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Improving the Mechanical Properties of Dune Sand for Construction Purposes by Using Nanosilica and Portland Cement as Additives

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Abstract - Dune sand is available in large quantities in different areas in the world. It can be easily collected from the site with minimal excavation and labor efforts and as a sequence this makes it a good candidate in construction. To be used as construction material for engineering work and to save the environment by reducing the number of quarries and fuel consumption needed to extract the traditional construction materials such as limestone aggregates, dune sand needs to be mixed with other additives in order to get the desired strength and capacity. In this work, an investigation program was conducted on dune sand collected from the eastern part of Saudi Arabia in order to explore the sand mix engineering behavior. The sand was mixed with 5% of Portland cement and different percentage of nanosilica (NS= 0%, 2%, 4%, and 6%) and tested at different curing time (7, 14, and 28 days). The major performed tests were the unconfined compressive strength (UCS) and California bearing ratio (CBR). The results showed that the UCS, CBR, and elastic modulus (E_s) of the treated sand are improved by adding the cement and nonosilica, with significant improvement when the mix tested after 28 days of curing. The effect of NS on the mechanical properties of the treated sand is more effective at high percentages (> 4%). Useful and practical relationships among UCS, CBR, and Es with high correlation coefficients, R^2, were developed at different percentages of NS and curing time.

***Keywords*:** dune sand; nanosilica; cement; stabilization; environment; construction

1. Introduction

Construction works for big projects such as roads need huge amount of competent earth materials to build their base and subbase course layers, as shown in Figure 1. Failing in selecting the proper material or construction process will lead to damage or failure to the facility, as shown in Figure 2. Quarries are considered the main sources used to extract the required amount of construction materials. The processes require huge amount of energy, different type of equipment, and manpower to do the work. Besides that, quarries and the subsequent related works and processes are considered non-green and harmful to the environment. To minimize the damage resulting from the use of quarries, the industry starts to use other sources as construction materials. Dune sand is a good candidate since it is available in huge quantities in many countries and it has good potential to be used as construction materials if its engineering properties are enhanced by additives because as a natural material, the sand has low shear strength and tend to collapse when loaded. The challenge with using stabilized materials for the construction work in the field is the mixing processes which might not lead to a homogenous mix that may lead to failures, as shown in Figure 3.

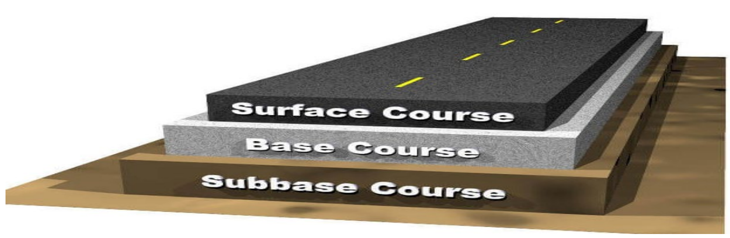

Fig.1: Base and subbase course layers of roads

Fig.2 : Earth material stabilization and construction process in the field.

(A) (B)

Fig. 3: Failure in: A) road foundation, B) building due to large settelemt and deformation

2. Material Used in the Testing Program

2.1. Dune Sand

The used sand was brought from a contracting company in Al-houfof city in Saudi Arabia. The material usually located in wide areas covering the eastern part of the country and can easily be collected in large quantities along Al-Houfof-Dhahran highway road. Figure 4a and b shows the location and a close photo of the used dune sand. Sieve analysis tests showed that the sand is classified as SP (poorly graded) according to USCS system [13] and A3 (non-plastic) according to AASHTO system [14]. As shown in Figure 5, the mean size of the sand, D50 is 0.45 mm with particle size distribution falling in a range between 0.1- 1.0 mm. Table 1 provides a summary of the properties and classification of the used sand.

(a)

(b)

Fig. 4: a) Areas covering dune sand in Saudi Arabia, b) Sample used in the testing program.

