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Enhancing the strength of Indian desert sand using gum and starch biopolymers

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Abstract. This study introduces an innovative approach, utilizing the ultrasonic pulse velocity (UPV) test, to assess the strength of desert sand samples treated with biopolymers, including various combinations of pore volumes (PV) and biopolymer concentrations. Consequently, unconfined compressive strength (UCS) and split tensile strength (STS) tests were performed on the treated desert sand to gauge the effectiveness of different biopolymers, specifically Starch and Gum varieties. The objective of this research is to highlight the significance of biopolymers as environment pleasant solution for enhancing the mechanical qualities of desert sand. The study incorporates five different biopolymers, including Corn starch (CS), Potato starch (PS), Tapioca starch (TS), Xanthan Gum (XG), and Guar Gum (GG) in varying concentrations (1%, 2%, and 3%), and two distinct pore volumes, 1PV and 0.75PV. The outcomes of UCS, UPV, and STS tests demonstrated that the strength of the sand increases as the biopolymer interacts with it up to a certain concentration. XG exhibited superior performance compared to GG, while among the starches, CS delivered the best results. Moreover, the study finds that pore volume plays an important role when interacting with sand. It was found that the 0.75 PV performs better than the 1 PV. The highest recorded UCS value was 891 kPa for the 3% CS treatment with 0.75 PV, whereas the lowest UCS value was 135 kPa for the 3% PS treatment with 1 PV. Likewise, the maximum STS value was 201 kPa for the 3% XG treatment with 0.75 PV, while the minimum STS value was 31 kPa for the 3% PS treatment with 1 PV. Furthermore, the minimum and maximum values from the UPV test were 798 m/s and 1270 m/s, respectively, which showed that all samples have strength. SEM and EDX tests for microstructure analysis have been performed to show bonding among particles.

Keywords: biopolymers; desert sand; gum; starch; UPV

1. Introduction

In India, a substantial portion of land, approximately 32 million hectares, falls within the hot arid ecosystem, predominantly located in the northwestern region of the country. Notably, this ecosystem is most pronounced in the Western province of India, specifically Rajasthan, where just 12 districts account for a significant 62% of the total hot arid ecosystem (Dagliya *et al.* 2022c). This region experiences a set of challenging environmental conditions. High evapotranspiration rates, coupled with recurrent droughts occurring once every three years, are common phenomena. The combination of elevated ambient air temperatures and soil erosion exacerbates the process of desertification in Rajasthan.

Numerous methods for enhancing ground conditions exist (Fu *et al*. 2022), including compaction, vibration, and consolidation, as well as the utilization of geotextiles, Geogrid reinforced soil (Sarfarazi *et al.* 2022) mud, bitumen, lime, cement, and even waste materials, which encompass both chemical and mechanical stabilization techniques (Dagliya *et al.* 2025). However, it is worth noting that these methods can be cost-prohibitive and pose considerable challenges when implemented in real-world field applications, as emphasized by (Sharma *et al.* 2022, Dagliya and Satyam 2024a, Rawat and Satyam 2024a). In addition to these practical considerations, there is a growing recognition of the importance of adhering to environmental protection standards, as outlined in the Kyoto Protocol of 2005. Reducing carbon emissions is a global imperative, and engineering solutions must align with these sustainability goals. Consequently, there exists a pressing need for the development of engineering approaches that are not only effective but also environmentally pleasant to counter the erosive effects of wind (Jang and Jia 2020). In the pursuit of environmental protection, several bio-mediated soil improvement techniques have emerged, including Microbial-induced calcite precipitation (MICP), Enzyme-induced carbonate precipitation (EICP), and the use of biopolymers to reinforce soil particles. Among both MICP and EICP, one of the issues is the release of by-products, such as ammonium chloride, as pointed out by the (Dagliya and Satyam 2022) and also in MICP, bacterial food (nutrient broth), is expensive to implement on a large scale testing (Dagliya *et al.* 2023a, Rawat and Satyam 2024b). Instead, biopolymers represent an altered approach. These are natural polymers derived from living organisms, and they are utilized as construction materials to enhance

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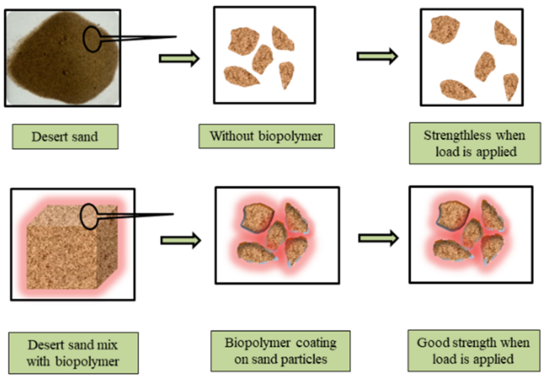

Fig. 1 Behaviour of desert sand and biopolymer coated desert sand in terms of strength

soil properties. Biopolymers are typically composed of substances sourced from plants or animals, and they possess several noteworthy qualities. They are characterized by their endless growth potential, making them a carbon-neutral and sustainable resource. Furthermore, biopolymers are inherently renewable and biodegradable, aligning with principles of long-term environmental sustainability (Ayeldeen *et al.* 2016).

