LABORATORY STUDY OF EFFECTIVE FACTORS ON THE REACTION OF FINE-GRAINED SOILS AGAINST WIND IN ORDER TO PREVENT DUST DISPERSION

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ABSTRACT
A laboratory research program was arranged to study the effect of different factors influence the stability of fine soils against wind action. For this purpose a laboratory wind tunnel was stabilized and several soil samples were examined by putting the sample trays inside the wind tunnel for different amounts of wind velocities. The tray for soil samples was 20×30 cm^2 with the depth of 5 cm, and the fine soil samples were chosen with different particles size and porosity. Because the main aim of this research was to investigate about the effect of some polymer additives to the soil, many samples were made of the soil samples which improved by different additives in different percent. Furthermore, the effect of infiltration of the liquid additives liquid through pouring to the soil samples which could show different infiltration height as functions of soil type, additive type and the height of pouring was also examined. Some of the results could be examined by using the software. The lab results in this research compared to some proposed theoretical relationships.

Keywords: Wind Erosion, Open-Loop Wind Tunnel, Dusts, and Polymeric Emulsions

INTRODUCTION
Wind erosion results in formation of fine particle deposits such as sand dunes and loess sediments, deflation, abrasion, sedimentation, soil erosion, variation in soil texture, loss of nutrients and reduction of soil fertility, loss of plants, landslide amplification and air pollution (Rafahi, 2006). Different direct stabilization methods of Aeolian soils consist of biological (Akbarian, 2010), physical and mechanical (Armbrust *et al.,* 1964), chemical (Vazei, 2010; Movahedan *et al.,* 2011), and modern stabilization techniques (Bouhicha *et al.,* 2005).

The main purpose of all stabilization methods is to prevent wind erosion and to achieve the appropriate additives whereby a uniform cohesive layer may be formed on the soil surface that can be resistant against the wind and rainfall, more durable and less detrimental to the health of those dealing with, has no adverse effects on crops and does not decrease soil nutrients. Apart from their useful effects, oil mulches inflict detrimental effects in terms of stabilization of dune sands such as high thermal absorption coefficient, environmental pollution, problems in plant growth and posing threats to groundwater tables and the lives of humans and other creatures.

Application of synthetic polymers in order to boost durability, particle size and soil stability has been the center of attention in this field in recent years. One of the most prominent features of polymers is their ability to cement the particles to each other, thus forming larger particles, which in fact leads to more stability of aggregates (Nateghi and Mohammadi, 2005). Results from Movahedan *et al*. (2011) study on effects of a polyvinyl acetate based polymer on wind erosion of soils suggest that the mentioned polymer material can decrease a 26 m/s wind erosion through forming a relatively solid crust which differs in essence from the layer formed with water on the surface. Moreover, Samaie *et al*. (2006) studies on effects of water soluble polymers of acrylic group suggest that addition of polymers leads to stability in aggregates and increases the mean weight diameter of dry aggregates.

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Kenneth and Nwankwo (2001) acknowledged the formation of coarser aggregates due to the impact of polymer molecules. Also, application of organic polymers for stabilization and reinforcement of strength parameters of soil has become the main focus of attention among the researchers. Barezi *et al*. (2010) studied the impact of polyvinyl acrylic polymer on behavior of soils and showed that the stabilized samples have respectively gained 80% and 90% of their strength in the first 7 and 14 days and that the strength would increase over time. The effects of various polymers of Urea-formaldehyde (Agarwal and Ram, 1981), urea-phenol-formaldehyde (Prakash and Kapoor, 1981), Urea-furfural-formaldehyde (Lukania, 1968), polyvinyl alcohol (Sakata *et al.,* 1970) and polyvinyl acetate (Siddiqi and Moore, 1981) on the compressive strength of stabilized soil samples have been studied by the researchers. These compounds may be used to reinforce the strength of Aeolian sands. Moreover, these compositions are not similar to grouting materials that tend to coagulate and are detrimental to growth of plants just like tar-based stabilizers. Among the important advantages of these compounds are the improvement the soil stability and strength, protection against erosion and plants growth fertility as they contain some nutrients (Shawqui *et al.,* 1998).

