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Sustainable Use of Marble Byproduct for Stabilizing Migrating Sand Dunes in Thar Desert, India

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ABSTRACT

Various sustainable practices explored the use of regionally available industrial byproducts for potential applications. Thar desert, extending about two lakh square kilometers in Rajasthan, India, is mostly covered by sand dunes formed with aeolian-natured soils. Due to the wind-led soil erosion, these sand dunes migrate intensely impacting the soil fertility, inundation of major infrastructure, increased particulate matter. Limited studies exist regarding the stabilization of Thar sand dunes with sustainable geomaterials. Rajasthan is the largest producer of marble output in the country and generates about six million tons of marble slurry per annum posing a major challenge of land requirement for scrapped marble disposal. Current study proposes to integrate these two challenges through sustainable utilization of scrapped marble slurry as a potential stabilizer to mitigate the wind-led sand dune migration in Thar Desert. Samples from sand dune and marble dump yards were collected and characterized for their index and strength properties. Four mixtures of varying marble slurry in sand have been prepared and utilized as sand dune stabilizer owing to the cementitious nature of the fine marble slurry powder. Wind-led erodibility was assessed for the mixtures through bench scale studies, and it is concluded that the surface crust formed using the marble slurry-sand mixtures could protect the dunes from intense erosion.

Keywords: Sand dunes; Marble slurry; Stabilization; Compressive strength; Surface treatment

1 INTRODUCTION

Rajasthan, a northern state in India, covers about 10% of country's geographical area (approximated to 3.42 lakh km^2) with more than 60% of Thar desert (about 2 lakh km^2) within it. The Thar Desert or the Great Indian Desert with an area of 2.38 lakh km^2, experiences arid and semi-arid climate with little or scanty rainfall of about 150mm (mean annual rainfall) during monsoons (Tandon et al., 1999). The quaternary phase of Thar Desert highlights the evolution of landforms and climate change impact over the past two million years. Overall, 58% of Rajasthan's geography is covered by several aeolian-led sand dunes of Thar Desert with various shapes (longitudinal, parabolic, transverse, star and complex shapes), sizes and orientations (Subramaniam and Kesava Rao, 1983). These sand dunes migrate at an average rate of 3m to 8m per annually (Bhadra et al. 2019) leaving several infrastructures (highways, railways, airports, power plants, solar parks, etc.) inundated and agricultural farms losing the yield due to reduced fertility. Also, during the dust storms season, sand dune migration leads to increased airborne particulate matter posing severe environmental challenges. In addition, the Government of India envisages to develop four major cities of Rajasthan as smart cities with significant infrastructure plans. Several researchers aimed for region-specific sand dune stabilization measures in Thar Desert including agronomic based (vegetation) measures (Kaul, 1996; Chauhan, 2003; Krishnan and Jindal, 2015) and biocementation, bio-polymerization and microbial induced calcite precipitation (MICP) in crust formation Devrani et al. (2021) and Dagliya et al. (2022). However, the environmental impact of such surface

treatments is often questionable. This calls for an environmental-friendly and sustainable surface treatment for arresting the migration of sand dunes in Thar Desert. In view of such enormous infrastructure expansion plans, it is of prime importance to investigate the solutions for sand dune migration mitigation (SDMM) scientifically, aiming for short-term and long-term sustainability.

