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Wind-Driven Erosion Control of Arid Sand Dunes Using Alkali-Activated Non-Erosive Crust: Wind Tunnel Experiments

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SUMMARY

Sand dunes in arid regions suffer severe wind erosion, with significant soil mass loss at higher wind speeds. This study developed an eco-friendly alkali-activated non-erosive stable crust using marble slurry (WM) powder (10 - 40%) and desert sand, activated by NaOH and Na_2SiO_3 solution. After 24 h curing scenario, wind tunnel experiments on scaled dune models showed 0% mass loss even at 30 m/s wind velocity. Crust thickness improved with increased WM, from 1.75 mm (10% WM) to 8.83 mm (40% WM), forming a strong, durable crust with particle entrainment. The method valorizes marble waste, requires minimal water, and offers a low-cost, sustainable alternative to vegetation or chemical stabilizers, presenting a highly effective solution for large-scale sand dune fixation and desertification control.

Keywords: Wind erosion, Sand dune, Crust formation, Alkali activator

1. INTRODUCTION

As dynamic landforms are prevalent in arid and semi-arid regions, sand dunes play a critical role in the ecosystem by acting as natural barriers against desertification, protecting coastlines, and preserving biodiversity. These structures are highly prone to erosion, driven mainly by wind through an aeolian dynamics process, where shear stresses induced by wind mobilize and move the sand particles along the ground surface (Dammala et al. 2025). Wind erosion of sand dunes takes place by three primary means: saltation (particle sized 0.1 to 0.8 mm), suspension (particle sized less than 0.1mm), and creep (particle sized 0.8 to 2mm), in which the sediment particles are lifted, bounced, and rolled, respectively, leading to progressive degradation of the dune morphology (Warren, A. 2013).The severity of such erosion is directly connected with the speed of the wind (Kolli et al. 2026a). Particles start to move at threshold velocities, which is generally in the 4-6 m/s range when the sand is dry and loose, and the erosion rate rises exponentially with the exceedance of the threshold velocity; a common equation modeling this, like the Bagnold formula, is $q \propto u*3$. The high rate of dune migration and deflation may be caused by sustained wind speeds that exceed 10-15 m/s in extremely windy areas, like deserts. This increases the rate of land degradation, soil erosion and environmental threats like dust storms, which affect the air quality, human health and any type of infrastructure in dry areas.

The challenge requires novel engineering responses, which are sustainable and in harmonious with wind engineering, the field of study that deals with the knowledge and prevention of fluid-structure interactions in the atmospheric boundary layers (Kolli et al. 2026b). Conversely, the traditional means of stabilization (planting vegetation or chemical adhesives) tend to be impracticable within severe desert environments because of water shortage, prohibitive price or ecological inappropriateness. In this regard, the application of waste marble powder and desert sand as feedstock of Alkali activated materials could be a viable green approach (Haq et al. 2025, Kolli et al. 2026c). Alkaline activation, through geopolymerization, would involve mixing aluminosilicate-rich wastes, such as marble dust mainly composed of calcium carbonate and silicates, with desert sand and its activation through the action of alkaline solutions, like sodium hydroxide or silicate, forming a durable, cementitious crust on the surface of the dune. This crust should increase surface cohesion, enhance the erosion threshold wind velocity by promoting a reduction of particle entrainment, and also mimic natural soil crusts while valorizing industrial residues, hence contributing to circular economy practices. The current study investigates the formation of a DS-WM-based alkali-activated crust on the dune surface. Wind tunnel tests were performed at varying wind speeds of 10, 20, and 30 m/s, and the mass loss and surface crust thickness were evaluated accordingly.