When biopolymer solution is mixed with desert sand, the solution starts penetrating in voids and starts saturating sand grains. This occurs speedily due to the hydrophilic character of the sand surface. As the biopolymer solution comes in contact with the sand surface, it encloses the individual soil grains and forms skin around them, which starts the bonding process. This skin formation works as a bridge for connecting sand particles. During the curing process, water evaporates from the system and the biopolymer matrix undergoes dehydration process. Due to the dehydration process the skin formation becomes stronger, and strength enhancement starts among sand particles (Dagliya *et al.* 2023b, c, Dagliya and Satyam 2024b). It achieves this by drawing the particles closer to each other, resulting in the compression of pore spaces within the sand matrix. The outcome of this compression is the formation of shorter connection chains between sand particles, rendering them more resilient against wind forces. Consequently, the geotechnical performance of the sand is notably improved throughout the drying procedure. Moreover, it's worth noting that an increase in the quantity of biopolymer used, up to an optimum level, leads to the development of stronger connections among sand grains and consequently greater shear strength (Haeri *et al.* 2019, Fatehi *et al.* 2021).

Fig. 1 illustrates the behaviour of desert sand and biopolymer coated desert sand in terms of strength. Desert sand, in its natural state have lack of strength. However, when combined with biopolymer solutions, a remarkable enhancement in strength occurs, enabling it to bear substantial loads. The introduction of biopolymer solutions prompts a reaction with the sand, filling the gaps between individual particles and facilitating the binding of these particles. This interaction substantially augments the overall strength of the sand. Moreover, the utilization of biopolymers has proven effective in reducing sand erosion (Shabani *et al.* 2022), reducing sand compressibility, and decreasing soil permeability (Burra *et al.* 2019, Refaei *et al.* 2020, Mahamaya *et al.* 2021). Studies have been performed on sand erosion resistance using biopolymers, and results indicated that wind-generated soil loss can be restrained by consuming biopolymers (Lemboye *et al.* 2021). Many studies have been performed using different biopolymers, i.e., SA (sodium alginate), P (Pectin), AC (Acacia Gum), XG (Xanthan gum), GLG (Gellan gum), and GG (guar gum), etc., for enhancing the quality of soil (Cabalar and Demir 2020, Choi *et al.* 2020, Sujatha *et al.* 2021, Dagliya *et al.* 2022a) but very few studies have focused (Elkenawy *et al.* 2023), on their application with desert sand. (Qureshi *et al.* 2017), assessed the study on the influence of cement and XG on the UCS value of biotreated sand. Remarkably, the maximum UCS strength achieved by applying 2% XG was found to be comparable to that obtained with 10% cement. Furthermore, research by (Ayeldeen *et al.* 2016) highlighted the impact of different biopolymers, such as XG, starch, and GG, on silt. In this context, the UCS values reached 337 kPa for XG, 575 kPa for starch, and 842 kPa for GG using 2% biopolymer with silt. Additionally, a study has been performed on bearing capacity and deformation of sandy soil foundations using XG. The test results show that the xanthan gum exerts cementation and filling effects between sand particles, enhancing the bearing capacity of sand (Zhang *et al.* 2025).

An essential factor to consider in the interface between soil and biopolymers is the amount of water present. (Chang *et al.* 2016) Conducted a study highlighting that higher soil moisture content plays a pivotal role in the soil biopolymer system. In such conditions, whether it forms a matrix or a dehydrated gel, it exhibited the capacity to absorb and transport water into hydrogels. This process results in the volumetric extension of the soil, leading to expanded space among soil grains and consequently, an elevation in the soil void ratio, as observed in the research by (Mendonça *et al.* 2021). Indeed, research on clay biopolymers has seen numerous developments, but investigations involving sand biopolymers, especially in the context of desert sand, remain relatively scarce.

The novelty of the current research lies in its exploration of the effectiveness of five commercially available biopolymers: Corn starch (CS), Potato starch (PS), Tapioca starch (TS), Xanthan Gum (XG), and Guar Gum (GG). These biopolymers are evaluated at different proportions, specifically 1%, 2%, and 3%, and applied to two different pore volumes i.e., 1 PV and 0.75 PV, to enhance the engineering properties of desert sand and investigate its strength improvement. To assess the impact of biotreatment, various tests were conducted, including Unconfined compressive strength (UCS), Split tensile test (STS), Ultrasonic pulse velocity (UPV), Scanning electron microscope (SEM), and Energy dispersive X-ray spectroscopy (EDX).