Though the state of Rajasthan suffers from arid and semi-arid climate with scanty rainfall, it is blessed with rich marble deposits accounting for around 94% of output in the country (CPCB, 2012). Since most of the quarries in Rajasthan are non-mechanized and follow traditional approaches of mining, approximately 70% of raw product forms as a marble byproduct. The recent decades have shown a significant demand for these marbles, and it is observed that in Rajasthan alone, approximately six million tons of marble slurry is generated annually, requiring enormous dumping yard sites (Singh et al., 2017). The main processing units in Rajasthan are housed in the regions of Udaipur, Makrana, Kishangarh, Rajsamand, Alwar and Abu Road. Marble slurry dust availed in Rajasthan is a very fine powder with approximately 40% particles finer than 75µm diameter out of which approximately 30% are finer than 25µm. Specific gravity of slurry powder is in the range of 2.70-3.00 gm/cm^3 with 5-20% water content. Due to the fineness and cementitious nature of the dolomitic-rich marble dust powder in the region, the same is being used in several applications including cement industries (replacing limestone with marble powder for its high MgO), as synthetic gypsum through chemical reactions, utilizing marble dust in road constructions, as a low-cost binding material for stone masonry, brick masonry and plastering work, manufacturing in brick (shows multifold compressive strength and high fire resistance compared to conventional bricks) and as a filler raw material in mineral grinding plants. The ability of marble slurry to act as binder was investigated in many studies (Benjeddou & Alwetaishi, 2021; Kore et al., 2020; Singh et al., 2017), however the possible utilization of Marble slurry as solution to the global problem of aeolian sand mitigation has not been comprehensively explored. Qureshi et al. (2017) study on improving geotechnical characteristics of Desert sand in Oman adopted the locally available marble waste powder. Most of the reported literature on sand stabilization employing marble waste have only examined the index and shear strength properties of the materials without considering their application to surface crust formation on sand dunes and resulting wind-led erodibility. Due to inherent fineness and cementitious nature, the marble dust when mixed with dune sand could be a sustainable alternative for sand dune migration mitigation. Improvement of stability of sand dunes enables the dune site to be fertile for agriculture or afforestation. As a result, the possible land degradation from aeolian sand dune migration can also be mitigated. The current study proposes to integrate these two challenges by proposing to utilize the scrapped marble slurry as a potential stabilizer to mitigate sand dune migration in Thar Desert through experimental testing.

2 METHODOLOGY

2.1 Materials

Sand dunes of Thar desert, Rajasthan were formed because of a major dry phase that terminated around 10000 years before present (Ghose et al., 1977). The existing dunes of Thar are classified under old and new system dunes by Pandey et al. (1992). Linear, parabolic, transverse, star, network, and major obstacle dunes under the old system dunes classification are of 20-40m average height, mostly formed during 15 to 18 ka before present due of climate change. Whereas new system dunes such as the crescentic barchans, barchanoids, nebkhas, sand streaks, zibars etc of 2-8m average height are formed as result of current arid conditions in Western India (Ghose et al., 1977; Kar, 1996).

The dune sand employed in the study was collected from Osian sand dunes of Jodhpur District, Rajasthan. As per the Unified Soil Classification System (USCS), the dune soil is classified as poorly graded sand (SP). Particle size distribution of osian sand indicated more than 50% fine content and the representative grain size characteristics are as listed in Table 1. The gradational characteristics of Osian sand infer the particle size range matching the Bagnold (1941) saltation phenomenon size range i.e., the particles in range of 0.07-0.5mm are prone to saltation phenomenon, one of the significant sand transport mechanisms in sand migration. Figure 1 depicts the location and grain size distribution of Osian sand sample.

Table 1 *Grain size characteristics of Osian Sand and Marble Slurry*

Parameters	Grain size range, mm	D_{10}, mm	D_{30}, mm	D_{50}, mm	D_{60}, mm	C_u	C_c	USCS Classification
Osian Sand (OS)	4.75-0.15	0.114	0.165	0.19	0.203	1.781	1.176	SP
Marble Slurry (MS)	0.075-0.002	0.002	0.028	0.064	0.067	33.5	5.85	CL

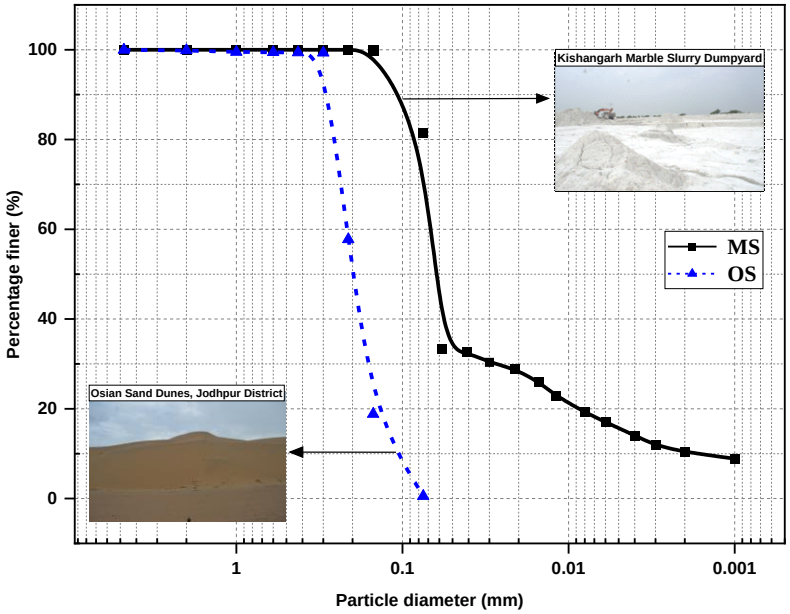


Figure 1 *Sampling location and Particle size distribution of Osian Sand and Kishangarh marble slurry samples*

