RESEARCH ARTICLE - HYDROLOGY

Biopolymer based stabilization of Indian desert soil against wind-induced erosion

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Abstract

Wind-induced soil erosion is a major global misfortune, which obliterates nearly one-third of worldwide soil. The wind-swept sand particles cover large areas including highways, and make the visibility vague. This results in accidents, damaged infrastructure, delayed flights, and various health issues. The erosive impact of the wind can be minimized by enhancing the intactness of the soil surface. There is a prerequisite to adopt viable measures to strengthen soil against wind erosion. There are certain nature-based solutions that can fortify soil against wind erosion and the application of biopolymers is one of them. The objective of this study is to examine the viability of non-toxic biopolymers for stabilizing desert sand by improving its erosion resistance property and strength. In the present experiment, three biopolymers, sodium alginate (SA), pectin (P), and acacia gum (AG), were used with 1, 2, and 3% concentrations for 1 and 0.75 PV as stabilizing agents. The treatment with biopolymers was performed either by surficial treatment (spraying or pouring of solution) or by mixing and compact method based on the viscosity of prepared biopolymer solutions. The biotreated sand samples were tested in a wind tunnel at varying wind speeds of 10, 20, and 30 m/s to assess sand erosion. Surface strengths were assessed by measuring compressive strength using a pocket penetrometer. Crust thickness measurement was performed to check the penetration depth of biopolymer solution and binding of sand particles. All three biopolymers with 1% concentration gave a feasible solution for erosion against wind and binding of particles through SEM analysis. SA and P could not be sprayed for 2 and 3% concentrations due to high viscosity. This solution is also not feasible for the field application. Simultaneously, AG with 2 and 3% concentration was highly soluble, less viscous, and gave more surface strength due to higher percentage of biopolymer concentration.

Keywords Biopolymers · Surface strength · Wind tunnel · Sustainable · Pocket penetrometer

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Introduction

The desert is an unproductive land area with scanty rainfall. Environment of desert is antagonistic for animal and plant survival. The Indian Desert (Thar) is a rolling sandy plain enclosed with sand dunes. It experiences an arid climate. The major portion of the Thar Desert lies in the north-western part of India. The temperature varies from 50 °C in summers to 0 °C in winters along with a high range of temperature differences between day and night. Strong wind carries fine sand and dust particles, resulting in sandstorms in many parts of the desert. The deleterious effects of sandstorms are manifold and lead to major environmental and agricultural issues including crop loss, plant damage and burial, and general soil infertility. Consequently, sandstorms give rise to desertification, environmental pollution, and ecological imbalance (Lemboye et al. 2021). Although

there are several ground improvement techniques in trend, still they have various limitations in terms of field application, environment friendliness and cost factor. Thus there is a strong need for renewable, soil strengthening material with a pleasing environmental impact. The recent trend has witnessed an emerging use of sustainable and environment-friendly materials, for soil retrieval process, that reduces negative effects on humans and the environment. Biobased soil quality reclamation methods can be categorized based on the microbial activities and biomaterials to be utilized. These microbial activities include biofilm generation, biomineralization, biopolymer and biogas formation, etc. (Choi et al. 2020).

One of the techniques people have used is Microbial-induced calcite precipitation (MICP) for mitigation of wind-induced soil erosion. General ground-improvement practices comprise industrial waste, ashes, agricultural waste, and fibres (Sharma and Satyam 2021). The MICP method has advancement over other ground improvement practices due to its better prospective to reinforce soil particles (Dagliya et al. 2022a; Sharma et al. 2021, 2022). Despite the lead, MICP has various limitations in terms of transportation, cultivation, fixation performance of bacteria and ammonium chloride as a by-product (Chang et al. 2020). Also, MICP is time-consuming method in comparison with biopolymers.

Biopolymers are renewable, carbon-neutral, sustainable, green, and environment friendly materials in every way since they are prepared from ever-available crops (Ayeldeen et al. 2016). There are varieties of biopolymers, either produced by microorganisms, plants, animals, or laboratory made. Biopolymers allies components like sugar, amino acid, and oil displayed unique properties. Industries, namely oil extraction, textile mills, construction companies, cosmetics, pharmaceuticals, and food preservation, consume different types of biopolymers due to its trussing characteristic. The unification of biopolymers with the soil particles blocks the voids resulting in elements binding. Thus biopolymers can be used to enhance strength (Fatehi et al. 2018; Reddy et al. 2021) and erosion resistance (Almajed et al. 2020; Fatehi et al. 2019; Mahamaya et al. 2021; Refaei et al. 2020). It also reduces the compressibility (Burra et al. 2019) and permeability of soil (Chang et al. 2016). Most of the studies have been performed using sodium alginate, xanthan gum, gellan gum, and guar gum to improve geotechnical engineering properties of the soil (Choi et al. 2020). Furthermore, studies have shown that wind erosion can be controlled by stabilizing soil using biopolymers (Alsanad and Kavazanjian 2011; Fatehi et al. 2019). Ayeldeen et al. (2018), Lemboye et al. (2021) conducted a study on resistance to wind-induced sand erosion using biopolymers. The result of study indicated that wind-induced sand erosion can be controlled using biopolymers. However, the effect of biopolymer on surface strength of sand samples was rarely discussed.

