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Investigation sand dune stabilization using the Acrylamide Co Acrylic Acid Polymer: a laboratory study

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ABSTRACT

This study sought to investigate the influence of chemical additives (AM-P-AA) on the engineering properties of sand dunes, which was polymerized by free radicals in presence of MBA[1] and APS[2], respectively, as a crosslinker and an initiator. Finally, 1 litter per 0.3 m^2 of this polymer composite was sprayed at the sample metal trays on 0.5%, 1%, and 2% levels and cured for 30 days to investigate their effects on soil properties. The study was conducted through a completely randomized design with three replications. First, the structure and composition of the stabilizers were determined using Fe-SEM, FTIR, XRD, and swelling capacity. Then, the effect of polymers on the anti-wind erosion ability was examined via a wind tunnel test, compressive strength, abrasion resistance, impact resistance, and crust diameter. The stabilization mechanism refers to a process whereby the sand particles and the polymer are thoroughly bounded to each other. On the other hand, the improvement of sand properties depended on the stabilizer's concentration, and the best concentration was found to be 2% (T3), with the sand showing, after 30 days, its highest resistance to any extraneous influence, abrasion, and pressure compared to other treatments. Meanwhile, in a threshold friction velocity experiment performed through a wind tunnel, all samples exhibited resistance to the maximum wind generated (15m/s). Thus, a polymer solution with 2% concentration is highly recommended to effectively stabilize sand dunes.

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Introduction

More than 40% of the global lands are covered by arid and semi-arid areas (Chen *et al.*, 1996, Liu *et al.*, 2012), a quarter of which is covered with dunes, accommodating 17% of the world's population. Considering the fact that sand dunes are, poorly graded materials characterized by a loose fabric structure, (Mohamedzein *et al.*, 2019) affected by wind erosion, it could be argued that wind erosion is the main problem worldwide. Therefore, it can be said that wind

[1] N, N0 -methylene double acrylamide
[2] Ammonium persulfate

erosion is the main problem on all continents. On the hand, wind erosion contributes by approximately 60% to desertification (Li *et al.*, 2009, Liu *et al.*, 2012). therefore, additives or stabilizers are used to control wind erosion and decrease its adverse consequences.

Soil stabilization refers to process whereby a product is added to the soil to improve its properties. stabilizing agents are typically classified into traditional and non-traditional types. Widely popular traditional additives such as physical barriers (Li *et al*., 2000), petroleum oil (Hashemimanesh and Matinfar, 2012), fly ash, and lime (Soltani *et al*., 2018), etc., possess calcium ions in their bodies that flocculate clay particles by creating a bond between clay soil particles and calcium, reducing the intraparticle space (Mirzababaei *et al*., 2017). On the other hand, non-traditional additives including composite, polymer, enzyme, etc., are being increasingly used for civil and military purposes, improving the engineering behaviour of the soil by establishing multiple connections between clay minerals and organic particles within the soil and its polar end groups (Mirzababaei *et al*., 2017, Wei *et al*., 2018).

A polymer with different properties and conformation is usually formed via polymerization of monomers (Hui *et al*., 2014). Hydrogel is a hydrophilic polymer with a three-dimensional network (Gu and Doner, 1992, Alvarez-Lorenzo and Concheiro, 2002, Mohamed, 2004), possessing a variety of properties including water permeability, biodegradability, and adaptability to environmental conditions (Panova *et al*., 2020).

In recent years, researchers have developed a series of polymers to be used for various purposes, including the enhancement of soil properties.

Han *et al*. (2007) showed that the distance between the sand particles was about 8 microns, arguing that when a liquid stabilizer with a droplet diameter of less than 8 microns was sprayed on the sand surfaces, the droplets penetrated into the space between the sand particles and attached the particles, while the larger droplets remained on the surface and acted as a cover.

Moreover, Tomar *et al*. (2007) investigated the influence of waterborne polymer on unconfined compression strength, and the effects of cement group on preventing liquefiable sandy soils, suggesting that the waterborne polymer significantly improved the unconfined compression strength of the sandy soils that are normally susceptible to liquefaction.

Ateş (2013) reported that following the spray of the polymer at the sand`s surface, three types of structures will be formed, 1) a film thin covering sand particles 2) connection between sand particles 3) development of adhesion. He also attributed the improvement in sand properties to hydraulic conductivity and mechanical strength.

Meng *et al*. (2013) used a cationic poly (vinyl acetate-butyl acrylate-2- hydroxyethyl acrylate-DMC) (P(VAc-BA-HEA-DMC)) copolymer emulsion as a sand fixation in their study, indicating that the emulsion improved sand properties and anti-wind erosion abilities.

Furthermore, Ma *et al*. (2015) reported a process in which the clay soils were stabilized by cationic polymer due to electrostatic interaction, where the polymer was adsorbed by the clay minerals, leading to the formation of stable flocculated particles.

On the other hand, Kargarzadeh (2017) used a novel and eco-friendly xanthan gum-g-poly (acrylic acid)/laterite (XG-g-PAA/laterite) composite polymer as a chemical and fixing agent in his study, proving that there was a positive direct correlation between the compressive strength and the content of a polymer.

In another study conducted by Mirzababaei *et al.* (2017) a polyelectrolytic gel was synthesized to stabilize the sand soil against wind erosion, suggesting that anionic microgel could be used for anti-wind erosion.