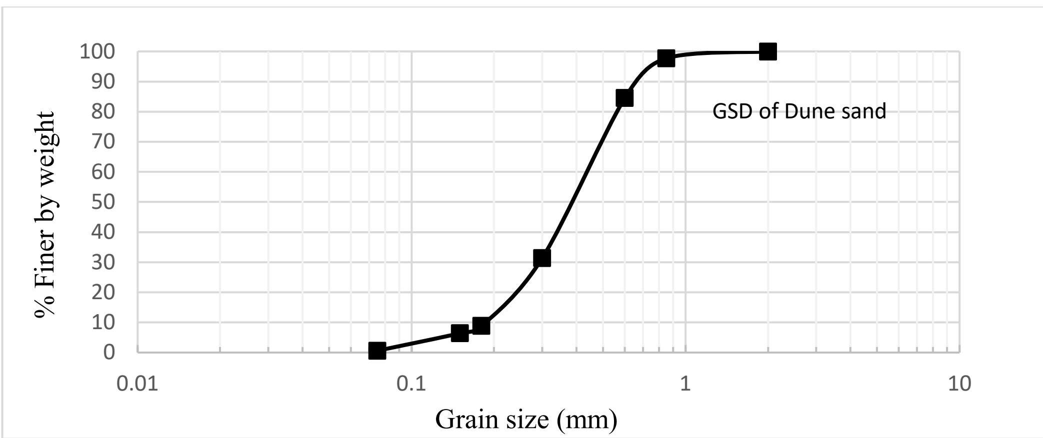

Fig. 5: Grain size distribution of the used dune sand

Table 1: Physical properties and classification of the used sand

Soil property	**Value/ Description**
G_s [15]	2.70
Color	Yellow to light brown
Coefficient of curvature, C_C Coefficient of uniformity, C_u	1.20 2.70
Particles shape	Rounded to sub-rounded
USCS	SP (poorly graded)
AASHTO	A3 material

2.2. Water and Cement

Water used in preparing the mixed samples was collected from the desalination unit at King Faisal University. Based on the information provided by the unit and according to ASTM C1602 [16] the water has less than 15,000 ppm of dissolved salts, less than 3000 of sulphates, less than 10,000 ppm of chlorides, and pH of 7.5.

For the cement, type V Portland cement was used for the testing program since this type of cement is widely used in the country for almost most of the construction works. According to [17], the cement has the following percentages of major oxides: CaO (63.7%) and SiO2 (21.2%) and with major chemical compounds: C_3S (59 %), C_2S (16%), and C_4AF (14.6 %). It also has average initial setting time of (155 min.) and fineness of (306 m^2/kg).

2.3. Nanosilica

Silicon dioxide (SiO_2) nanoparticles usually appear in the form of a white powder. The main applications of nanosilica particles are as additives for the manufacture of rubber and plastics and also as fillers to increase the strength of concrete and other construction materials. Table 2 shows the main physical and chemical properties of nanosilica particles [18]. Figure 6 shows a sample of nanosilica particles.

Table 2: Chemical and physical data of the used Nano silica.

Used Nanosilica	
Chemical symbol	SiO2
Group	Silicon 14, Oxygen 16
Electronic configuration	Silicon [Ne] $3s^2$ $3p^2$, Oxygen [He] $2s^2$ $2p^4$
Element content (%)	Silicon: 46.7, Oxygen: 53.3
Density	2.4 g/cm^3
Molar mass	59.96 g/mole
Melting point	1600°C
Boiling point	2230°C

Fig. 6: Nanosilica particles

3. Testing Plan and Methodology

A testing scheme was planned and implemented to fulfill the outcomes of this work. The scheme mainly concentrates on investigating the mechanical properties and behavior of dune sand stabilized with different percentages of NS (0.0, 2.0, 4.0, & 6.0%) and a fixed percentage of Portland cement of 5% by dry weight of the sand. NS and cement were mixed with sand and compacted at the optimum water content (OWC) and maximum dry unit weight (γ_{damx}) of the sand using standard Proctor ASTM D698-07-A [19]. Two major mechanical tests were considered in this work, namely: UCS and CBR, following ASTM D2166-85 [20] and ASTM D1883-07 [21] standards, respectively. After compaction, sand-mix samples were wrapped and sealed using thin plastic films and thereafter tested after 7, 14, and 28 days of curing time. Figure 7 shows the standard Proctor compaction curve of the dune sand with OWC and γ_{damx} of 7.8% and 17.0 kN/m^3, respectively.