Further, the morphological aspects and elemental composition of the Osian sand determined through Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) analyses are shown in Figures 2 and 4(a). It was observed that the sand is a mixture of rounded and sub angular shaped particles matching the topographical features of Jaisalmer sand with a predominant presence of Quartz mineral (Padmakumar et al. 2012). Formation of conchoidal shape structures on the surface of grain (Figure 2(c)) is due to the continuous abrasion from wind action. Other Index, thermal and geotechnical characteristics of the soil were also evaluated and presented in Table 2.

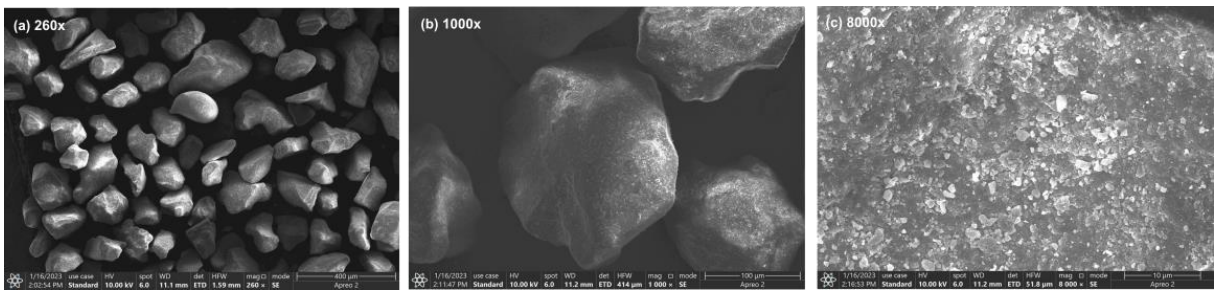


Figure 2 *SEM pictures of Osian sand at different magnifications*

Aiming to assess the feasibility of using marble slurry for mitigating sand dune migration, an extensive elemental analysis was carried out on a sample collected from the Kishangarh marble dumping yard in Ajmer, depicted in Figure 1. The results of this characterization are outlined in Table 1 and Table 2. Particle size distribution of the oven-dried marble slurry sample indicated more than 70% fine content (passing through 75µm) and silt fraction near to 10%. As per USCS classification, marble slurry is classified as low compressible medium plastic clay (CL) with dominant angular shaped particles compared to the Osian sand particles from the SEM analysis, at various magnifications as depicted in Figure 3. The sampled marble slurry powder predominantly consists of Calcite ($CaCO_3$) and Dolomite ($CaMg(CO_3)_2$)) rich elements supporting cementitious nature with observed UCS of 105 kPa, as

depicted from EDS analysis presented in Figure 4. The Atterberg limits, compaction characteristics, unconfined compressive strength, pH and electrical conductivity are evaluated and listed in Table 2.

