raises the maximum dry density while lowering the optimum moisture content in both soils. The decrease in moisture uptake is a result of molasses-induced soil aggregation and agglomeration, which enhance coarse aggregate formation and lower the clay colloidal content. According to

Tables 3 and 4, adding molasses resulted in a slight enhancement of the maximum dry density, increasing from 1.927 g/cm³ to 1.955 g/cm³ for ab01 soil and from 1.902 g/cm³ to 1.942 g/cm³ for ab02 soil. Molasses' adhesive properties are likely responsible for the observed increase, as they cause soil particles to bind together, enhancing the maximum dry density.

Table 3. Compaction test results for AB01 soil

Additive	Maximum Dry Density (MDD) ($^{gr}/_{cm^3}$)	Optimum Moisture Content (OMC)%
AB 01 soil	1.927	13
1% molasses	1.932	12.8
2% molasses	1.942	12.5
3% molasses	1.950	12
5% molasses	1.955	11.6

Table 4. Compaction test results for AB02 soil

Additive	Maximum Dry Density (MDD) g/cm^3	Optimum Moisture Content (OMC)%
AB 02 soil	1.902	13.7
1% molasses	1.914	13.2
2% molasses	1.926	12.45
3% molasses	1.936	12
5% molasses	1.942	11.6

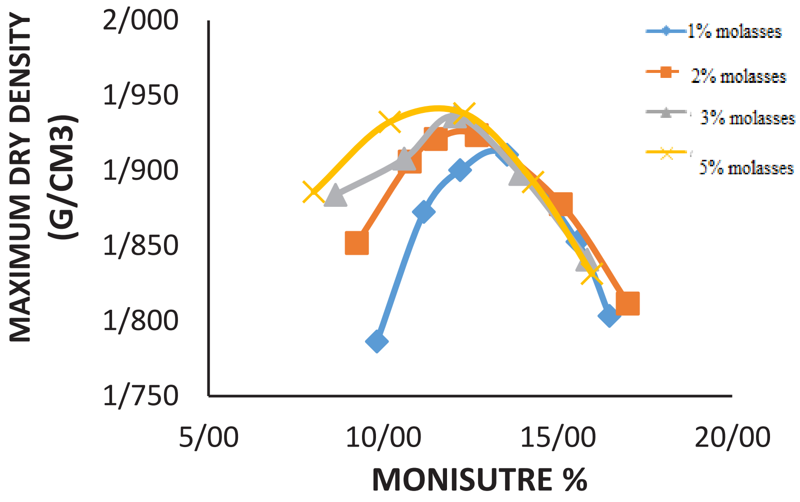

Fig. 6. Compaction curve for AB01 soil

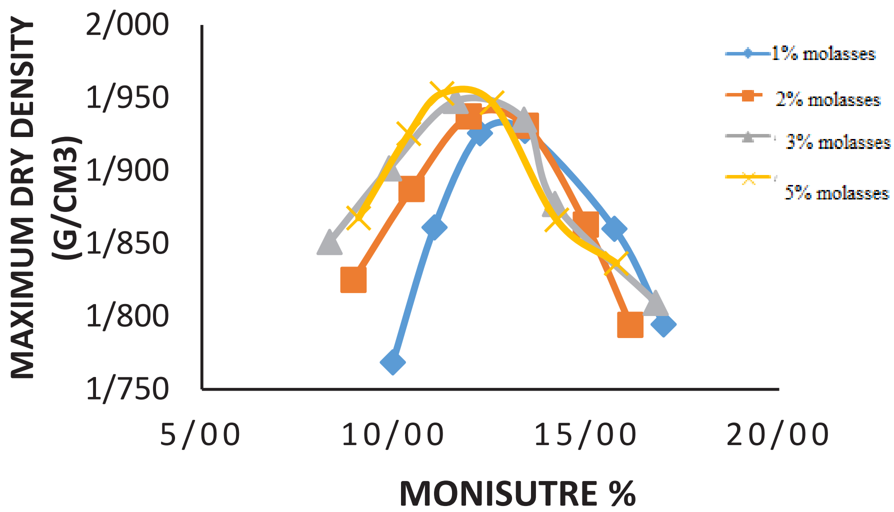

Fig. 7. Compaction curve for AB02 soil

Direct shear test

According to the ASTM 3080 standard, the direct shear test was performed to measure the cohesion (C) and angle of friction (ϕ) of soils, including untreated samples and those treated with 1%, 2%, 3%, and 5% molasses by weight [19]. According to Fig. 8, the