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Improvement of the bearing capacity of confined and unconfined cement-stabilized aeolian sand

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HIGHLIGHTS

- The paper shows the characterization of dune sand from Jeddah and its improvement with cement.
- A new testing procedure to evaluate the bearing capacity under unconfined conditions is proposed.
- Two empirical indices are presented to evaluate the effects of the improvements.

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ABSTRACT

The improvement reached on the compaction and bearing capacity of aeolian sand collected in Jeddah (Saudi Arabia) after its stabilization with Portland cement is evaluated, comparing the behavior for both treated and untreated samples. With the aim of using this type of soil in the construction of embankments for road or railway applications, the results obtained have been evaluated in terms of maximum dry density, optimum moisture content (compaction test) and bearing capacity (CBR). Special attention has been paid to the influence of the confining conditions on the results, scarcely analyzed in the literature, by comparing the load-displacement curves during penetration stage in the CBR tests for both confined and unconfined specimens. Different contents of Portland cement have been explored (out of 6% of dry soil weight) to stabilize this material. The results obtained show a clear linear correlation between of compaction characteristics and CBR respect to the percentage of cement, obtaining, as expected, higher improvement for treated-material with higher content of cement, also strongly influenced by the confinement state. Thanks to this treatment, it is possible to employ this material in applications with low-confinement support, which is impossible without a previous proper stabilization. Finally, two practical indices have been defined to measure the degree of improvement reached, involving both cement content and confinement.

1. Introduction

From the construction application point of view, aeolian sands are very particular materials due to their poor grading because of their very uniform particle size distribution, fine mean size and rounded shape of their particles. In general, these soils are suitable for construction purposes, as they are granular materials with low fines content, and even without plasticity, and with a relative high permeability which makes them to perform properly in contact with water. However, several difficulties arising during the construction determines their utilization, mainly under compaction process, particularly for low-confinement geotechnical structures like in the lateral sides of embankments. Because of that, this material is usually substituted by alternative soils when available nearby the construction site. However, in so many areas in the world, especially in extensive arid locations, aeolian sands are the only available materials, and therefore it is absolutely necessary to improve their workability conditions and to overcome their drawbacks to make them suitable as well as to ensure the engineering requirements.

Along the 19th and 20th centuries, so many relevant researches were published focused on the origin and characterization of aeolian sand [1], particular cases studies [2,3] and paying special

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attention to the geological aspects [1], as well as to geomorphology and sedimentology properties [4–10]. Respect to the characterization of aeolian sands, recent studies mainly exploring their mineralogical composition and textural features can be found in the literature [11–13].

The first attempts to evaluate the suitability of this soil as construction material was published by Khan (1982) [14], based on the analysis of several samples from Libya, where relevant implications of its utilization in highways are discussed, whereas Al-Sanad and Bindra (1984) [15] analyzed different samples collected from dune sands in Saudi Arabia. After those preliminary investigations, the early systematic geotechnical characterizations of aeolian sands, supported by laboratory-tests, were published in [16–25], concluding with guidelines for its application for construction purposes. A comprehensive review of the most common geotechnical properties of aeolian sands in the world, extracted from a huge collection of bibliographic sources, can be found in Elipe and Lopez-Querol [26].

As brief, the most representative geotechnical characterization and properties of aeolian sand can be summarized as follows: uniform material, with particle sizes usually ranging from 0.08 mm to 0.40 mm. The particles are also very rounded (i.e. small spheres) with a main chemical composition of silica. The specific gravity, which is obviously related to the mineralogy of the particles, ranges from 2.4, in Egypt dunes, to 2.87, in India dunes. The differences between minimum and maximum dry densities are small, the later ranging from 1640 kg/m^3 to 1765 kg/m^3, while the optimum moisture content varies between 11 and 14.5%. The compaction curves exhibit a very flat shape without a clear maximum value, and therefore a maximum density cannot be clearly established. Unlike common soils, aeolian sands usually present a minimum dry density for low water contents, at around 2–4%. The cohesion is negligible for these soils, while the friction angle is very significant, varying between 39° and 42°. The permeability of this material is quite high, typical for sands with small fines content, ranging between 10^{-2} m/s and 10^{-4} m/s. In general, these soils are classified as SP or SP-SM according to USCS classification system, or as A-1, A-3 or A-2 according to AASHTO. Both classifications identify these soils as suitable for embankment construction purposes, and also The World Road Association (PIARC) prescribes their suitability for construction if they are conveniently treated [27].