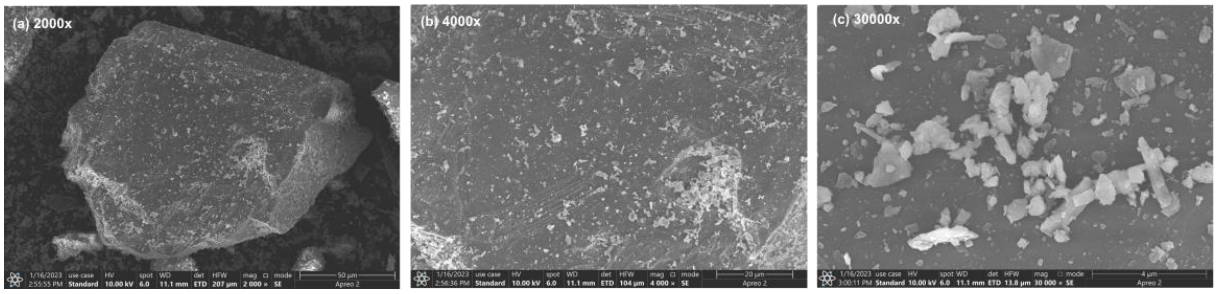


Figure 3 *SEM pictures of marble slurry at different magnifications*

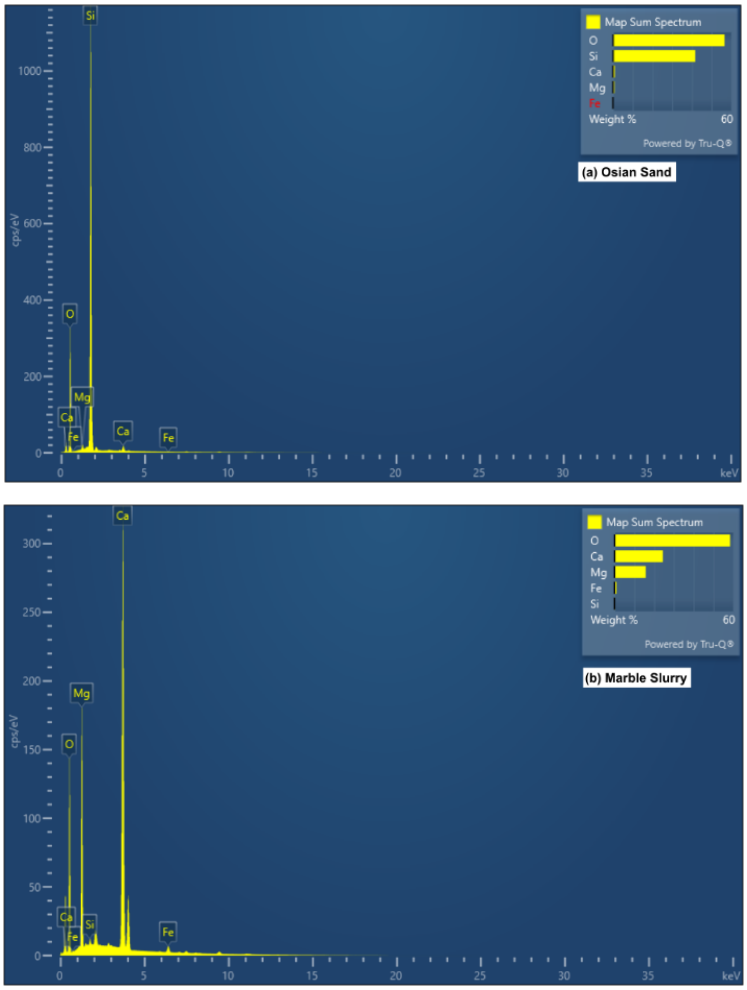


Figure 4 *EDS for (a)Osian sand (b) Marble dust*

Table 2 *Index, thermal and geotechnical properties of Osian sand and Marble slurry*

Parameters	G_s[1]	MDD [2], kNm^{-3}	OMC[3], %	pH value	EC[4], µS/cm	Atterberg Limits			UCS[8] kPa
						LL[5], %	PL[6], %	SL[7], %	
Indian Standards	IS 2720 (Part 3) 1985	IS 2720 (Part 3) 1985		IS 2720 (Part 3) 1985	IS 2720 (Part 3) 1985	IS 2720 (Part 5,6) 1985			IS 2720 (Part 10) 1991
OS	2.527	16.75	14.5	8.98	87.5	--	--	--	--
MS	2.532	17.17	14.2	8.5	95	27.1	16.6	10.6	105

[1]Specific gravity; [2]Maximum dry density; [3]Optimum moisture content, [4]Electric conductivity; [5]Liquid limit; [6]Plastic limit; [7]Shrinkage limit; Unconfined compressive strength

2.2 Specific Gravity and Void Ratio

Specific gravity (G_s) of MS-OS mixtures investigated using standard pycnometer test were found to be in the range of 2.58-2.77. The void ratio of samples was obtained using relative density apparatus where in the soils were filled in the loosest and compacted conditions to get the minimum and maximum void ratios possible. It was observed that as the proportion of marble slurry increased the specific gravity and void ratio (minimum and maximum states) of mixtures tend to increase due to the fine-grained nature of MS. The obtained dry density and void ratio for different mixtures are shown in Figure 5.

