Postprint: Grain Size Characteristics of Surface Sediments in Three Types of Low Vertical Sand Barriers

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Abstract

Taking three types of sand barriers (PLA sand barrier, Salix sand barrier, HDPE sand barrier) of identical specifications but different materials that had been installed for 3 years on the south side of the Xingba Expressway in the Kubuqi Desert as the research object, surface sediment samples (0-2 cm) were collected within the sand barriers, and the mechanical composition of the samples was measured using a laser particle size analyzer to analyze parameters including mean particle size, standard deviation, skewness, kurtosis, and fractal dimension. The results showed that: (1) The sediments were dominated by medium and fine sand, with contents of approximately 77.83%-98.00%, while the contents of clay and silt did not exceed 5%; PLA and HDPE sand barriers at the bottom of the windward slope of the dune exhibited slight wind erosion, with relatively coarse particle sizes; for the Salix sand barrier, particle size within the barrier grids gradually increased from the bottom to the top of the slope, with an erosion-deposition transition occurring at the slope top. (2) Overall, the sediments within the sand barriers were poorly sorted, with skewness developing toward positive or negative skewness, kurtosis tending toward sharp and narrow peaks, fractal dimension ranging from 1.94 to 2.20, and the dominant particle grade shifting toward fine sand. (3) Different sand barrier types had differential effects on sediments; the distribution of sediment particles within HDPE and PLA sand barriers was more extensive, whereas that within Salix sand barriers was relatively concentrated, with all tending toward fining; the optimization of soil particle composition followed the order HDPE sand barrier > Salix sand barrier > PLA sand barrier.

Full Text

A Study on the Grain Size Characteristics of Surface Sediments Within Three Types of Low Vertical Sand Barriers

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Abstract

This study investigated surface sediments (0–2 cm depth) within three types of low vertical sand barriers (PLA, Salix, and HDPE) of identical specifications that had been installed for three years on the southern side of the Xingba Expressway in the Kubuqi Desert. The mechanical composition of sediment samples was measured using a laser particle size analyzer, and parameters including mean grain size, standard deviation, skewness, kurtosis, and fractal dimension were analyzed. The results revealed that sediments were dominated by medium and fine sand (77.83%-98.00%), with clay and silt contents not exceeding 5%. At the base of the windward slope, PLA and HDPE sand barriers exhibited mild wind erosion with relatively coarse particle sizes. In contrast, particle sizes in Salix barriers gradually increased from slope base to crest, where an erosion-deposition transition occurred. Overall, sediments within the barriers were poorly sorted, with skewness developing toward positive or negative deviation, kurtosis becoming sharper and narrower, fractal dimension ranging from 1.94 to 2.20, and the dominant grain size shifting toward fine sand. Different barrier types exhibited distinct effects on sediments: HDPE and PLA barriers showed more extensive particle distributions, while Salix barriers displayed relatively concentrated yet refined distributions. The optimization of soil particle composition followed the order: HDPE > Salix > PLA barriers.

Keywords: low vertical sand barrier; windward slope; grain size characteristics; fractal dimension; Kubuqi Desert

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Mechanical sand barriers represent one of the primary measures for preventing wind-sand hazards and have been widely applied in desertification control efforts across China. By altering surface properties and increasing aerodynamic roughness, these barriers effectively reduce wind velocity, intercept aeolian sand flow, diminish wind erosion, and thereby fulfill windbreak and sand fixation functions. However, due to variations in barrier materials, specifications, shapes, and the diverse wind regimes and geomorphic conditions in different application areas, the effectiveness of different sand barriers varies considerably. Scientific selection of appropriate barriers constitutes a critical foundation for ensuring their long-term, stable performance in sand fixation.

Numerous researchers have evaluated barrier effectiveness using indicators such as wind-sand flow structure, surface roughness, wind velocity profiles, sediment transport flux, and erosion-accumulation characteristics. Sediment particles are products of long-term weathering, erosion, transport, and deposition processes. The percentage content of different particle sizes is closely related to soil structure, fertility, and water movement, and reflects the wind erosion status of soils. Grain size characteristics also serve as a primary indicator in aeolian geomorphology research and have been widely applied in comparative and genetic analyses of both aeolian and lacustrine deposits. Consequently, the grain size characteristics of sand within barriers can reflect the transport, sorting, and deposition conditions of aeolian sand flow. Compared with single measurements of windbreak and sand fixation benefits, sediment grain size characteristics provide a more comprehensive representation of barrier protective effectiveness.

Building upon this foundation, the present study selected the Duguitala section of the Kubuqi Desert as the research area, focusing on 2 m $\times$ 2 m low vertical sand barriers installed on both sides of the highway at slope base, mid-slope, and crest positions. By comparing and analyzing the sediment particle composition, mean grain size, standard deviation, skewness, kurtosis, and fractal dimension within different barriers, this research aims to elucidate differences in protective benefits and soil particle composition improvement effects among the three barrier types, thereby providing reference for barrier selection and configuration in arid and semi-arid regions.

