The Study on the Stability of Sand-filled Road Subgrade in Gobi Desert

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Abstract. Road subgrade earthwork engineering requires a large amount of high-quality filling materials. The extensive exploitation of natural resources causes environmental damage. Based on a highway construction project in the Gobi Desert, this study utilized aeolian sand as the filling material for road embankments. Mechanical properties, compaction characteristics, and shear strength characteristics experiments were conducted to explore the stability of sand-filled embankments. The research revealed that the stability of sand-filled embankments depends not only on the composition of the proper structure, including the sand-filled core, surrounding zone, geotextile, and capping layer but also on factors such as the embankment height, slope ratio, roadside protection method, and quality control in the field. The findings of this study serve as a valuable reference for future similar highway construction projects.

Keywords: subgrade structure; fine sand; filling; stability; desert.

1 INTRODUCTION

In the Gobi Desert, high-quality filling materials are rare, often requiring the transportation of well-graded gravel or fine-grained soil from distant locations for road embankments. Subgrade earthwork engineering requires a large amount of high-quality filling materials. The extensive exploitation of natural resources causes environmental damage. Aeolian sand in the Gobi Desert region has unique characteristics such as fine particles, low viscosity, and poor water retention [1-2]. However, it is widely available, with abundant reserves and easy extraction, making it a convenient filling material for the subgrade in desert areas [3-4]. If aeolian sand is used as fill material for roadbed construction, it would be a reuse of abandonment, making it a green and low-carbon construction technique that is environmentally friendly. When used for road embankments, aeolian sand must have sufficient stability, strength, and water resistance, similar to conventional embankments [5-6]. Research on aeolian sand is frequently confined

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to indoor physical parameter experiments alone. There are substantial variations in particle size, mineral composition, and mechanical behavior of aeolian sand across different regions. When compared to conventional soil embankments, aeolian sand exhibits low cohesion, is susceptible to looseness, and has high permeability. In consequence, the compaction qualities as a subgrade material and the stability of embankments are not yet clear enough. There remains considerable research scope for the special structural design, roadside protection, and compaction construction techniques of sand embankments.

To verify the stability of sand-filled road embankments, this study analyzes the particle composition, compaction characteristics, and mechanical properties of aeolian sand on a desert road section in Aksai where a highway project is under construction. Proper embankment structures and roadside protection methods are proposed.

2 MATERIALS AND METHODS

Fine sand has unique characteristics, including large particle size, small surface area, weak particle-water interaction, limited voids, low compressibility, and high bearing capacity [7-9]. This study conducted laboratory and field experiments to validate the use of aeolian sand as a filling material for embankments earthworks. The experiments assessed the particle composition, CBR, compaction characteristics, and shear strength of aeolian sand on a desert road project in the Gobi Desert in Aksai, as Figure 1 shows.

Fig. 1. Schematic diagram of the location of the sand-filled embankment

2.1 Particle Composition

Representative samples of aeolian sand were chosen from the construction site for particle composition analysis. A set of sieves with different mesh sizes is arranged in decreasing order, with the finest sieve at the bottom. The sand sample is placed on the top sieve, and the stack of sieves is placed in a mechanical shaker for a specific duration. After shaking, the retained sand on each sieve is weighed, and the percentage of soil retained on each sieve is calculated.

The result reveals that the samples primarily consist of fine sand, with a minor portion of fine-grained particles (particle size less than 0.075mm). Coarse-grained particles larger than 2mm constitute less than 15% of the sample. Additionally, the proportion of particles ranging from 0.075mm to 2.0mm for samples A, B, and C was found to be 76.86%, 73.4%, and 74.0%, respectively. Consequently, the classification for these samples falls under the category of fine sand (SF), according to ASTM D2487 [10]. The gradation curves are shown in Figure 2.