Fig. 2 provides a flowchart illustrating the diverse types of biopolymers employed, the treatment combinations explored, and the array of tests conducted as part of the present study, offering a comprehensive overview of the research methodology and objectives.

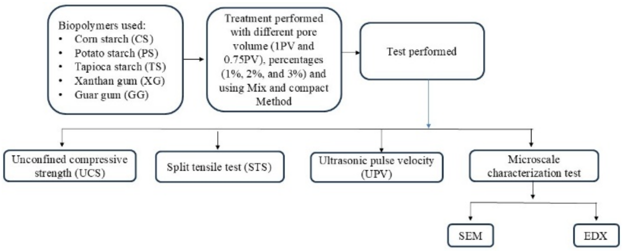

Fig. 2 Details of Biopolymers used and test performed for the strength enhancement of Desert sand

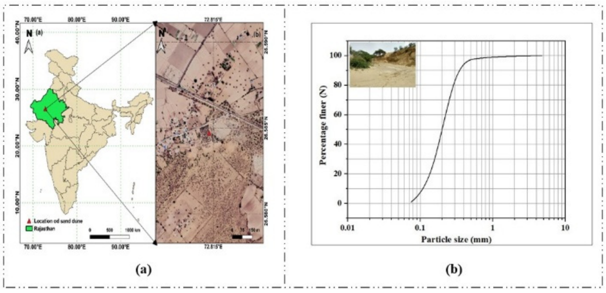

Fig. 3 Desert sand (a) Location of sand collected (b) Particle size gradation curve

2. Materials and methods

2.1 Desert sand properties

The sand utilized in the present study was sourced from the western region of Rajasthan, India, as depicted in Fig. 3(a). An examination of this sand revealed it to be classified as poorly graded, as illustrated in Fig. 3(b). The specific gravity of the sand was determined to be 2.75. The sand particles exhibited a mean size of 0.21 mm, with a coefficient of uniformity of 1.83 and a coefficient of curvature of 1.09. The range of void ratios spanned from a minimum of 0.62 to a maximum of 0.90, as indicated in Table 1. To gain insight into the micro-scale properties of the untreated desert sand samples, micro-scale testing (SEM and EDX) was conducted. Fig. 4 offers a visual representation of these analyses. Fig. 4(a) reveals the absence of bonding between individual sand particles through SEM analysis, and Fig. 4(b) provides a glimpse of the elemental composition present within the desert sand, as observed through electron microscopy (EDX).

Table 1 Properties of sand used

Properties	Value
C_u	1.83
C_c	1.09
D_{10} (mm)	0.13
D_{30} (mm)	0.18
D_{60} (mm)	0.23
D_{50} (mm)	0.21
e_{max}	0.90
e_{min}	0.62

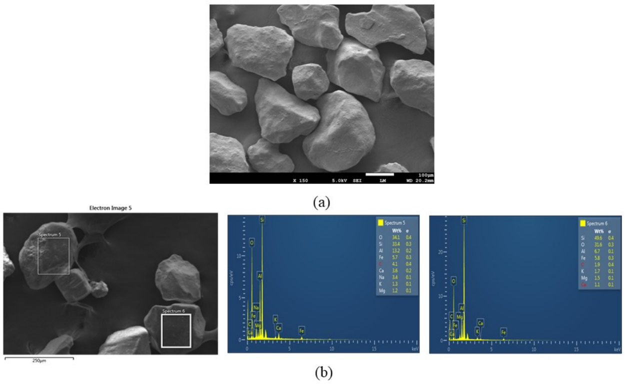

Fig. 4 Microscale testing for desert sand sample (a) SEM image at 150x magnification (b) EDX analysis

2.2 Biopolymers

Guar gum (GG)

Guar gum is a naturally occurring, neutrally charged polysaccharide obtained from the sows of the leguminous shrub known as Cyamopsis tetragonoloba. It comes under the Galactomannan group of polysaccharides. The structural composition of GG comprises 1,4-linked β-D-mannopyranose units, with the inclusion of α-D-galactose units at random branch points. One of the most notable characteristics of GG is its remarkable ability to rapidly hydrate in chill water, resulting in the formation of extremely viscous mixtures even when used in low quantities (Chen *et al.* 2013). GG finds widespread application in various industries. In the realm of food products, it serves as a versatile additive, functioning as a thickener, stabilizer, or emulsifier. Typically, it is employed in food processing in amounts less than 1% of the total food weight.

