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Comparative study on the effect of high and low viscous biopolymers for dust suppression – An experimental investigation

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Abstract. Wind erosion is an alarming environmental threat that affects the balance of the biodiversity of an ecosystem. Preventive measures like vegetation, tillage and mechanical methods are currently in practice to limit the soil loss caused by wind erosion. Biological alternatives are gaining traction as they aid the sustainable development of degraded regions. Biopolymers offer an excellent alternative to improve the resistance of soil to erosion. The present study investigates the potential of two anionic biopolymers, xanthan gum (XG) and sodium carboxymethyl cellulose (CMC) to control wind erosion of fine sand. Results indicate that fine sand treated with 2.0% XG and 1.5% CMC offered more strength in 7 days, when subjected to open-air curing. Jar and crumb immersion tests suggest that CMC can sustain immersion at lower doses, whereas XG can sustain water immersion at higher doses. The model wind erosion test done for five different wind velocities (4.2, 8.4, 12.3, 16 and 20 m/s) at three different durations (2 hours, 3 days and 7 days of open-air curing) indicated that wind erosion resistance of treated soil improved with ageing. A minimal dosage of 0.75% CMC and 0.5% XG deters the loss of fine sand. For example, at a velocity of 20 m/s soil loss reduced from 100% to 1.97% and 2.4% at 0.75% CMC and 0.5% XG respectively. Experimental investigation ascertains that both XG and CMC can effectively be used to control soil loss caused by wind erosion and promote vegetation on the degraded areas.

Keywords: cellulose; fine sand; strength; wind erosion; xanthan gum

1. Introduction

Topsoil is rich in nutrients and has many beneficial micro-organisms that promote plant growth. Soil erosion is a threatening global concern that denudates the topsoil by water, wind and glacial agents. Although topsoil is not a prime concern for engineering constructions where it is usually excavated and discarded, it's erosion is the primary cause for desertification and loss of the region's biodiversity. Among the various agents, wind (aeolian) is the primary erosive agent in arid and semi-arid regions. The European Soil Data Centre reported that 28% of global soil loss can be attributed to wind erosion (European Soil Data Centre 2024). Asia and Africa account for 62% of global wind erosion loss (Yang *et al.* 2022). Another specific reason for concern about the losses caused by wind erosion is drought (Duniway *et al.* 2019). The lack of vegetation to bind the topsoil leads to aeolian erosion of the barren lands. According to a UN climate and environment report, global drought has increased by nearly 33% since 2000 (United Nations; World economic forum). In other words, the risk of wind erosion also increases every day.

Soil particles can be moved in three different ways during wind erosion, namely, surface creep, saltation and suspension (Hateren *et al.* 2020). Surface creep refers to the movement of soil particles by wind action and is applicable on the sand with particle sizes ranging between 0.5 mm to 2 mm (Department of Environment and Resource Management, Queensland 2011). Saltation is lifting soil with particle sizes ranging between 0.05 mm and 0.5 mm, followed by abrading their surface by bouncing actions (Department of Environment and Resource Management, Queensland 2011). However, such particles are not small enough to be suspended in the wind and carried away. Tiny particles less than 0.1 mm will be raised during saltation and lifted further by the turbulence known as suspension. Those finer than 0.01 mm would be transported to longer distances. Queensland's report on wind erosion mentioned that Australian soil had been transported beyond New Zealand through suspension (Department of Environment and Resource Management, Queensland 2011). These reports indicate that soil particles finer than 500 μm would suffer from wind erosion.

Researchers and engineers have proposed several feasible methods to lessen the action of wind erosion. Some standard methods to reduce wind erosion are vegetation (Yan *et al.* 2013), crop residue (Toure *et al.* 2011), shelterbelts (Kong *et al.* 2022) and chemical stabilizers. Plant growth helps by reducing soil exposure to the wind (Yan *et al.* 2013). Also, the roots hold the soil mass and

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prevent erosion. Crop residue is left over from the cultivation field after harvest, covering the topsoil and helps in reducing soil loss caused by wind erosion (Liang and Wang 2020). Shelterbelts are rows of trees planted to reduce wind speed and the wind erosion effect (Kong *et al.* 2022). All these three methods, in one way or another, depend on plant growth, which is not a rapid process. Also, it is not easy to cultivate crops in desert areas or degraded land to mitigate the erosion effect. Hence chemical stabilization techniques come in handy to achieve a relatively faster rate of erosion control.

The commonly used chemical stabilizers are synthetic polymers, geopolymers, biopolymers, microbial cementation, etc. Genis *et al.* (2013) experimented with polyacrylamide (PAM) to study its effectiveness in reducing wind erosion in the deserts of Israel. Experimental investigations showed that a dosage of less than 1 kg per hectare could effectively reduce wind erosion at a velocity of 27.5 m/s. Similarly, He *et al.* (2008) used PAM to control wind erosion at a velocity of 14 m/s. Results indicated that 2 g/m^2 of PAM offered appreciable resistance to erosion, and the results improved with an increase in dosage to 4 g/m^2. However, the authors reported that the prophase PAM degradation accumulated in the soil and the tillage could not help the wind erosion resistance process (He *et al.* 2008).