Some control measures have to be adopted in this field by taking into account the technical, economic and time criteria through study and identification of optimum problem-solving methods for desert areas especially in case of blown sands in the problematic and vulnerable areas. The impact of additive emulsions of various concentrations on soils with given particle size distributions was studied in this research and effect of pouring height of emulsions, concentration of polymer emulsions, particle sizes and wind velocity on erodibility of soils and infiltration depth of emulsions are also aimed to be discussed.

MATERIALS AND METHODS
The fine-grained soil used in the present tests was obtained from the Siahkal region in Guilan Province in Iran. Soil classification and strength tests were conducted on required amount of samples shipped to the laboratory in order to determine the type of soil as well as its shear strength parameters. According to the conducted results and based on Unified Soil Classification System, the used soil is classified as CL with liquid limit of 43, plastic limit of 23 and dry density of 1.61 g/cm^3.

The open-loop wind tunnel device was designed and launched in order to conduct studies on behavior of various effective factors on Aeolian soils. Laboratory wind tunnel was designed and constructed similar to that of Ekhtesasi (1991) and Movahedan *et al.,* (2011) with some minor modifications. The launched apparatus consists of four main parts. The first part is a 2800 rpm, 18 Amp, 3 kW single-phase electric motor with an impeller 35 cm in diameter. Due to rotation of motor in both directions, the system may either blow or suck the air. According to the conducted tests and the wind velocity determined by manual anemometer, the velocity of wind blowing over the sample container within the tunnel in suction mode is 10 km/h higher than that of a ventilation fan mode. Of course, this facilitates the application of multiple wind velocities in order to conduct the required tests. The procured anemometer is 32*72*180 mm in size, with a maximum velocity of 90 km/h. The maximum velocity over the sample container was measured at 38 to 42 km/h. The adjustment of platform is such that the impeller rotor is arrayed along the center line of wind tunnel chamber. The applied impeller is made of cast iron, resistant to impact of soil particles and equipped with vanes at 45° angle relative to the direction of rotation axis. A tube axial fan is used in the constructed wind tunnel device.

The second part consists of an inlet with an initial circular cross-section followed by a square cross-section designed for attachment to other parts. The inlet cross section area is 1590 cm^2 with a 45 cm diameter while the area of a 30*30 cm outlet cross-section is nearly 900 cm^2. Different sections of wind tunnel are made of galvanized iron connected together by special joints. The third section consists of a cubical cell with dimensions of 1*0.3*0.3 meters equipped with three chambers for imaging and measurement of required properties of samples. This section consists of a sample container, a tray of 0.3*0.4m size that is placed nearly in the center of device. The final part (fourth section) is a cone-shaped section that concentrates the air blown into the device. Figure 1illustrates various parts of the wind tunnel device.

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Figure 1: Various parts of the laboratory wind tunnel device

The emulsified polymer applied in these tests is a complex compound derived from carbohydrates. Biochemically, it is formed out of two types of carbohydrates of Amylose and Amylopectin. Several tests were performed in order to study the effective parameters on stabilization of fine grained soils. The tests were arranged in different series to evaluate some certain parameters. Generally, blowing the wind lasted for 3 minutes in the tests. In the most tests, about 74% of the total weight of soil sample was eroded during 3 minute period of tests. Thus, this period would yield the maximum optimum erosive effects for soil and is considered an appropriate period for conducting tests in the open-loop wind tunnel device. The variations of soil erosion against time intervals are presented in figure 2. Also, the tests were carried out in two or three iterations. The soil erosions were compared to the erosions in 5 series of tests conducted on the same class of soil with constant wind velocity and similar period. The obtained results showed no considerable difference in erosion of soils (Table 1).
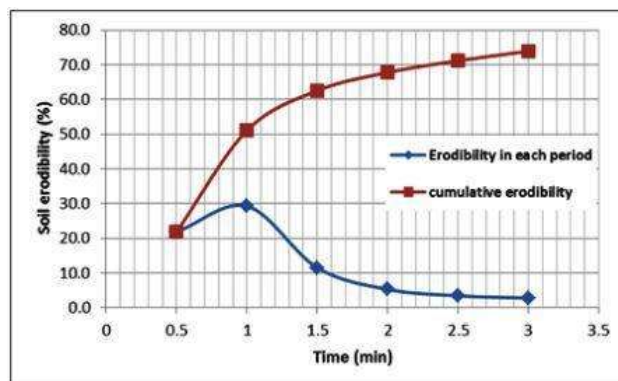