Also, Mohamedzein *et al.* (2019) used in their study a polymer mixture to fix the sand dune, indicating that the sand’s shear strength could be improved if a polymer is added to the sand dune.

Having said that, this study applied poly (AM-Co-AA) to dune sand samples as the main stabilizing additive and a crosslinking agent. In other words, as AM-Co-AA is a polymer network with the ability to absorb and store water up to several times its weight due to its hydrophilic groups, using this water-absorbing polymer appears to be a suitable method to stabilize sand fields, taking into account the connection between sand particles in such a polymer and their connection to each other, and, therefore, their cohesion against wind erosion. It is worth mentioning that due to the existence of large sandy areas and critical erosion centres inside and outside Iran and various damages caused by sand and dust storms on the one hand, and the increase in the price of petroleum mulches and the destructive effects of their application on the hand, it seems that some new study need to be carried out on identifying alternative stabilizers.

In this regard, this study sought to investigate the applicability and effectiveness of co-acrylamide acrylic acid hydrogel and determine its optimal concentration as a stabilizer of sand surfaces. To achieve the optimal concentration, a completely random experiment design was performed in the SPSS environment with three repetitions for all three concentrations of 0.5, 1, and 2%.

The outline of the process followed in this study is as follows: 1) a copolymer of acrylic acid and acrylamide was developed via a free radical method; 2) the polymer characteristics were determined through detailed analyses 3) the synthesized polymer was sprayed with different percentages.

Material and methods

Collected from the Siyazgeh desert in northern Isfahan province, Iran, the samples of sand dunes used in this study have been formed during the Quaternary period, the chemical properties of which including EC, pH, SAR, and organic matter were identified based on ASTM. Moreover, the samples were classified as fine sandy according to the American Standard Test Mesh (ASTM). The grain size analysis was also performed to determine the soil's sand properties, indicating the existence of 80% sand particles. Table 1 shows the sand properties of the soil.

On the other hand, as acrylic acid, acrylamide, ammonium persulfate (APS), N, N-methylene bis acrylamide (MBA), sodium hydroxide (NaOH), and absolute ethyl alcohol were of analytical grades, they were purchased from Merc and Sigma companies.

Table 1. Some properties of the studied sand

Properties	Electrical conductivity (ds/m)	Sodium Adsorption Ration (SAR)	Organic Mater (%)	pH	Classification (USCS)
Treated sand	2.9	2.0	1.0	7.5	sandy

Preparation of p (AM-co-AA) stabilizer

A set of hydrogel composites comprised of acrylic acid and acrylamide was synthesized via free radical copolymerization in the presence of MBA and APS as a crosslinker and an initiator, respectively, according to the following procedure (Dai *et al*., 2019): first, 1 cc Acrylic acid was dissolved in 15 mL distilled water within a three-necked flask using a magnetic stirrer and a nitrogen line. Simultaneously, 0.5 g NaOH was added to the mixture solution. Then, 0.25 g AM, 0.009 g MBA, and 0.06 g APS were subsequently added to the reaction mixture. Finally, the whole solution was stirred for 30 minutes at 80 °C.

Experimental program

To investigate the efficiency of the chemical additives used in this study on the sandy soil's properties, the polymer was used at three levels (0.5, 1, and 2%) with 3 replications.

Accordingly, metal trays with 100 × 30 × 2 cm dimensions were used to administer the wind erosion test and determine the threshold of friction velocity, and the sand surface was flatted. Then, three different concentrations (0.5, 1, and 2 %) of the polymer (AM-co-AA) (l/0.3m^2) were sprayed on the surface of the trays. Finally, the trays were kept at room temperature in the laboratory to be dried.

Table 2. The code of the treatments tested.

treatment	AA+AM (%)	repetition	Code
T1	0.5	1.0	T1.1
		2.0	T1.2
		3.0	T1.3
T2	1.0	1.0	T2.1
		2.0	T2.2
		3.0	T2.3
T3	2.0	1.0	T3.1
		2.0	T3.2
		3.0	T3.3

Evaluation of stabilizer emulsions effect

The wind erosion was measured by a wind tunnel consisting of a wind generator (blower), a test section (the prepared sand-fixing specimens were placed here), and sediment chamber (Meng *et al*., 2013) at the faculty of natural resources, University of Tehran. After preparing the treatments and transferring the trays to the wind tunnel, the erodibility of the treatments was investigated. Then, the control tray and the treatments were tested under different wind velocities (the comparison of the samples' weight before and after the wind tunnel test showed a weight loss). Finally, the effect of polymers on anti-wind erosion ability was studied in terms of compressive strength, abrasion resistance, impact resistance, and crust diameter.

Polymer characterization

The chemical structure of the polymer (AM-co-AA) was studied via Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD) pattern, and field-emission scanning electron microscope (FESEM).