The purpose of the present study is to investigate the efficacy of biopolymers in suppressing wind-induced erosion. Further, the influence of biopolymer on surface strength is also quantified. In the present study, sodium alginate, pectin, and acacia gum have been used as binding agents. The desert sand was mixed with 1, 2, and 3% biopolymers of 1 and 0.75 PV. Treated specimens were tested for wind tunnel, surface strength, and thickness formation. SEM analysis was performed for micro-characterization and interpretation of results. The novelty of the study was to examine effect of pore volume against the varying percentages of biopolymer on biotreated sand samples. Wind tunnel testing up to 30 m/s wind speed and surface strength measurement test were also conducted on biotreated sand samples.

Materials and methods

Sand properties

Figure 1 shows the site of sand dune from where the sand sample was collected for current study. The sand dune is located in the Tinwari village (26.584715 °N and 72.814687 °E) near Jodhpur city of Rajasthan, India. Figure 2 shows the grain size distribution curve of desert sand. As per the Indian standard classification system (IS 1498–1970, 2002), soil can be classified as poorly graded sand. Table 1 synopsizes various geotechnical engineering properties of the sand sample.

Properties of biopolymers used

Sodium alginate is a natural polysaccharide. It is a sodium salt form of alginic acid and gum, which is obtained from the cell walls of brown algae with chelation. It is usually white or yellow in colour and available in fibre or coarse powder form. It has been extensively used in the food preservation industry. Also due to its high water retention capacity, it is used in industrial and pharmaceutical fields (Almajed et al. 2020). Pectin is a regular polysaccharide having extreme galacturonic acid. It is a by-product obtained from vegetable and fruit wastes. For commercial purposes, it is made from apple pomace and citrus shells. It has been broadly used as a stabilizer, water binder, and thickener (Martau et al. 2019). Acacia gum is composed of D-galactose, L-arabinose, L-rhamnose, and D-glucuronic acid. It is highly soluble in water and contemplated to be a low glutinous polysaccharide. It has been extensively consumed in the food industry as a preservative, thickener, emulsifier, and gives flavour to food products (Lemboye et al. 2021).
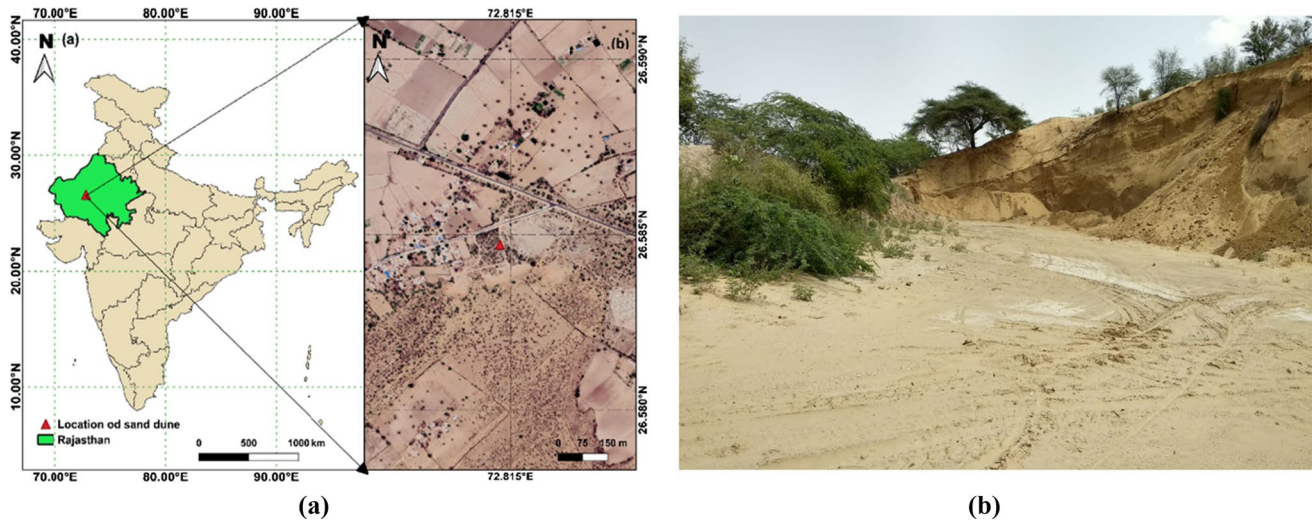
Fig. 1 **a** Location of the sand dune (Dagliya et al. 2022a); **b** Sand dune site at Tinwari village Rajasthan, India
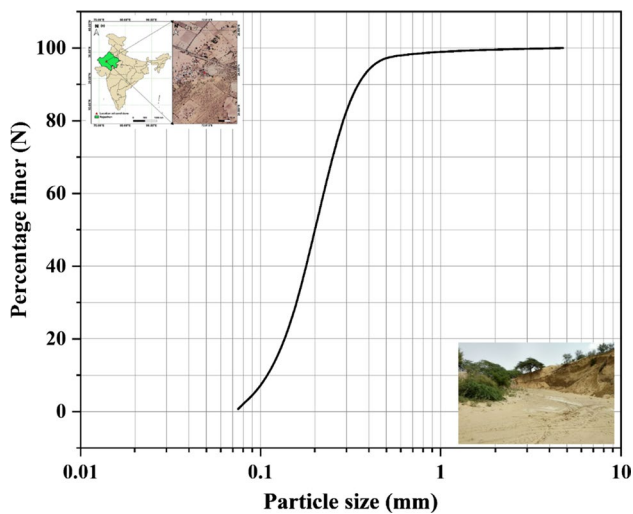