Figure 2: Soil erodibility variations (in %)vs. time

Table 1: Soil erosion in tests for the same soil sample

Iteration	1	2	3	4	5
erosion (gr)	697	560	535.5	600	642

The variable parameters studied in these tests were as follows:
a) Soil particle size distribution: between sieve No. 30 and 8, soil retained between sieve No. 30 and 50, and soil passing through sieve No. 50
b) Type of additives: dry mode, water, polymer emulsions
c) method of additive pouring: emulsion spraying, gravity pouring
d) Concentration of additives: 0, 20 and 50 gr/lit solved in water
e) Height of pouring: 30, 150 and 200 cm
f) Wind velocity: 6, 16, 25, 33 and 45 km/h

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g) Test schedule: after dried under normal conditions, and after 15 days
h) Soil erodibility (gr and gr/m^2.min)
i) Infiltration depth of emulsions (mm)
j) Water content and the room temperature

All the tests were conducted in a sample tray of 0.2m*0.3m (Figure 3). As the soil samples were carried to the laboratory, both classification and strength tests were conducted to determine the type and properties of samples which resulted in classification in three categories. Each soil sample was placed in special trays and then weighed. The tests were carried out under three conditions: dry mode, water and polymer emulsion treatment in order to observe the effect of the type of additives. The pouring of both water and polymer emulsions was carried out in the form of spraying, gravity pouring and free fall through special sprinklers.

Figure 3: Prepared samples of different particle size for placing in wind tunnel

The amount of polymer emulsion poured is 1 lit for each square meter of sample. Accordingly, the required amount for tray of 0.2m*0.3m surface is 60 ml. The infiltration depth of emulsions after pouring on samples was measured for each class of soil. Also, the prepared samples were weighed by digital scales both prior and after the application of wind in the device in order to measure the erosion. Discussions and conclusions on obtained results from the tests, as well as the impact of variables in each series of tests, are presented in the following section.

RESULTS AND DISCUSSION

Six series of tests were conducted to study the influence of particle size of soil on its erosion by wind, the results of which are presented in Table 2. These experiments showed that as the particles sizes increase, the erodibility of soils decreases. The example of this judgment is that the values have declined from 368.65 g for soil passing through sieve No.50 to 106.6 g for soils retained between sieves No. 8 and No. 30. The obtained results are consistent with those of Safaii *et al*. (2011). The erodibility of the soil samples as a function of particles sizes is plotted in figure 4.

Table 2: Results obtained from tests to see the effect of particles size on wind erosion

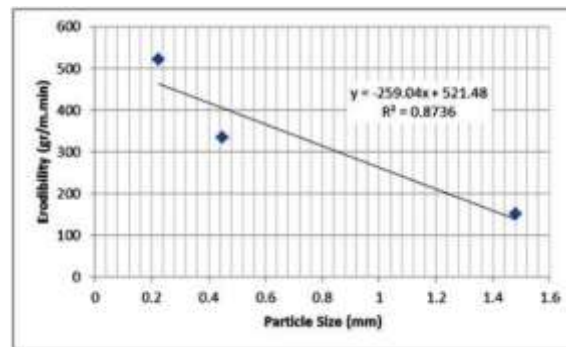| Test Series	Particles Size Range	Average Particle size (mm)	Erosion (gr)	Average Erosion (gr)	Erodibility (g/m/min)
A1	between Sieves8 & 30	1.48	90.9	106.6	128.7
A2	≈		122.3		173.1
B1	Between Sieves 50& 30	0.45	302	235.6	427.5
B2	≈		169.2		239.5
C1	Passing No.50	0.225	427.2	386.65	604.7
C2	≈		310.1		438.9

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Figure 4: Erodibility variations vs. particle size

One of the most important issues with respect to the wind erosion of soils is the effect of variations in wind velocity on the soil erosion. The values of wind velocity measured over the top of samples by a manual anemometer are 6, 16, 25, 33 and 45 km/h. The obtained values from erosion in each test are presented in Table 3. The wind erosion threshold increases as the particle sizes increase; so for particles sizes between No.8 and No. 30 are resistant to wind velocities up to 25 km/h and erosion may only start at higher velocities. In the case of finer soils, erosion threshold comes down to the lower velocities. Erosion rates at maximum velocities were 10, 12.3 and 13.7 kg/m^2/min for soil sizes between sieves No.8 and No.30, between sieves No.30 and No.50, and soils passing through No. 50, respectively.