Results

Hydrogel characterization

FTIR Spectroscopy Analysis

The chemical structure of the polymer (AM-co-AA) was examined over the spectral ranges of 600-4000 cm^{-1} to know the formation and cross-linkage between AA and AM monomers and identify the functional groups involved in the hydrogel with sodium carboxylate (-COONa), as evidenced by absorbance at 1556 cm^{-1} (Dai *et al*., 2019, Ayala-Rincón *et al*., 2020). It should be noted that the intense characteristic band at 1563 cm^{-1} is due to C=O asymmetric stretching in carboxylate anion. The peaks observed at 1401 cm^{-1} and 1658 cm^{-1} corresponded to C–N and C=O stretching vibration of the acrylamide unit, respectively. (Alvarez-Lorenzo and Concheiro, 2002). Moreover, solid samples containing water showed a band in 3400 –3500 cm^{-1} (Wang *et al*., 2020) and a band near ~1650 cm^{-1} (Eshghi *et al*., 2014, Chen *et al*., 2020). On the other hand, a small broad peak at ~2946 cm^{-1}, 1087 cm$^{-1,}$ (Alvarez-Lorenzo and Concheiro, 2002, Ayala-Rincón *et al*., 2020, Chen *et al*., 2020) and 1175 cm^{-1} corresponded to the acrylate unit's asymmetric stretching vibration of C–H and –CO–O–, respectively. The bending vibration of N–H which was observed at 1565 cm^{-1} could be attributed to the successful copolymerization of the AM monomer (Jayaramudu *et al*., 2018). Also, some peaks were observed at 1488 cm^{-1} which corresponded to the –CH_2 groups. Furthermore, the band between 1655 and 1731 cm^{-1} indicated the stretching vibration of the C=O (Chen *et al*., 2020, Wang *et al*., 2020).

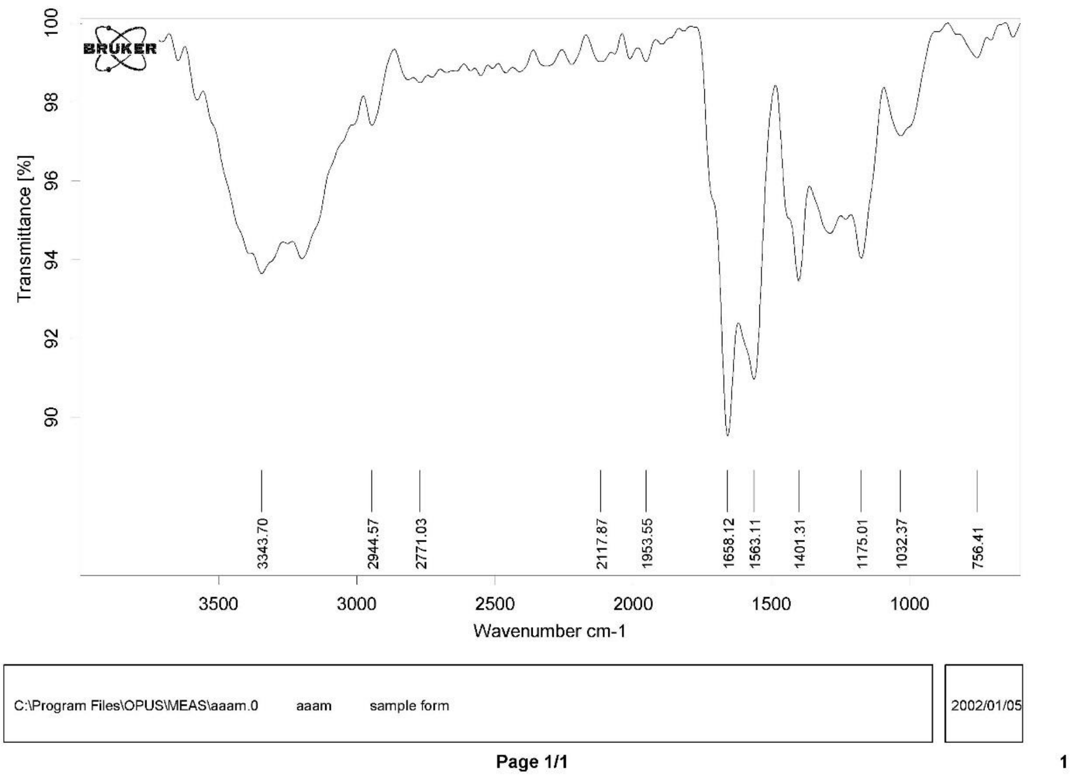


Figure 1. FTIR spectra of poly (AM-co-AA)

X-ray diffraction (XRD) pattern

The X-ray diffraction (XRD) pattern of the AM-co-AA polymer revealed diffraction peaks at 2θ = 10.9◦, 22.6◦, 26.9◦, 31.3◦, 34.98◦, 51.8◦, 56.18◦, and 61.66°.

As shown in Figure 2, the polymer AM-co-AA had a main characteristic peak angle of 22.6◦ (002). Moreover, the first peak (001) appeared in ~ 10◦, and the peak at 2θ of 22.6 was related to quartz (SiO2) as a major crystalline structure. Also, the peaks at 2θ of 34.98 and 61.66 were associated with the calcite phase ($CaCO_3$) (Kargarzadeh, 2017).

Morphology of hydrogel

Figure 3 shows the hydrogel surface morphologies for AM-co-AA polymer with different magnifications. The surface morphology of the sample was determined using scanning electron microscopy. As shown in Figure 3, the sample displayed an irregular and multilayer structure and a rough outside surface. The polymer caused sand particles to bond to each other, thereby enhancing the sand strength and preventing wind erosion. This result corresponds with what was found by the study carried out by Ma *et al*. (2015). According to Figure 3, the hydrogel has a porous structure which would be beneficial and consequently enhance the absorption ability of the water; a finding corroborated with the results found by Tomar *et al*., (2007); Kargarzadeh (2017), and Dai *et al*., (2019).