Table 3 *Designation and parameters of MS-OS mixtures*

Designation	MS, %	OS, %	G_s	Void ratio (e)		OMC, %	MDD, %	Crust thickness, cm
				e_{max}	e_{min}			
20MS+80OS	20	80	2.584	0.868	0.447	14.42	17.27	0.3
40MS+60OS	40	60	2.655	0.971	0.433	11.9	18.3	0.5
60MS+40OS	60	40	2.667	1.299	0.573	12.4	18.79	0.5
80MS+20MS	80	20	2.763	1.554	0.736	12.5	18.7	0.4

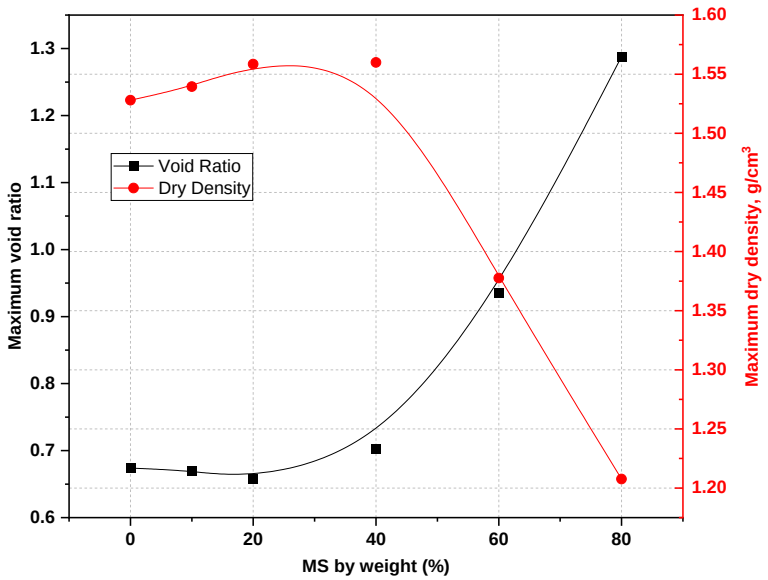


Figure 5 *Variation of void ratio and dry density with MS content in mixture*

2.3 Compaction Characteristics

Modified proctor test as per IS: 2720 Part 8 was used to determine the optimum moisture content (OMC) and maximum dry density (MDD) of Osian sand and marble slurry samples. The obtained results for different mixtures are shown in Figure . It can be observed that MDD increases up to 60% of MS content beyond which it decreases. The addition of MS in initial stages fills the voids in the sand, however in later stages as voids are filled, further addition of MS would reduce the maximum dry density. Similar trends of OMC and MDD with addition of MS was reported for desert sand of Oman (Qureshi et al. 2017).

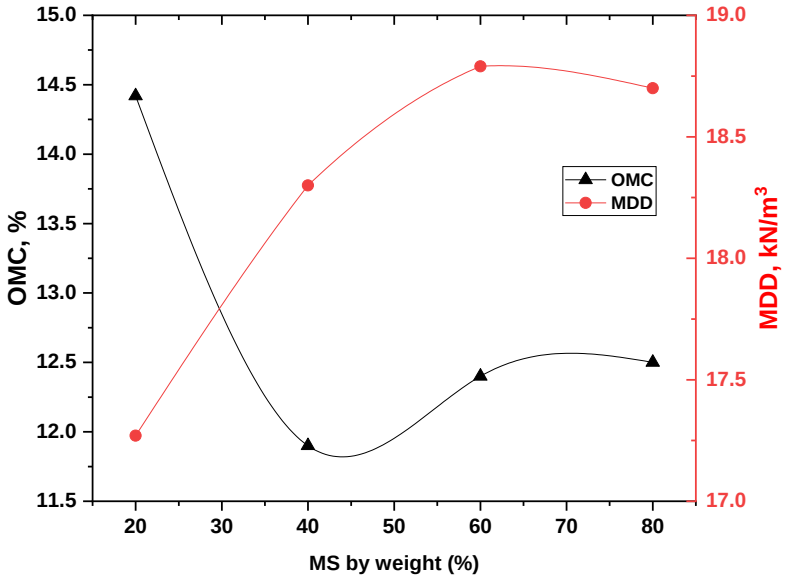


Figure 6 *OMC and MDD for MS-OS mixtures*

2.4 Crust Formation Using OS-MS Mixtures

The test specimens for the bench scale study (discussed in Section 3) were prepared using four different mixtures of MS-OS by weight, as listed in Table 3. Marble slurry (MS) utilized for the mixture was oven dried and powdered before mixing it with Osian Sand (OS) at four different mixing proportions (20%, 40%, 60% and 80%). Summary of properties of adopted mixtures and their designation is listed in Table 23. To develop a small-scale sand dune model in laboratory, dry pluviation technique is employed as depicted in Figure 7(a). Further, the OS-MS mixtures are evenly spread on dune surface (Figure 7(b)) and distilled water is sprayed on top for the formation of crust (Figure 7(c)). Twenty-one days of laboratory open drying was adopted for the complete drying of moisture content and formation of the surface crust on the sand dune. As the surface of sand is most prone to erosion, crust formations on the top enhances the erosion resistivity. Hence, the binding ability of marble slurry in the MS-OS mixtures is evaluated through crust formation and its erosion resistance in bench scale study, as depicted in Figure 7.