Koohestani *et al.* (2021) used sodium silicate-based geopolymer solution to reduce the wind erosion effect. A dosage of 50% solution sustained the wind erosion entirely in 2 hours. However, reducing the dosage to 20% solution showed progressive loss with time. Hanegbi and Katra (2020) used a 30% metakaolin-based geopolymer with sodium silicate and sodium hydroxide as a cementation solution. The test results showed negligible emission of particulate matter at a wind velocity of 6.5 m/s and 9.5 m/s. Although the geopolymer showed more promising results, the dosage of chemicals used in the geopolymerization process is large in quantity.

The environmentally friendly stabilizers that can be used for soil resistance against wind erosion are microbial calcite precipitation (Gu *et al.* 2018) and biopolymers (Ayeldeen *et al.* 2018). Meng *et al.* (2021) used *Sporosarcina pasteurii*-based calcite precipitation to reduce the effect of wind erosion. For a spray volume of 4 l/m^2, the treated soil sustained a wind velocity of 30 m/s. Dagliya *et al.* (2022a) used *Sporosarcina pasteurii* bacteria for inducing microbial calcite precipitation. A solution of 0.5M in one treatment cycle for 24 hours imparted the soil a rock-like behaviour for 0.8 pore volume in 7 days and 0.4 pore volume in 14 days. Despite the advantages, microbial calcite precipitation is time-consuming, and the sample should be continually treated for one complete treatment cycle. Also, the optimal atmospheric condition is required for the effective performance of bacteria to produce the cementation precipitate. On the other hand, biopolymer application is an eco-friendly, economical and relatively faster technique to enhance soil strength and improve erosion resistance with better control in the improvement process.

In recent times, research on the choice of biopolymers like xanthan gum, guar gum, carrageenan, modified starches, sodium alginate, pectin, acacia gum, and cellulose, etc., for wind erosion control is gaining importance (Ayeldeen *et al.* 2018, Dagliya *et al.* 2022b, Owji *et al.* 2021). Ayeldeen *et al.* (2018) used four different biopolymers: xanthan gum, guar gum, carrageenan and modified cellulose to reduce the wind erosion potential of sand. At a wind velocity of 13.9 m/s, all four biopolymers offered an erosion resistance of a minimum of 45.9% in both wet and dry conditions (Ayeldeen *et al.*, 2018). Dagliya *et al.* (2022b) used 1% to 3% of sodium alginate, pectin, and acacia gum to reduce the soil loss due to wind erosion of Indian desert sands at 10 m/s to 30 m/s. At a velocity of 30 m/s, untreated sand experienced almost 60% loss while with 1% of all three biopolymers, the soil showed an almost negligible soil loss. The authors suggested that pectin and sodium alginate are not suitable for field application owing to their high viscosity and acacia gum was more effective for field applications.

It is evident from the results of Dagliya *et al.* (2022b) that the viscous biopolymers pose difficulties in practical application. Also, the cost optimization of biopolymer should be taken into consideration, considering the market price. In line with these observations, comparing the effect of high and low viscous biopolymer needs detailed investigations, as low concentrations of high viscous polymer would yield a feasible outcome. Among several biopolymers available in the market, xanthan gum (XG) and carboxymethyl cellulose (CMC) are cost-effective and commercially easily available compared to other alternatives like gum acacia, gellan gum, etc. Hence the present study compares the wind erosion resistance potential of fine sand treated with high viscous XG and low viscous CMC based on their performance on the model wind tunnel erosion test for different dosages, curing periods and wind velocity. Additionally, the strength and dispersion behaviour of these biopolymers were studied to ensure their performance in extreme environmental conditions.

2. Materials

2.1 Soil

Dry sand and silt with no cohesion and clay particles are more susceptible to wind erosion. The study used locally available sand unearthed from the banks of the Cauvery basin, Tamil Nadu, India, and was sieved to a fineness of less than 425 µm to simulate the erodibility behaviour. The fine sand predominantly has quartz and traces of other minerals. The grain size distribution of the fine sand is shown in Fig. 1. The specific gravity of the sand is 2.64, with an average particle size is 250 µm. The Queensland Environment and Resource Management Department stated soil with particle sizes between 50 µm and 2 mm would experience wind erosion, confirming that the selected soil is suitable for wind erosion studies (Department of Environment and Resource Management, Queensland 2011).