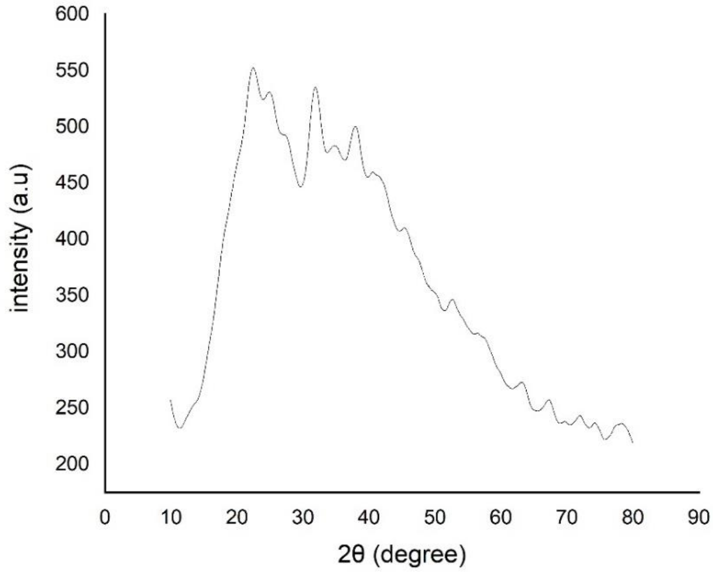


Figure 2. X-ray diffraction (XRD) patterns of p(AM-co-AA)

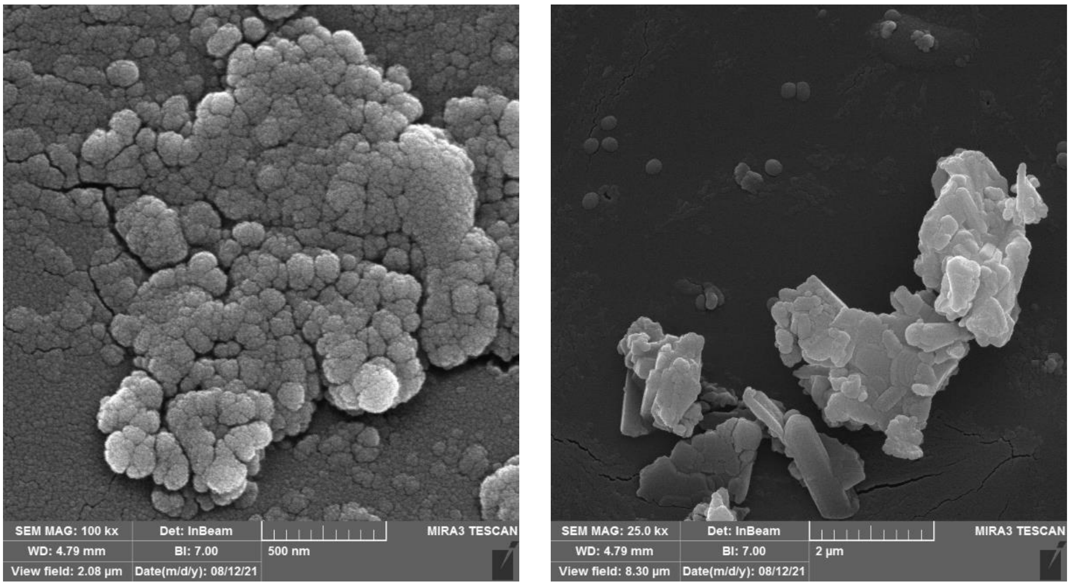


Figure 3. FE-SEM of poly (AM-co-AA)

Water Absorbency Measurement

A sample (0.01 mg) of the polymer's (AM-co-AA) hydrogel was immersed in 25 ml distilled water at room temperature until equilibrium was reached. Absorbency was determined after the removal of the excess surface water by weighing the swollen gel. Moreover, the water absorbency was obtained using the following Eq. (1) (Tomar *et al*., 2007).

swelling capacity (g/g) $=(w_t-w_d)/w_d$ (1)

where Wt (g) is the weight of swollen hydrogels at time t (min), and Wd (g) represents the weight of dried hydrogels (Tomar *et al.*, 2007). Figure 4 shows the water absorbency of the polymer. The hydrogel exhibited a rapid water absorption behaviour, getting decreased as time passed.