first soil sample was prepared, and the soil total weight was calculated by adding the mentioned moisture based on the mold volume of 350 cm^3 and the maximum specific weight of the soil. Then, the sample was crushed and prepared in the specific shear mold. The shear test was performed under 10, 20, and 30 kg over-load. The displacement was read in the system using LVDT up to 9 mm. Loading speed was considered 0.9 mm/min. Finally, the strain stress curve was drawn for a 7mm displacement. Overload stress curves were also plotted based on the final stress at each stage, and the cohesion and angle of friction were calculated.

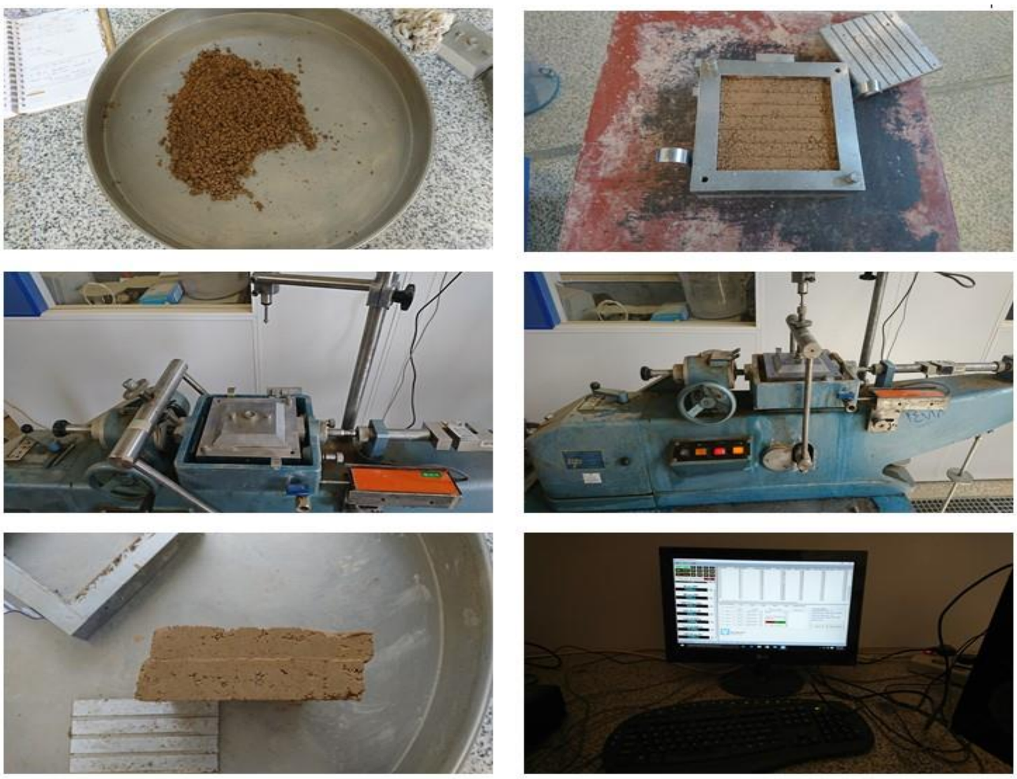

Fig. 8. Direct shear test

Table 5. Direct shear test results for AB01 soil

Angle of friction (φ)	Cohesion (kpa)	Additives
21.33	49.79	AB01
19.68	44.825	1% molasses
20.79	51.57	2% molasses
22.65	16.153	3% molasses
19.63	13.07	5% molasses

Molasses influence on direct shear properties

Results obtained from the direct shear tests and maximum shear stress - vertical stress curves were shown in Tables 5-6 and Figs. 9-10. Adding molasses in ab01 soil first decreases the cohesion and then increases by 2% and decreases by 3% and 5%. The highest cohesion is related to 2% molasses additive in soil ab01. Adding molasses to ab02 soil increases cohesion This means that the adhesion of molasses in ab02 soil binds the soil particles together, which increases the cohesion. Also, the angle of friction according to the inverse cohesion table in both soils should be reduced first and then increased.