The GG has been used to improve the stability of materials in mine tailings. The undrained shear strength of mine tailings has been increased as a result of the addition of GG. The shear strength increased from 2 to 22 kPa when the material had 30% water (Chen *et al.* 2013).

Xanthan Gum (XG)

The biopolymer XG is made of polysaccharides and was produced by the bacteria Xanthomonas campestris (Bozyigit *et al.* 2021). Two glucose units, two mannose units, and one glucuronic acid unit make up its molecular structure, which primarily forms helical configurations. Depending on elements like the dissolution temperature and salt content, XG solutions conformation can either be a helix or a random coil. One characteristic of XG is its capacity to linearly raise the viscosity of solutions as XG content increases. Due to this property, it is extremely stable throughout a wide range of temperatures, pH levels, and electrolyte concentrations. Due to its thermal stability, compatibility with different food additives, and pseudo-plastic rheological qualities, XG has found extensive use in the food sector. Additionally, it serves as a gelling and suspending agent and is employed for viscosity control in the oil industry, where it acts as a drilling mud thickener.

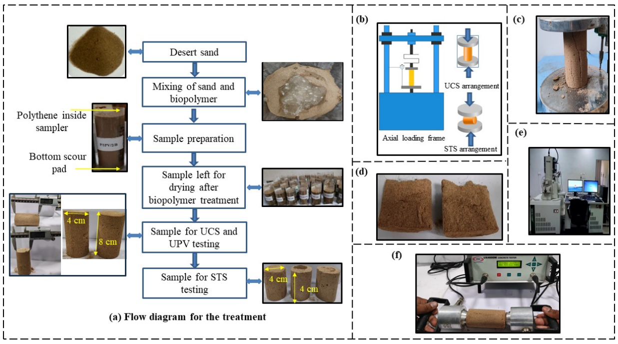

Fig. 5 Sample preparation and experimental setup, (a) Flow diagram for the treatment, (b) Experimental setup for UCS, STS test, (c) Sample failure after UCS test, (d) Sample failure after STS test, (e) Experimental setup for SEM, and EDX analysis and (f) Experimental setup for UPV test

More recently, researchers have begun to explore the application of XG in geotechnical engineering practices. This is due to its remarkable efficiency in strengthening soil, making it a promising addition to soil stabilization methods in the field of geotechnical engineering (Bağrıaçık and Mahmutluoğlu 2023).

Starch

Starch stands out as one of the most prevalent natural biopolymers, widely present in seeds, grains, and plant roots, with sources encompassing maize, rice, wheat, corn, potatoes, and cassava. The characteristics and properties of this natural biopolymer can vary significantly based on its source. Starches are fundamentally composed of sugar molecules or monosaccharides, featuring α-D-1,4 and/or α-D-1,6 linkages. Starches find extensive applications across diverse industries, including food, textiles, cosmetics, plastics, paper, and pharmaceuticals. In these domains, it serves various roles such as thickeners, stabilizers, disintegrants, diluents, strengtheners, and adhesives. In the realms of construction and geotechnical engineering, starch has been harnessed as an adhesive in drilling fluids. Additionally, it has shown potential in improving mechanical characteristics of soil, such as UCS, shear strength, elastic modulus, and permeability function, particularly when applied as pre-gelatinized powder (Khatami and O'Kelly 2013). Starch binds soil particles and helps effectively to reduce soil erosion (Orts *et al.* 2000). Results from the use of maize starch in soil reinforcement demonstrated that a soil treated with 16.6% starch can increase UCS values of up to 26 MPa (Kulshreshtha *et al.* 2017).

2.3 Specimen preparation

The samples were prepared using the wet mixing method. The concentrations of the biopolymer solutions (refer to Table 2 for different combinations) in the current investigation were 1%, 2%, and 3% and 1PV and 0.75PV. To make the appropriate samples, the oven-dried sand is mixed with various biopolymer solutions. Then, these samples were prepared for two distinct tests, the UCS and STS. The samples were arranged in a 1:2 ratio for the UCS test, resulting in cylindrical specimens that measured 4 cm in diameter and 8 cm in height. The surface of the cylindrical plastic bottles was coated with polythene to make it easier to remove samples after they had dried. Similar to this, samples were arranged for the STS test in a ratio of 1:1, resulting in cylindrical specimens that measured 4 cm in diameter and 4 cm in height. These samples were also packed in three compact layers and allowed to undergo a 28 days air drying period, as depicted in Fig. 5(a). This methodology ensured consistency and precision in the experimental setup for the subsequent testing of the mechanical properties of the treated desert sand.