1 Study Area Overview

The study area is located on the southern side of the Xingba Expressway in Duguitala Town, Hangjin Banner (40°43 N, 108°58 E), situated in the transitional zone between arid and semi-arid regions with a typical temperate continental climate. The area has an elevation of 1000–1400 m, mean annual precipitation of 203–418 mm, mean annual wind speed of 4.5 $m \cdot s^{-1}$, and 25–35 days of strong winds annually. The primary landscape consists of mobile, semi-fixed, and fixed dunes, with aeolian sandy soils as the main soil type. Dominant plant species include *Agriophyllum squarrosum*, *Psammochloa villosa*, *Caragana korshinskii*, *Corispermum declinatum*, and *Artemisia ordosica*.

[Figure 1: see original paper] Geographical location and sand barrier types of the study area

2 Materials and Methods

2.1 Sample Collection and Analysis

In 2017, PLA, Salix, and HDPE sand barriers were installed on the southern side of the Xingba Expressway in Duguitala, all configured as 2 m × 2 m low vertical barriers. Sampling was conducted on April 25, 2020, within the barrier grids, with no strong winds or rainfall occurring within a week before or after sampling. Following the principle of similarity, three dunes with comparable morphology, slope gradient, and length were selected. The windward slopes had gradients of approximately 15-20°, lengths of about 50 m, consistent east-west orientation, and vegetation coverage not exceeding 5%.

Samples were collected from 0-2 cm depth within barrier grids at the crest, mid-slope, and base of the windward slopes using a self-designed stratified soil sampler, with five replicates per position. Bare dunes served as controls, yielding a total of 84 samples. Replicate samples were mixed uniformly and air-dried in the laboratory.

After removing impurities and coarse particles >2000 m through sieving, 0.5 g of each air-dried sample was placed in a 50 mL glass beaker with 45 mL of Grade III ultrapure water. To fully remove organic matter, 10 mL of 30% H_2O_2 solution was added and the mixture was left to stand until bubbling ceased, then heated on an electric plate until completely dry. After cooling, 10 mL of 10% HCl was added to dissolve carbonate materials. The sample was left to stand again, rinsed repeatedly with ultrapure water until pH reached neutral as tested with a PH173 meter, then diluted with pure water.

Particle size analysis was performed using a German Analysette 22 MicroTec Plus laser diffraction instrument with a measurement range of 0.01-2100 m, resolution better than 1%, measurement time of 5-10 s per run, and a cycle time of 60 s. Each sample was measured in triplicate.

General information of the different sand barrier types

2.2 Calculation Models

Soil mechanical composition was classified according to the USDA standard: gravel (>2000 m), very coarse sand (1000-2000 m), coarse sand (500-1000 m), medium sand (250-500 m), fine sand (100-250 m), very fine sand (50-100 m), silt (2-50 m), and clay (<2 m). The Krumbein algorithm was applied for logarithmic transformation of particle size values:

$$\Phi = -\log_2 D$$

where D is the sediment particle diameter (mm). Grain size parameters including mean size (D_m), standard deviation (σ), skewness (SK), and kurtosis (K_g) were calculated using the graphical method.

Fractal dimension was calculated based on volume content of different particle sizes:

$$D = 3 - \frac{\log\left(\frac{V_i}{V_t}\right)}{\log\left(\frac{r_i}{r_{\max}}\right)}$$

where D is the soil fractal dimension; r_i is the particle diameter (mm); V_i is the volume content of particles smaller than r_i (%); V_t is the total volume content of all particles (%); and $r_{\max}$ is the maximum particle diameter (mm).

2.3 Data Processing

Data calculations and charting were performed using Excel 2010 and Origin 2018. One-way ANOVA and multiple comparison tests were conducted using SPSS 25.

3 Results

3.2.1 Mean Grain Size

The mean grain size of bare dunes ranged from 1.68Φ to 2.02Φ, averaging 1.87Φ. Within PLA barriers, mean grain size ranged from 1.59Φ to 2.15Φ (average: 1.92Φ); within Salix barriers, 2.10Φ to 2.26Φ (average: 2.18Φ); and within HDPE barriers, 1.97Φ to 2.25Φ (average: 2.08Φ). Following barrier installation, grain size on the windward slope increased significantly ($P < 0.05$), with fine particle content increasing substantially. The magnitude of increase followed the order: Salix > HDPE > PLA > bare dune. Barrier installation caused redistribution of particles across slope positions: mean grain size in bare dunes first increased then decreased from slope base to crest, while PLA barriers showed the opposite trend, and Salix barriers exhibited gradual increase.