Table 3: Parameters derived from soil erodibility vs. variations in wind velocity

Test Series	Range of soil particles	Wind Velocity (km/h)	Erosion (gr)	Erodibility (kg/m^2.min)
1	Between Sieve sizes No. 8 and 30	6	0	0
		16	0	0
		25	0	0
		33	72	1.2
		45	599	10
2	Between Sieve sizes No. 30 and 50	6	0	0
		16	3.4	0.1
		25	240	4
		33	530	8.8
		45	739	12.3
3	Passing No. 50	6	0	0
		16	70	1.2
		25	289	4.8
		33	618	10.3
		45	822	13.7

In order to predict the transport rate of soil under field conditions and to generalize the relationships, statistical analyses were performed via SPSS software on all available data. As Table (4) suggests, in the tables of correlation analyses of the values of Pearson correlation coefficient, a two-tailed significance level value is expressed for correlation or dependency tests between two variables and N number of observations. The values of correlation coefficient approaching +1 represent the dependency between the stated parameters. The best-fitting line for data derived from soil erosion tests in the wind tunnel device with R^2=0.8 are expressed as the following quadratic equation.

$R=0.1511U^2-1.4402U-16.308$, U>16 Km/h(2)

Erosion variations in gr (R) with respect to wind velocity in km/h (U) are shown in figure 5. According to the abovementioned relationship, average predicted erosion at wind velocities of 100, 150 and 200km/h at 2m elevation from ground surface in case of soils sustainable to erosion is nearly 1350, 3167 and 5739gr.

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Table 4: Descriptive statistics and results of correlation analyses

Descriptive Statistics				
	Mean	Std. Deviation	N	
Erosion	265.6533	309.13305	15	
Velocity	41.9000	23.33480	15	
Correlations				
			Erosion	Velocity
Erosion	Pearson Correlation		1	.868[**]
	Sig. (2-tailed)			.000
	Sum of Squares and Cross-products		1337885.417	87631.640
	Covariance		95563.244	6259.403
	N		15	15
Velocity	Pearson Correlation		.868[**]	1
	Sig. (2-tailed)		.000	
	Sum of Squares and Cross-products		87631.640	7623.180
	Covariance		6259.403	544.513
	N		15	15

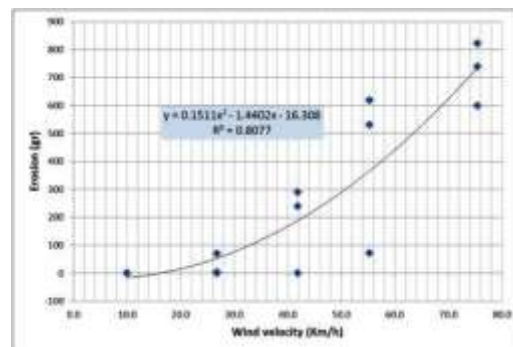**. Correlation is significant at the 0.01 level (2-tailed).

Figure 5: Variations of soil erosion vs. various wind velocities

The effect of polymer emulsion on wind erosion of soil was studied and compared to dry mode through 9 series of tests. A 20 gr/lit polymer emulsion was used in the entire tests. The summary of obtained results is presented in Table 5. Accordingly, erosion of soil treated with sprinkled polymer emulsion decreases from 63.14%, 75.06% and 78.78% to 0.91%, 0.34% and 0.29% respectively for soils retained between sieves No.30 and No.8, between sieves No.30 and No.50 and soil passing through No.50 when an average wind velocity of 40 km/h is applied to the soil surface. Stabilizing effect of polymer emulsions for finer soils is more efficient which could be attributed to chemical reactions occurring between finer particles and the polymer. The 20 g/lit polymer emulsion controls the wind erosion for different classes of soils.