Table 6. Direct shear test results for AB02 soil

Angle of friction (φ)	Cohesion (kpa)	Additives
27.27	57.82	AB02
24.82	77.67	1% molasses
33.05	60.75	2% molasses
26.90	53.97	3% molasses
24.53	59.67	5% molasses

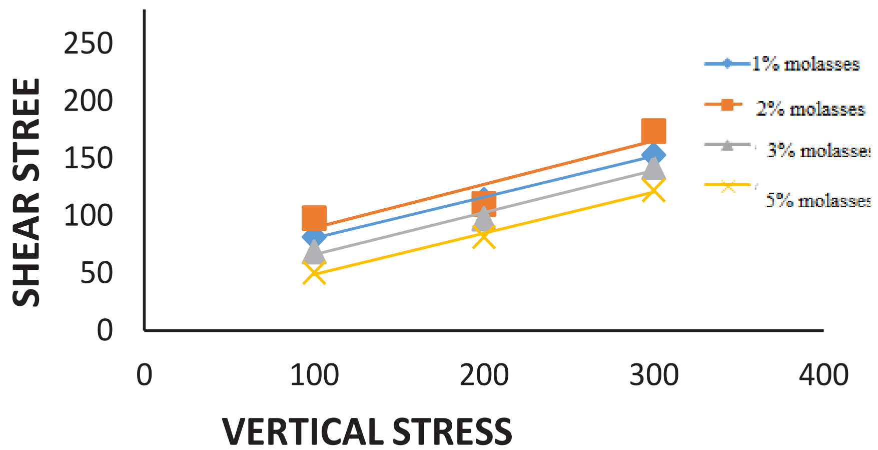

Fig. 9. Maximum shear stress vs. vertical stress for AB01 soil

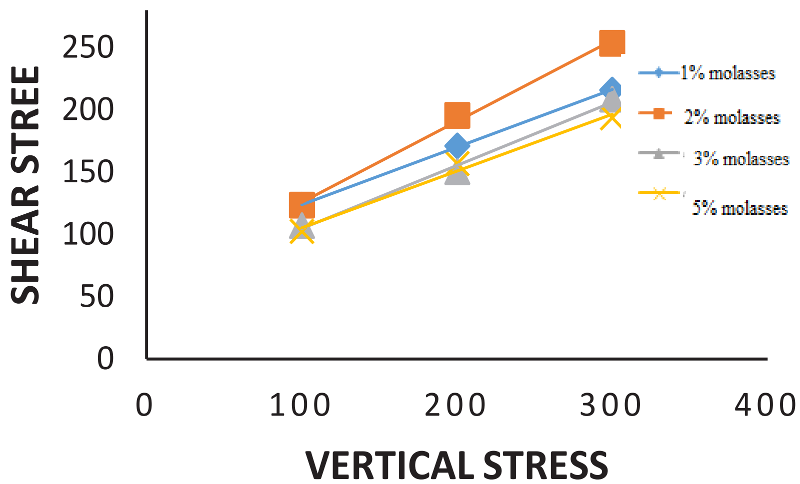

Fig. 10. Maximum shear stress vs. vertical stress for AB02 soil

Unconfined compressive strength test

An unconfined compressive strength test was conducted for both soil types based on ASTM 2166 standard to determine the quick and approximate uniaxial compression on soil samples without adding molasses, mixed with 1, 2, 3, and 5 wt% of molasses [20]. Based on the optimum moisture content and maximum dry weight from the density test, the sample was prepared. The soil was blended with specific amounts of molasses and water until the mixture was uniformly homogenized. The soil was subsequently compressed into a mold, with a diameter of 50 mm and height of 100 mm, in five distinct layers; each layer was hit 25 times by a plastic hammer. According to Fig. 11, the samples were put in their place in the testing device in a way that its vertical vector was loaded near the loading center on the surface. The loadings in various strains were measured by LVDT sensors, and pressure was continuously imposed on the sample until cracks; they were recorded in the system. Afterward, the sample was taken out of two jaws of the device by putting the lower jaw down.