3.2.2 Standard Deviation

Standard deviation values averaged 0.48, 0.61, 0.53, and 0.54 for bare dunes, PLA, Salix, and HDPE barriers, respectively. The study area was dominated by fine and medium sand (77.83%-98.00% average content), with clay and silt contents not exceeding 5%. Compared with controls, medium sand content decreased significantly at slope base and crest positions ($P < 0.05$), while coarse and very coarse sand contents decreased from base to crest—a pattern opposite to that of the control. Except at the base of PLA barriers, very fine sand, clay, and silt contents increased significantly compared with controls ($P < 0.05$). This reflects the differential and complex nature of soil particle changes under aeolian activity, with barrier protection effectively reducing airflow sorting of soil particles and broadening the grain size distribution.

3.2.3 Skewness

At the slope base, PLA barrier sediments showed negative skewness, while Salix barriers exhibited near-symmetric distribution. At mid-slope and crest positions, both PLA and Salix barriers were near-symmetric, whereas HDPE barriers showed positive skewness. These results indicate that barrier installation caused skewness to develop toward either positive or negative deviation, with dominant grain sizes shifting accordingly. Reduced shear stress and increased threshold velocity for particle entrainment led to diminished surface wind erosion.

3.2.4 Kurtosis

Kurtosis trends mirrored those of sorting coefficients. Bare dunes and PLA barriers showed medium kurtosis, Salix barriers exhibited platykurtic distributions, while HDPE barriers displayed leptokurtic distributions. Following barrier installation, kurtosis developed toward sharper, narrower peaks, indicating that barrier protection reduced airflow sorting and broadened the grain size distribution range on windward slopes, with particle composition gradually becoming finer—particularly in HDPE barriers where fine sand became dominant.

3.2.5 Fractal Dimension

Given the intense wind erosion and poor structure of aeolian sandy soils in the study area, both bare dunes and barrier sediments exhibited relatively low fractal dimensions. However, fractal dimension increased significantly at all slope positions following barrier installation ($P < 0.05$), with the magnitude of increase following: HDPE > Salix > PLA barriers. Fractal dimension showed a consistent pattern across slope positions: crest > mid-slope > base for all barrier types.

Grain size composition of sediments in different sand barriers

Grain size characteristics of sediments in different types of sand barriers

4 Discussion

4.1 Terrain-Related Differences in Sediment Distribution Within Barriers

Salix barriers showed gradually fining particles from slope base to crest, with the most significant wind speed reduction effects in interdune lowlands and lower windward slopes. At dune crests where wind speeds are highest, barrier effects on wind speed reduction are less pronounced than in interdune areas. Consequently, at slope bases where wind speeds are far below the threshold for sand movement, very fine sand, silt, and clay particles cannot be easily eroded. At mid-slope positions, increased medium sand content results from airflow acceleration during upslope movement, where barrier effectiveness falls below the threshold velocity, causing increasing shear stress and instability that initiates erosion of smaller particles, leading to increased medium sand content from mid-slope to crest. As airflow becomes saturated during upslope transport, massive sand deposition at crests buries Salix barriers, greatly diminishing their effectiveness and causing erosion that reduces fine particle content.

4.2 Influence of Barrier Properties on Sediment Distribution

For square-grid barriers of identical planar dimensions, greater exposed height yields more significant wind protection, with markedly reduced wind velocities below the barrier top—an effect most pronounced near the surface. Above the barrier top, wind speed increases rapidly due to airflow uplift. Salix barriers, being permeable, allow partial airflow through pores where energy dissipation promotes deposition. HDPE barriers, as solid cylindrical structures, only block and uplift airflow, creating turbulence and vortices that cause minor erosion after crossing the barrier. Within the 0–10 cm height range, particles of 2.32Φ–2.74Φ (fine sand) are most susceptible to wind erosion. Barrier protection results in fine sand dominance within barriers, contrasting with medium sand dominance on bare dunes. Taller barriers contain more fine particles and fewer coarse particles, as barrier height correlates positively with wind protection effectiveness while porosity shows a negative correlation.

5 Conclusions

Based on grain size characteristic analysis of surface sediments within PLA, Salix, and HDPE low vertical sand barriers on windward slopes of the Kubuqi Desert, the following conclusions were drawn:

1) Soil particle size distribution in the study area was relatively concentrated, with medium and fine sand comprising approximately 77.83%–98.00% of content. Barriers significantly uplifted airflow, creating vortices downstream that caused wind erosion within barrier grids and increased coarse sand content by 16.14% (PLA) and 15.97% (HDPE) compared with controls.

2) Sorting within all barrier types was poorer than in bare dunes, with skewness developing toward positive or negative deviation and kurtosis becoming sharper and narrower. Fractal dimension increased to varying degrees, showing the pattern: crest > mid-slope > base. Following barrier installation, surface particle size distribution became more extensive and finer, particularly in areas with stronger aeolian activity at slope crests.

3) Comprehensive evaluation of particle composition, grain size characteristics, and fractal dimension across the three low vertical barrier types on windward slopes revealed that optimization of soil particle composition followed the sequence: HDPE > Salix > PLA barriers.

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Note: Figure translations are in progress. See original paper for figures.