Fig. 2 Particle size distribution curve for desert sand

Table 1 Properties of natural desert sand

Properties	Value	Unit	Indian Standard (IS) Code
Specific Gravity	2.57		IS: 2720 (Part III)—1980
Silt Content	10	%	IS: 2386 (Part II)—1963
Permeability	$6.06 \cdot 10 - 6$	m/s	IS: 2720 (Part XVII)—1986
e_{max}	0.90		IS: 2720 (Part XV)—1986
e_{min}	0.62		
OMC	12	%	IS: 2720 (Part VIII)—1983
MDD	1.65	g/cc	
D_{10}	0.13	mm	IS: 1498—1970, 2002
D_{30}	0.18	mm	
D_{60}	0.23	mm	
D_{50}	0.21	mm	
C_u	1.83		
C_c	1.09		

Preparation of biopolymers solution

The biopolymers (Sodium alginate of Himedia, Pectin and Acacia Gum of Sisco research laboratories Pvt. Ltd.) were commercially procured. All biopolymers (in powdered form) were dissolved in water and a solution was prepared. The known weight (equal to the define percentage of pore volume) of biopolymer powder was added to water slowly for the desired concentration. Shaking was carried out to ensure homogeneous solution. The solutions were prepared for 1 and 0.75 PV with 1%, 2% and 3% biopolymer powder. Prepared solutions were either sprayed, poured, or mixed with sand samples depending on viscosity of the prepared solution.

Specimen preparation with different biopolymers

Sand sample of 790 gm was kept in a black coloured, rectangular shaped, microwave safe, plastic throwaway box, which weighed 13.8 gm and had measurements of $150 \times 90 \times 40$ mm. Biopolymer solution was prepared and treatment of sand was performed as per viscosity of prepared solution as shown in Table 2. In case of lower viscosity biopolymer concentration, spraying was performed, whereas in case of average viscosity, pouring of solution was applied, while in case of higher viscosity, mixing and compact process was used to treat sand samples. The specimens were prepared for the wind tunnel laboratory tests and surface strength test including thickness of crust measurement. Three replicas of each combination were prepared to

Table 2 Details of experimentation of biopolymer percentage with different pore volumes and treatment methods

Sample designation	Percentage biopolymer (B%)			Pore volume (PV)		Treatment method		
	1%	2%	3%	0.75 PV	1.0 PV	Spray	Pour	Mix & Compact
SA11S	√				√	√		
SA10.75S	√			√		√		
SA21P		√			√		√	
SA20.75P		√		√			√	
SA31M			√		√			√
SA30.75 M			√	√				√
P11S	√				√	√		
P10.75S	√			√		√		
P21P		√			√		√	
P20.75P		√		√			√	
P31M			√		√			√
P30.75 M			√	√				√
AG11S	√				√	√		
AG10.75S	√			√		√		
AG21S		√			√	√		
AG20.75S		√		√		√		
AG31S			√		√	√		
AG30.75S			√	√		√		

Three replica of each test is prepared

confirm the tests results. The specimens prepared for the surficial application (spraying and pouring of the biopolymer solutions) were prepared by placing the known weight of natural sand in a container. After tapping the sides of the box, top surface has been levelled. Then the prepared biopolymer solution was sprayed or poured directly on the surface. In mix and compact technique, the known weight of sand was placed on a plate for mixing it with biopolymer solution. After hand mixing, the specimen was filled in three layers with 25 times compaction using 850 gm weight hammer. After complete filling and compaction of sand, the top layer was smoothened and levelled. Biotreated samples by all methods were allowed to dry in the laboratory for 14 days (Fig. 3).