Fig. 11. Unconfined compressive strength test

Molasses influence on inconfined compressive strength

Fig. 12 represents the stress-strain diagram of treated soils (ab01 and ab02) with different dosages of molasses. As shown in Tables 7 and 8, by increasing the amount of molasses to 1% in ab01 soil, the uniaxial strength increases but decreases by more than 2%. The highest unconfined compressive strength obtained in ab01 soil was related to 1% additive which is considered as the optimal additive percentage. This observation indicates that molasses-treated AB01 soil experiences ductile failure. At molasses contents over 1%, the molasses coats the soil particles, causing them to be pushed apart rather than sticking together. However, the addition of molasses in ab02 soil has increased the unconfined compressive strength.

Table 7. Findings of unconfined compressive strength test for AB 01 soil in moisture mode

Additive	Test method	Test no.	Unconfined compressive strength (UCS)	The average of unconfined compressive strength (UCS)
AB01	ASTM D2166	1	169.42 kPa	203.3 kPa
		2	214.59 kPa	
		3	225.89 kPa	
1% molasses	ASTM D2166	1	192.01 kPa	233.41 kPa
		2	237.18 kPa	
		3	271.06 kPa	
2% molasses	ASTM D2166	1	135.53 kPa	162.32 kPa
		2	170.72 kPa	
		3	180.71 kPa	
3% molasses	ASTM D2166	1	135.53 kPa	158.12 kPa
		2	135.53 kPa	
		3	203.30kPa	
5% molasses	ASTM D2166	1	135.54 kPa	146.83 kPa
		2	135.53 kPa	
		3	169.42 kPa	

Table 8. Results of unconfined compressive strength test for AB 02 soil in moisture mode

Additive	Test method	Test no.	Unconfined compressive strength (UCS)	The average of unconfined compressive strength(UCS)
AB02	ASTM D2166	1	225.89 kPa	271.06 kPa
		2	282.36 kPa	
		3	304.95 kPa	
1% molasses	ASTM D2166	1	293.66 kPa	323.78 kPa
		2	316.25 kPa	
		3	361.43 kPa	
2% molasses	ASTM D2166	1	316.25 kPa	338.80 kPa
		2	362.72 kPa	
		3	327.54 kPa	
3% molasses	ASTM D2166	1	271.07 kPa	350.13 kPa
		2	372.72 kPa	
		3	406.60 kPa	
5% molasses	ASTM D2166	1	225.89 kPa	331.31 kPa
		2	361.43 kPa	
		3	406.61 kPa	