Table 2 Details of various treatment combinations encompassing different biopolymer percentages, different pore volumes (PVs), and the test sample prepared

Label	Biopolymer percentage			Pore volume (PV)		Test sample prepared (Three replicas for each)	
	1%	2%	3%	0.75 PV	1.0 PV	STS	UCS
CS11	*				*	*	*
CS10.75	*			*		*	*
CS21		*			*	*	*
CS20.75		*		*		*	*
CS31			*		*	*	*
CS30.75			*	*		*	*
TS11	*				*	*	*
TS10.75	*			*		*	*
TS21		*			*	*	*
TS20.75		*		*		*	*
TS31			*		*	*	*
TS30.75			*	*		*	*
PS11	*				*	*	*
PS10.75	*			*		*	*
PS21		*			*	*	*
PS20.75		*		*		*	*
PS31			*		*	*	*
PS30.75			*	*		*	*
XG11	*				*	*	*
XG10.75	*			*		*	*
XG21		*			*	*	*
XG20.75		*		*		*	*
XG31			*		*	*	*
XG30.75			*	*		*	*
GG11	*				*	*	*
GG10.75	*			*		*	*
GG21		*			*	*	*
GG20.75		*		*		*	*
GG31			*		*	*	*
GG30.75			*	*		*	*

3. Test setup

3.1 Test setup for UPV

The research included a UPV test to assess the strength of the biotreated sand samples. An ultrasonic pulse was generated and transmitted through the samples, and the time taken for the pulse to travel through the material was recorded. The UPV test is capable of providing valuable insights into the quality and continuity of the material being tested. Higher velocity values typically indicated a material with good quality and continuity, while lower values suggested the presence of discontinuities, such as cracks and voids, which are indicative of poor quality. In preparation for the UPV test, a greasing gel was applied to the receiving and transmitting transducers (Sharma and Satyam 2021). This was performed to ensure proper contact with the potentially rough surface of the biotreated samples. The UPV testing process adhered to the standards outlined in IS: 13311 (Part 1) - 1992. Fig. 5(f) provides a visual representation of the UPV testing setup and procedure.

3.2 Test setup for UCS & STS

Following a 28 days air drying curing period, all the samples were carefully removed from the specimens and subsequently placed in an oven set at a temperature of 105°C. This step was undertaken to ensure thorough and complete drying of the samples and lasted for 24 hours. After this drying process, the samples were taken out of the oven and allowed to acclimate to room temperature for 1 hour. To prepare the samples for testing, both the top and bottom surfaces were carefully smoothed to ensure uniform loading during the subsequent tests. The UCS testing was conducted using a fully automatic machine, adhering to a strain rate of 1.25 mm/min, by IS: 2720 (Part 10) – 1991 standards. For the UCS testing, a load cell with a capacity of 2.5 kN and an LVDT with a displacement range of 25 mm were employed (Dagliya *et al.* 2022b). During the testing, this equipment was utilised to measure the applied load as well as the associated displacement. The STS testing also utilised the same machine configuration and testing tools. According to IS: 10082 - 1981 specifications, the sample was positioned laterally during STS testing. Fig. 5(b) shows the machine setup and sample orientation for both types of testing and Figs. 5(c) and 5(d) show the actual tested samples for UCS and STS, respectively.

3.3 Microscale characterisation

Samples for the microscale analysis were collected for 1% biopolymer concentration. The morphological characterization of these samples was performed through SEM images. SEM tests were performed on fine powder samples coated with a layer of gold at varying magnifications. The SEM tests were conducted using a beam intensity of 15 kV (Fig. 5 (e)). Through the SEM images, the bonding among sand particles was observed and analysed. EDX analysis was used for a comprehensive qualitative and quantitative analysis. This analysis included the detection of the types of elements and its percentages in the samples.