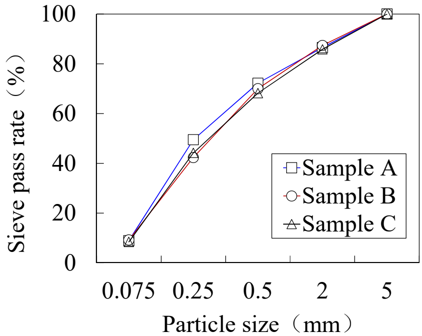


Fig. 2. Gradation curves for samples A, B, and C

2.2 California Bearing Ratio (CBR)

The CBR test provides a comparative strength index for samples and helps in evaluating their suitability for subgrade design. It is important to note that the CBR test is specific to the soil type, compaction energy, and moisture content. Therefore, it is essential to conduct the test under standardized conditions to ensure accurate and meaningful results. The CBR values of the samples selected were measured at different levels of compaction. CBR specimens are typically prepared using a mold that has a diameter of 150 mm and a height of 177 mm. The mold is filled with the prepared soil sample in several layers, each of which is compacted using a specified number of blows from a standardized compaction hammer. The compaction effort is determined based on the moisture content and soil type.

Table 1 indicates that as the compaction degree *K* varies, with a range of 90% to 96%, the average *CBR* values of the fine sand sample increased from 6.11% to 16.90%. These values demonstrate conformity to the "Highway Subgrade Design Specifications" (JTG D30-2015). Thus, the sand samples exhibit an excellent bearing capacity under compression.

Table 1. Values of CBR

K（%）	*CBR*(%)				Requirements
	Sample A	Sample B	Sample C	Average	
96	17.29	16.94	16.45	16.90	≥8
94	11.90	10.72	11.68	11.40	≥4
93	8.05	7.99	8.12	8.05	≥3
90	6.24	5.96	6.13	6.11	≥2

2.3 Compaction Characteristics

The compaction curve test for Aeolian is conducted to determine the relationship between the moisture content and dry unit weight of the soil at various compaction levels. This test helps in evaluating the optimal moisture content *OMC* and maximum dry unit weight ρ_{dmax} required for achieving the desired compaction in embankment earthwork. The compaction test is performed using a compaction mold and a compaction hammer. These parameters are crucial in ensuring the stability and performance of the sand-filled subgrade.

The compaction curve in Figure 3 displays the relationship between moisture content w_c and dry density ρ_d for samples A, B, and C. As the moisture content w_c rises from 3.2% to 8.4% for sample A, 3.5% to 8.3% for sample B, and 3.2% to 8.6% for sample C, the maximum dry unit weight ρ_{dmax} changes from 1.78 g/cm^3, 1.77 g/cm^3, to 1.75 g/cm^3, respectively. The optimal moisture content *OMC* and the corresponding maximum dry unit weight ρ_{dmax} for each sample tested can be observed on the curves. Essentially, *OMC* ranges from 6.0% to 6.2%, whilst ρ_{dmax} ranges from 1.72 g/cm^3 to 1.78 g/cm^3. The compaction curves indicate that the three samples exhibit comparable maximum dry density, with an average value of 1.76 g/cm^3. The average value of the optimal moisture content is 6.1%. It's worth noting that within the w_c range from 3.5% to 7.5%, the dry density values for all samples are greater than 1.70 g/cm^3. This outcome implies the insensitivity of fine sand to moisture content during compaction, facilitating a broad range of compaction moisture content throughout construction. As a result, fine sand is less influenced by external environmental conditions.

