

Article

Cement-Stabilized Waste Sand as Sustainable Construction Materials for Foundations and Highway Roads

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Abstract: In this study, cement-treated waste sand as a by-product material produced from Al-Ahsa quarries (Saudi Arabia) was experimentally tested and investigated as a base course material for the foundation of structures and roads. The study aimed to use the waste sand as a construction material by improving its strength, bearing capacity, and stiffness. The waste sand was mixed with different percentages of Portland cement content (0, 2, 4, 6, and 8%) at the maximum dry density and optimum water content of the standard Proctor compaction conditions of a non-treated sample. Unconfined compressive strength and California Bearing Ratio (CBR) tests for different curing times were conducted. X-ray diffraction (XRD), laser-scanning microscopy (LSM), and X-ray spectroscopy (XPS) were used to explore the microstructure and composition of the treated sand. The results showed that the compressive strength, initial tangent modulus, and CBR of the treated sand increase with the increase in cement content and curing time. Furthermore, good correlations were established among the strength, initial tangent modulus, and CBR. Based on the obtained results, cement-stabilized waste sand is a potential material for use in construction. This is expected to save the environment and reduce the cost of road construction.

Keywords: sustainable materials; cement-stabilized waste sand; foundation; roads; CBR; strength; initial tangent modulus; XRD; XPS; LSM

1. Introduction

The conservation of the Earth's natural resources has become an important and critical issue for the continued existence and prosperity of human environments. Huge amounts of natural resources have been utilized for the last two centuries due to rapid industrialization, enormous growth in our population, and the continuous trend of urbanization. The construction industry consumes huge amounts of these natural materials, exhausts natural resources, and causes associated ecological issues. For the last few decades there has been enormous pressure on the construction industry to incorporate sustainability. Searching for new materials, especially the utilization of waste materials from different industries, will help preserve the Earth's natural materials and sustain the natural environment. The use of waste sand in the construction industry has manifold advantages. It can help in the protection of our natural resources, decrease environmental and health hazard issues, reduce a burden on landfills, and contribute to the economy.

Aggregate materials, mined through quarrying processes, are the most extensively used materials for different applications in the construction industry. The estimated production of crushed aggregate in the USA was 1.48 billion tons in 2016 [1]. During the production of these aggregates, large quantities of fine waste or dust are produced. Most of this waste is generated during the extraction and crushing of main rock for the production of aggregates. This waste, mainly consisting of limestone, may cause severe environmental problems during the handling and disposal stages. Its use for different applications in the construction industry will contribute to a sustainable and safe environment and economy [2–6].

Saudi Arabia has huge reserves of sedimentary rocks, mainly limestone and dolomite rock in the central and eastern regions. Soft limestone and dolomite produce more waste during the cutting, crushing, and washing stages than granite and basaltic rocks. An enormous amount of aggregates were produced for concrete and road application from different quarries located in the Eastern region of the country. As most of the rock in this region consists mainly of soft limestone and dolomite, a huge amount of waste sand is produced during the cutting, crushing and washing stages for the production of aggregates [7–9]. Consequently, this waste causes severe environmental and health hazards during sandstorms in these areas. Therefore, there is a need for proper utilization of the waste for different applications in the construction industry to minimize the related environmental and landfill issues.

Many researchers have investigated its beneficial use as a cement replacement and a fine-aggregate replacement in concrete production [10–14]. However, the utilization of the quarry waste in concrete industry is very small compare to the overall waste production. Furthermore, there is a massive network of roads and highways spread all over the country that needs a huge amount of earth materials. Therefore, there is a need to investigate the effectiveness of using waste sand in road construction as an alternative to natural material, especially in the eastern part of the country where easily accessible quarries are widely spread. Cement is considered the most conventional additive, being used for purposes of soil stabilization [15–17].

Several studies were carried out to investigate the effect of cementitious additives (steel slag, Portland cement, lime, fly ash, gypsum, cement slag, aluminum filler, marble dust, and magnesium oxides) on the engineering properties of soils used for road construction and foundations [18–24]. Most of these studies showed a considerable increase in strength and stiffness and a decrease in the swelling potential and compressibility of the treated soils. In particular, sandy soils were investigated as base and sub-base materials for road construction by using different types of additives to improve the materials mechanical and engineering properties. Dune sand collected from Jeddah, Saudi Arabia, and treated with Portland cement showed a strong correlation between cement content and the CBR (California bearing ratio) for both confined and unconfined conditions [25]. Tests on graded aggregates for high-speed railway road foundation found that the binding effect of cement is more dominant than the filling effect, and the optimum cement content was estimated to be 5% [26]. Recent work on the effect of using nanosilica as a stabilizer showed that adding the optimum amount of nanosilica to cement-stabilized sand soil improved its mechanical and microstructural properties [27]. Other studies focused on many other aspects concerning stabilized soils used in road construction. These included mixture design, testing procedures, practice and control during construction, and adequacy of classification and specification of the material used for stabilization considering different methodologies of design supported by laboratory or field-testing programs [28–32].

No attention was given to the use of waste sand as a construction material, especially not to its use in road foundations. Therefore, in this work, cement was used as a stabilizing agent to improve the engineering properties of the waste sand as a base course material in road construction projects. Different percentages of Portland cement (2, 4, 6, and 8% of the dry weight of the waste sand) were selected. The sand used in this study was collected from one of the quarries in the Al-Ahsa area (East Province, Saudi Arabia). The main objectives of this study are to: (1) Protect the environment by using the waste from quarry materials in engineering projects, (2) investigate the effect of using cement as a stabilizer on the engineering properties of the waste sand, and (3) develop useful and practical

relationships between strength, initial tangent modulus, and the California bearing ratio (CBR) of the treated waste sand materials for practical use in the construction industry.