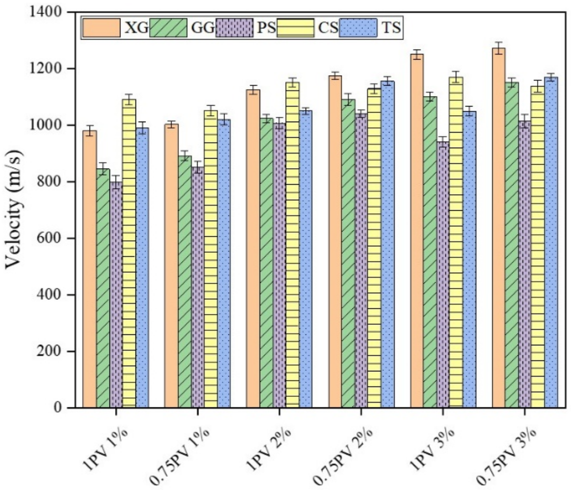

Fig. 6 Impact of varying biopolymer percentages and PVs on the UPV values

4. Result and discussion

4.1 Analysis of treated sand sample through UPV

UPV test has been conducted to measure the velocity of the bio treated desert sand samples. In Fig. 6, the UPV values for various treatment conditions are displayed. It was observed that the maximum UPV values were 1270 m/s for XG, 1150 m/s for GG, 1040 m/s for PS, 1170 m/s for CS, and 1169 m/s for TS. On the other hand, the minimum UPV values were 980 m/s for XG, 845 m/s for GG, 798 m/s for PS, 1050 m/s for CS, and 990 m/s for TS. In the current study, the maximum UPV values fall within the range of 760 m/s to 1500 m/s. This suggests that after biotreatment, all samples show high velocity which means high strength and less porosity. These results indicate a significant improvement in the desert sand samples treated with biopolymers, further highlighting the effectiveness of biopolymer treatment in enhancing the mechanical properties of the sand.

4.2 Impact of varying biopolymer percentages and PVs on the UCS values

The research investigated the effects of different biopolymer percentages and pore volumes on UCS testing. The UCS values for various combinations are illustrated in Fig. 7. It is evident from Fig. 7 that as the concentration of biopolymer increases, the UCS values also increase. For reference, it was found from the literature that the UCS value of untreated dune sand was approximately 21 kPa (Fatehi *et al.* 2019). However, after the incorporation of biopolymers, a significant improvement in strength occurred due to the adhesion between the biopolymer and the sand particles. When comparing the values obtained with different biopolymers, it was noted that among the two