Testing setup

Test setup for wind tunnel

Figure 4 shows the wind tunnel setup having total length of 1.5 m. out of which working section was 0.6 m in length and cross section dimension was $0.3\ m \times 0.3\ m$. The treated and natural sand sample were tested in the wind tunnel for a 1 min duration at increasing order wind velocities of 10, 20, and 30 m/s to calculate wind erosion resistance (Dagliya et al. 2022b; Miao et al. 2020). Anemometer was used to validate the wind speed of complete setup (Poulsen et al. 2020). Treated and natural sand samples were placed and fixed in the test section before starting the test (Wang et al. 2018). Sand loss was evaluated by mass variance and visual action. Mass loss was recorded by finding difference between pre- and post-weighing of the tested sample (Fattahi et al. 2020).

Surface strength test

Figure 5a shows the pocket penetrometer, used to assess surface strength of the biotreated sand samples. It can be used in the laboratory as well as in the field to measure penetration resistance of the surface of biotreated sand sample. The gadget is extensively consumed as it imparts immediate outcomes and is easy to operate (Cheng and Cord-Ruwisch 2012; Fick et al. 2020; Kou et al. 2020; Omoregie et al. 2018). However, constraint of the device is its range of gauging strength which is 0–4.5 kg/cm². The least count of the device is 0.25 kg/cm². To compute the surface strength (unconfined compressive strength) of the biotreated sample, device was punched at five different locations (see Fig. 5b) to check uniformity in treatment (Dagliya et al. 2022b).
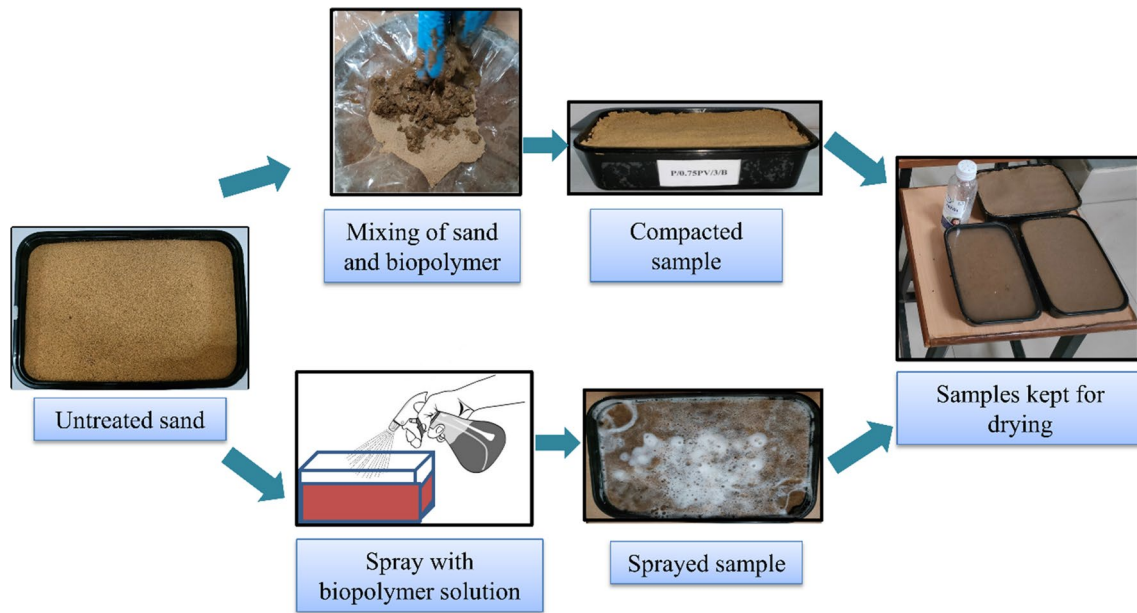
Fig. 3 Overview of sample preparation using biopolymer solution

Fig. 4 Wind tunnel laboratory setup (Dagliya et al. 2022b)
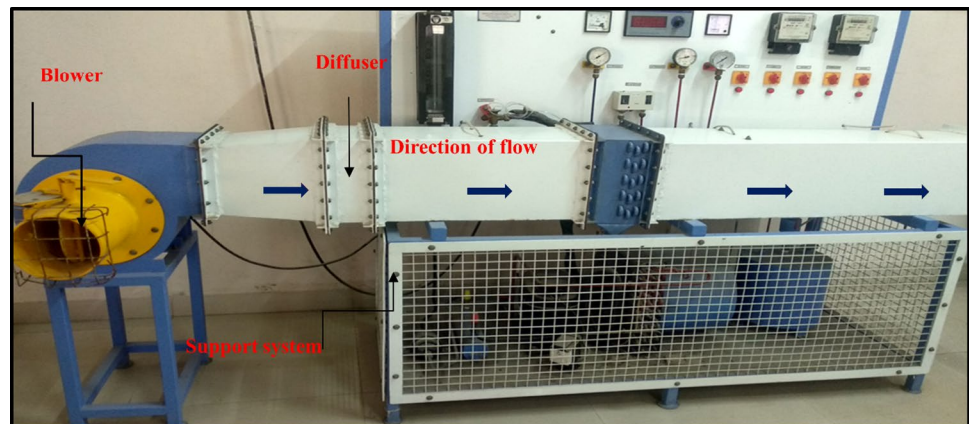
SEM images of biotreated sand particles