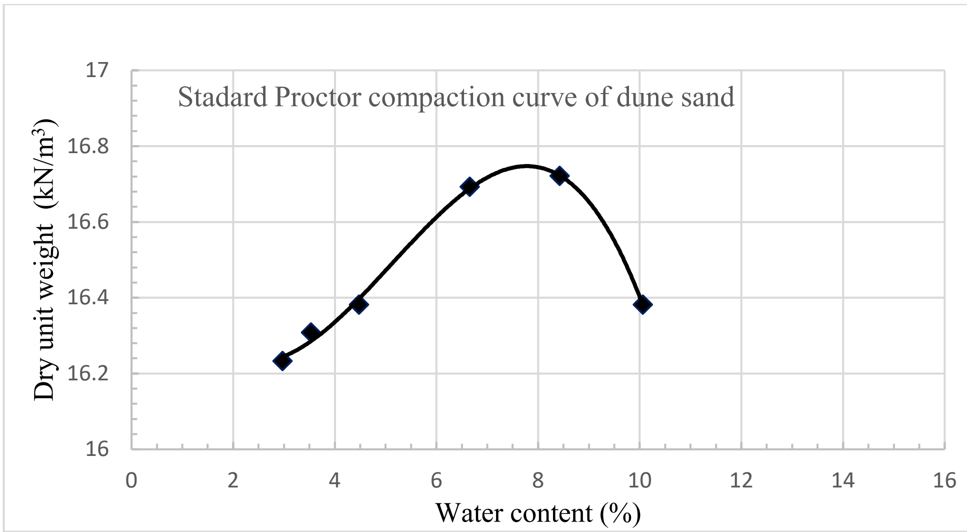

Fig. 7: Standard Proctor compaction curve of the used dune sand

4. Results and Discussion

4.1. UCS of the Treated Sand

Results of UCS of the treated dune sand tested at cement content of 5% and NS contents of 0%, 2%, 4%, and 6% for curing time of 7d, 14d, and 28d are shown in Figure 8. The samples were prepared at the maximum dry density and optimum moisture content of the compacted sand using standard Proctor by first mixing the dry sand with the cement and NS and then the specific amount of water is gradually added and mix thoroughly with the other components to get a homogenous mix. The samples were then compacted inside the compaction mold that has the dimensions of 11.6 cm in height and 10.2 cm in diameter. After extraction form the mold, each sample was rapped and tightly sealed by fine plastic film and stored at a room temperature of 22ºc for curing. The results in Figure 8 shows that the UCS increases with the increase in both NS content and curing time. For 7d curing time, the UCS increases from 0.8 MPa for 0% NS to 1.4 MPa for 6% NS (75% increase in UCS). As the samples get enough time to gain most of the strength, the UCS for 28d curing time increases from 2.4 MPa for 0% NS to 3.3 MPa for 6% NS (37.5% increase). The effect of NS content on the increase in UCS is mainly due to the formation of calcium silicate hydrate gel (CSH) that tend to coat the sand particles and develop strong bonds at the contact areas. As the % of NS increases within the mixture, more silica compound is involved in the development of CSH. Figure 8 is also showing that the effect of curing time on the UCS of the sand mix is very obvious. As can be seen, for 0% NS, the UCS for 7d curing time is 0.8 MPa while for 28d it is 2.4 MPa (200% increase).

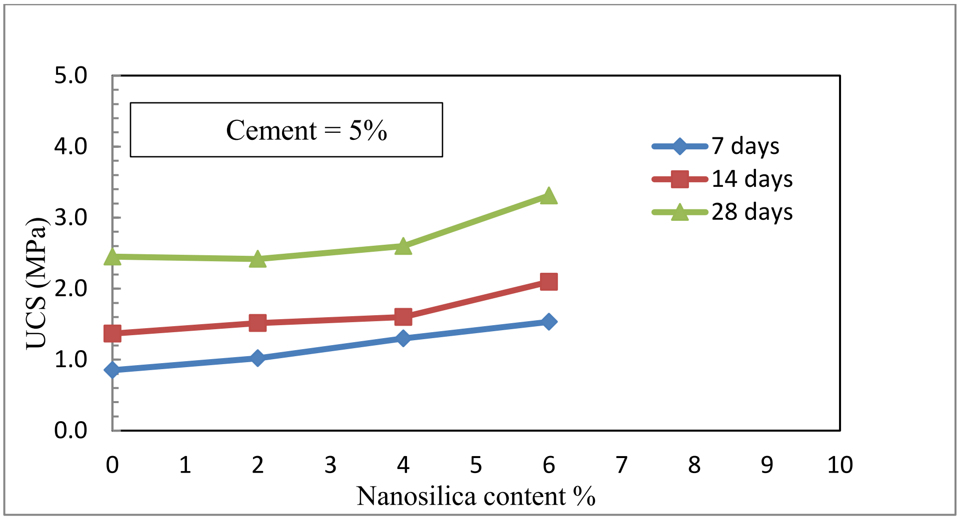

Fig. 8: UCS vs. NS content of the dune sand mix for different curing time.