2.2 Biopolymers

The study used two different biopolymers to reduce the susceptibility to wind erosion - high viscous xanthan gum (XG), and low viscous sodium carboxymethyl cellulose

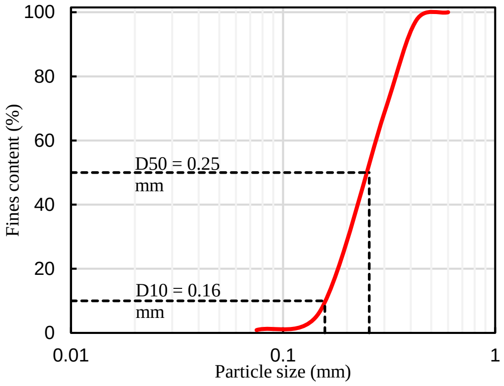


Fig. 1 Grain size distribution of the fine sand

(CMC). XG is a bacteria-derived polysaccharide obtained by fermenting glucose using *Xanthomonas campestris* (Petri 2015). The main chain of XG has β(1-4) glycosidic bond and a side chain with trisaccharide followed by mannose, glucuronic acid, and mannose (Hu *et al.* 2019). It is anionic with a high molecular weight of 2 x 10^6 g/mol and a dynamic viscosity of 2639 cP (2% solution) (Kumar and Sujatha 2021). The viscous and binding nature of XG finds several applications in industries like food production (Blok *et al.* 2023), drug delivery (Sethi *et al.* 2020) and drilling fluids (Akpan *et al.* 2020), etc.

CMC is a natural cellulose-derived anionic polysaccharide (Chen 2015). It is obtained by partially substituting 2, 3 and 6 hydroxyl groups of cellulose with carboxymethyl groups (Aslam *et al.* 2019). The molecular weight of CMC is 90000 g/mol, and the viscosity of 1% solution is 222 cP (Sigma-Aldrich, Sujatha and Kannan 2022). CMC has excellent moisture absorbing and retaining capability and is used in food (Zorba and Ova 1999), cosmetic (Lopez *et al.* 2015) and pharmaceutical (Guo *et al.* 1998) industries. Additionally, literature shows that both XG and CMC offered excellent binding to the loess particles and enhanced their strength (Dehghan *et al.* 2019, Ma and Ma 2019), advocating their suitability for the present study.

3. Methods

The primary objective of this study is to investigate the wind erosion resistance potential of biopolymer-amended fine sand using a model wind tunnel setup. A preliminary investigation (immersion and strength tests) was carried out to ensure the suitability of the chosen biopolymers prior to wind tunnel testing and these tests also helped in fixing the dosages of the two biopolymers for further experimental investigation.

3.1 Soil preparation

Biopolymers can be mixed with the soil either by dry or wet mixing methods. Dry mixing involves a homogeneous blending of soil and biopolymer followed by the addition of water. The dry mixing method constrains the coiled biopolymers from proper bonding with the soil (Mahamaya *et al.* 2021, Theng 2012). In contrast, the wet mixing method allows the expansion of the biopolymers and facilitates easy coating and binding over the soil particles (Mahamaya *et al.* 2021, Theng 2012). Therefore, the study adopted wet mixing of biopolymer with soil for this study. Unlike fine-grained cohesive soils, cohesionless sand does not have an optimum moisture content at which the soil offers higher strength. Hence a constant water content of 10% by the dry weight of the sand is adopted throughout the study. Biopolymer of the required dosage (in percentage by dry weight of soil) is gradually added to water and stirred continuously to avoid lumps. The prepared viscous biopolymer gel is then transferred to air-lock bags and kneaded carefully to break the lumps and air pockets, if any. Then the gel is added to the soil and blended uniformly to prepare the soil-biopolymer mixture and again transferred to an air-lock bag for 2 hours to ensure uniform dispersion of the gel in the soil.

3.2 Strength tests

The biopolymer-treated soil specimens were tested for their strength to determine the magnitude of resistance developed with the addition of biopolymers to the soil. Strength tests were carried out on sand treated with 0.5%, 1.0%, 1.5%, 2.0% and 2.5% biopolymers. The study adopted ASTM D2166 (2006) guidelines for unconfined compression tests on biopolymer-treated soil. The samples were prepared using a cylindrical split mould (38 mm in diameter and 76 mm in height). Unlike cohesive soils, cylindrical specimens of moist cohesionless sand will break longitudinally during demoulding. Hence the split mould is wrapped internally with a thin polyethylene sheet before moulding. The prepared cylindrical samples were air-cured for seven days, and then the wrapping was removed. The cured samples were tested for unconfined compression strength (UCS) at a 1.25 mm/min strain rate.