SEM tests were performed to examine the binding matrix of biotreated sand particles. Natural sand and biotreated sand with 1% biopolymer were chosen to study surface morphology. After wind tunnel testing, the sample was accumulated from surface and kept in an oven at 105 °C temperature for 1 day. Completely desiccated sample was crushed to fine powder and used for SEM analysis. For obtaining SEM images, the samples were coated with gold sputter and pictures were taken at different beam intensities.

Results and discussions

Observation through surface images

Biotreated sand samples were observed visually, pre- and post-wind tunnel testing. Figure 6 shows some selected images of natural and biotreated sand samples for 1 PV. Representative images were selected, that include all three treatment methods and biopolymers, to display comparison. Rest of the images were presented in the Appendix as supplementary figures. It was observed from images that

Fig. 5 **a** Pocket penetrometer used to measure surface strength; **b** Surface strength measurement at five positions (Dagliya et al. 2022b)
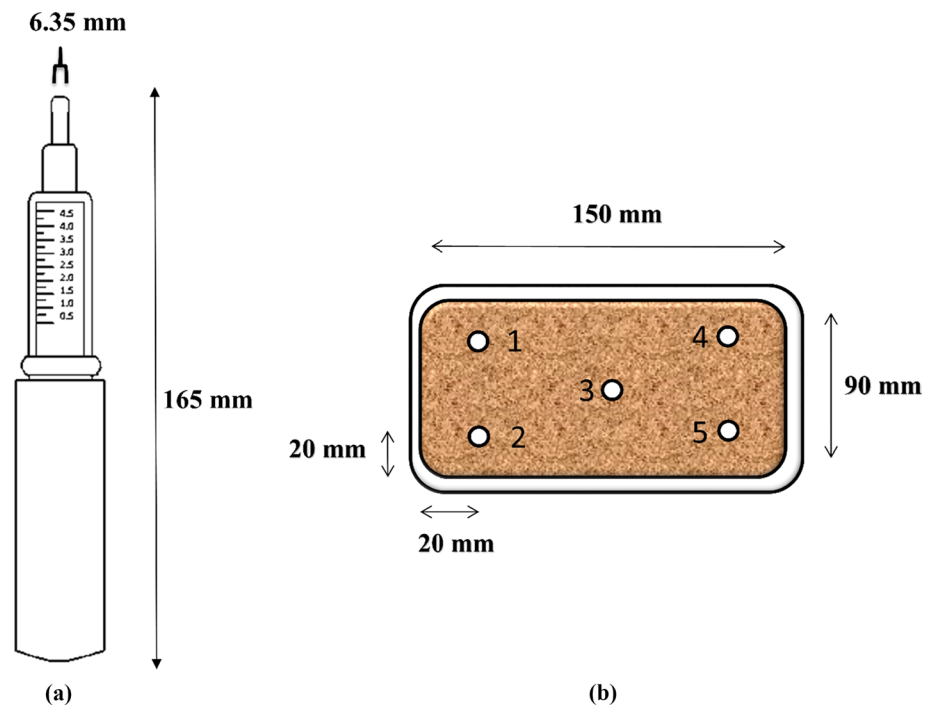
(a)

(b)

Fig. 6 Overview of natural and biotreated sand samples pre- and post-wind tunnel testing for different biopolymers at different wind velocities

untreated sand blows off from the surface, while no changes were perceived in biotreated sand samples for all proportions. Biotreated sand with all combinations and methods of treatment gave almost 100% result in terms of resistance to sand erosion, even at wind speed up to 30 m/s. This result was consistent with observation of Ayeldeen et al. (2018). Increase in biopolymer percentage enhanced trussing property of sand and reduced sand erosion. Also, none of the biopolymer treated soil samples showed any crack development on the surface. It was noted from images that in the pouring method black spots (fungus) were observed on the treated surface, which exhibited that biopolymer solution did not penetrate deeply and dried on the surface.

Measurement of soil erosion through wind tunnel testing

Table 3 summarizes the sand loss percentage, post-wind tunnel testing at varied wind speed for all treatment conditions. Sand specimens were weighed pre and post-wind tunnel testing with 0.01 gm accuracy. The mass loss percentage for natural sand were 9.2%, 36% and 59.5% for 10, 20, and 30 m/s wind speed, respectively. It was found that all three biopolymers (SA, P, and AG) minimized wind-induced erosion significantly. Maximum weight loss in percentage with biopolymers was 0.3%, 0. 5% and nil against the wind speed of 30, 20 and 10 m/s, respectively, which is negligible.