2. Materials Used and Methodology

2.1. Classification of Waste Sand

Two major quarry areas are producing limestone aggregates for construction purposes near the Al-Ahsa area. The first quarry is located east of Al-Ahsa City in the Abu Hadriyah area (Dammam road) and the second is located west of the city on Riyadh-Khuraish road. The waste sand used in this work was collocated from the second quarry. Figure 1 shows the location of the used waste sand and Figure 2 shows the stockpiled sand produced at this location. According to the Unified Classification System [33,34] the waste sand is classified as poorly graded sand, while according to the American Association of State Highway and Transportation Officials (AASHTO) system [35] the sand is classified as A3. Figure 3 shows the grain-size distribution of the waste sand and Table 1 summarizes its physical properties and classification.



Figure 1. Location of the waste sand used in this study as base course material, Riyadh Road, Saudi Arabia.

Table 1. Summary of the physical properties of the waste sand.

Soil Property	Value/Description
Specific Gravity [29]	2.66
Color	Yellow to red
D ₁₀ (mm)	0.15
D ₃₀ (mm)	0.26
D ₆₀ (mm)	0.45
C _C	1.0
C _u	3.0
Shape of Particles	Coarse portion: Angular in shape Fine portion: Homogenously rounded in shape
Classification, USCS system	Poorly graded sand (SP)
Classification, AASHTO system	Non-plastic fine sand (A3)



Figure 2. One of the stockpiles of waste sand produced in the Al-ahsa quarries, Riyadh Road, Saudi Arabia.

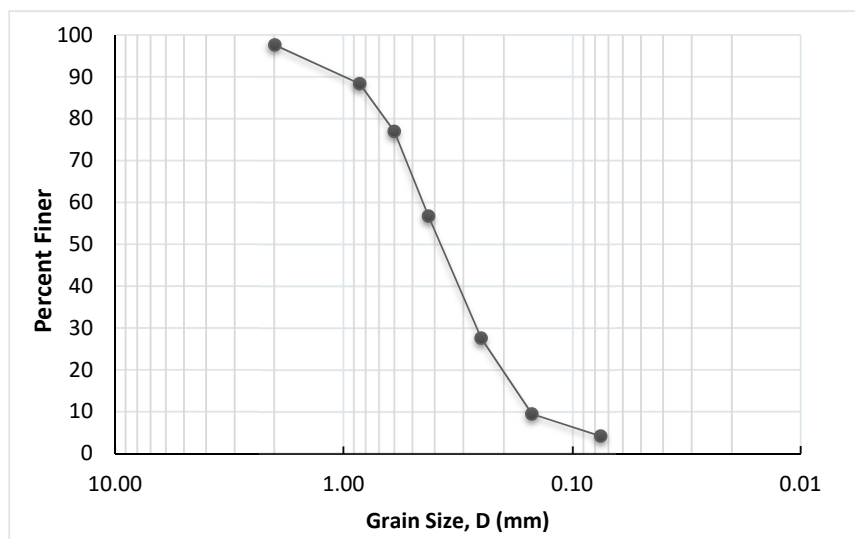


Figure 3. Grain-size distribution of the waste sand.

2.2. Mineralogical Analysis

Mineralogical analysis using x-ray diffraction (XRD) was carried out using a Rigaku Mini Flex II X-Ray Diffractometer at 10° to 80° . The step size maintained throughout the test was 0.01. The results showed that most of the waste sand particles consist of calcite mineral and small amount of quartz, as shown in Figure 4.

2.3. Morphologic Analysis

A morphologic analysis was performed using a laser-scanning microscope (LSM). Sand samples were separated into two portions (a fine portion with particle size smaller than 0.425 mm, and a coarse portion with particle size greater than 0.425 mm). Images of the coarser portion were first obtained in the tile-scan (combination image) mode using the $5\times$ objective lens. A tiles-scan image was collected on a large sampling area $\sim 12.5 \times 12.5 \text{ mm}^2$ with each tile showing $\sim 2.5 \text{ mm} \times 2.5 \text{ mm}$. A high-magnification laser microscopic Z-scan image was obtained for the fine portion of sand keeping the fixed X scale bar at 200 μm . A confocal hole of 70 μm was used for the 402 nm diode laser reflection.

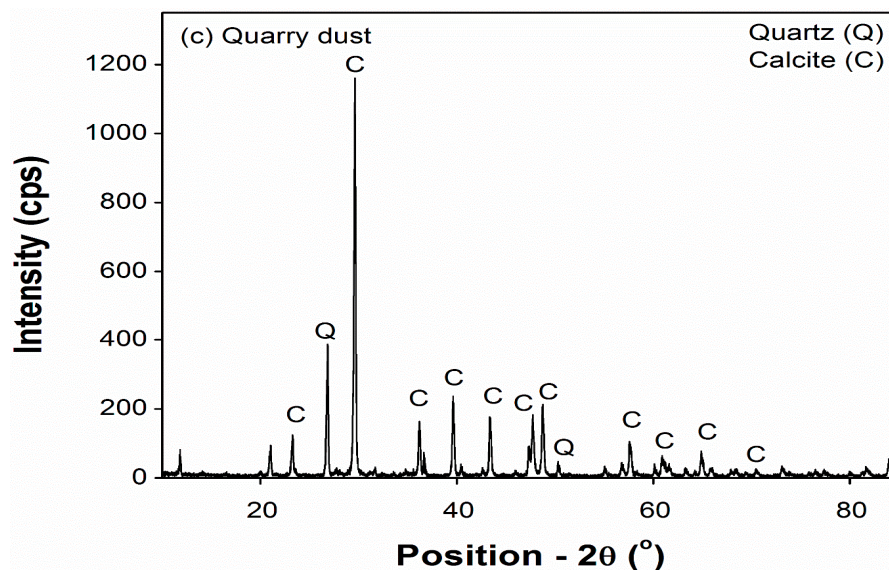


Figure 4. X-ray diffraction (XRD) analysis of the waste sand used in the study.