3.3 Immersion tests

Two different immersion tests were conducted to study the dispersion behaviour of the biopolymers-treated soil. One is the jar immersion test on cylindrical samples (Reddy *et al.* 2018), and the other is the crumb dispersion test (Swain *et al.* 2018). The jar immersion test was done on the cylindrical samples (38 mm in diameter and 76 mm in height) with three-fourths of the sample submerged in water. Likewise, the crumb dispersion test was done on cuboidal samples (60 mm x 60 mm x 30 mm) under complete submergence. Sand-biopolymer mixtures compacted as per ASTM standard compaction test (ASTM D698 2012) were cut with cylindrical and cuboidal casting moulds and stored in an air-lock bag for one day. Then the samples were immersed in water to observe their dispersion pattern. The additive dosages were the same as the strength tests; however, the dosage of CMC was further fine-tuned based on the test conditions. The cylindrical sample preparation, procedure of jar immersion test and crumb immersion test are shown in Fig. 2.

3.4 Wind erosion test

The wind erosion test on the treated soil is conducted


(a) (b) (c)

Fig. 2 (a) Cylindrical sample preparation for strength and immersion tests, (b) Jar immersion test and (c) Crumb dispersion test


(a) (b) (c)

Fig. 3 (a) Wind tunnel, (b) airflow duct and (c) fan motor

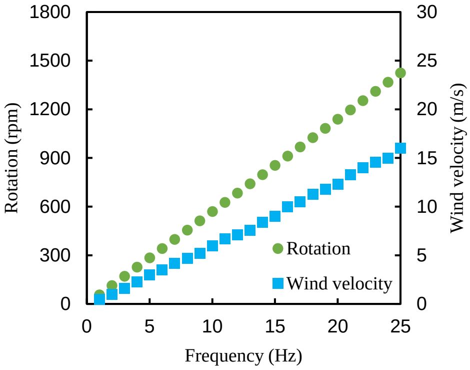


Fig. 4 Wind tunnel calibration chart

with a low-noise axial blow open circuit wind tunnel with an open flow diameter of 30 cm (Fig. 3).

The tunnel can create a maximum wind velocity of 40 m/s using a 3.7 kW fan motor. The wind tunnel was calibrated using a handheld digital anemometer, and the corresponding calibration chart is presented in Fig. 4.

Beaufort, in 1805 established an empirical scale that describes the nature of wind based on its velocity called the 'Beaufort scale' (National Weather Service). This scale can conveniently categorize land- and sea-based winds (National Weather Service). The present study adopted five different wind velocities, and their corresponding Beaufort classification is shown in Table 1.

The study intended to investigate erosion resistance (in terms of mass loss) of biopolymers-treated sand for three different curing periods (2 hours, 3 days and 7 days). Three different dosages for each biopolymer, namely 0.5%, 1.0%, and 2.0% for XG-treated soil and 0.25%, 0.50% and 0.75% for CMC-treated soil, were investigated for wind erosion test. The soil sample treated with biopolymer was sprinkled on a plate (10 cm diameter) and left to dry at room temperature until the testing.

Table 1 Wind velocity adopted for the study based on the Beaufort scale

Wind velocity range (m/s)	Description	Beaufort Number	Velocity adopted for the study (m/s)
3.6 – 5.4	Gentle breeze	3	4.2
8.4 – 10.7	Fresh breeze	5	8.4
11.2 – 13.9	Strong breeze	6	12.3
14.3 – 16.9	Near gale	7	16
17.4 – 20.6	Gale	8	20

During testing, the plate was placed at a distance of 30 cm from the mouth of the wind tunnel. The plate was fixed to the surface firmly with adhesives to ensure that the plate would not be displaced during the testing. The soil was exposed to the wind as per the recommendations of Fattahi *et al.* (2020). Each sample was exposed to the wind for 5 minutes. In the first minute, the wind velocity gradually increased from zero to the desired value and maintained constant for the next three minutes. At the last minute, the velocity is gradually reduced to zero.

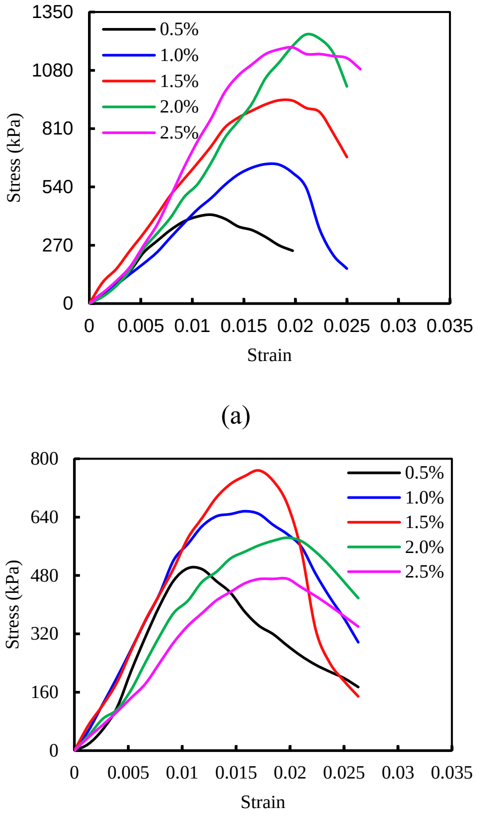
4. Results and discussion

4.1 Strength tests

The strength test indicates an increase in soil resistance with biopolymer treatment. In a way, the strength test confirms the stiffness of the specimen at which its binding capability with the sand holds good. The seven days curing of the treated sand induced cohesion, making the samples split vertically with brittle cracks upon failure. This can be observed from the distinct vertical peaks in the stress-strain response of the treated soil (Fig. 5).