Table 5: Results obtained from tests determining the effect of polymer emulsions on soil stability

| Group	Test No.	Range of soil particles	Type of Additives	Erosion (gr)	Average Erosion (gr)
1	SP01	Between Sieve sizes	Without Polymer Cover	786	786
	SP02	No. 8 and 30	with Polymer Cover	4.3	11.05
	SP03			17.8	
2	SP04	Between Sieve sizes	Without Polymer Cover	739.3	739.3
	SP05	No. 30 and 50	with Polymer Cover	1.3	1.4
	SP06			6.9	
3	SP07	Passing No. 50	Without Polymer Cover	722.3	722.3
	SP08		with Polymer Cover	5.6	3.5
	SP09			1.4	

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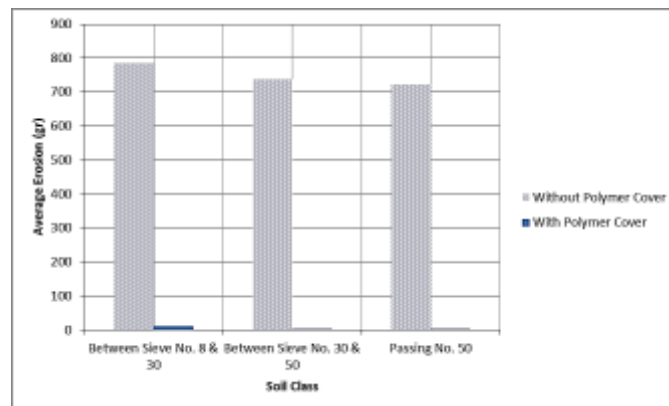
Figure 6: Pouring effect of polymer emulsion on soil stabilization

In order to examine the effect of the time of treatment, the dried prepared samples were placed in the constructed wind tunnel at room temperature and assessed under an applied wind velocity both in the day of treatment and 15 days after the treatment. The variations taking place in the erodibility of soil are depicted in Figure 7. Erodibility in case of type A soils (retained between No.8 and No.30) has decreased over time and due to impact of emulsified polymers so that it has degraded from 11.05 g to nearly 0.9 g. It is noteworthy that the soil erosion increases over time for type 2 and 3 classes. This may be attributed to removal of laminated foliates of soil due to wind suction and considerable erosion of soil. As the laminated layers are detached from the soil surface, the underlying soil layers are still subject to erosion as before without any additives. Thus, it would be inevitable to control soil erosion.
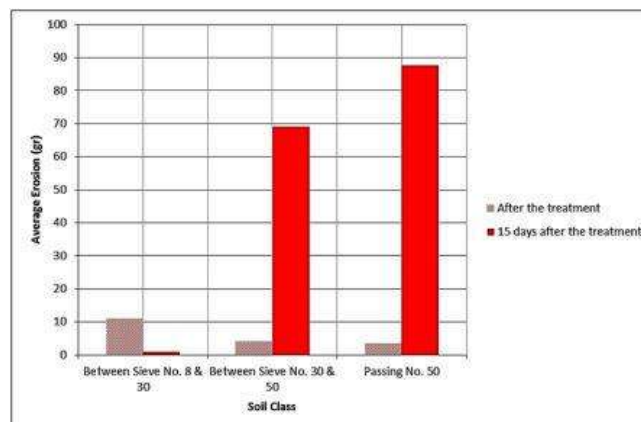

Figure 7: The effect of time parameter on stability of fine grained soils

The effect of pouring height of polymer emulsions on infiltration depth and wind erosion was this time evaluated in the conducted series of tests. The additives were sprinkled from 0.3, 1.5 and 2.5 m heights above soil surface. Polymers were applied to the samples by manual sprinklers. Compared to the previously conducted results, spray sprinklers were used to provide uniformity of sample surface as this type of pouring does not apply excessive pressure onto soils. It should be noted that the infiltration depth of low-height sprays are more than that of gravity pouring. Results of the relevant tests showing the effect of pouring height of emulsions are presented in Table 6.

Soil erosion decreases as the pouring height of polymers increases. The effect of non-uniformity of sample surface due to treatment with polymer emulsions increases as a consequence of increase in the pouring height of additives. The increase in erodibility due to application of sprays in the past may be attributed to this theorem. But what is clear and evident in the present tests is the higher released energy of emulsion droplets as the pouring height increases which would lead to local deformations and collapse

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in the drop point. This would lead to deeper infiltration of emulsions subsequent to increase in pouring height. Figure 8 shows the variations in emulsion infiltration.