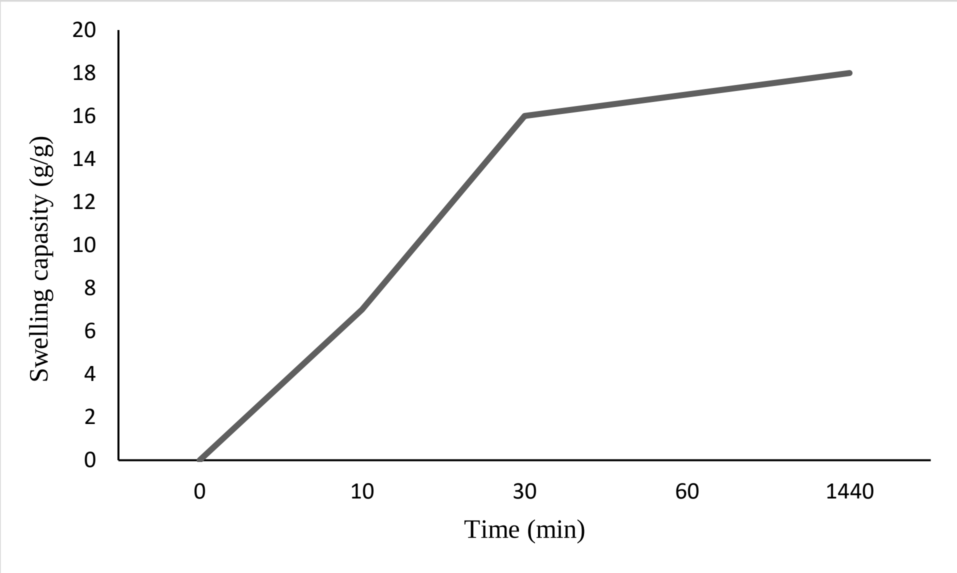


Figure 4. Swelling capacity curves of the prepared hydrogels in distilled water

Analysis of sand stabilization

After spraying different concentrations of the polymer solution on the surface of the trays, the polymers penetrated the sand through pores and attached the sand particles. This linkage between sand particles and polymer created a structure that was resistant to wind erosion. (Meng *et al.*, 2017). To determine the best concentration for sand stabilization, some experiments including threshold friction velocity, compressive strength, abrasion resistance, impact resistance, and crust diameter were performed.

Data Analysis

The study was carried out as a completely randomized experiment with tree replications. Data analysis was performed via SPSS 22 software. The one-way ANOVA and Duncan's Multiple Range test (DMRT) were used to determine the homogeneity of the variance and identify significant differences between the group means, respectively.

Determination of wind friction velocity

The wind erodibility of the treated samples was compared with different concentrations of the polymer (AM-co-AA) using a wind tunnel. The relative wind erodibility was defined in terms of wind friction velocity. The samples were subjected to wind at a wind tunnel, and the wind velocity was increased until crust breakage occurred. The effect of three different concentration solutions on the shear strength suggested that all three treatments were resistant to maximum wind velocity (15 m/s, duration time was 20 min) and they didn't lose weight. On the other hand, the control treatment showed 5 m/s for the threshold of friction velocity.

Penetration Resistance

Penetration resistance was measured using a hand cone penetrometer (Mombeni *et al*., 2021). Moreover, the strength of the layers formed on the soil surface of each treatment was measured at 10 points with the same dispersion, and their average values were calculated. The results of variance analysis revealed a significant difference among the treatments with different concentrations (sig <0.05), whose compressive strength increased compared to that of the control sample (Figure 5). According to Table 7, while treatment 3 had the highest resistance (1.61±0.18), no significant difference was found between treatments 1 and 2.

Table 3. Statistical parameters for compressive strength in different treatments

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4.433	3.000	1.477	391.444	0.000

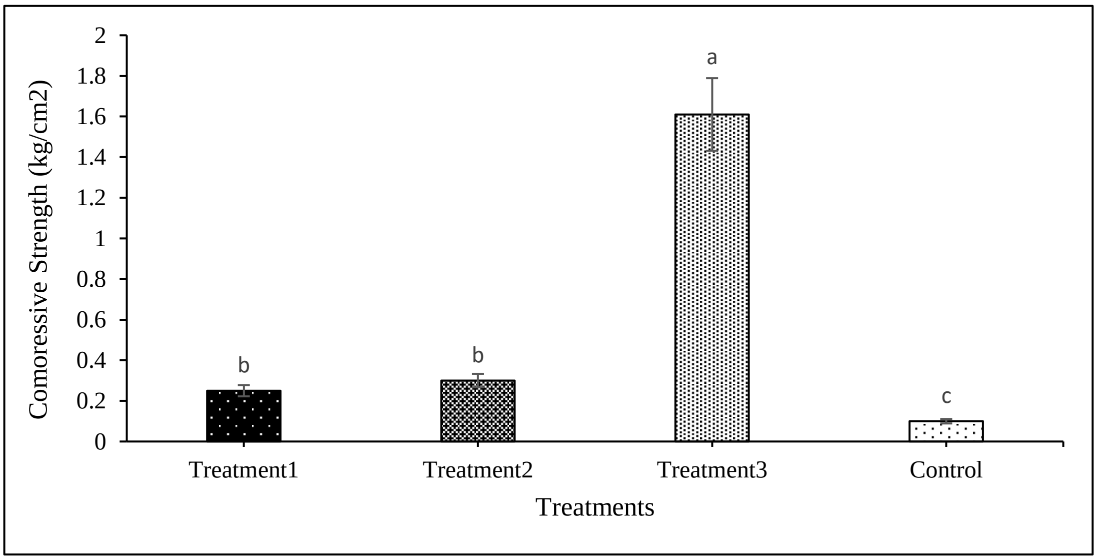


Figure 5. Effect of mulch types on compressive strength of sand samples

Sheer Strength

This study used a geo Tor vane shear tester, a device with the ability to measure stress between 0 and 250 kPa, to measure sheer strength (Jamshidsafa *et al*., 2015). As shown in Figure 6, the resistance of treatments 1 and 2 and that of the control sample were found to be around zero, getting increased with an increase in concentration in a way that the mulched surface became so intense after being sprayed with 2% concentration of mulch that the sheer Tor vane was unable to dig into the sand sample. As shown in Table 7, the samples treated with 2% polymer revealed the highest sheer resistance (5±0.56).