A study was performed (Ayeldeen et al. 2018) using different biopolymers, i.e. xanthan gum, guar gum, carrageenan and modified starch at varying percentages to reduce wind-induced sand erosion. It was observed that with an increase in percentage of biopolymer, sand erosion can be reduced. However, biopolymer percentage has its own demarcation and can be increased to a certain limit due to its effect on viscosity. Almajed et al. (2020) demonstrated study on sand erosion control against wind speed up to 58.32 km/h and found that EICP (1:0.67) with SA 1% gave highest results in terms of surface strength and thickness formation.

Lemboye et al. (2021) performed study to control sand erosion up to 16.2 m/s wind speed using biopolymers and shown similar results. Experimental work was performed by (Mahamaya et al. 2021) to stabilize fly ash and coal mine overburden soil using xanthan gum, guar gum and carboxymethyl cellulose, and results shown that 1% of biopolymer could mitigate soil erosion and SEM results were also consistent with this study.

Crust thickness measurement

To examine the effectiveness of biopolymers treatment, crust formation test of the samples was performed. After wind tunnel testing, all samples of different proportions were removed from the container and were tested for crust thickness formation. Figure 7 displays crust thickness formation of treated samples with different percentage and pore volumes. Table 3 summarizes the thickness formation for all treatment conditions. To comprehend penetration and bonding of biopolymers with sand, study was performed to measure thicknesses formation as well as surface strength of the sand. It was observed from thickness measurement test that an increase in biopolymer percentage resulted in high viscosity due to which they were neither able to penetrate and nor mixed with the soil. Although surface strength was found good in mix and compact method with 100% thickness formation, but the process was not suitable for field application, and hence, spray method should be considered for surface treatment.

Figure 7 depicts that crust formation of biotreated samples SA11S, SA10.75S, SA21P, SA20.75P, P11S, P10.75S, P21P, P20.75P, AG10.75S, and AG20.75S was poor and the crust broke during reclamation and handling, while samples SA31M, SA30.75 M, P31M, P30.75 M AG11S, AG21S, AG31S, and AG30.75S were eventually harder and remained intact during reclamation and handling.

Table 3 Soil weight loss in percentage following wind tunnel testing at varying wind speeds and thickness crust formation

Biopolymer	Mass loss in percentage at different wind speeds			Surface thickness (mm)
	10 m/s	20 m/s	30 m/s	
Natural sand	9.2	36	59.5	–
SA11S	0.0	0.01	0.3	3–4.9
SA10.75S	0.0	0.03	0.15	7.1–13.2
SA21P	0.0	0.23	0.035	2.1–3.8
SA20.75P	0.0	0.01	0.02	3.9–10.2
SA31M	0.0	0.01	0.03	35.2–36.93
SA30.75 M	0.0	0.03	0.07	35.9–38.5
P11S	0.0	0.10	0.2	14.92–22.9
P10.75S	0.0	0.05	0.14	12.2–20.2
P21P	0.0	0.03	0.065	6.4–9.4
P20.75P	0.0	0.02	0.01	3.79–6.3
P31M	0.0	0.01	0.02	35.21–40.16
P30.75 M	0.0	0.043	0.076	34.2–36.06
AG11S	0.0	0.30	0.5	13.2–35.43
AG10.75S	0.0	0.08	0.149	6.25–12.9
AG21S	0.0	0.07	0.087	14.5–33.14
AG20.75S	0.0	0.06	0.02	7.25–22.6
AG31S	0.0	0.06	0.08	29.28–35.23
AG30.75S	0.0	0.04	0.08	27.9–36.41