2.4. Elemental Composition Analysis

Elemental composition analysis was performed using x-ray photoelectron spectroscopy (XPS). The data was recorded in an Omicron (ESCA) spectrometer using a Mg K_{α} X-ray line (1254 eV photon energy) and all the spectra were calibrated by adventitious carbon peak position (284.8 eV). The survey spectrum of the XPS was recorded with 0.5 eV energy resolution while high-resolution XPS for the signature peaks of elements was recorded with 0.02 eV energy resolution.

2.5. Cement

High sulfate resistance (type V) Portland cement with low tricalcium aluminum (C_3A less than 5%) was used in this work. Type V cement is available in the market and it is suitable for use in roads and foundation construction, since those structures are expected to be exposed to high levels of sulfate ions. Tables 2–4 show the chemical, physical, and mechanical properties of the used cement produced in Saudi Arabia [36].

Table 2. Chemical composition of type V Portland cement (% by weight).

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	Loss on Ignition
21.16	4.00	4.79	63.67	1.37	1.95	0.13	0.20	2.54

Table 3. Average chemical compound composition of type V Portland cement (%).

C ₃ S	C ₂ S	C ₃ A	C ₄ AF
59.1	16.1	2.5	14.6

Table 4. Physical and mechanical properties of type V Portland cement.

Fineness (m ² /kg)	Time Setting (min) (Initial, Final)	Unconfined Compressive Strength (MPa) (3, 7, 28 days)
306	(155, 200)	(17, 24, 35)

2.6. Water

The water used in the test was tap water and, according to AASHTO T-26, it has less than 1000 ppm of chloride (Cl^{-2}) and less than 3000 ppm sulfates (SO_4^{+2}).

3. Experimental Program

The testing program was designed to achieve the objectives of this work. The program focused on the investigation of the behavior of the treated waste sand at different percentages (0, 2, 4, 6, and 8%) of Portland cement added to the waste at the maximum dry density and optimum water content of the non-treated sand, using the standard Proctor compaction ASTM D698-07 method A [37]. The major tests included in this work were: the unconfined compressive strength (q_u) test according to ASTM D2166 [38] and the California bearing ratio (CBR) test according to ASTM D1883-07 [39]. The two types of tests were performed for different curing times (7, 14, and 28 days). After molding, the treated sand samples were tightly wrapped and sealed in plastic sheets to maintain the optimum water content. Table 5 shows the tests performed at different percentages of Portland cement and different curing times. Figure 5 shows the standard Proctor compaction curve of the waste sand.

Table 5. Testing program of the treated waste sand as a base course material.

Test	Percentage of Cement	Curing Time (days)	Used Standard
Specific Gravity	0	-	ASTM D854 [40]
Grain-Size Analysis	0	-	ASTM D6913
Standard Proctor Compaction	0	-	ASTM D698-07
Material Classification (USCS)	0	-	ASTM D2487-17 and
Material Classification (AASHTO)	0	-	AASHTO M145-82
Unconfined Compressive Strength	0,2,4,6,8	7,14,28	ASTM D2166-85 (Method A)
California Bearing Ratio (CBR)	0,2,4,6,8	7,14,28	ASTM D1883-07 (Method C)

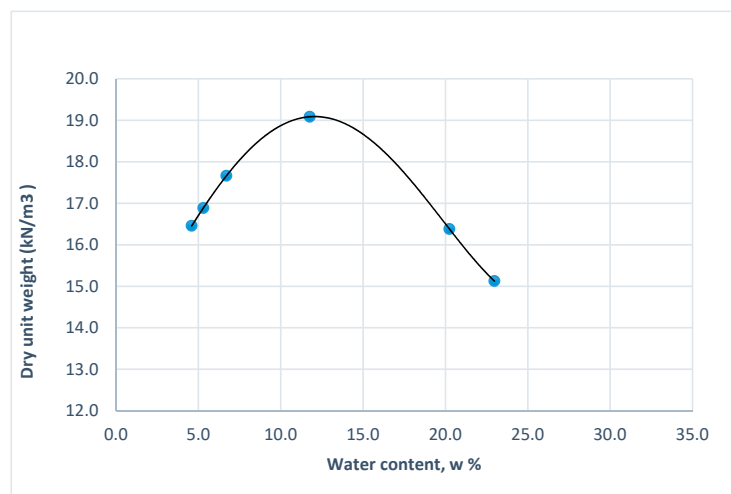


Figure 5. Standard proctor compaction curve of the untreated waste sand (0% cement).

4. Results and Discussion

4.1. Physical and Chemical Characteristics of the Waste Sand

Results of laser-scanning microscope (LSM) analysis showed that the coarse part of the sand (particle size greater than 0.425 mm) are non-homogenous and angular in shape with sharp edges. In contrast, the fine part (particle size less than 0.425 mm) is almost homogeneously rounded in shape, as shown in Figure 6. The composition details of the waste sand from x-ray photoelectron spectroscopy (XPS) are presented in Figure 7. Figure 7a demonstrates the presence of calcium, silicon, oxygen, and some atmospheric carbon in the waste sand samples. The photoelectron count per second (cps) for the three-high-resolution XPS peaks, Si2p, Ca2p and O1s, are shown in Figure 7b–d. XPS peak areas calculated for the Si2p and Ca2p peaks are 221 and 329 sq.-cps, respectively. Using the standard empirical atomic scattering peak factors, which are 0.27 (Si2p_{3/2}) and 1.58 (Ca2p_{3/2}), we found actual atomic percentages by multiplying them with the observed sq.-cps values [41]. The amount of lime

and silica in the sample were found to be 89.7% and 10.3%, respectively. Moreover, the native oxide, also known as crystalline oxide, was present in the waste sand sample. A clear deconvolution in the XPS O1s peak of the native oxide was observed at 530 eV energy as shown in Figure 7d. Similarly, the sub-micron sized nature of the waste sand particles was evident from the presence of the significant surface oxide O1s peak at 532.3 eV. Lee and Oh (2004) [42] reported similar higher-energy O1s peak positions in the surface oxides placed at 532.5 eV in the XPS spectrum. A high ratio of surface oxides compared to native oxides means higher surface reactivity (due to the smaller micro crystallize structure). This structure is expected to work effectively with the cement and develop a strong bond between the sand grains.