4.2. E_s of the Treated Sand

Results of the E_s of the sand mix at different NS content and curing time are demonstrated in Figure 9. The data shows that E_s increases with the increase in NS content specially for higher curing time. The increase in E_s with NS content is almost negligible for the 7d curing time (37% increase in E_s when NS content increased from 0% to 6%). For 14d and 28d curing time, E_s is considerably increases with the increase in NS content. For example, for 14d curing time and for NS content of 0 %, E_s is 500 MPa. When 4% of NS is used, E_s increases to 560 MPa (12% increase), while for 6% NS content, E_s is 1250 MPa (150% increase). For the 28d curing time, and for NS content of 0%, Es is 900 MPa. When the NS content is increased by 4%, E_s increases to 1460 MPa (62% increase) whereas increasing NS by 6% NS, E_s increases to 2000 MPa (120% increase). The increase in E_s with the increase in NS content is mainly due to the formation CSH as the silica in the sand and NS compound interacts with the lime in the cement, leading to a powerful interaction among the sand particles [1].

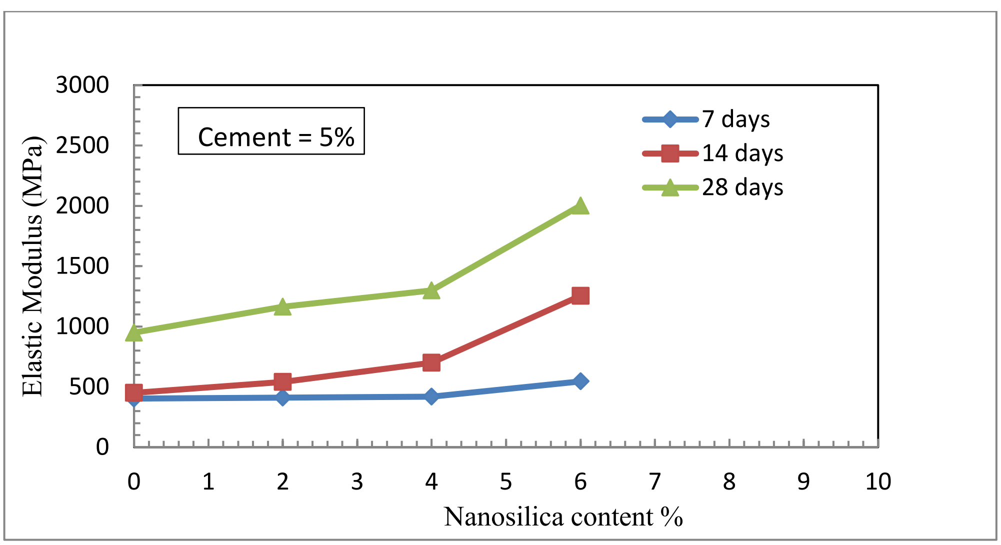

Fig. 9: E_S vs. NS content of the dune sand mix for different curing time.

4.3. CBR of the Treated Sand

The CBR tests were conducted on the sand mix at the same water content and maximum unit weight used for the UCS tests. The results in Figure 10 show that there is medium to high increase in CBR value with the increase in NS content. On the other hand, the effect of curing time on CBR value is noticeable. For 7d curing time, increasing the NS content from 0% content to 6% increases the CBR value from 200 to 375 (87.5% increase). For the same increase in NS content, the CBR value for 14d curing time increases from 250% to 550% (120% increase) and for the 28d curing time it increases from 500% to 650% (30% increase). The increase in the CBR value with the increase in NS content is again attributed to the formation of CSH as discussed previously in sections 4.2 and 4.3.