2. METHODOLOGY

2.1 Materials - Marble slurry-based crust formation

The stepwise preparation of alkali-activated treated desert dune sand is depicted in Fig. 1. First, the desert sand sample was sieved through a 0.3 mm sieve based on the gradation curve to remove debris. Then, a scaled dune model was prepared with a 32° slope on both the stoss and lee sides to maintain the desert sand friction angle, with dimensions of 160 mm in length, 60 mm in width, and 50 mm in height. In the next step, 10% of the total scaled sand dune weight was taken as the binder (DS), which was mixed with WM in proportions of 10%, 20%, 30%, and 40%, and a uniform pour was made onto the sand dune model. After pouring the DS - WM mix, the alkali activator solution (AAS) was prepared using NaOH and Na_2SiO_3 chemicals, where a 4M NaOH solution (the lowest molar concentration used; Tchakouté et al., 2017) and a Na_2SiO_3 to NaOH ratio of 1 were used (Haq et al., 2025). The AAS spray was applied to the surface of the dune model corresponding to an alkali activator-to-binder ratio of 0.4 (Haq et al., 2025) and then left for 24 hours at ambient temperature. In the final step, wind tunnel testing was performed. After wind tunnel testing, the surface crust thickness was measured using Vernier calipers, as shown in Fig. 3(b).

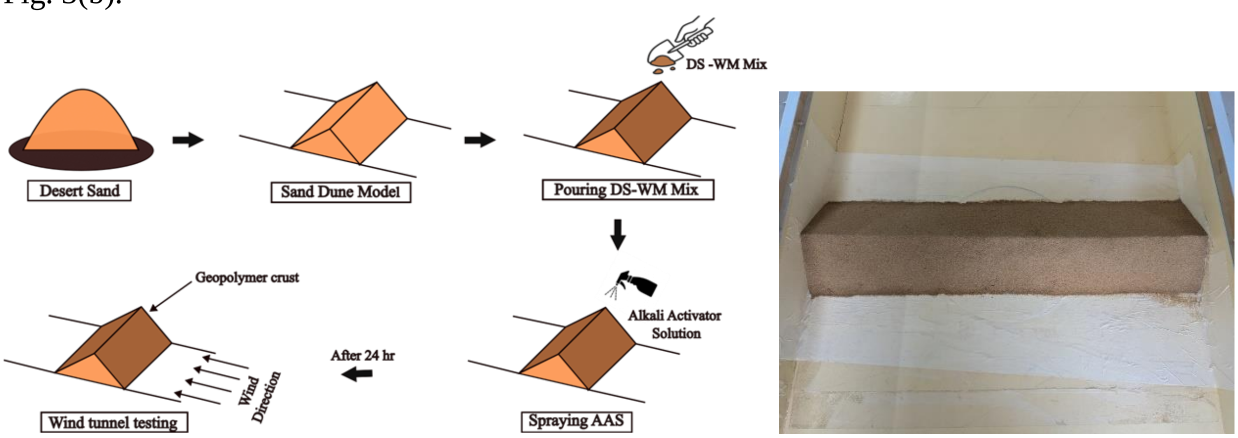

Figure. 1 (a) Step - wise sample preparation, (b) Alkali activated crust formed dune sample.

2.2 Wind Tunnel Setup

Fig 2 illustrates the wind tunnel setup, which has a total length of 10m, including a 4m test section with a cross-sectional area of 0.6 m × 0.6 m. Untreated and treated sand dune samples were tested in the wind tunnel for durations of 15 minutes at increasing wind velocities of 10, 20, and 30 m/s to measure soil mass loss (Dagliya et al., 2022, Miao et al., 2020). An anemometer was used to measure the wind profile across the entire setup. Both untreated and treated dune models were constructed in the test section, with the treated dune model cured for 24 hours at ambient temperature before testing. Dune mass loss was calculated as the difference between the samples' pre- and post-test weights.