Fig. 7 Crust thickness measurement of different biopolymer treated sand samples

Fig. 8 Effect of various percentages of biopolymer on UCS at different test positions
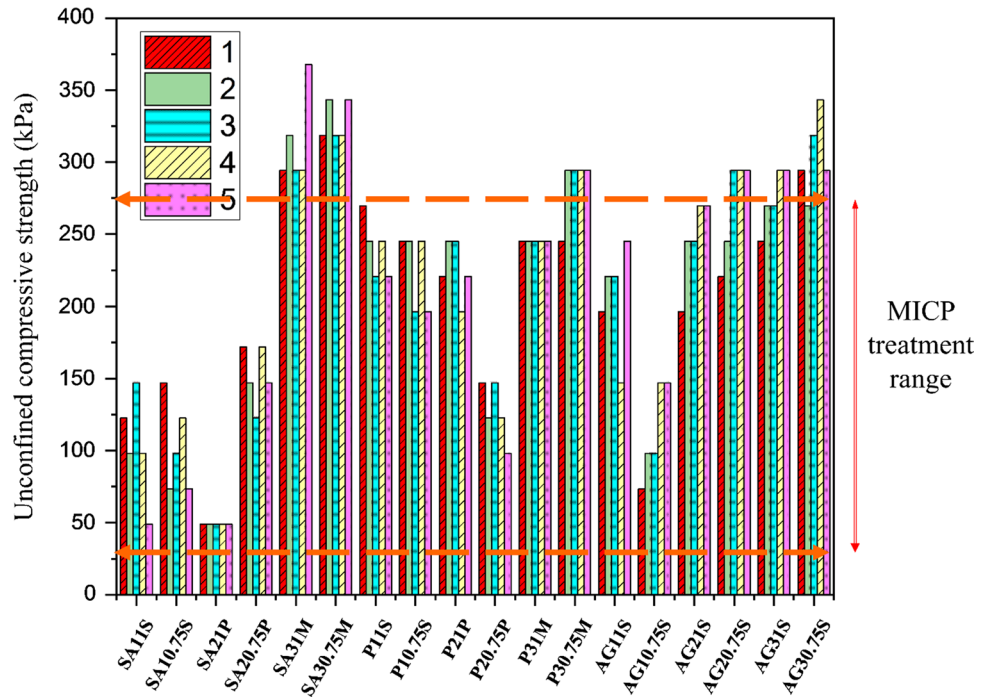
Surface strength test

Figure 8 displays the unconfined compressive strength (UCS) for all treatment condition. In present study, pocket penetrometer was used to quantify surface strength of biotreated sand samples. Surface strength was measured at five different positions to examine the variability in treatment (if any). The maximum strength was found for SA and P with 3% biopolymer solution using mix and compact method. Treatment with AG using 3% biopolymer with the

spraying method also provided significant strength. Average surface strength value for pouring method was lower in comparison with other two methods due to lack of penetration in solution. Average surface strength for SA11S, SA21P, and SA31M was 102.96, 49.03, and 313.81 kPa, respectively. Compressive strength which was measured at five different positions was varied more with SA, compared to other two biopolymers. It was observed in case of AG bioplymer that surface strength enhanced with increase in the percentage of biopolymer and also variation in surface strength at different locations were less.

Figure 8 also shows the minimum and maximum value of MICP-treated sand samples in dotted line, which was adopted from previous study (Dagliya et al. 2022b). MICP treatment was conducted with minimum 5 days and maximum 20 days treatment cycle. It was observed that both minimum and maximum values were higher in case of biopolymer-treated specimen compared to MICP. Also MICP expended consistent 20 day's treatment while biopolymer required single treatment only.

(a)

AG11S   P11S   SA11S

AG10.75S   P10.75S   SA10.75S

(b)
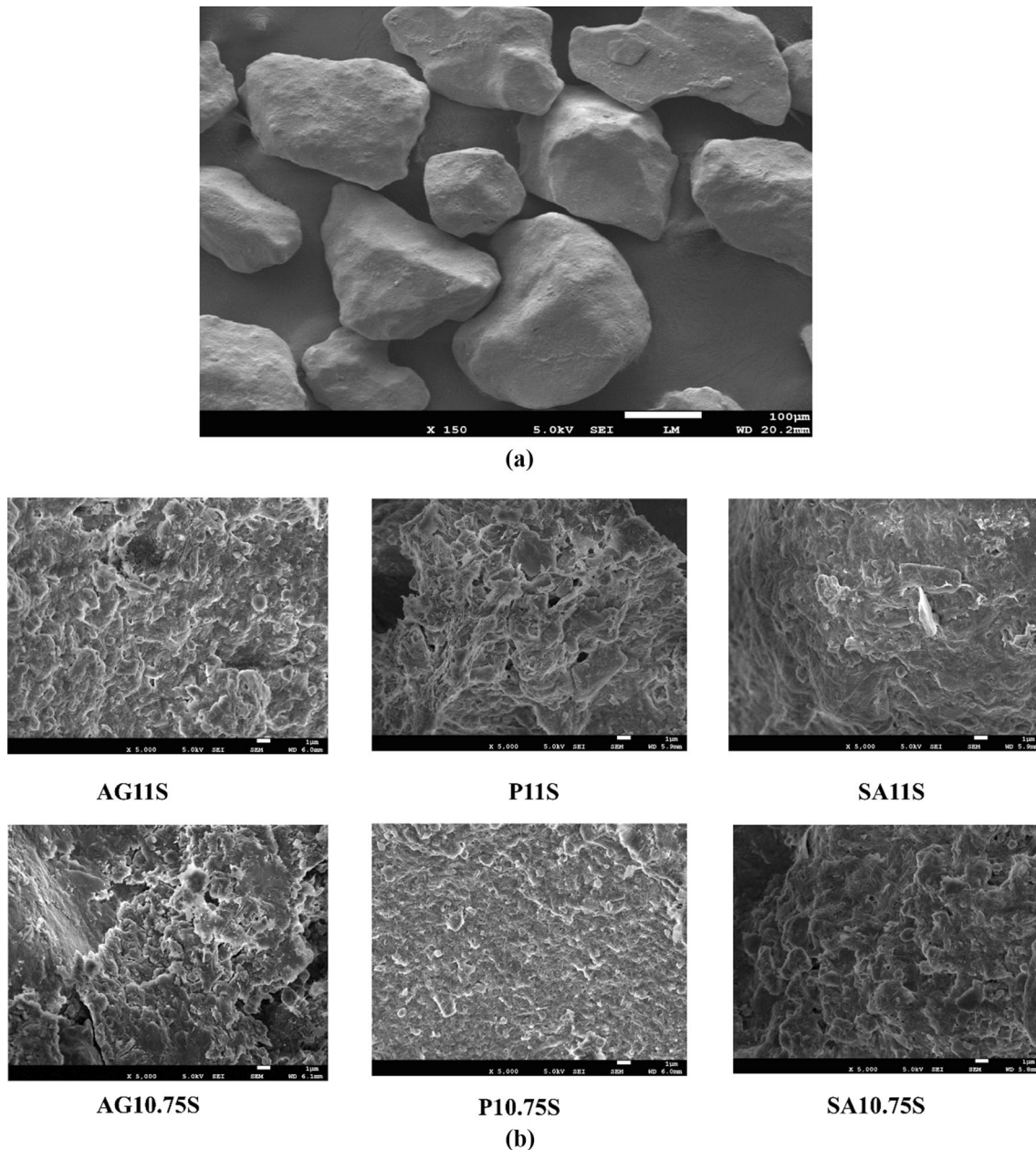
Fig. 9 **a** SEM image of the natural desert sand sample; **b** SEM images of biotreated sand samples with different biopolymers for 1% concentration at 5000X magnification