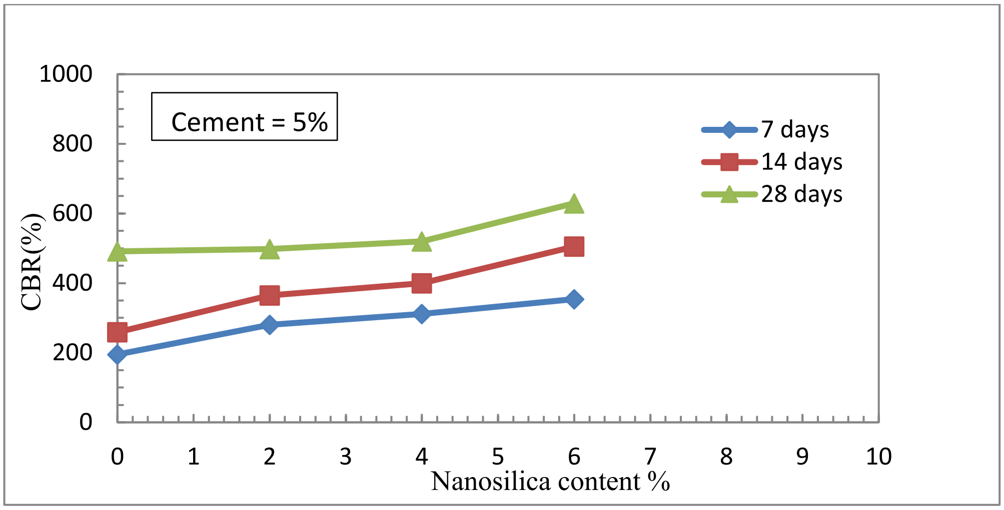

Fig. 10: E_S vs. CBR value vs. NS content of the dune sand mix for different curing time.

4.4. Useful and Practical Relationships

The results of UCS, E_s, and CBR obtained at 5% cement content and different NS contents for different curing time helped in achieving practical and useful relationships that can be utilized by professionals for design work mainly in construction of earth fill dams, foundation of roads and structures, and landfills. Figure 11 shows a strong linear relationship between UCS in MPa and CBR value in % expressed as "UCS = 0.005 CBR" with correlation factor, $R^2 = 0.94$. Figure 12 illustrates a powerful second degree relationship between E_s and UCS that is expressed as "$E_s = 105\ UCS^2 + 236.5\ UCS$" with correlation factor $R^2 = 0.94$. and Finally, Figure 13 also demonstrates a strong second degree relationship between E_s in MPa and CBR value in %. The relationship is expresses as "$UCS = 0.005\ CBR^2 + 0.02\ CBR$" with correlation factor of, R2 = 0.96.