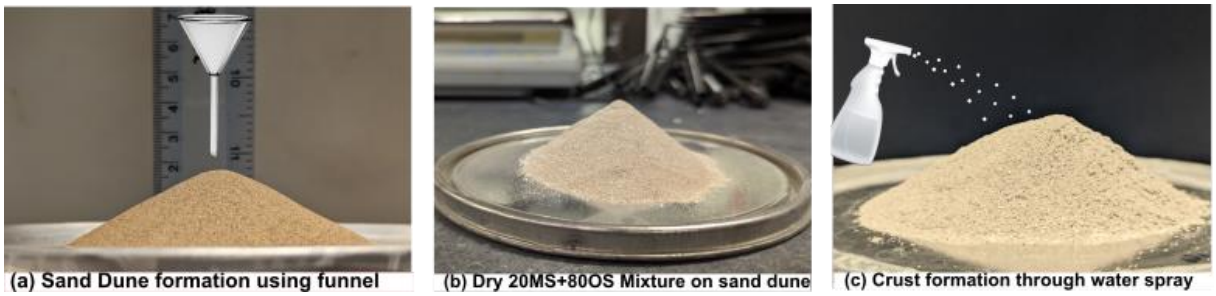


Figure 7 *Schematic procedure of crust development on sand dune*

3 BENCH SCALE INVESTIGATION OF SAND EROSION

The bench scale setup in the current study aims to investigate the erosion resistivity of the MS-OS mixture-based crust on sand dune. The setup includes a blower fan to simulate the wind, a digital anemometer to measure the wind speeds and a few laboratory trays for MS-OS mixtures testing at room temperature. The wind speed range at Osian sand dune location (Jodhpur district) ranges from 5-18.5 kmph (1.38 - 5.14 m/s) with peak winds during the summers (Bhadra et al. 2019; Saraswat and Singh 2021). Noting this wind speed range in Jodhpur district, current test setup simulates field wind speed conditions ranging from 0.5 m/s to 7 m/s. The objective of the first series of experiments (a total of six tests) was to determine the controlled case parameters using only Osian sand, whereas the second set of experiments (set of five tests) investigates the wind-driven erodibility of crust on the dune using OS-MS mixtures. The tray filled with Osian sand alone is blown using the wind simulator at varying wind

speeds (1-6.5 m/s) and testing duration (1-30 minutes) in the first set of experiments. The second set tests crusted dunes at different wind speeds and duration to determine the erodibility of crust produced using OS-MS combinations. The cumulative soil mass loss is calculated by weighing the sand tray at each wind speed. The investigations were permitted to controlled case environments of laboratory, however an extended case study investigation simulating the field temperature could be investigated in further studies.

4 TEST RESULTS AND DISCUSSION

4.1 Erodibility of Untreated Osian sand

To investigate the efficiency of crusted MS-OS mixes in the second set of experiments, the initial tests focused on erodibility of Osian sand alone at different test duration and wind speeds. The aerodynamic drag and lift forces on soil particles outweigh soil grain gravitational and frictional forces as wind speed increases (Pye and Tsoar, 2009). However, the particles start to roll over and initiate saltation once it crosses the threshold friction velocity (TFV). Figure 8 presents the pictorial representation of wind-led erosion of Osian sand dunes for different wind speeds and durations. It is evident that Osian sand has endured soil erosion until a wind velocity of 2 m/s consistent to the threshold friction velocity (TFV) range of Thar soils reported by Kar (1992). The observed cumulative losses (Figure 8) increased significantly with the wind speed i.e., from 2.04% at 2 m/s to 75% at 6.5 m/s for a duration of 10 min. As the prevailing wind speed conditions at Jodhpur district range until 5.14 m/s, significant erosion of Osian sands is highly anticipated if no surface treatment is employed.