A wide collection of different treatments and techniques of stabilization have been tried and reported in the literature over the last decades although, nowadays neither of them has been considered as a predominant procedure for the stabilization of aeolian sands. The options of improvement of the geotechnical behavior of these soils, avoiding substitution, vary from compaction to admixture with different additives, like cement, bitumen emulsions, chemical emulsions, reinforcement materials, wastes, ceramic tiles, etc. [26], and also with different combinations of two of them trying to enhance their individual benefits. Among them, Portland cement has been the most employed additive for the improvement of aeolian sand [28–32], although traditionally the use of cement in soil stabilization is well-established for many other types of soils.

Regarding the cement-stabilization for aeolian sand, the dosages reported by different researchers are significantly high, ranging from 8% until 20%, which in general is far from practical and economic considerations. Thanks to that, excellent results in terms of higher strength and bearing capacity have been obtained in the testing specimens. However, scarce attention has been devoted so far to the improvement and analysis of the material behavior under low confinement conditions, in spite of its well-recognized poor performance under such conditions, including the difficulty in its compaction during the construction of embankments. To fill this gap in the treatment of aeolian sand, particularly for cement stabilization, a novel variation of the California Bearing Ratio (CBR) has been employed in this research to take into account the confinement of the testing specimen. Moreover, a tool to evaluate the improvement reached by means of the treatment, under high or low confinement conditions, is provided.

Whereas Proctor and CBR tests are the reference laboratory experiments employed in road engineering in the practice, they are almost omitted in the literature related to stabilization of aeolian sands [26] and usually substituted by UCS (Unconfined Compressive Strength) which cannot be employed directly for bearing capacity analyses. Because of that, and thanks to the relative low dosage of cement adopted in this research, Proctor and CBR have been maintained as reference experiments.

In this paper, an experimental research has been developed to analyze the influence on compaction and bearing capacity response of aeolian sand stabilized with three different contents of Portland-cement, equal to 2%, 4% and 6% of dry weight of soil, as ground improvement technique, paying special attention to the influence of confinement condition. The sand employed in this research was collected in Jeddad (Saudi Arabia), 78 km far from La Meca, and very close to the new high speed train line from Medina to La Meca.

First, a detailed description of the Jeddah aeolian sand is presented, including a Laser-ray diffraction, a mineralogical analysis by means of X-ray diffraction (XRD) and a morphologic analysis with electronic microscope (SEM), apart from sieving analyses. After that, the samples preparation and testing procedures following along the experimental work are described. The effects of the treatment on the compaction properties and bearing capacity, which is the main objective of this research, have been investigated by means of variations of the conventional Modified Proctor tests and CBR test, respectively. Finally, the main results obtained from these tests are presented. The influence of the confinement degree on the tested specimen in terms of bearing capacities is explored and discussed, since as it has been exposed previously, it has been identified as the main drawback of this material in the construction of different types of geotechnical structures such as embankments. Two new indices to evaluate the effectiveness of the treatment on bearing capacity of aeolian sands are proposed as a very simple but efficient and practical procedure to evaluate the degree of improvement reached for this type of soil. At the end of the paper, the most relevant conclusions are highlighted.

2. Materials

The materials used in this research are aeolian sand from Jeddah (Arabia Saudi), cement (as additive) and water. The cement employed is a high initial strength Portland cement class I with strength of 42.5 MPa [33]. For the Jeddah aeolian sand, the necessary laboratory tests were conducted to determine its physical and engineering properties. A detailed characterization is included next.

2.1. Sieving analysis

The particle size distribution analysis by sieving [34] demonstrates that the vast majority of particles are ranging from 0.08 to 0.63 mm, Fig. 1, with a fines content equal to 1.38%. This sand does not exhibit plasticity but displays positive qualitative carbonate content. The characteristics of this sand are listed in Table 1. According to the USCS classification system [35], this sand is classified as SP (poorly graded sand) and according to AASHTO system [36] it is A3. For clarifying, Fig. 2 presents a picture of the different sizes of the aeolian sand.