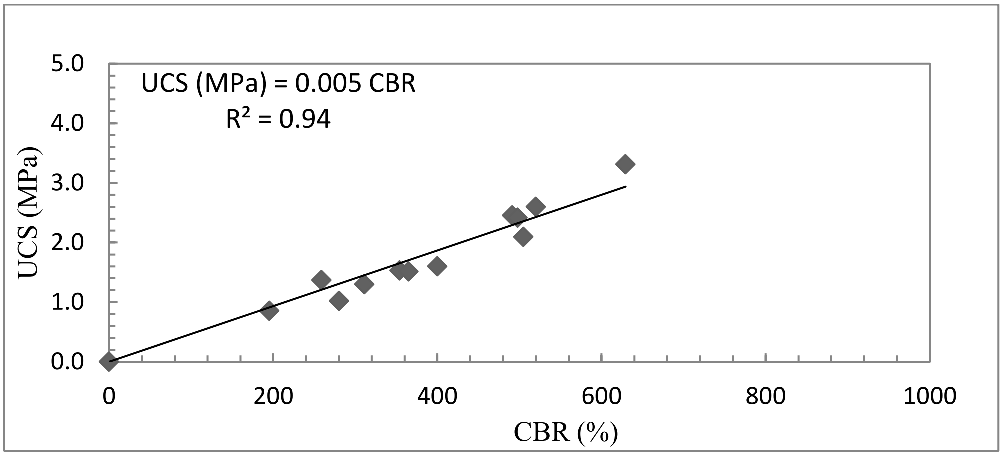

Fig. 11: UCS vs. CBR value of the stabilized dune sand

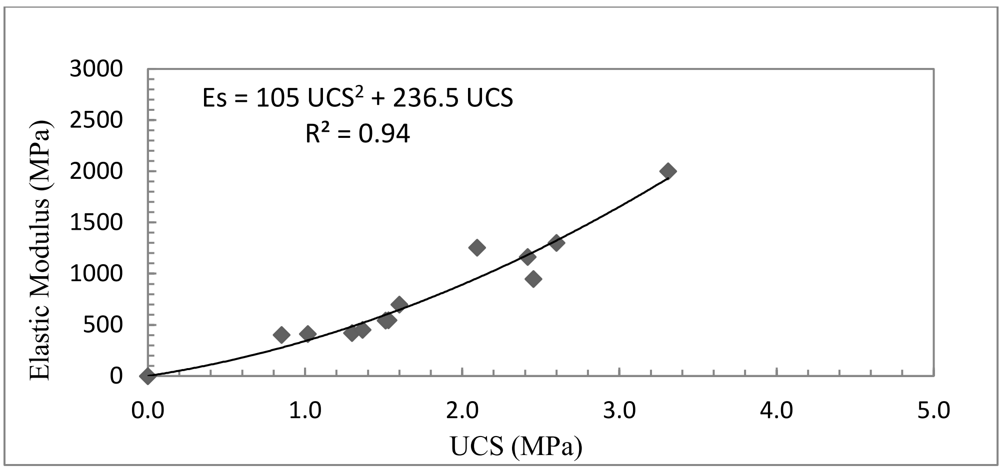

Fig. 12: Es vs.UCS of the stabilized dune sand

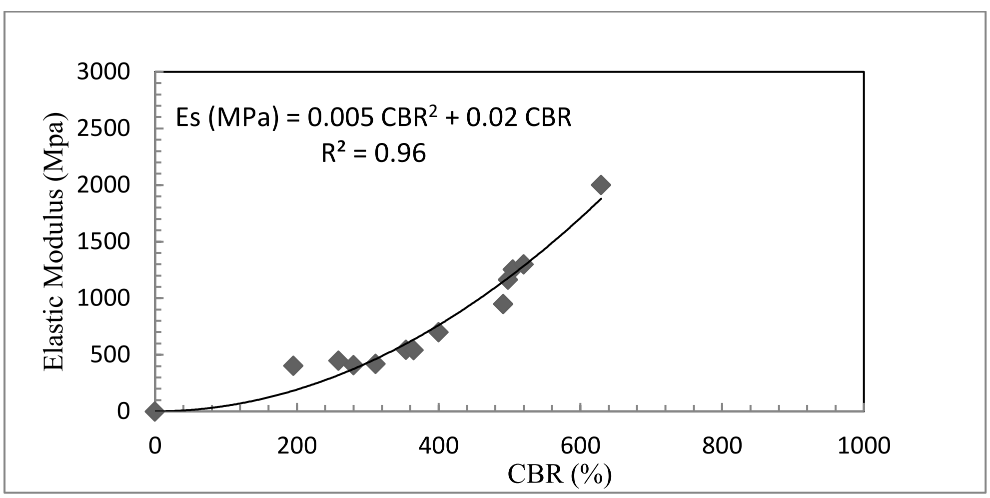

Fig. 13: Es vs. CBR value of the stabilized dune sand

5. Conclusion

An experimental program was executed to evaluate the mechanical properties of stabilized dune sand treated by using 5% of Portland cement mixed with different percentages of NS (0%, 2%, 4%, and 6%) tested at the optimum water content and maximum dry density of standard Proctor compaction and tested for UCS and CBR after 7d, 14d, and 28d of curing. Based on the results obtained, the following conclusions are drawn:

1) Cement and NS can be effectively used to stabilized the dune sand for construction projects and works. Considerable enhancement in UCS, E_s, and CBR values were achieved for the sand mix upon treatment. The level of improvements in the sand mix mechanical properties depends on both, the NS content and curing time. For examples, for 28d curing time, the UCS of the sand mix increases from 2.4 MPa for 0% NS to 3.3 MPa for 6% NS (37.5% increase). For the E_s, and for the same increase in NS content (from 0% to 6%) and for the same curing time, E_s of the sand mix increases from 900 MPa to 2000 MPa (120% increase). Considering the improvement in CBR value, for 28d curing time and NS increase from 0% to 6% increase, the CBR valued increases from 500% to 650% (30% increase). The improvement in the mechanical properties of the sand mix is mainly due to the formation of CSH as a results of the chemical interaction between the lime in the cement and the silica from both the sand grains and added NS that tend to coat the sand particles and develop strong bonds at the contact points of the grains.
2) Useful and practical relationships were developed among UCS, CBR, and E_s of the treated sand with high correlation factors, R^2 greater than 0.94. Hence, designers and professionals can rely on these observed relationships when cement and NS are used as stabilizers for the dune sand as a construction material.

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