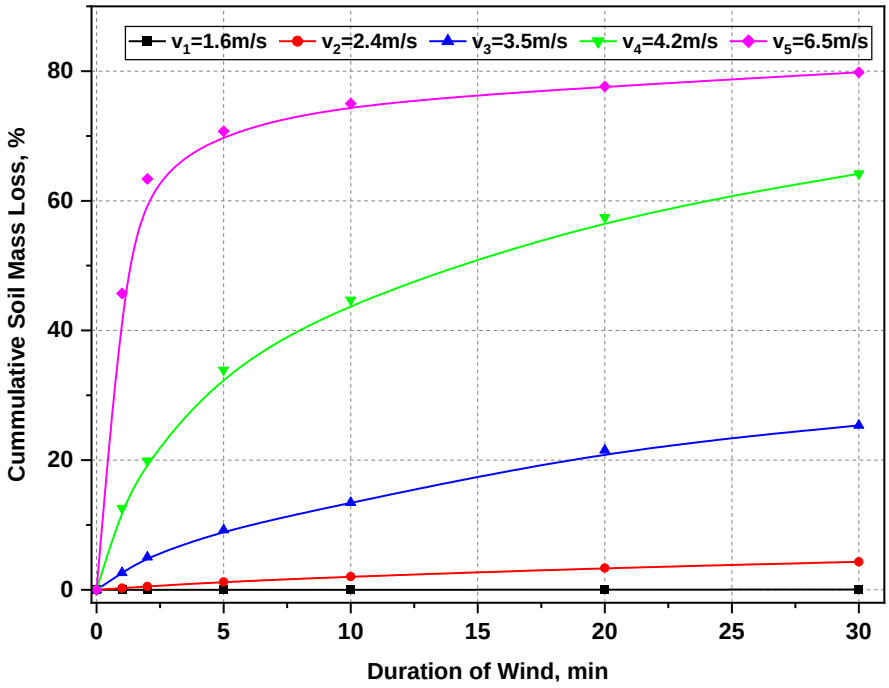


Figure 8 *Erodibility of Osian sand at different wind speed and duration*

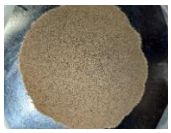
4.2 Erosion Resistance of Crusted Sand Dunes using MS-OS mixtures

Realizing the significant threat of soil erosion to Osian sand dunes, the erosion resistance of crusted sand dunes using MS-OS mixtures was investigated. As the surface of sand is most prone to erosion, thickness of the crust plays a critical role in erodibility studies. It could be inferred from Table 3 that as the percentage of MS increased in mixture, increased thickness of crust is noted until 60% MS like sand-tire mixtures (Sodom et al., 2016). Initially, the MS content increase successfully occupied up to 60% of the voids in the OS. However, once the voids were filled, further increases in MS content led to an increase in voids due to the small particle size of MS.

Table 4 briefs the soil erodibility to varying wind speeds and duration for crusted MS-OS mixtures. Significant reduction in cumulative soil mass loss (%) compared to OS alone and with increase in %MS content is perceptible from analogy in Figure 9. Maximum erodibility for 5-minute testing duration was

70.7% for Osian sand alone at 6.5m/s whereas the same reduced to 0.56% (at 20%MS). However, the erodibility of mixtures increased with increase in testing duration until certain time. During peak summers, the Thar desert regions experience dust storms sustaining more than 30-minute duration. The soil mass loss was almost 0% in case of 80%MS at 6.5m/s and for longer durations (see Figure 9 and Figure 10). This signifies that the proposed crusted MS-OS mixtures are effective in resisting the wind-led erodibility of the Osian sand dunes from the anticipated wind speed even at sustained longer durations. It is worth mentioning that the crust thickness varies along the dune with the thick crust at the crest followed by thin crust at the toe for all the MS-OS mixtures.

Table 4 *Erodibility of Osian sand and OS-MS mixture at different wind speeds*

%	Initial state	After V1 = 1.2m/s (after 5 minute)	After V2 = 2.2m/s (after 5 minute)	After V3 = 3.4m/s (after 5 minute)	After V4 = 4.2m/s (after 5 minute)	After V5 = 6.5m/s (after 60 minute)
0						
20						
40						
60						
80						