Table 4. Statistical parameters for sheer strength in different treatments

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	54.022	3.000	18.007	578997.600	0.001

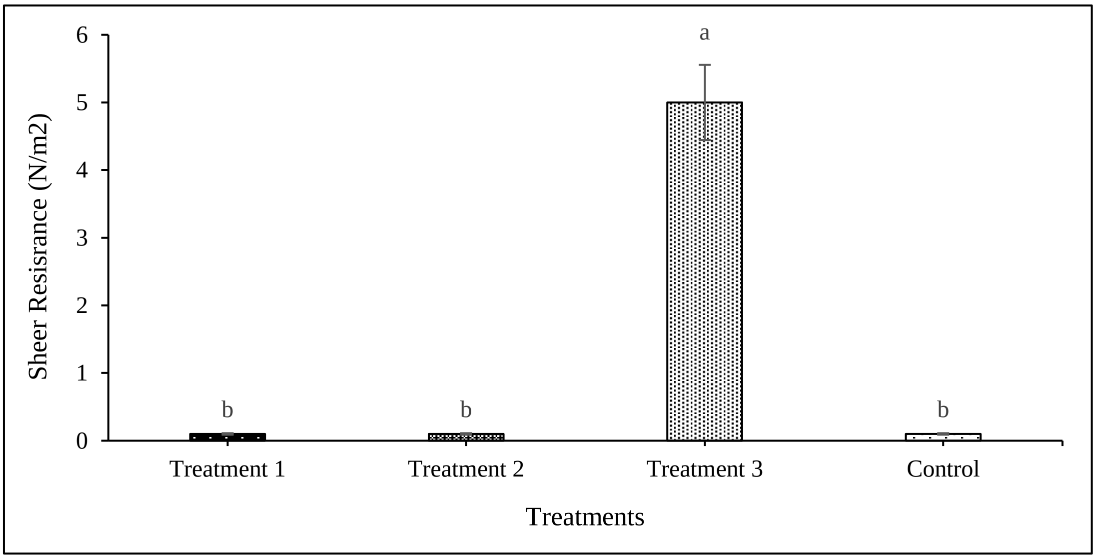


Figure 6. Effect of mulch types on sheer strength of sand samples

Abrasion Resistance

The abrasion resistance of the crusts was obtained by sanding the surface of the samples with a sandpaper of 100 microns grit size (Diouf, 1990). Abrasion resistance is typically measured by a number of abrasions until the crust is completely removed. As shown in Figure 6 and Table7, treatments 3 and 1 had the highest and lower resistance against the sanding (46.67±5.19 and 8.67±0.96), respectively.

Table 5. Statistical parameters for abrasion resistance in different treatments

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3654.910	3.000	1218.300	3609.760	0.001

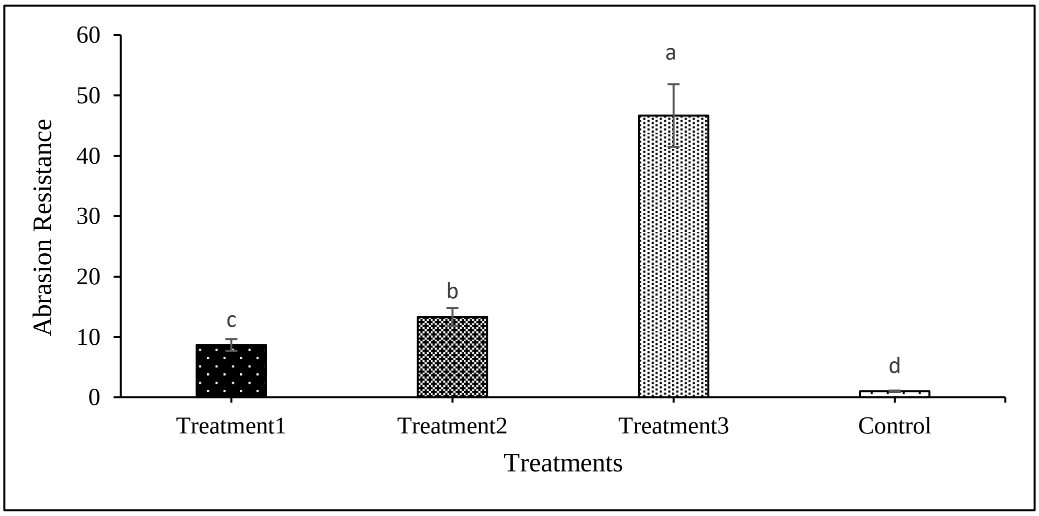


Figure 7. Effect of mulch types on abrasion resistance of sand samples

Impact Resistance

Impact resistance was obtained by a 150 grams tapered tip steel bar from a half a meter heigh on the surface of the tray, where the impact resistance was measured at ten different points with the same dispersion (Zare *et al*., 2020). As shown in Figure 6, only treatment 3 was impact resistant.