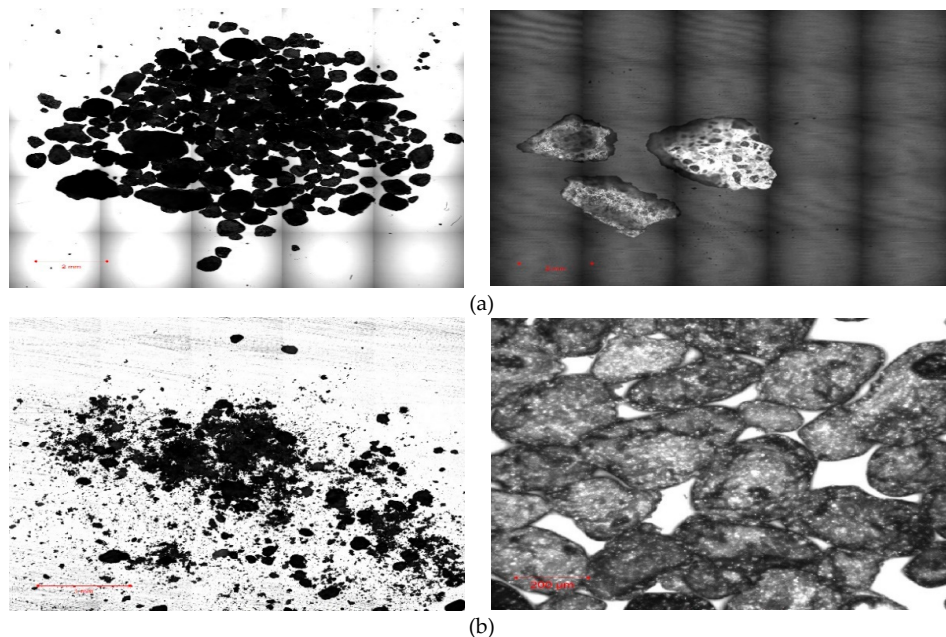


Figure 6. Laser scanning microscope images of the waste sand. (a) Coarse portion with particle size greater than 0.425 mm. (b) Fine portion with particle size smaller than 0.425 mm.

4.2. Unconfined Compressive Strength (q_u)

Unconfined compression tests were performed at the maximum dry density and optimum water content of the waste sand prepared at standard Proctor compaction (Method A). The sample dimensions were 102 mm in diameter and 116 mm. in height. Different percentages of cement were added to the sand (0, 2, 4, 6, and 8%). The samples were sealed with plastic sheets and subjected to curing times of 7, 14, and 28 days at room temperature (22–23 °C). A universal testing machine was used to perform the tests as shown in Figure 8a. The results of the tests showed that the unconfined compressive strength increased tremendously with the increase in cement content, as shown in Figure 9. In addition, the results showed that the strength of the treated sand increased with the increase in curing time, especially for the 28 days curing time. This behavior was expected since the cement particles coat and bind the sand grains, which in turn increase the resistant forces at the contact points of the sand grains. The obtained compressive strength results were supported by XPS spectrum analysis that showed a high ratio of surface oxide and surface reactivity of the waste sand particles, which in turn contributed to developing strong bonds at the contact areas of the sand grains. As the curing time increased, more hydration (cement reaction with water) took place, and consequently the strength increased. Figure 10 shows the percentage increase in q_u with cement content. In this figure, it can be seen that with adding just 2% cement, the increase in q_u of the treated waste sand was 500% of the non-treated sample, and with an 8% increase in cement, the q_u was 2500%.