Failure strain indicates the deformation of the sample at failure. The failure strain of the treated soil increased with dosage. For a 0.5% to 2.5% dosage range, both XG and CMC had a failure strain of around 1.2% to 2.1%, respectively. The addition of both biopolymers showed an increased strength with dosage but beyond optimum dosage the strength reduced. For instance, in Fig. 6, it can be observed that 2.0% XG and 1.5% CMC had the highest UCS of 1246.43 kPa and 767.86 kPa, respectively. Failure modulus indicates the sample's stiffness against external force on the verge of failure. Despite an increase in the failure strain, the failure modulus followed a trend similar to UCS (as observed in Fig. 6(b)).

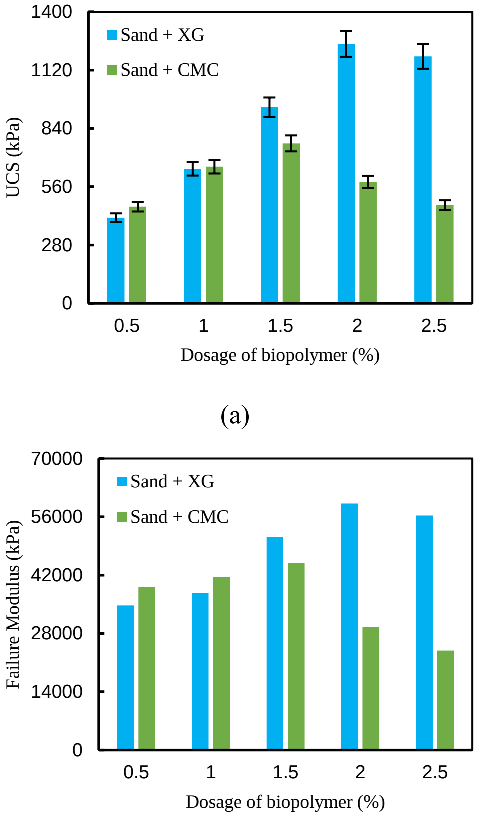
The increased strength and stiffness are typical behaviours of XG and CMC-treated soil (Lee *et al.* 2019, Ma and Ma 2019). These viscous biopolymers form hydrogels that bind the sand particles together resulting in increased strength (Lee *et al.* 2019). Although literature reports a continuous increase in the strength with dosage (Kumar and Sujatha 2021, Lee *et al.* 2019), the present study contradicts the idea, with a strength reduction beyond the optimum dosage. This could be due to the fact that the present study limited the water content to 10% by dry weight of the soil for all the biopolymer dosages. Therefore,



(a)

(b)

Fig. 5 Stress-strain responses of (a) XG-treated sand and (b) CMC-treated sand



(a)

(b)

Fig. 6 (a) UCS and (b) Failure modulus of biopolymers treated sand

at higher dosages, sufficient water was not available to form the hydrogel, which is required to create biofilm for binding the soil particles. Instead, the polymers formed a rubbery mass with the available moisture that was insufficient to form a viscous bond.

4.2 Immersion tests

The immersion tests gave insights into the durability of the treated soil under submergence. Although the study focuses on wind erosion, an understanding of the additive behaviour under submerged conditions is necessary prior to field application. This is particularly useful in extending the choice of these biopolymers in collapsible deposits which are often found in arid and desert regions that suffer aeolian erosion. Further, the test results also helped to narrow down the additive dosage for the wind erosion tests.

Although 0.5% CMC-treated soil sustained the jar immersion for 45 seconds, it was difficult to predict the relationship between dispersion and the dosage of CMC. Hence, the initial dosage of CMC is further refined to 0.25%, 0,50% and 0.75%, respectively. The soil sample with 0.25% CMC sustained the crumb dispersion test for 2 minutes and the jar immersion test for 30 minutes. The resistance against dispersion in jar immersion test was reduced to 30 seconds at an increased dosage of 0.75% CMC indicating that a lower dosage of CMC showed better performance.

XG exhibited a typical behaviour as shown by other biopolymer immersion tests, where the resistance to dispersion improved with dosage (Reddy *et al.* 2018, Swain *et al.* 2018). However, the immersion test on CMC holds good only till the optimum dosage. The results can be critically interpreted based on the state of the biopolymer during sample preparation and testing. At lesser dosages up to 1%, XG blended well with the 10% water; however, the gel strength was insufficient to withhold the cylindrical samples when immersed in water. But at higher dosages, although XG became rubbery with little water, the additive plugged the voids and resisted the water penetration for some time. Lee *et al.* (2017) also suggest that XG treatment is effective on the sand with a dosage above 1.0%. Although both XG and CMC are hydrophilic biopolymers, their viscosity differs by many folds (Kumar and Sujatha 2021, Sujatha and Kannan 2022).