Table 6. Statistical parameters for impact resistance in different treatments

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	6.250	3.000	2.083	250000.000	0.000

Table 7. Comparison of the mean measured between different treatments

standard error ± mean					
Sheer strength (N/cm2)	Abrasion resistance	Crust diameter (mm)	Compressive strength (kg/cm2)	Impact resistance (cm)	treatments
0.1±0.01[b]	8.67±0.96[c]	9.11±1.01[c]	0.25±0.03[b]	2±0.22[a]	T1
0.1±0.01[b]	13.33±1.48[b]	13.27±1.47[b]	0.3±0.03[b]	2±0.22[a]	T2
5±0.56[a]	46.67±5.19[a]	15.63±1.74[a]	1.61±0.18[a]	0.33±0.04[b]	T3
					Control

means with at least one letter in common do not have a significant difference.

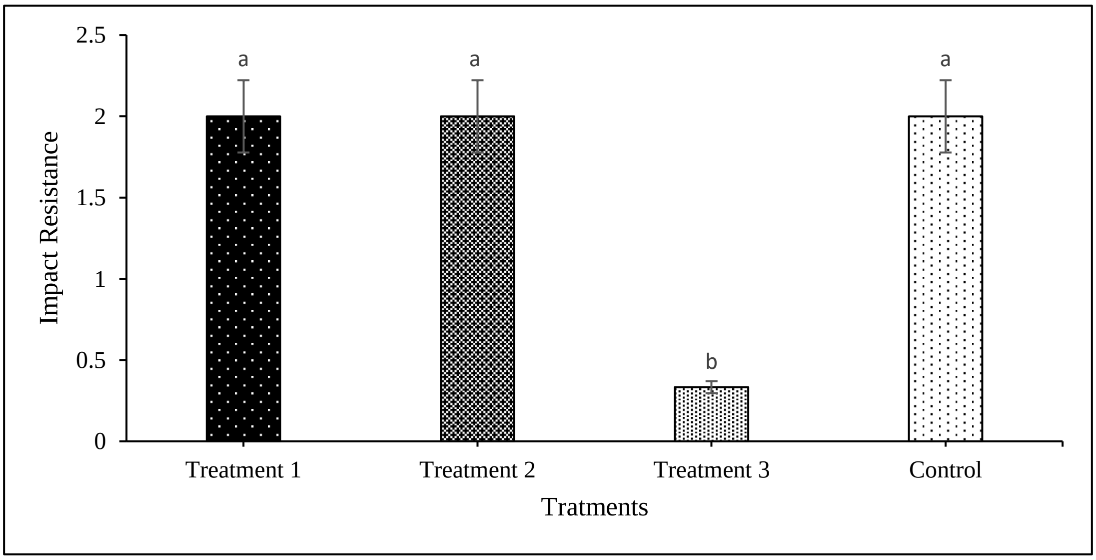
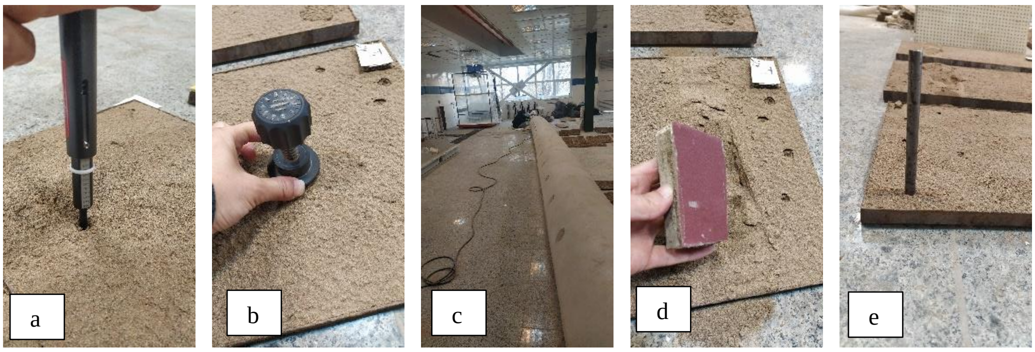


Figure 8. Effect of mulch types on impact resistance of sand samples



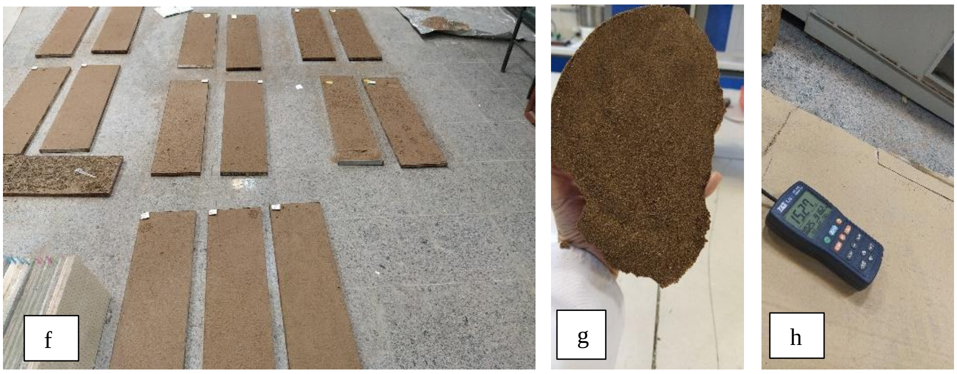


Figure 9. a: hand core penetrometer b: geo Tor vane sheer tester c: wind tunnel d: abrasion tester e: steel bar for impact resistance f: metal trays of treatments g: sand attachment with mulch utilization h: maximum wind created by wind tunnel