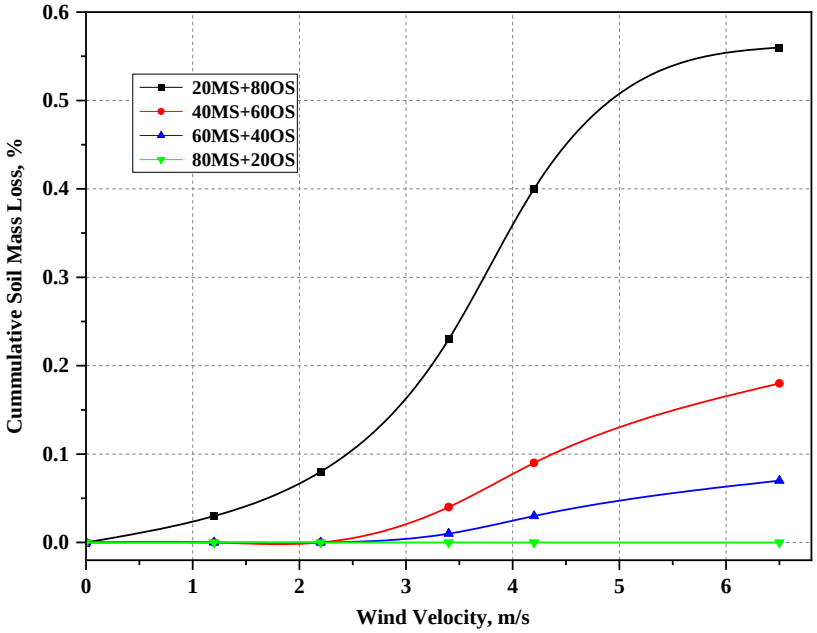


Figure 9 *MS-OS mixture erodibility with variation in wind velocity for 5min duration*

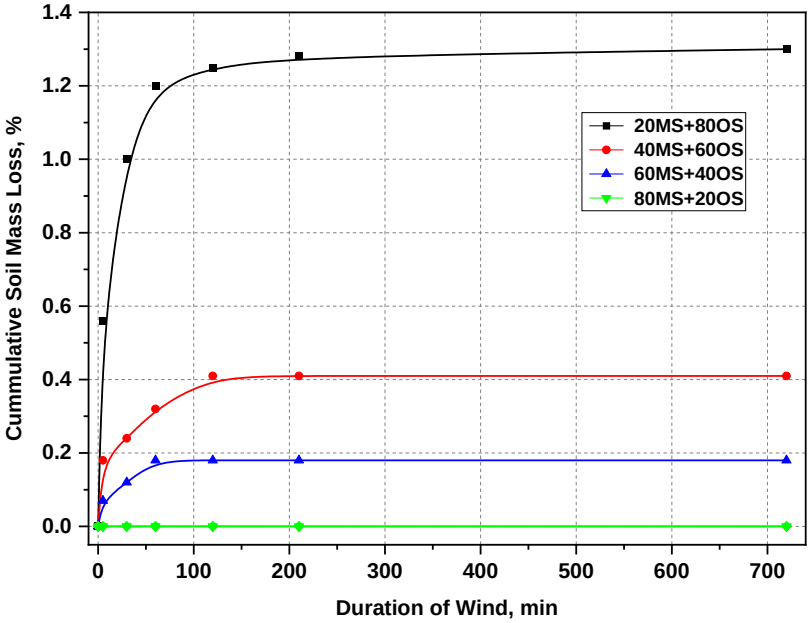


Figure 10 *MS-OS mixture erodibility with variation in duration of wind at 6.5m/s*

5 CONCLUSIONS

Bench scale studies are conducted to propose sustainable valorization of scrap marble slurry powder as a potential sand dune stabilizer in the current study. Samples of scrap marble slurry from Kishangarh dump yard and desert sand from Osian sand dunes were used. The mixtures were prepared by weight with MS content varying from 20-80% in the dune sand. Comprehensive characterization of dune sand, marble slurry and the mixtures have been conducted and it is realized that an optimum mixture could exist yielding an increased density. A wind-erosion resistive crust was formed over the top of scaled dunes using the MS-OS mixtures and erosion resistivity of the crusted dunes is monitored using wind simulating blower approximating the field wind speed conditions. The thick crusted MS-OS mixture on the top of dune successfully reduced the erodibility for prevailing high wind speed conditions and sustained duration testing.

The proposed solution in the current study could successfully integrate both the challenges of the sand dune migration and marble waste disposal management through sustainable valorization. However, the

current findings are limited to bench scale study investigations and could be further experimentally investigated and verified using scaled model studies and field studies incorporating the field conditions such as wind direction, humidity and temperature.

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