In addition, CMC is known for its moisture-retaining capacity, which increases with dosage (Sujatha and Kannan 2022). Irrespective of the dosage, CMC held the soil particles together by binding them in a dry state before immersion. When submerged in water, 0.25% CMC held soil particles together for a longer time. In fact, Ning *et al.* (2019) also reported that CMC increased the infiltration time of moisture in the soil. However, with an increase in the dosage of CMC, its moisture-holding capacity also increased. It was observed during the experiments that CMC-treated soil dried slower,

Table 2 Jar immersion and crumb dispersion test results

Additive	Dosage	Crumb test (Number of minutes the sample sustained in the bowl)	Jar test (Number of minutes the sample sustained in the bowl)
XG	0.50%	1	Instantaneous dispersion
	1.00%	Instantaneous dispersion	Instantaneous dispersion
	1.50%	Instantaneous dispersion	0.2
	2.00%	Instantaneous dispersion	0.25
	2.50%	Instantaneous dispersion	3
CMC	0.25%	2	30
	0.50%	Instantaneous dispersion	0.75
	0.75%	Instantaneous dispersion	0.5
	1.00%	Instantaneous dispersion	Instantaneous dispersion
	1.50%	Instantaneous dispersion	Instantaneous dispersion
	2.00%	Instantaneous dispersion	Instantaneous dispersion
	2.50%	Instantaneous dispersion	Instantaneous dispersion

with a little moisture present on the surface even after 24 hours, when compared with XG-treated soil. CMC in the soil adsorbed more water from the surrounding medium and started dispersing the soil held by the CMC upon immersing in water, thus explaining the rapid dispersion at the higher dosages.

With these observations in mind, it is inferred that the wind erosion test will be meaningless at higher doses of CMC. Hence wind erosion tests were carried out on soil treated with 0.5%, 1.0% and 2.0% of XG and 0.25%, 0.5% and 0.75% of CMC.