Micro-scale characterization analysis

SEM analysis was performed for natural and biotreated sand samples to observe pore structure. Figure 9a displays the image of natural desert sand. A clearly visible gap between particles can be observed. This suggests dearth of bonding between particles and also lack of shear resistance against wind-induced shear stress. Figure 9b shows SEM images of the biopolymer samples with 1% biopolymer concentration prepared using spraying method. It illustrated that biopolymer tends to fill the vacuums between sand particles, thereby enhanced bonding between them. This bonding helped to enhance resistance to wind-induced stresses. The spraying method can be used more easily in the field in comparison with the pouring method and mix and compact method.

Conclusion

The current study explores the utilization of distinct types of biopolymers at various proportions of pore volumes for stabilizing desert sand. The biotreated samples were examined for visual observations, wind erosion resistance, crust thickness measurements, unconfined compressive strength, and SEM analysis. The subsequent conclusion can be depicted from the current experiment study:

1. The penetration depth of biopolymer solutions fluctuated due to the viscosity of the solutions. Solutions prepared using AG (ranging from 1 to 3% biopolymer concentration) were able to penetrate easily due to low viscosity. Conversely, solutions prepared by SA and P (ranging from 1 to 3% biopolymer concentration) depicted resistance to penetration due to high viscosity. These observations will help to narrow down the selection of appropriate biopolymer for stabilizing desert sand.

2. Results from wind tunnel testing revealed that untreated sand had loss of 9.2, 36 and 59.5% at the wind speed of 10, 20, and 30 m/s, respectively. In contrast, the percentage of sand loss in case of biotreated sand samples were almost negligible. This was mainly an outcome of binding between particles, due to the presence of biopolymer (as visible from SEM images).

3. Maximum surface strength was observed in 3% concentration for all biopolymers. It should be noted that biotreatment performed with AG biopolymer, using the spraying method, was more feasible for field application than the other method (mix and compact method).

Appendix

Sample Designation	Before test	Wind Speed (10 m/s)	Wind Speed (20 m/s)	Wind Speed (30 m/s)
SA10.75S				
SA20.75P				
SA30.75M				

Sample Designation	Before test	Wind Speed (10 m/s)	Wind Speed (20 m/s)	Wind Speed (30 m/s)
SA11S				
SA21P				
SA31M				

Sample Designation	Before test	Wind Speed (10 m/s)	Wind Speed (20 m/s)	Wind Speed (30 m/s)
P10.75S				
P20.75P				
P30.75M				

Sample Designation	Before test	Wind Speed (10 m/s)	Wind Speed (20 m/s)	Wind Speed (30 m/s)
P11S				
P21P				
P31M				

Sample Designation	Before test	Wind Speed (10 m/s)	Wind Speed (20 m/s)	Wind Speed (30 m/s)
AG10.75S				
AG20.75S				
AG30.75S				

Images of biotreated sand samples pre- and post-wind tunnel testing for different biopolymers at different wind speeds

Declarations

Conflict of interest There is no conflict of interest with any third party.

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