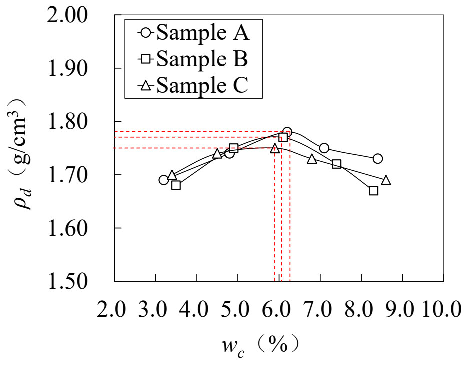


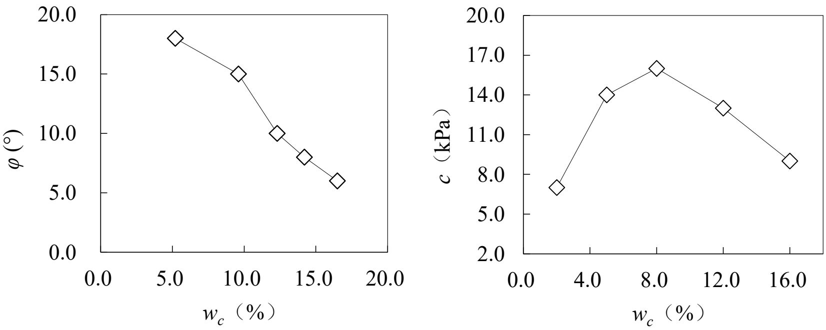
Fig. 3. Compaction curves

3 SHEAR STRENGTH

The shear strength of fine sand greatly impacts the stability of sand-filled embankments. The shear strength of fine sand exhibits variations due to its unique physical properties, primarily influenced by factors such as particle size, gradation, shape, moisture content, and compaction level. By evaluating the gradation curve and conducting compaction tests, variations in internal friction angle φ and cohesion c in response to changes in moisture content and density can be compared and analyzed. The shear test is conducted by applying a shearing force or displacement to the specimen. The force or displacement is gradually increased until the specimen experiences failure or exhibits significant deformation. The shear stress and shear strain are measured during the test.

3.1 The Influence of Moisture Content w_c

In Figure 4 (a), it can be observed that the internal friction angle φ of the fine sand decreases as the moisture content w_c increases, while under the same initial dry density conditions. This decrease can be attributed to the small abrasive resistance and good roundness of the particle sizes, resulting in an increased lubrication effect. In Figure 4 (b), the cohesion c of the fine sand initially increases and then decreases with increasing moisture content w_c, again under the same initial dry density conditions. The cohesion c reaches its maximum value of 16.0 kPa at approximately 8% moisture content. The particle composition test results reveal that the sand sample contains fewer clay particles and a small amount of fine particles filling the gaps between larger particles, leading to relatively low cohesive strength. As the moisture content increases, the cohesion shows a gradual increase within a certain range. However, once the moisture content exceeds a certain threshold, the water film between particles thickens, resulting in a decrease in cohesion.

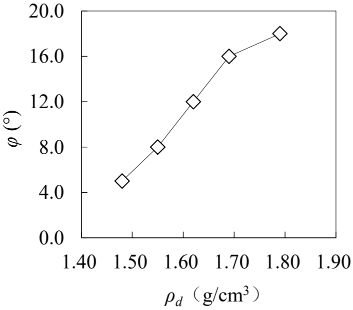


(a) Correlation between w_c and φ (b) Correlation between w_c and c

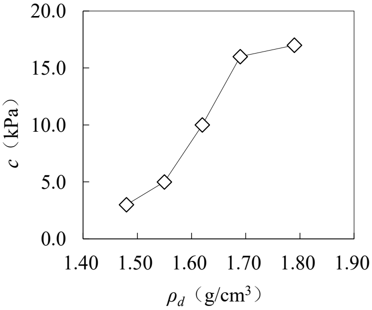
Fig. 4. The correlation between shear strength and moisture content

3.2 The Influence of Dry Density ρ_d

According to Figure 5, it can be observed that both the internal friction angle φ and the cohesion c of the fine sand show a clear increasing trend with an increase in the initial dry density, under the same moisture content conditions. This increase is particularly significant within the dry density range of 1.50-1.80 g/cm^3, and the change in cohesion becomes less pronounced after reaching a dry density of 1.75 g/cm^3. These findings indicate that the compaction level has a significant impact on the shear strength of the fine sand, and enhancing the compaction degree has a more noticeable effect on improving the structural strength of the fine sand filling.



(a) Correlation between ρ_d and φ



(b) Correlation between ρ_d and c

Fig. 5. The correlation between shear strength and dry density

4 STRUCTURE OF SAND-FILLED ROAD EMBANKMENT

By using a locally available material like aeolian sand, the need for importing construction materials can be minimized, reducing transportation emissions and enhancing the cost-effectiveness. Subgrade filled with aeolian sand can help reduce the demand for traditional road construction materials like aggregate, well-graded soil, or gravel which is often extracted from quarries with significant environmental impacts.

Figure 6 shows the details of the sand-filled embankment structure. Before constructing the embankment, the foundation was treated with the sand-gravel backfill method. The average height of the embankment is better typically controlled at less than 2.5m, with a slope ratio of 1:4 to facilitate sand transportation. The filling sand embankment structure consists primarily of the foundation, sand-filled core, surrounding zone, geotextile, and capping layer, with the pavement structure on top.