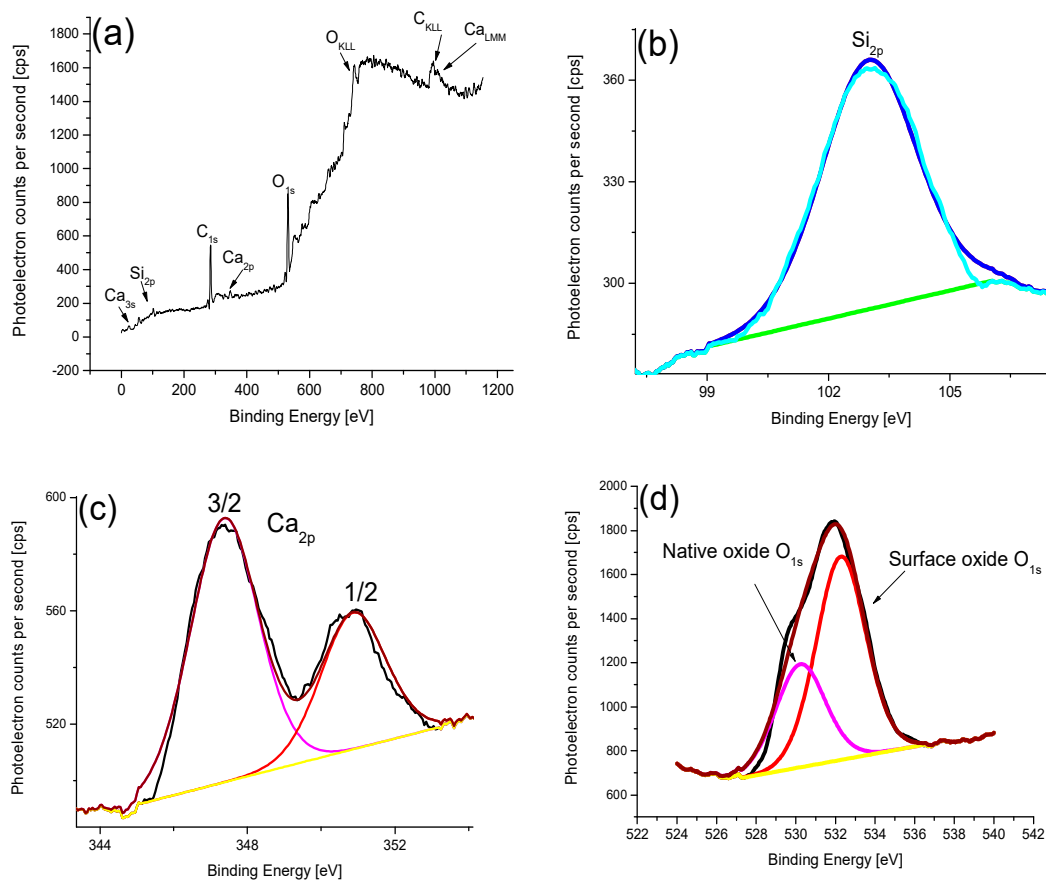


Figure 7. (a) X-ray photoelectron spectroscopy (XPS) survey spectrum of waste sand sample showing XPS peaks for silicon, calcium oxygen, and atmospheric carbon. High-resolution XPS spectra for Si_{2p}, Ca_{2p} and O_{1s} XPS peaks are shown in (b–d), respectively.

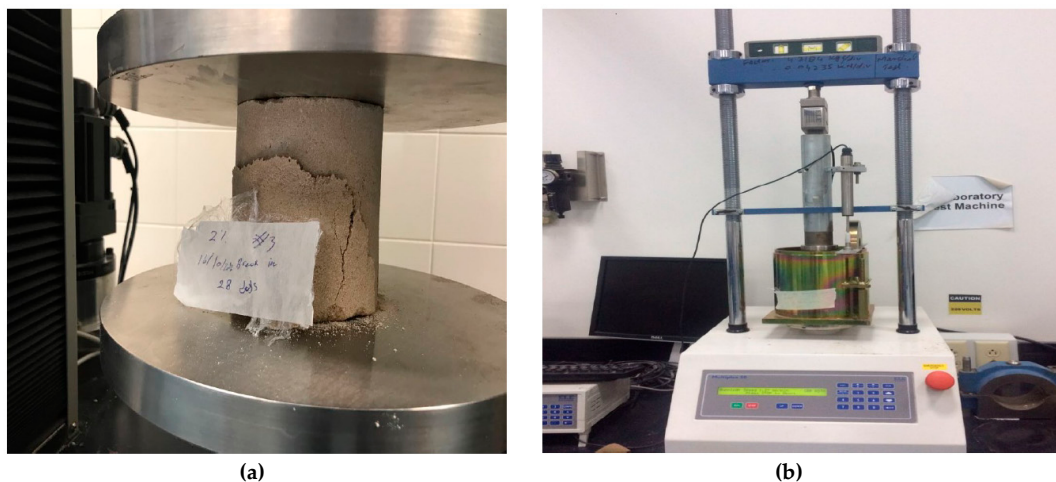


Figure 8. Unconfined compression test (a) and California bearing ratio (CBR) test (b).

4.3. Initial Tangent Modulus (E_i)

The initial tangent modulus of the treated waste sand was also evaluated at different percentages of cement and curing times. The results in Figure 11 show that the initial tangent modulus increased with the increase in both the percentage of cement and curing time. The increase in E_i with cement content and curing time, as discussed before, was due to: (i) The bonding effect of cement at the contact points of the sand grains, and (ii) the hydration process that is a function of the curing time. Figure 12

shows the percentage increase in E_i with cement content. In this figure, it can be seen that, by using a small percentage of cement (between 2 and 4%), the E_i increased by 200–700%. The substantial improvement in the initial tangent modulus of the treated sand is expected to reduce the deformation in the base course layer, which in turn will reduce the damage in the road surface. As seen in the same figure, with 8% added cement, which is a relatively high amount, the increase in E_i of the treated sand is 2000%.

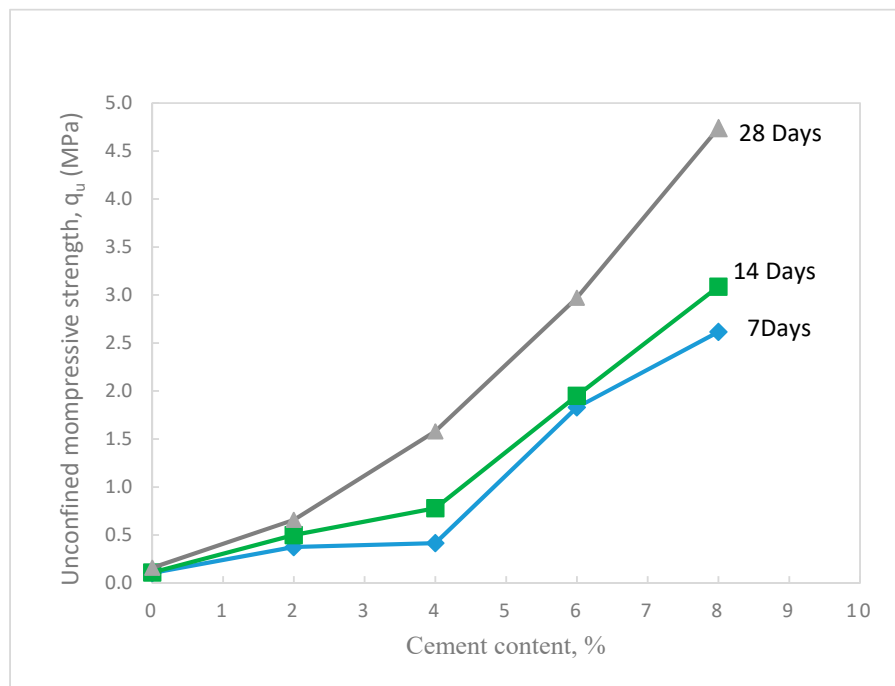


Figure 9. Variation of unconfined compressive strength of the treated waste sand with cement content for different curing times.