Table 6: Results derived from tests indicating the effect of pouring height on erodibility and infiltration depth

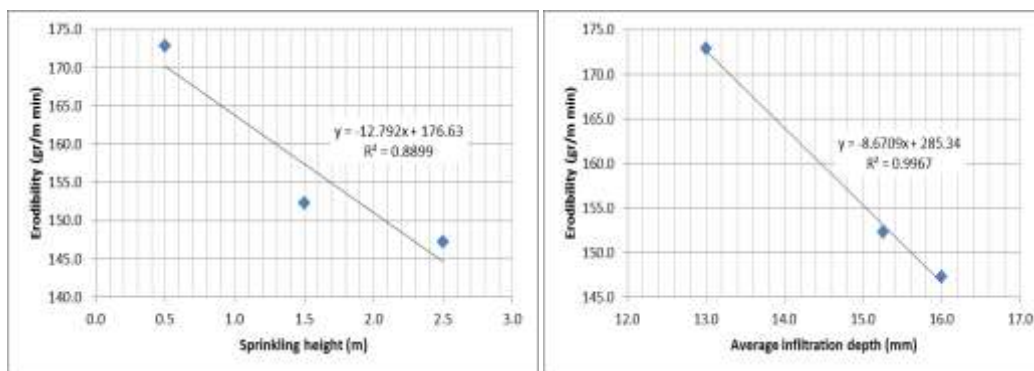| Test No.	Range of soil particles	Pouring Height (m)	Erosion (gr)	Average Erosion (gr)	Erodibility(gr/m.min)	Average Infiltration Depth (mm)
1	Between Sieve	0.3	47.7	69.1	172.8	13
2	No. 8 and 30		92.5			
3			67.2			
4		1.5	54.8	60.9	152.3	15
5			65.6			
6			62.3			
7		2.5	53.8	58.9	147.3	16
8			60.5			
9			62.4			

Figure 8: Impact of pouring height on erodibility and infiltration depth

As the infiltration depth of emulsions increases the result of pouring height of additives, less erosion takes place due to wind action. It is necessary to consider that the increase in pouring height must be accompanied with uniform coating of soil surface with emulsions. Otherwise, the impact of emulsions in a number of limited points would lead to erosion in the vicinity of stabilized soil particles and since the infiltration depth is limited (Figure 9.a), general shear erosion and mass movement of soil would occur. Figure 9 shows the infiltration depth of the polymer inside the soil layer and mass movement of soil due to applied wind pressure (b).
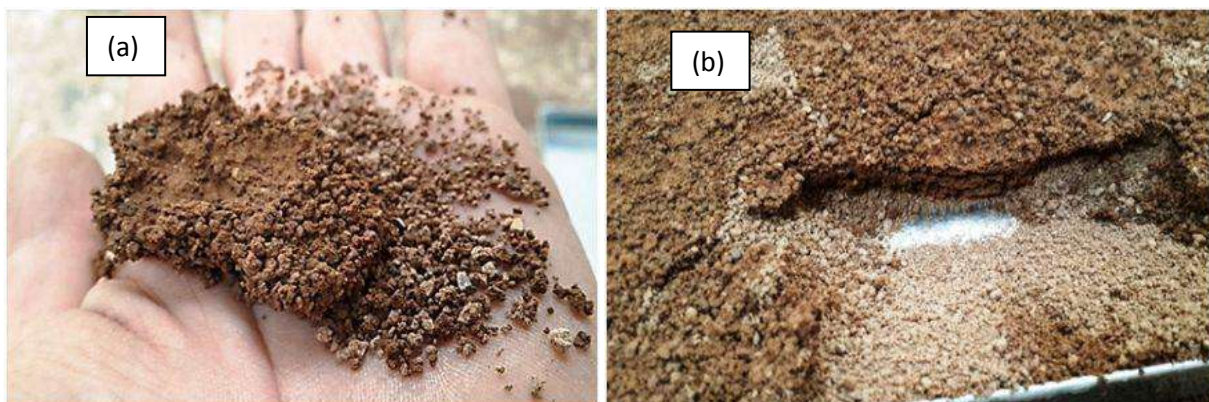

Figure 9: Infiltration depth of emulsions and solid mass movement of soil

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In order to study the results of this theory, the transport rate of soil was assessed based on relationships in terms of friction velocity. The force component responsible for soil detachment was derived from the fluid shear stress which depends on the shape of wind profile. Friction velocity is the most appropriate term to apply which is expressed as square root of fluid shear stress to fluid density ratio. Singh *et al.* (1989) suggested the following equation for determining the friction velocity under neutral profile condition:

$$U_* = \frac{K(0.4)U_Z}{\ln[(Z-D)/Z_0]} \qquad (3)$$

where U_*- is Friction Velocity (m/s), U_z- is wind velocity at elevation Z (m/s), Z- is the elevation above soil surface at which the velocity is measured (m), D- is the average height of roughness elements (m), and Z_0 is the aerodynamic roughness (m).