4.3 Wind erosion test

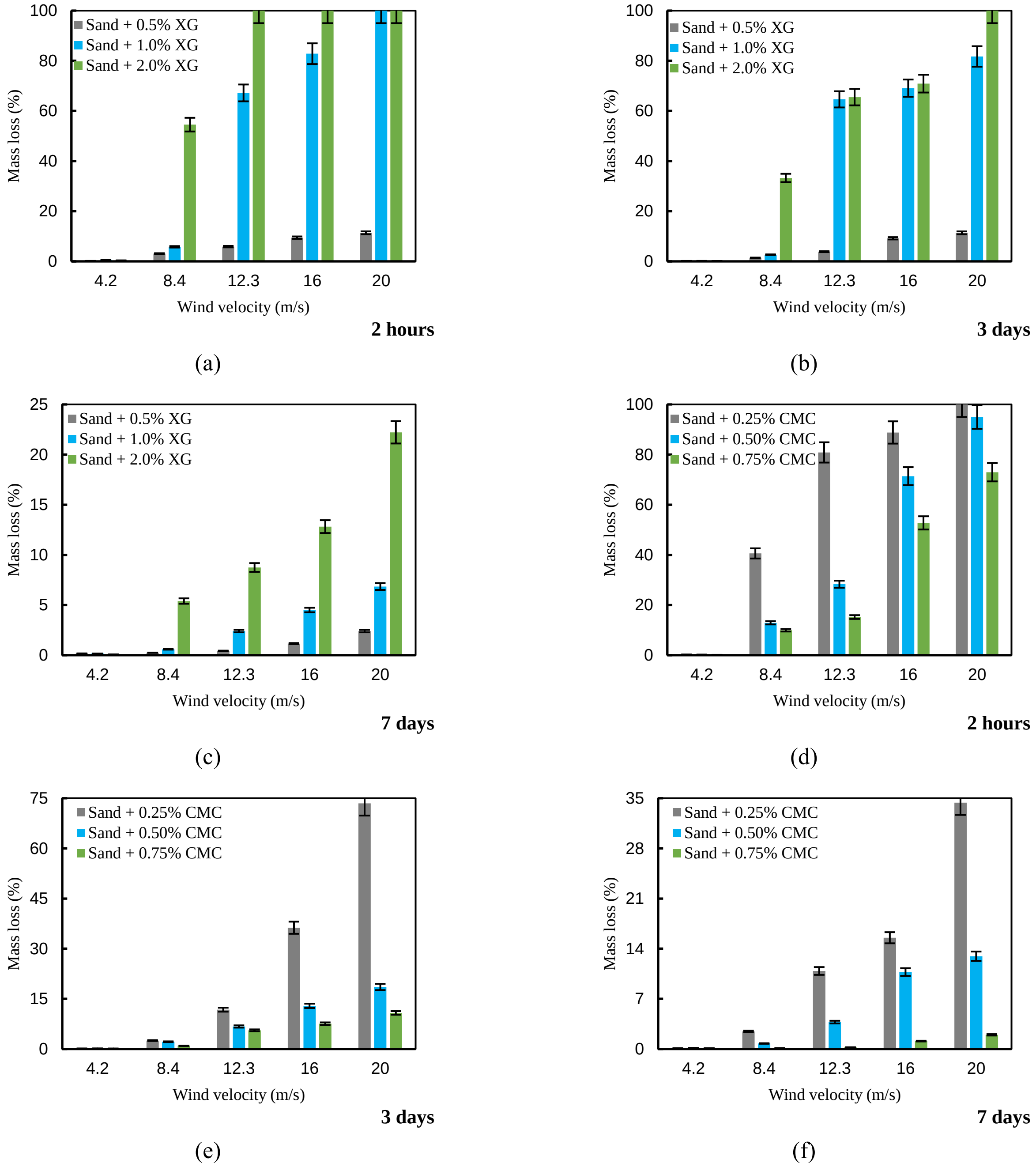
The wind erosion test was conducted on untreated soil, followed by biopolymer-treated soil after 2 hours, 3 days and 7 days to compare the effect of treatment with time. The loss of untreated soil at 4.2 m/s, 8.4 m/s, 12.3 m/s, 16 m/s and 20 m/s is 1.02%, 69.39%, 100%, 100% and 100%, respectively. The results of biopolymers-treated soil for different curing period is shown in Fig. 7. In general, it is observed that XG-treated soil showed an increase in mass loss with dosage, whereas CMC offered a reduction in mass loss with dosage. However, both biopolymers showed a reduction in mass loss with time. The velocity of a gentle breeze (4.2 m/s) did not significantly impact the soil mass on any of the dosage combinations. Similarly, up to a dosage of 1.0% XG, the velocity of a fresh breeze (8.4 m/s) did not create any loss in the soil mass. However, at the highest dosage of 2.0% XG, a 54.53% mass loss was observed in 2 hours which reduced to 5.40% in 7 days. A visible loss of soil mass was observed from a velocity of 12.3 m/s in XG-treated soil. Among all the combinations, 0.5% XG sustained the erosion test much better than the higher dosages. Technically, 0.5% XG sustained even a gale (20 m/s) with just 2.40% erosion in 7 days. In comparison, 1.0% and 2.0% XG suffered a soil loss of 6.85% and 22.22% in 7 days.

Like XG, CMC-treated soil remained undisturbed at a velocity of 4.2 m/s for all the dosages and durations. With an increase in wind velocity to 8.4 m/s, 0.25% and 0.75% CMC-treated soil suffered 40.59% and 9.93% mass loss in 2 hours, which reduced to just 2.45% and 0.12% loss in 7 days. A similar trend was observed at higher wind velocities as well. At the highest wind velocity of 20 m/s, 72.96% of the soil was lost with 0.75% CMC in 2 hours, which further reduced to 1.97% in 7 days. The wind erosion results of 0.75% CMC and 0.5% XG at 8.4 m/s in 2 hours is shown in Fig. 8.

The mechanism of wind erosion resistance of treated soil can be interpreted based on the moisture available to bind the sample and the ageing effect as shown in Fig. 9. Although the literature has proof that XG would offer an increased resistance with dosage during erosion tests (Ayeldeen *et al.* 2018), the present study results contradicted the results of Ayeldeen *et al.* (2018). The lack of sufficient moisture to form viscous gel made the higher doses of XG a rubber-like material. Lower doses of XG sufficiently formed the gel film to bind the soil firmly, whereas the higher doses, the XG withheld the soil without proper binding. The drying effect increased the stiffness of the soil mass, and hence the wind erosion resistance improved, consequently.

Unlike XG, the viscosity of 0.25% CMC was much lesser and was almost similar to water. With an increase in the dosage, the viscosity of CMC slightly increased and formed the required gel film to bind the soil. Thus, the results show that with a very small dosage of 0.75% CMC and 0.5% XG, the wind erosion of fine sand to gale (20 m/s) reduced to 1.97% and 2.4%, respectively. Also, it should be noted that the additives behaved differently in immersed and dry conditions, depending upon the initial moisture conditions.

In addition to their excellent erosion resistance, both XG and CMC-treated soil enhance plant growth, which would be an added advantage in suppressing wind erosion. Sorze *et al.* (2023) proved that adding XG to the soil improved its moisture retention capacity and acted as topsoil cover, thus enhancing plant growth. Similarly, Bauli *et al.* (2021) stated



(a) (b) (c) (d) (e) (f)

Fig. 7 Wind erosion test results of XG-treated soil in (a) 2 hours, (b) 3 days, (c) 7 days and CMC-treated soil in (d) 2 hours, (e) 3 days and (f) 7 days

that CMC could act as a nutrient carrier to promote plant growth. Reports indicate that both XG and CMC offer better wind erosion resistance along with sustainable development.