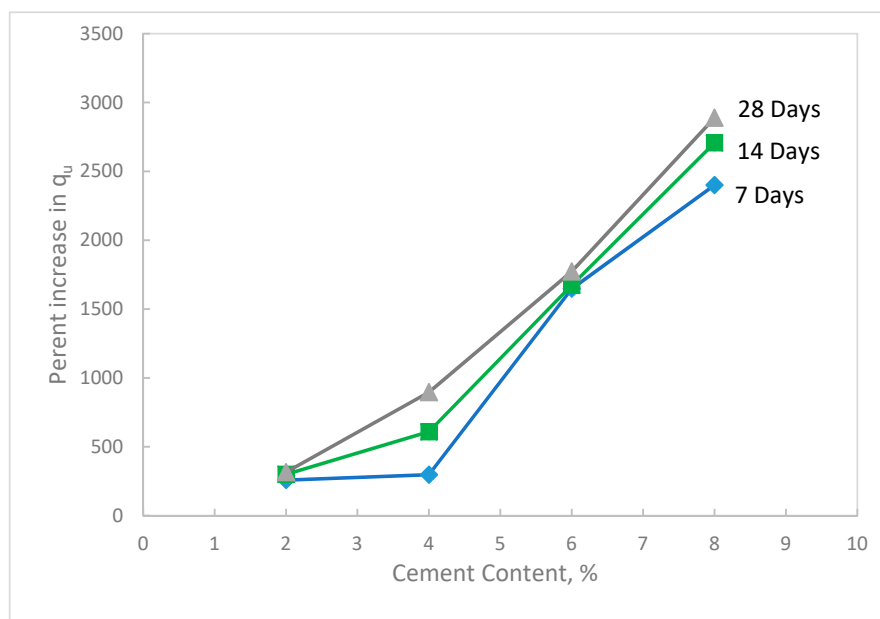


Figure 10. Percent increase in the unconfined compressive strength of the treated waste sand with cement content for different curing times.

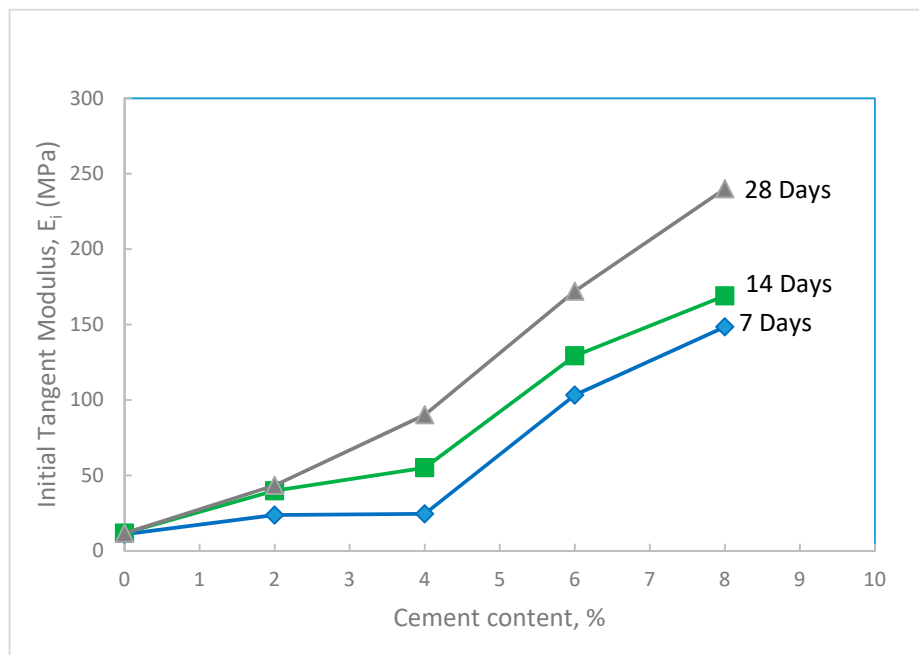


Figure 11. Variation of initial tangent modulus of the treated waste sand with cement content for different curing times.

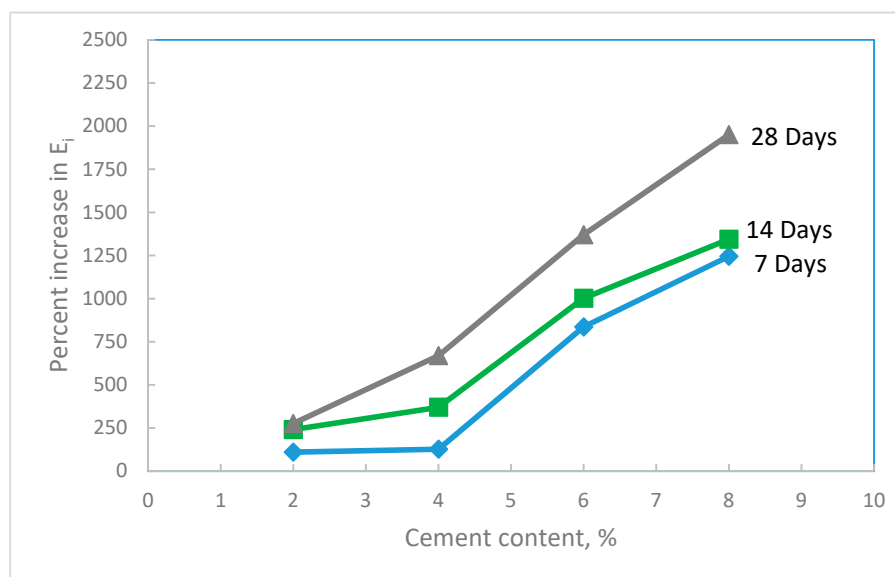


Figure 12. Percent increase in the initial tangent modulus of the treated waste sand with cement content for different curing times.