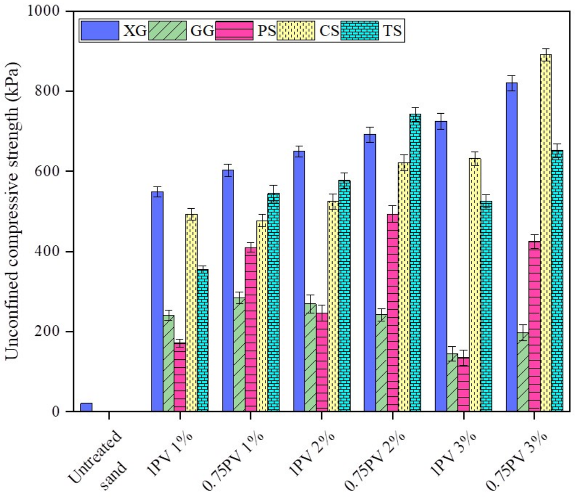

Fig. 7 Impact of varying biopolymer percentages and PVs on the UCS values

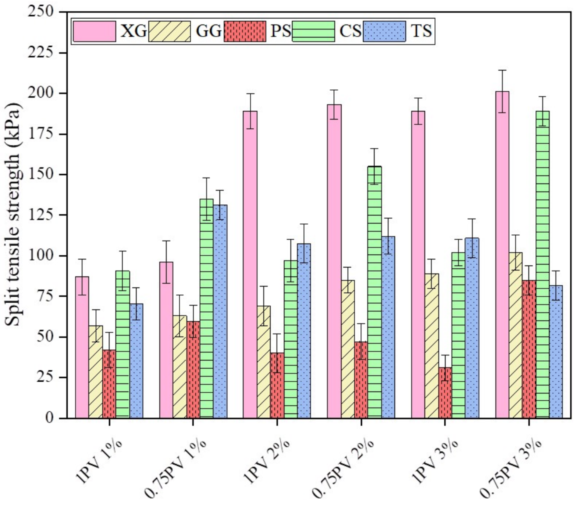

Fig. 8 Impact of varying biopolymer percentages and PVs on the STS values

gums, XG provided the highest UCS values, and among the three starches, CS yielded the highest values. Specifically, the maximum UCS value for XG was 820 kPa with a 3% biopolymer concentration and 0.75 PV, while the minimum was 549 kPa with 1% biopolymer and 1 PV. It is worth mentioning that due to its high viscosity, it became challenging to prepare and mix XG at higher percentages. On the other hand, for GG, the maximum UCS value was 284 kPa with 1% biopolymer and 0.75 PV, while the minimum was 145 kPa with 3% biopolymer and 1 PV. Similar to XG, GG also exhibited high viscosity, making it challenging to work with at higher concentrations. Notably, GG showed better performance up to a 1% biopolymer concentration with 0.75 PV due to its higher viscosity compared to the XG solution. Comparing the results between 1 PV and 0.75 PV, it was observed that the 0.75 PV configuration provided superior strength compared to 1 PV. The superior performance of xanthan gum (XG) over guar gum (GG) can be attributed to the molecular and rheological differences between the two. XG possesses a semi-rigid helical backbone with charged side chains that enable strong hydrogen bonding and stable gel formation. This helical structure maintains viscosity even at low water content, resulting in a dense, cohesive matrix around sand grains. Conversely, GG forms a less ordered network that is more sensitive to moisture loss, leading to weaker bonding and reduced load transfer. These properties explain the higher UCS values observed for XG-treated samples. Regarding different types of starches, the UCS values initially increased as the biopolymer percentage increased. The maximum UCS value for CS was 891 kPa with a 3% biopolymer concentration and 0.75 PV, while for PS and TS, it was 493 kPa and 742 kPa, respectively, with a 2% biopolymer concentration and 0.75 PV. The minimum UCS value for CS was 477 kPa with 1% biopolymer and 0.75 PV, for PS, it was 135 kPa with 3% biopolymer and 1PV, and for TS, it was 355 kPa with 1% biopolymer and 1PV. These findings illustrate the impact of biopolymer type, concentration, and pore volume on the strength characteristics of the treated desert sand.

4.3 Impact of varying biopolymer percentages and PVs on the STS values

The study also investigated the effects of varying biopolymer percentages under different PVs on the STS of the treated desert sand. The STS values for biopolymer concentrations of 1%, 2%, and 3% with both 0.75PV and 1PV are depicted in Fig. 8. The findings show a clear relationship between biopolymer concentration and STS, with increasing biopolymer dosage resulting in higher STS values. When comparing the effects of different biopolymers, it was observed that, similar to the UCS results, XG yielded the maximum STS values among the two gums, while CS produced the highest values among the three starches. The maximum STS value for XG was 201 kPa with a 3% biopolymer concentration and 0.75 PV, while the minimum was 87 kPa with 1% biopolymer and 1 PV. For GG, the maximum STS value was 102 kPa with a 3% biopolymer concentration and 0.75 PV, while the minimum was 57 kPa with 1% biopolymer and 1 PV. These results highlight the substantial improvement in tensile strength achieved through biopolymer treatment. Comparing the results between 0.75 PV and 1 PV, it was evident that 0.75 PV consistently provided higher STS values than 1 PV. In terms of different starch types, the STS values also initially increased as the biopolymer percentage increased. The maximum STS value for CS was 189 kPa and for PS 84.92 kPa, with a 3% biopolymer concentration and 0.75 PV, and TS 131.43 kPa with a 1% biopolymer concentration and 1 PV. The minimum STS value for CS was 90.65 kPa, for TS 70.3 kPa, with a 1% biopolymer concentration and 1 PV, and for PS, 31 kPa with a 3% biopolymer concentration and 1 PV. These findings underscore the positive influence of biopolymer treatment on the tensile strength of desert sand and offer insights into the optimal conditions for achieving improved tensile properties. Moreover, the study noted that XG exhibited a significant increase in tensile strength, which was consistent with the enhancement observed in compressive strength. Importantly, the ratio of tensile strength to compressive