5. Conclusions

The study attempted to use XG and CMC as eco-friendly binding agents to subside the effect of wind erosion on fine sand. A series of laboratory experiments were done to verify the strength, immersion and erosion effects of the treated soil. Test results revealed that the treated soil showed exemplary strength at 1.5% CMC and 2.0% XG dosages. The restriction on the moisture content of the samples to 10% exhibited a unique behaviour with the treated soil. Almost every sample tested failed in the crumb dispersion test; however, cylindrical samples of jar immersion test sustained well in the lower doses of CMC and higher doses of XG. Wind erosion test results show that untreated soil sustained wind velocities of 8.4 m/s. However, 7 days after biopolymer addition, 0.75% CMC and 0.5% XG reduced the erosion to 1.97% and 2.40% at the highest velocity of 20 m/s. These results indicate that


(a) (b) (c)

Fig. 8 Erosion of fine sand at 8.4 m/s in 2 hours (a) untreated sand, (b) 0.5% XG and (c) 0.75% CMC

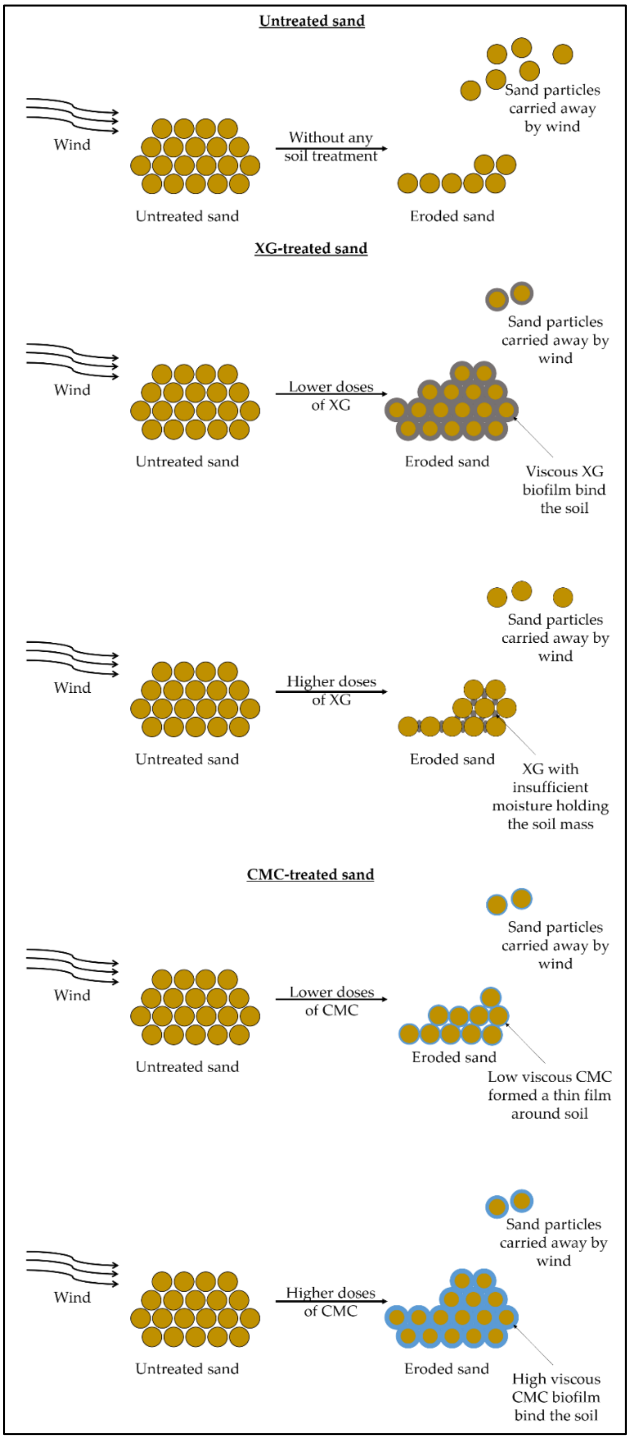


Fig. 9 Mechanism of XG and CMC interaction with the sand

the treated soil would sustain a gale with negligible loss of less than 2.5%. Also, compared to other biopolymers available in the market, XG and CMC are the most abundant and cost-effective and can easily be applied to the soil by spraying methods. The promising results indicate that XG and CMC can effectively resist wind erosion. However, a detailed investigation of soil behaviour with other biopolymers, long-term wind erosion resistance behaviour, and the durability of the material with wet and dry cycles are required before field application for an effective outcome.

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