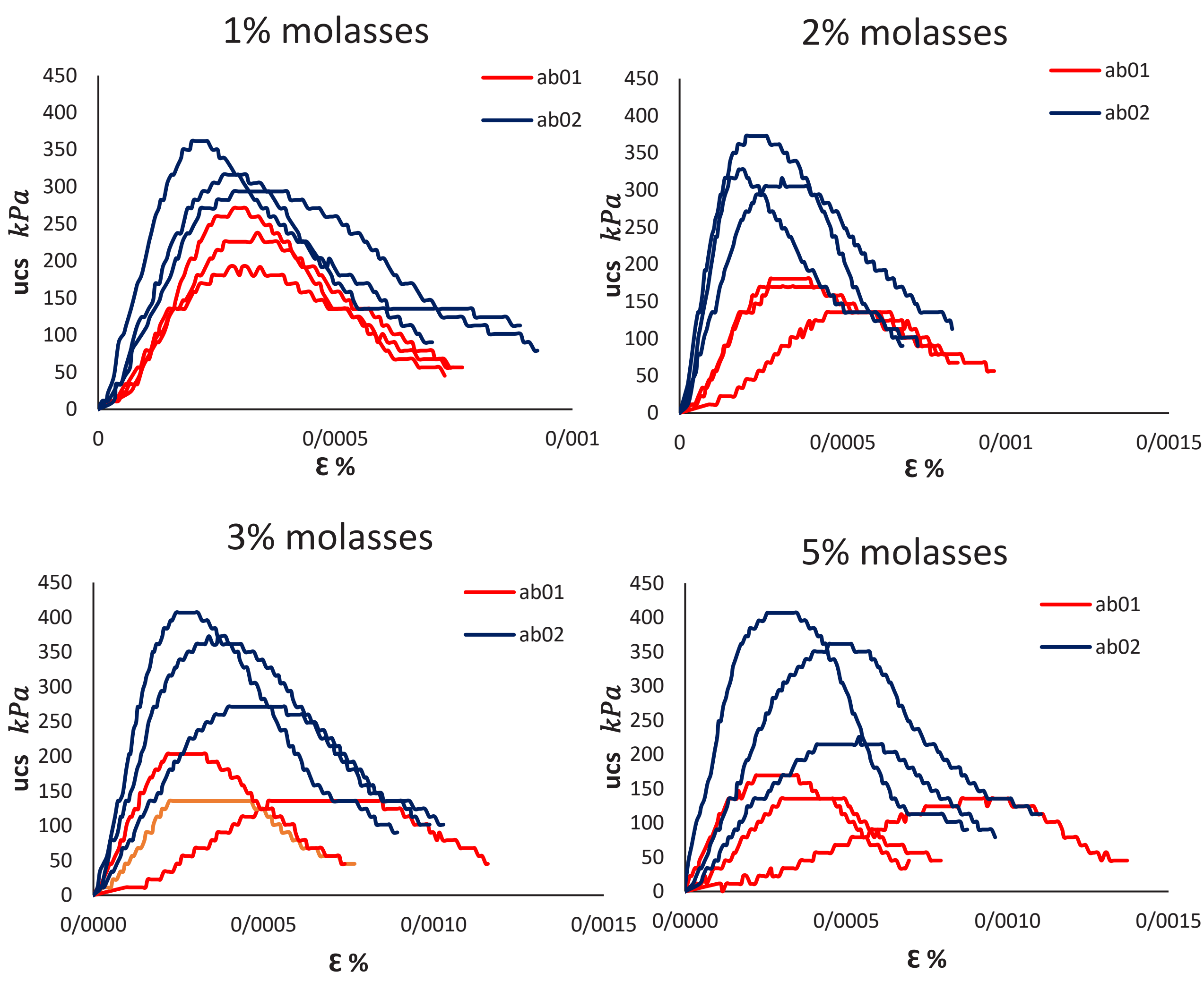

Fig. 12. The unconfined compressive strength of soil AB01 and AB02

Results and discussion

The adoption of direct shear and Unconfined Compressive Strength (UCS) tests is appropriate for evaluating haul road materials, as shear stresses dominate at the tire–aggregate interface under heavy machinery traffic, leading to surface abrasion and dust generation. These parameters effectively quantify improvements in cohesion (c), internal friction angle (φ), and bearing capacity, which are pivotal for dust suppression and structural longevity.

Compaction results (Tables 7 and 8) show that molasses addition elevates Maximum Dry Density (MDD) while lowering Optimum Moisture Content (OMC) in both AB 01 and AB 02 soils, with peak MDD at 5% molasses (1.955 g/cm³ for AB 01; 1.942 g/cm³ for AB 02). This enhancement arises from molasses' viscous properties and sugar content, which facilitate particle lubrication during compaction and subsequent binding as the material dries, improving inter-particle contacts and reducing void spaces.