4.4. California Bearing Ratio (CBR)

Un-soaked CBR tests (Figure 8b) were performed on the treated waste sand at the maximum dry density and optimum water content of standard Proctor and at the same percentages of cement content and curing times used for the unconfined compression tests. The results in Figure 13 shows that the CBR value increased with the increase in the cement content and the curing time. Figure 14 shows the percentage increase in the CBR value with cement content. The results indicated that by just using a small amount of cement (1.0–2.0%), the CBR value increased by 4000–8000%. For cement content of 8%, the CBR value increased by 12,000%, which is extremely high.

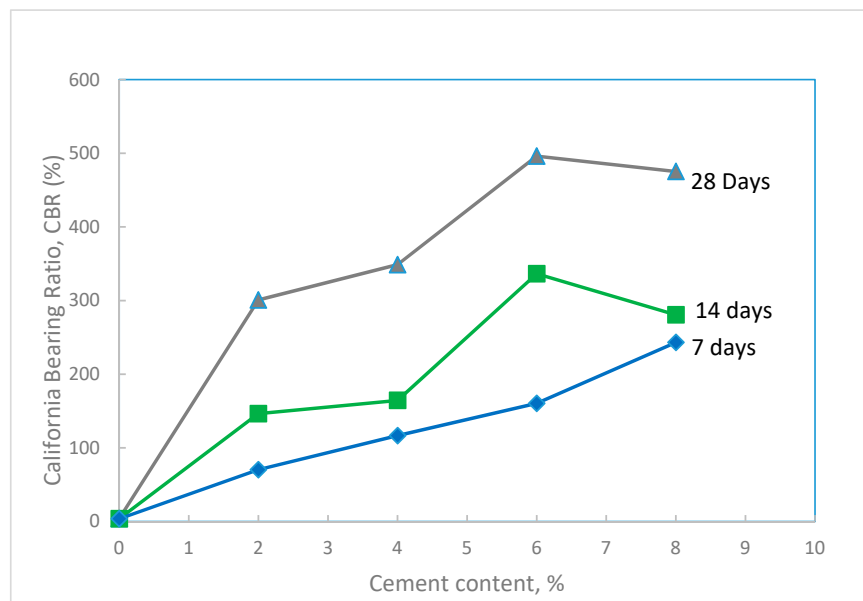


Figure 13. Variation of the CBR value of the treated waste sand with cement content for different curing times.

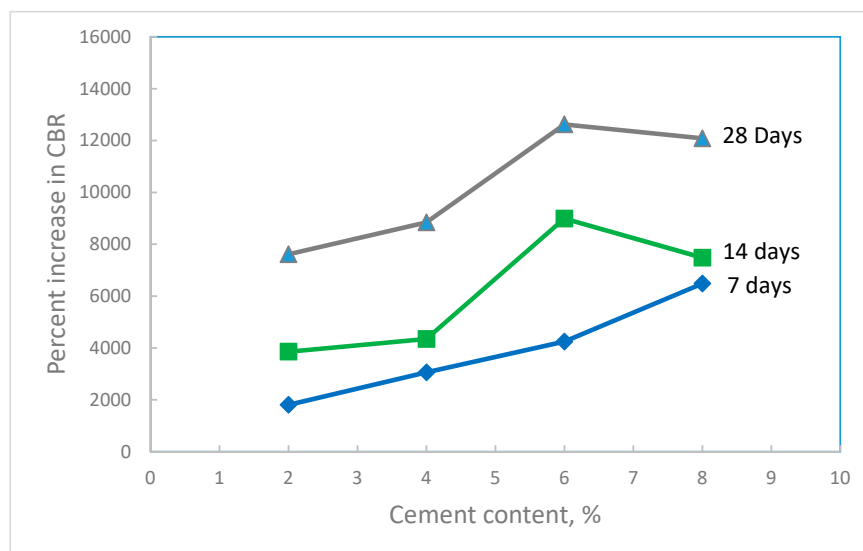


Figure 14. Percent increase in the CBR value of the treated waste sand with cement content for different curing times.

4.5. Relationships among q_u , E_i and CBR Value of the Treated Waste Sand

Based on the results obtained from the unconfined compression and CBR tests of the treated waste sand, useful and practical relationships can be drawn among the unconfined compressive strength (q_u), initial tangent modulus (E_i), and CBR values, as shown in Figures 15–17. Figure 15 shows that as the q_u increased, the E_i increased. Furthermore, the data shows a strong linear relationship between q_u and E_i . The relationship is simple and can be expressed as, $E_i = 55q_u$ with a correlation factor, $R^2 = 0.98$. Figure 16 shows the relationship between the E_i and CBR values in %. In this figure, it can be seen that as the CBR value increased, the E_i increased. The data can be also correlated with a simple linear regression as, $E_i = 0.4 \text{ CBR (\%)}$, with regression factor, $R^2 = 0.82$. Figure 17 shows the relation between the q_u and CBR values. In this figure, it can be seen that as the q_u increased, the CBR value increased. The data can also be presented in a simple relation such as $\text{CBR (\%)} = 120 q_u$, with a correlation factor, $R^2 = 0.80$.