Threshold friction velocity may also be calculated according to Bagnold (1941) and Gregory and Darwish (1990) relationships (Singh *et al.*, 2001) as in the following:

$$U_{*t}(\text{Gregory and Darwish}) = 0.118[21.2D_{50}(1 + 0.01W_a + \frac{0.0045}{D_{50}^2} + \frac{1.2}{D_{50}}exp^{-0.1\frac{W_a}{W_w}}(W_a - W_c)]^{0.5}(4)$$

$$U_{*t}(Bagnold) = 0.1(\frac{\rho_a}{\rho_P}gd)^{0.5}$$

(5)

where D_{50}-average particle size of soil (mm), W_a- water content of soil, W_w-wilting point of soil in percentage, W_c- water attached to clay, in scratches on the particle surface,ρ_a-air density, ρ_P-the particle density, g- gravity and d-particle diameter.

First the friction velocity and threshold friction velocity are obtained based on the measured wind velocities, and then the erosion rate of soil is determined. Friction velocity and threshold friction velocity are calculated for three ranges of particles sizes and based on the average size of particles in dry mode. Erosion rate of soil (q) in kgm^{-1}s^{-1} may be calculated with respect to friction velocity and particle size as follows:

	Bagnold (1943)
	Zingg (1953a)
	Kawamura (1964)
	Lettau (1978)

Erosion rate of soil is calculated based on the proposed relationships and illustrated in Figure 10 as a comparison with test results.
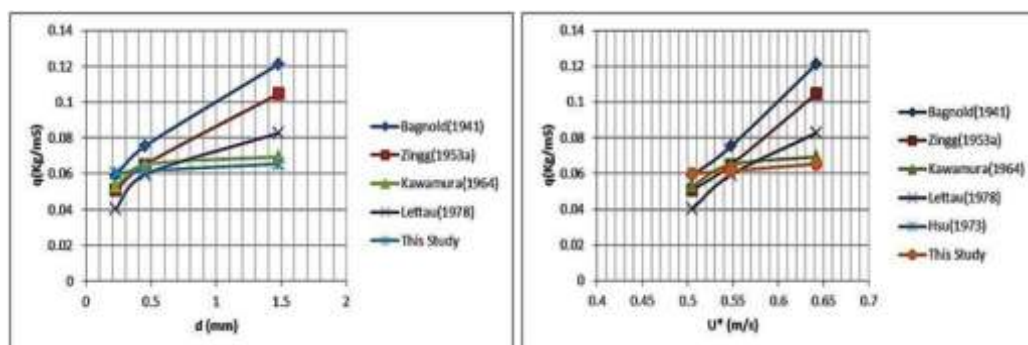

Figure 10: Erosion rate of soil vs. Friction velocity and Average particle diameter

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Considering the identical conditions of sampling and wind loading for different tests, the erosion rate would increase as does the friction velocity. Moreover, with increasing the particles sizes, both values of friction velocity and threshold friction velocity increase. This may be attributed to the gravity of particles which is the main factor against movement.