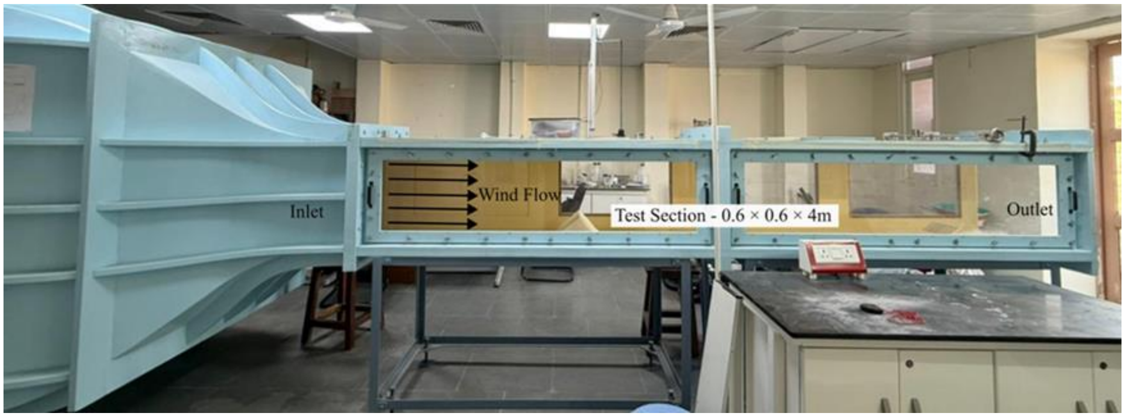

Figure.2 Wind tunnel setup.

3. Results and discussion

3.1 Soil mass loss by wind action

Fig. 3(a) illustrates the percentage of soil mass loss in dune sand samples, both untreated and alkali activator-treated, with various WM contents (10%, 20%, 30%, and 40%), following wind tunnel experiments conducted at varying wind velocities (10 m/s, 20 m/s, and 30 m/s) for15 min durations for untreated and alkali activator-treated samples, respectively. The dune sand specimen weights were measured before and after testing to a precision of 0.01 g. For untreated dune sand, the mass loss percentages were recorded as 100%, 100%, and 100% at 10 m/s, 20 m/s, and 30 m/s wind speeds, respectively. However, the alkali activator-treated sand dune samples showed 0% mass loss at all wind velocities (10 m/s, 20 m/s, and 30 m/s) due to the formation of a strong alkali activator surface crust by the precursor WM (rich in CaO), which reacts with DS (rich in silica). The crust thickness of alkali activator-treated dune samples with varying WM contents (10%, 20%, 30%, and 40%) is presented in Table 1. The crust thickness increased from 1.75 mm to 8.83 mm as the WM content rose from 10% to 40%. This increase in crust thickness with higher WM content is attributed to the elevated alkali activator content. Higher alkali activator application enhances the reaction between DS and WM particles, resulting in greater crust thickness.

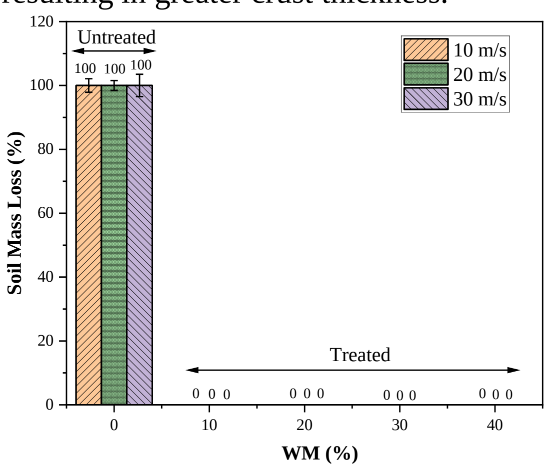

Table 1: Crust formation with various WM content.

WM (%)	Crust Thickness (mm)
10	1.75
20	3.93
30	5.92
40	8.83

Figure 3. (a) Soil mass loss of untreated sand dune and treated sand dune.

4. Conclusions

- The alkali-activated crust, formed by combining marble slurry powder (WM) and desert sand (DS), completely prevented wind erosion of dune sand models at extreme wind speeds of up to 30 m/s, even at WM contents as low as 10-40%.
- Mass loss was reduced from 100% in untreated samples to 0% in treated samples, demonstrating the exceptional erosion resistance of the alkali-activated treatment.
- The geopolymer crust thickness increased progressively from 1.75 mm to 8.83 mm as the WM content rose from 10% to 40%, indicating a direct relationship between WM content and crust development.
- The increased crust thickness significantly raised the erosion threshold velocity, enhancing the overall mechanical resistance of the stabilized dune surface against high wind forces.
- The alkali-activated treatment offers a highly effective, low-cost, and eco-friendly solution for sand dune stabilization in arid regions, utilizing industrial waste (marble slurry powder) as a key precursor material.

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