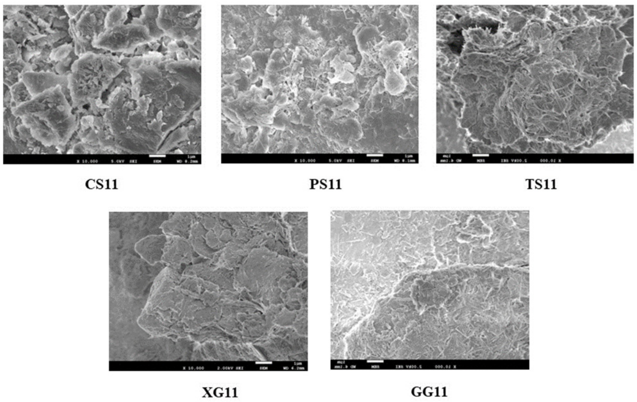

Fig. 9 SEM images of natural and 1% biopolymers concentration with 1 PV

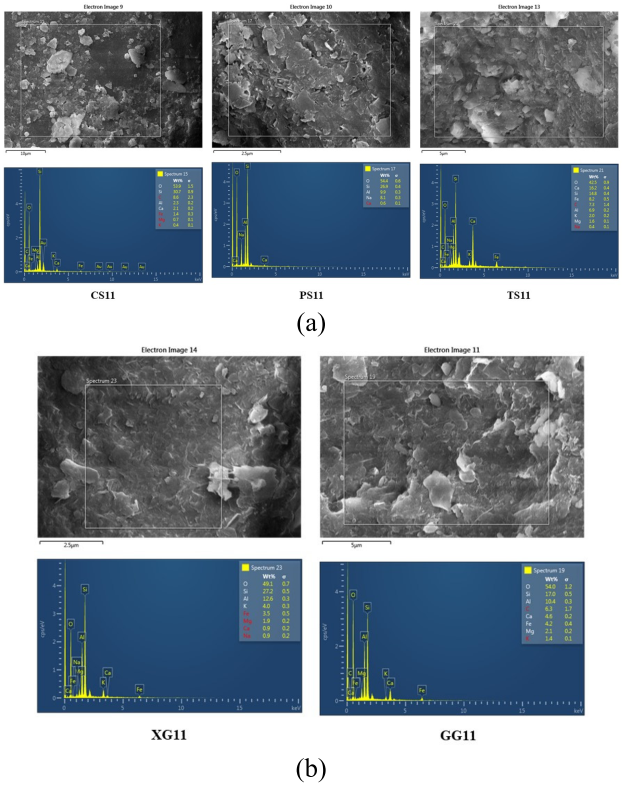

Fig. 10 EDX Analysis for all biopolymers with 1PV and 1 % concentration (a) showing elements present in the starch-treated desert sand and (b) showing elements present in the Gum-treated desert sand

strength remained constant regardless of the biopolymer content, as previously demonstrated (Chen *et al.* 2016).

4.4 Effect of pore volume on the microstructure of sand

Scanning Electron Microscopy (SEM) images were utilized to visually examine the bonding between sand particles in both natural and biotreated sand samples. In the case of desert sand, the SEM images revealed that there was no bonding between the particles, and they were free to move without any force of attraction. To develop a bond between grains, biotreatment was carried out using different percentages of biopolymers. SEM analysis was performed on biotreated sand samples with 1% biopolymer concentration and 1 PV (Fig. 9). The images showed a reduction in pore spaces and coating around grains due to the formation of gel. The SEM images were taken at a scale of 1 μm and a magnification of 10,000X.

EDX analysis was performed on both the natural and biotreated sand samples. Fig. 10 shows the EDX analysis for sand samples with a 1% biopolymer concentration and 1 PV. The EDX analysis showed peaks of quartz and oxygen for biotreated and desert sand samples, which indicate minimal changes in the mineralogical composition of the sand. These findings suggested that there were no significant alterations in the mineral composition of the sand and that the observed increase in strength was primarily attributed to the formation of a gel-like substance that facilitated particle bonding. This aligns with previous research findings (Reddy *et al.* 2021), which also reported negligible mineralogical changes and attributed the enhanced sand strength to particle bonding facilitated by the gel formation.

5. Conclusions

The current study aimed to enhance the strength of dune sand through the application of five different biopolymers (CS, PS, TS, XG, and GG) at various proportions (1%, 2%, and 3%) of 1 PV and 0.75 PV. Biotreated samples were subjected to UCS, UPV, and STS testing, and micro characterization was performed using SEM and EDX analysis. The following conclusions were drawn from the study:

1. All biopolymers contributed to the enhancement of sand strength. Among the gum type biopolymers, XG was more effective than GG, while among the starch-type biopolymers, CS was more effective than PS and TS. These choices were based on good results across UCS, STS, and UPV testing, as well as cost-effectiveness and availability.
2. Sand particles have a neutral charge, and biopolymer adhesion occurs through coating soil particles and forming bridges between them. Using biopolymers as binders required relatively low content to achieve comparable compressive strength to traditional materials like cement and lime. It was crucial to determine the optimal biopolymer content, as excessive amounts may lead to a reduction in soil strength.
3. As the biopolymer percentage increased, binding strength also increased. XG and CS were effective binders and yielded good results, particularly with 0.75 PV. The study recommends using a 0.75 PV concentration in all cases due to its optimal and economic performance.
4. UPV results indicated an increase in velocity for all biopolymers, signifying their effectiveness in enhancing sand strength. Velocity measurements revealed that the treated samples showed continuity in samples after mixing with biopolymers.
5. SEM analysis demonstrated that all biopolymers exhibited adhesion properties with dune sand, acting as

effective binders. This suggests that biopolymers offer an eco-friendly solution for strengthening dune sand.

In summary, the study highlights the effectiveness of biopolymers in enhancing the mechanical properties of dune sand, offering an ecofriendly and cost effective solution for soil stabilization and strength improvement. The choice of biopolymer type and concentration should be carefully considered to achieve optimal results.

Overall, studies manifested that biopolymers is an eco-friendly solution and a one-time treatment process. Large-scale testing is recommended before applying it to the field, which simulates all field conditions. Also, the durability of the biopolymer-treated soil requires more attention because of various environmental conditions, including wetting-drying cycles, freeze-thaw cycles, microorganisms, and ultraviolet radiation that could significantly decrease the strength.

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