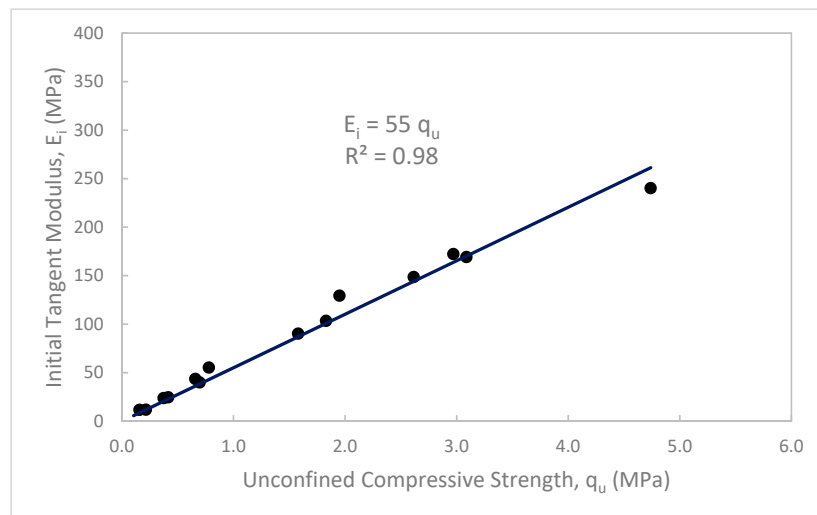


Figure 15. Initial tangent modulus (E_i) vs. unconfined compressive strength (q_u) of the treated waste sand.

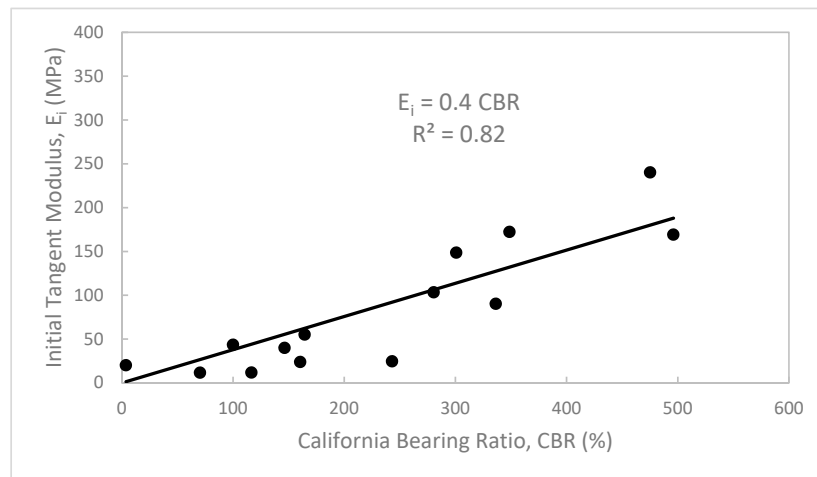


Figure 16. Initial tangent modulus (E_i) vs. California bearing ratio (CBR value) of the treated waste sand.

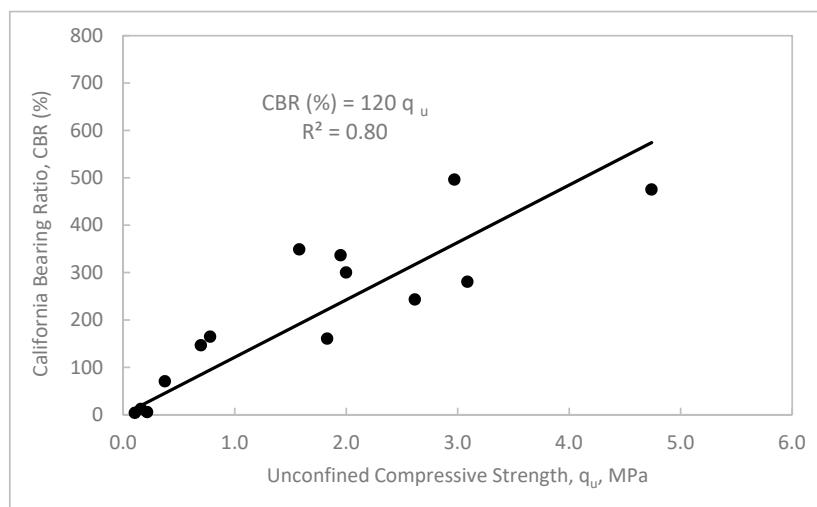


Figure 17. California bearing ratio (CBR value) vs. unconfined compressive strength (q_u) of the treated waste sand.

5. Conclusions

An experimental program was performed to investigate the effect of adding different percentages of Portland cement as a stabilizer in the engineering properties of waste sand used as base course materials for the foundations of roads and buildings. In general, and based on the results of the unconfined compressive strength and the California bearing ratio, cement-stabilized waste sand has a promising potential to be used as base a course material in engineering construction. The use of stabilized waste sand is expected to save the environment and reduce the cost of projects since the cost of waste sand is almost neglected. Specifically, the following conclusions were derived from this work:

1. X-ray photoelectron spectroscopy (XPS) analysis showed that the waste sand had a high ratio of surface oxides compared to native oxides. This means higher surface reactivity due to the smaller microcrystalline structure present in the samples, which is expected to lead to higher bonding between the sand grains when interacting with cement. These results were consistent, aligned with, and explained the results obtained from the compressive strength and CBR tests.

2. Laser-scanning microscope (LSM) analysis showed that the coarse grains of the waste sand were non-homogenous and angular in shape with sharp edges. This texture is expected to pack the grains in a well-interfering and interlocking structure, and consequently to lead to a significant increase in the strength and stiffness of the waste sand when treated with cement.

3. The unconfined compressive strength and bearing resistance of the treated waste sand was found to increase with the increase in cement content and curing time. Using a small amount of cement (about 2%), can significantly improve the engineering properties of the waste sand.

4. An initial tangent modulus of the treated sand, which describes the soil stiffness and deformation, was also found to be affected by the cement content. The results indicated that, as the cement content and curing time increased, the initial tangent modulus increased. By adding just 2% of cement to the waste sand, the modulus increased by 250%.

5. Useful and practical relationships were developed between the unconfined compressive strength, CBR value, and initial tangent modulus of the cement-treated waste sand. These relations are simple and can be used in the design of the foundations of roads and structures.

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