The sand core, located in the middle of the roadbed, is compacted fine sand that meets the necessary standards and serves as the main load-bearing structure for the pavement and vehicle loads. Specifically, the surrounding zone plays a crucial role in improving the stability of the embankment slope and the compaction quality during construction. Well-graded gravel is commonly used for this purpose, with a 3-meter-wide strip used as the surrounding zone for fine sand roadbeds. This facilitates compaction and improves erosion resistance. To prevent water pressure from washing fine sand particles out of the sand core, a geotextile is placed between the surrounding soil and the sand core. The capping layer, with a thickness of 50cm or more, is constructed using well-graded gravel or stabilized soil obtained from the borrow pit.

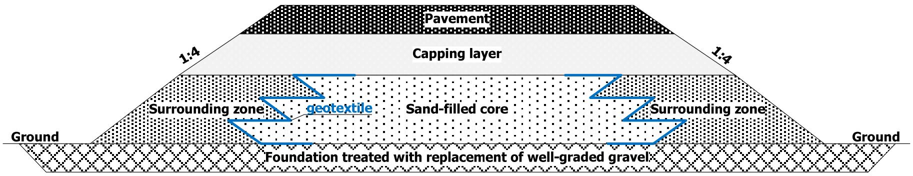


Fig. 6. Sand-filled embankment structure

5 ROADSIDE PROTECTION AND QUALITY CONTROL IN THE FIELD

To ensure the stability of a sand-filled subgrade using aeolian sand, several recommendations and methods can be implemented, including roadside protection and quality control during the process of construction in the field.

Figure 7 exhibits the schematic diagram of the roadside protection method. On both roadsides, the sand dunes are cleaned and leveled and a crushed gravel leveling strip is installed. The function of the plant protective area is to alter the wind flow pattern on the windward side of the embankment. By causing sand particles to settle on the lee side of the windbreak wall, the wind speed on the windward side of the road shoulder and its surroundings is effectively reduced. Any sand particles not deposited under the influence of the high-speed airflow will bypass the roadbed surface and settle beyond the sand-filled subgrade, effectively preventing wind erosion and sand buildup that could damage the embankment.

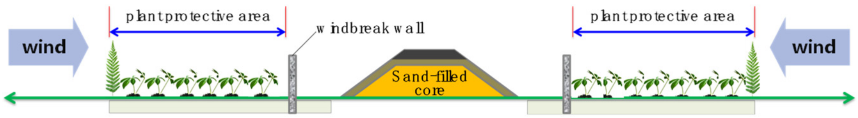


Fig. 7. Schematic diagram of roadside protection method

In addition, it is crucial to construct a sturdy surrounding zone with sufficient thickness to ensure the specified compaction density on the outer side slope when filling the sandy roadbed. This provides proper lateral confinement capacity, enhancing stability and preventing shallow instability or sand leakage. Excess moisture in the filling material can be dried off the road or on the roadbed, while insufficient moisture can be supplemented with water spraying to meet the required moisture content for proper compaction. The paved fine sand can be compacted at a dryer moisture content for each layer at the bottom of the sand-filled embankment, while at the optimal moisture content for the top layers of the roadbed. This approach effectively minimizes water consumption, addressing the challenges of water scarcity and extraction difficulties prevalent in the Gobi Desert region.

6 CONCLUSION

This study focuses on analyzing the stability of sand-filled embankments in the Gobi Desert highway. The following conclusions have been drawn:

- The fine sand used for embankments demonstrates high-quality material, with a CBR value ranging from 6.11% to 16.9%.
- Maintaining a moisture content of 3.5-7.5% for the fine sand ensures better compaction control and allows for a wider range during construction.

- A small amount of clay content in aeolian sand reduces cohesion, but within a certain moisture range, cohesion increases. Excessive moisture, however, decreases cohesion and slightly reduces the internal friction angle.
- The level of compaction significantly impacts the shear strength of the fine sand. Enhancing the degree of compaction exhibits a noticeable effect on improving the structural strength of the fine sand filling.
- The stability of sand-filled embankments depends not only on the composition of the basic structure, including the sand-filled core, surrounding zone, geotextile, and capping layer but also on factors such as the embankment height, slope ratio, roadside protection method, and quality control in the field. The combination of these multiple factors ensures overall stability.

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