In order to evaluate the wind velocity inside the tunnel the device was modeled in FLUENT software. Velocity and its pressure inside the tunnel were examined with respect to velocities measured at different intervals. Variations in wind velocity and applied pressure in the wind tunnel are illustrated in figure 4. As the diagrams suggest, the wind velocity inside tunnel varies from 0 to 23 m/s. These variations are nearly 10 to 16 m/s around the sample tray which are well-consistent with the values measured by the anemometer (about 40 to 50 km/h). In addition, the pressure due to wind load in the wind tunnel varies from -233 to 148 Pascal as shown in figure 11.
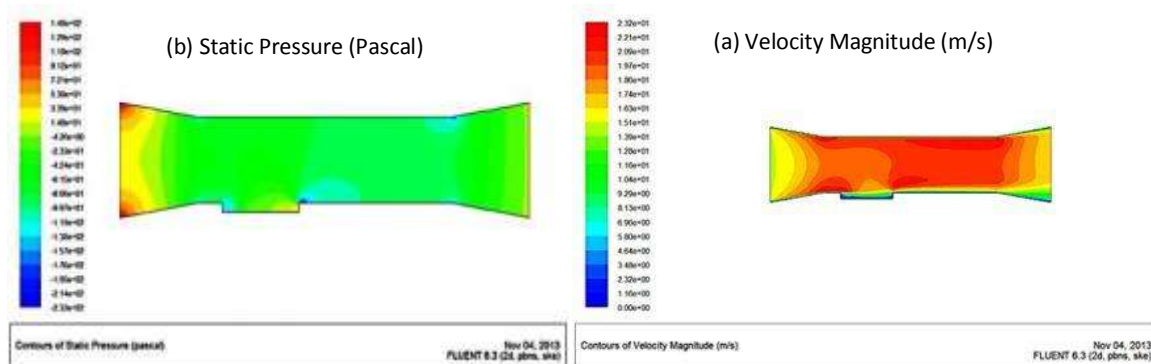

Figure 11: Variations of wind velocity and static pressure in wind tunnel device

In field tests, the datum for wind velocities measured by Meteorological Organization is at the elevation of 2m above the ground surface. The measured velocity in lab (U_0) at a given height (Z_0) may be converted to desirable velocity (U) at any given height (Z) with the help of available theoretical relationships that are proposed for estimation of wind velocity at different heights above ground surface. Following formula is an appropriate one (Rafahi, 2006):

$$\frac{U}{U_0} = \left(\frac{Z}{Z_0}\right)^{0.14} \tag{1}$$

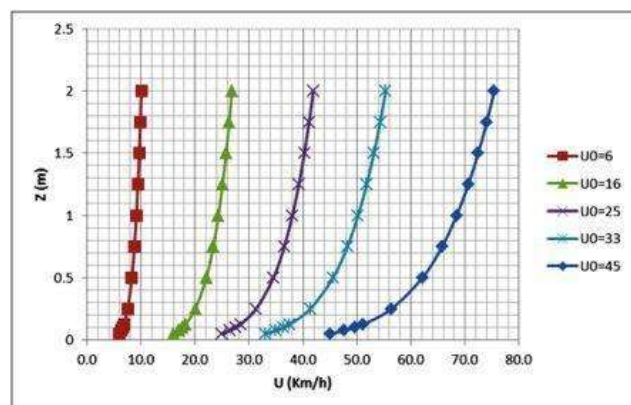The variations of wind velocity in terms of distance from datum are presented in figure 12.

Figure 12: Variations in wind velocity vs. elevation above the ground surface

Conclusions
Studies and assessments were conducted on the factors having influence on erodibility of fine grained soils. The effects of particles size, the porosity of soil, type of additives, pouring height of emulsions were

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studied on the infiltration depth of emulsion. On the other hand, the effect of the above mentioned factors were examined on the wind erosion possibility in different wind velocities and time.

Local and general erosion of stabilized soils were examined. Movement of particles in case of coarser soils is local and periodic while erosion in finer soils is general and in form of steady mass movements relevant to infiltration depth of emulsions. As the average diameter of particles increases, erodibility under the same wind velocity will be decreased and the applied polymer emulsions decrease the erodibility up to 90% compared to initial condition after dried. Impacts of dust emission due to suspended dispersion of fine particles and creeping movements of coarse particles are mitigated as a result of treatment with these emulsions.

Variations in erosion of soils at various wind velocities depend on the value of threshold friction velocity such that the soil erosion values in case of coarser soils after the increase in velocity would be higher than those of threshold friction velocity. As a result of the conducted studies, a relationship is proposed for estimation of soil erosion in terms of wind velocity. As the pouring height of emulsions increases, soil erodibility would decrease due to deeper infiltration of emulsions which is a highly significant notion in controlling the uniformity of soil coating and preventing general erosions in case of increased height from soil surface. The studies and tests results are well-consistent with transport rate relationships proposed by different scholars.

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