Direct shear responses are dosage-dependent and non-linear. In AB 01 soil (Table 7), 1% molasses reduced c and φ, likely due to initial lubrication effects predominating. At 2% molasses, cohesion increased markedly while φ decreased, indicating optimal bonding. Higher dosages (3–5%) diminished both parameters, consistent with excess organic content causing over-saturation and loss of frictional resistance.
In AB 02 soil (Table 8), 1–2% molasses boosted both c and φ, with 2% offering the best balance; beyond this, declines occurred, aligning with patterns observed for organic stabilizers in fine-grained soils.
UCS trends reinforce dosage optimization. For AB 01 (Table 8), UCS peaked at 1% molasses, with reductions at higher contents possibly from retained moisture or disrupted natural cementation. AB 02 exhibited consistent UCS gains with increasing molasses (Table 5.5), highlighting soil-specific variability linked to differences in fines content, mineralogy, and plasticity.
Optimal dosages—1% for AB 01 and 2% for AB 02—maximize strength gains while ensuring practicality. Molasses thus serves as a sustainable organic binder that promotes aggregation without the brittleness of cementitious alternatives.

Economic feasibility and regional availability of molasses

Molasses, a by-product of sugar beet processing, confers substantial economic advantages for haul road stabilization in Iran. With extensive sugar beet cultivation in provinces such as Khuzestan, Fars, Khorasan, and West Azerbaijan, annual beet production supports molasses output exceeding 300,000 tons (derived from beet sugar processing capacities). Proximity to sugar factories ensures reliable supply and low transportation costs.
Current industrial/bulk molasses prices in Iran (2025–2026 data) range from approximately IRR 280,000–390,000 per kg retail, but lower-grade or by-product volumes for non-feed applications (e.g., stabilization) trade significantly lower, often equivalent to USD 0.08–0.30/kg (or ~IRR 4,000–15,000/kg in large-scale industrial deals, adjusted for inflation and volume discounts).
Comparative analysis underscores cost superiority:
Portland cement for stabilization typically costs IRR 1,500,000–2,500,000 per ton domestically (export averages ~USD 39/ton; import higher), requiring 5–10% dosage → treatment costs per cubic meter often exceed IRR 100,000–300,000.
Lime follows similar pricing (IRR 800,000–1,500,000/ton) with added curing demands.
At 1–2% optimal molasses dosage and conservative IRR 10,000/kg industrial rate, costs approximate IRR 50,000–100,000 per ton of treated soil (1–2 tons molasses per 100 tons soil), delivering 50–80% savings over cement/lime, excluding reduced CO_2 emissions and simpler application.
These benefits are pronounced in beet-producing regions, positioning molasses as a low-cost, locally abundant stabilizer.

Comparision with existing Iranian literature

The present findings align with Iranian studies on molasses for soil enhancement and dust mitigation. Investigations into forest/mining road dust control using beet/sugarcane molasses (e.g., 20% concentrations for high-fines surfaces) reported improved cohesion and shear resistance, corroborating the current shear gains. Research on dispersive soils treated with molasses (optimal 2–2.5%) showed enhanced cohesion and erosion resistance, paralleling the 1–2% dosages here. Microbial carbonate precipitation with molasses as a carbon source (e.g., Bacillus applications in Khuzestan) and organic mulches for wind erosion further validate molasses as an eco-friendly binder.
This study distinguishes itself by targeting haul

roads under heavy traffic, achieving comparable or superior UCS/shear improvements at lower dosages than some erosion-focused or dispersive soil treatments (up to 5%). In contrast to common cement- or geopolymer stabilizations in Iranian research (e.g., glass powder or carbide additives), molasses provides a greener, lower-embodied-energy option ideal for temporary mine/haul infrastructure.

Conclusion

Molasses stabilization substantially improves the geotechnical performance of AB 01 and AB 02 soils for haul road applications. Optimal dosages of 1% (AB 01) and 2% (AB 02) enhanced compaction characteristics, shear strength parameters, and UCS, thereby mitigating dust emission and increasing load-bearing capacity under heavy machinery.

Beyond technical efficacy, molasses offers clear economic superiority over conventional stabilizers like cement or lime. With abundant domestic production (>300,000 tons/year from sugar beet processing) and competitive industrial pricing (often 50–80% lower material costs, especially regionally), this method supports cost-effective, sustainable road engineering.

Future work should evaluate long-term field durability under wetting–drying cycles, scale-up trials, and hybrid by-product combinations to advance eco-friendly practices in resource-constrained settings.

Financial supports

There is no funding information available for the work..