Discussion

FTIR analysis showed the existence of hydroxyl, carboxyl, carbonyl, and calcium carbonate functional groups in the polymer hydrogel chain, causing the polymer interact with sand particles. It was also found that the number of binding functional groups increased with an in increase in the amount of hydrogel, leading to the formation of stronger cells, which is consistent with the results found by Almajed *et al*. (2020) who reported that increasing the amount of biopolymer led to an increase in the functional group of calcium carbonate (which acted as a particle binding agent). On the other hand, while the XRD pattern shows the presence of the calcium carbonate group (2θ = 30˚), the existence of calcium carbonate is known as a binding factor for sand particles, which is consistent with the findings reported by Almajed *et al*. (2019; 2020).

It could be argued that using a polymer can help the sand dunes resist against erosion for the following reasons: 1) the polymer make multiple contacts (as seen in polymer analyses, Figure 1, Figure 2) with the soil's mineral and organic particles, fixing the soil structure and enhancing the soil's resistance ability, which is consistent with the results reported by Wei *et al*. (2018) and Huang *et al*. (2021). On the other hand, Tomar *et al.* (2007) and Dong *et al*. (2008) presented a number of contacts between particles' effects on shear strength. Moreover, sodium carboxylate of hydrogel increases the cation exchange capacity (CEC) of the samples, which in turn influences the strength of the stabilized soil; due to the polymer's composite, ionization occurs on the sand surface. The composite fills up the space between the sand's particles, creating physiochemical bonds between them, which in turn improves their strength. The mechanism involved in creating hardened membrane in and improving the resistance of the samples when a polymer with higher concentration is applied could be attributed to the existence of more hydroxyl groups within the polymer's chain, making hydrogen bonds by getting placed on the surface and within the space between sand's particles. On the other hand, the hydroxyl groups and, therefore, the hydrogen bonds among the sand's particles and the particles' water absorption capacity will increase with an increase in the polymer's concentration, improving the intermolecular resistance of the created membrane, which in turn leads to the creation of thicker membranes and the improvement of the samples' resistance against erosion. This finding is consistent with the results reported by Meng *et al* (2013); 3) Polymer covers sand particles and increases the anti-wind properties of sand. In this regard, Li *et al.* (2009) suggested that the polymer composite produced crusts on the sand surface, aggregated the sand particles, and increased anti-wind erosion ability.

Considering the results of this study discussed above, it could be argued that composite concentration plays a key role in the influence of polymer adsorption on the soil's particles. on the other hand, using the geo Tor vane shear tester (shear strength test), it was found that the sand's strength and stiffness increased with an increase in the concentration of the polymer solutions, which could be justified by an increase in the concentration of the polymer's composite, the molecular weight, cross-linkage density, electrostatic interaction, functional and structural groups, and therefore the interaction between sand particles and the added stabilizer agent. These findings are consistent with the those reported by Dong *et al*. (2008); Liu *et al*. (2011); Bai *et al*. (2019), Mohamedzein *et al.* (2019); and Huang *et al*. (2021). Therefore, the third treatment, created a thicker and more resistant membranes compared to the ones created by other treatments. This result is well established in Figure 6.

Conclusion

This study sought to investigate the best concentration for sand dunes and the possibility of their stabilization by adding a polymer solution to them. To this end, samples of sand dunes were collected from the Siyazgeh desert in northern Isfahan province, Iran. Moreover, polymer solutions with 0.5, 1, and 2% concentrations were used to stabilize the sand. Also, the polymer was synthesized by grafting copolymerization of acrylic acid and acrylamide, followed by a series of soil strength tests to examine the influence of such chemical additives on the quality of sand dunes. Finally, the properties of Polymer's (AM-co-AA) network hydrogels were determined via swelling capacity, FTIR, FE-SEM, and XRD analyses.

Based on the results obtained in this study, the following conclusions were drawn:

a) The hydrogel had a porous structure, acting as a depot for water and other substances. The swelling capacity agreed well with the structure.
b) The results indicated that polymer connected the particles together and exerted a significant influence on sand resistance.
c) The polymer substantially increased the sand resistance. On the other hand, the magnitude of the sand's response to the polymer depends on the concentration of the sand dunes, with the sand resistance being greater for a polymer with a higher density (2%).
d) Geo Tor vane shear tester showed that the stiffness of the stabilized sand increased with an increase in polymer content and the confining pressure.
e) Threshold of the sand detachment's wind speed increases when a polymeric stabilizer is used, with the resistance of all treatments to maximum wind velocity being created by the wind tunnel after 30 days.

Suggestions

Considering the fact that Hydrogel polymer is an unstable material, the improvement of its efficiency requires its combination with other materials such as nano celluloses, which has been discussed in detail by the authors in another study.

Since the study was conducted in a laboratory environment and under controlled conditions, it is suggested that this mulch be used in a natural environment for better results.

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