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors express their sincere thanks to the editor and the anonymous reviewers for their valuable and constructive comments and suggestions which have led to a significant improvement of the manuscript.

Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc) have been completely ob-served by the authors.

References

1. Anlimah F, Gopaldasani V, MacPhail C, Davies B. A systematic review of the effectiveness of dust control measures adopted to reduce workplace exposure. Environ Sci Pollut Res Int. 2023;30(19):54407-28.

2. Reed WR, Westman EC, Haycocks C. An improved model for estimating particulate emissions from surface mining operations in the eastern United States. In: Securing the Future, International Conference on Mining and the Environment, Proceedings. Skellefteå, Sweden: The Swedish Mining Association; 2001. p. 693-702.

3. Thompson RJ, Visser AT. Mine haul road fugitive dust emission and exposure characterisation. [Unknown publication]; 2001 Jan.

4. Thompson RJ, Visser AT. Selection, performance and economic valuation of dust palliatives on surface mine haul roads. J S Afr Inst Min Metall. 2007;107(7):435-50.

5. Gillies JA, Etyemezian V, Kuhns H, Nikolic D, Gillette DA. Effect of vehicle characteristics on unpaved road dust emissions. Atmos Environ. 2005;39(13):2341-7.

6. US Environmental Protection Agency. AP 42, Fifth Edition Compilation of Air Pollutant Emission Factors, Volume 1: Stationary and Point Sources. [Internet]. Washington, DC: US EPA; 1995 [cited 2026 Feb 21]. Available from: https://www3.epa.gov/ttnchie1/ap42/c00s00.pdf.

7. Gebhart DL, Denight ML, Grau RH. Dust control guidance and technology selection key. 1999.

8. Valenzuela P, Palma JH, Vega S. Dust suppressant treatments. Quality control. Rev La Construcción. 2014;13(3):27-35.

9. Du Plessis JJL, van Rensburg L, van Rensburg LP. Effectiveness of applying dust suppression palliatives on haul roads. 2016.

10. Li S, Hu X, Zhao Y, Wu M, Feng Y, Li X, et al. Evaluation of dust fixation effect of urease-based biological dust suppressant and its field application. J Environ Manage. 2024; 371:123119.

11. Sieger JL, Lottermoser BG, Freer J. Effectiveness of protein and polysaccharide biopolymers as dust suppressants on mine soils: large-scale field trials. Mining. 2023;3(3):428-62.

12. Sanders TG, Addo JQ, Ariniello A, Heiden WF. Relative effectiveness of road dust suppressants. J Transp Eng. 1997;123(5):393-7.

13. Du C, Cai S, Jiang ZA. Experimental study on controlling road dust raising in the open mine with the YCH dust suppressant. Chin J Eng. 2007;29(S2):45-8.

14. Du Plessis JJL, Janse van Rensburg L, Jansen van Rensburg LP. Effectiveness of applying dust suppression palliatives on haul roads. 2016.

15. Omane D, Liu WV, Pourrahimian Y. Comparison of chemical suppressants under different atmospheric temperatures for the control of fugitive dust emission on mine haul roads. Atmos Pollut Res. 2018;9(3):561-8.

16. Huang J, Ho CH, Wu Z, Gao Y, Zhang Y, Zhang Z. Evaluation of co-polymer-based dust suppressant mixed with soil in unpaved road: lab experiment. In: Civil Infrastructures Confronting Severe Weathers and Climate Changes Conference; 2018. p. 10-9.

17. Kovshov S, Kovshov V. Chemical technology of dust suppression on open-pit mines. Int J Ecol Dev. 2015;30(3):55-67.

18. ASTM International. Standard test methods for laboratory compaction characteristics of soil using standard effort (12 400 ft-lbf/ft^3 (600 kN-m/m^3)) (D698-07e1). West Conshohocken, PA: ASTM International; 1992.

19. ASTM International. Standard test method for direct shear test of soils under consolidated drained conditions (D3080-03). West Conshohocken, PA: ASTM International; 2003. p. 1-7.

20. ASTM International. Standard test method for unconfined compressive strength of cohesive soil (D2166). West Conshohocken, PA: ASTM International; 2006.