JCE
JOURNAL OF CIVIL ENGINEERING
ISSN 2086 - 1206 E-ISSN 2579 - 9029

Mechanical Behavior Of Cement Treated Sand With Ordinary Portland Cement (OPC)

Syirly A. W. Hariono[a], Bambang Piscesa[a], Wahyuniarsih Sutrisno[a], Laras L. Lestari[a]

Correspondence

[a]Civil Engineering Department, Sepuluh Nopember Institute of Technology, ITS Campus, Surabaya, East Java 60111, Indonesia.

Corresponding author email adress:

Submitted : 08 July 2025
Revised : 22 November 2025
Accepted : 26 November 2025

Abstract

Cement Treated Sand (CTS) plays a pivotal role in enhancing poorly graded sandy soils, which inherently lack cohesion and pose challenges for infrastructure development. This study investigates the influence of varying cement percentages (6%, 8%, 10%, and 12% by dry weight of sand) on the mechanical properties of CTS. Tests were conducted for Unconfined Compression Strength (UCS) and California Bearing Ratio (CBR) to evaluate compressive strength and soil bearing capacity, respectively. The findings demonstrate that increasing cement content improves compressive strength but may diminish ductility. Therefore, optimizing cement ratios is essential to strike a balance between strength enhancement and material durability. This research underscores the critical role of CTS in stabilizing poorly graded sandy soils, offering valuable insights for enhancing infrastructure resilience in coastal areas prone to these soil types.

Keywords

Cement treated sand, Poorly greaded sand, Sandy soil, Unconfined Compression Test, Ordinary Portland Cement, Mechanical behavior

INTRODUCTION

The soil exhibits complex mechanical behavior influenced by factors such as density, confining pressure, grain size distribution, among others. Highway projects often encounter challenges related to soil behavior, such as low soil strength and excessive settlement. Sandy soil exemplifies poor characteristics due to its lack of cohesion, also known as frictional soil, owing to the absence of bonds between its particles [1]. Therefore, special techniques are necessary to stabilize sandy soil, one of which is the Cement Treated Sand (CTS) method.

Cement Treated Sand (CTS) is a ground improvement method that extensively utilizes a cement mixture to enhance the mechanical properties of soil [2][3][4][5][6][7].Adding cement to sandy soil is more recommended compared to using other mixtures [2][3][8]. Various researchers have studied CTS and have reported satisfactory responses, as its engineering properties can significantly improve, including compressive strength, shear strength, elasticity modulus, and others [2][9][10][11].

It's crucial to carefully select the type of cement used for CTS, as it significantly affects the mechanical behavior of the treated sand. Ordinary Portland Cement (OPC) is one of the types commonly used by researchers for CTS mixtures [2][10][12][13][14]. Despite the advantages of adding cement to CTS, it's important to note that excessivecement can lead to brittleness and alter the cement can lead to brittleness and alter the mechanical characteristics of the treated sand [3][11][15][16][17].

In this study, poorly graded sand (SP) from sea sand, classified according to ASTM D-2487 [18], was used. Stabilization with CTS was necessary because poorly graded sand requires treatment, with cement stabilization being one suitable method. This study formed the basis for the journal article, where four different cement percentages were tested: 6%, 8%, 10%, and 12%. Unconfined Compression Test and California Bearing Ratio Test were conducted to investigate the mechanical properties of CTS.

RESEARCH SIGNIFICANCE

Generally, sea sand is not commonly used as a subgrade for infrastructure due to its lack of cohesion, which increases the risk of liquefaction. However, Indonesia, being a maritime nation with extensive coastal areas, cannot avoid the construction of highways and other infrastructure projects. Given this background, there is a critical need for further research on soil reinforcement, particularly using cement mixtures. Research in this area is still limited, thus necessitating additional investigation as discussed in this study. Studies on adding cement mixtures with various percentages to non-cohesive sandy soil have shown significant results in improving such soil types.

EXPERIMENTAL INVESTIGATION

A. MATERIALS

The materials employed in this study comprise sea sand and OPC cement. The sandy soil was sourced from Dalegan Beach, Gresik City, following successful screening through sieve analysis number 4. Ordinary Portland Cement (OPC) was utilized for the cement component. Both the sand and cement underwent meticulous laboratory testing to ascertain their physical properties and constituents.

1. PHYSICAL PROPERTIES OF SAND

In this section, testing was conducted on the properties of sand, encompassing parameters such as specific gravity, soil classification, granulometry, and other variables. Through a series of relevant laboratory tests, sandy soil underwent analysis to ascertain its physical properties and classification in accordance with prevailing standard. The test results revealed the moisture content is 7.143%, the specific gravity is 1.456 g/cm³, and the relative density is 12.195%. The minimum and maximum density index values are 1.34 g/cm³ and 1.51 g/cm³, respectively. The specific gravity of the sand is 2.65, and the internal friction angle is 23.17°. The sand is classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS) and as A-3 according to the AASHTO classification. The composition of the sand is 98.4% sand, with 1.56% silt, and no clay or gravel fractions were detected. The Optimum Moisture Content (OMC) was recorded as 7.15%, with a Maximum Dry Density (MDD) of 1.352 g/cm³, and the California Bearing Ratio (CBR) was found to be 7.607%. These findings indicate that the beach sand possesses predominantly sandy physical characteristics, with good shear strength and suitable support capacity for engineering applications such as road construction. The results of this study can be compared with other research [19] regarding similar physical properties of beach sand, and further details can be viewed in Table 1.

Table 1. Soil Properties of Gresik Sand

Soil Properties	**Result**	**Test**
Physical Properties		
Water Content, w (%)	7.143	ASTM D 1556
Unit Weight, γ (gr/cm3)	1.456	ASTM D 1556
Min Index Density, γmin (gr/cm3)	1.34	ASTM D4254
Max Index Density, γmax (gr/cm3)	1.51	ASTM D4254
Relative Density, Dr (%)	12.195	ASTM D 1556
Spesific Gravity, Gs	2.65	ASTM D 854-58
Shear Strength Parameter		
Internal Angle Frinction	23.17	ASTM D 3080
Classification		
Unified Classification (UHCS)	SP	ASTM D 2487
AASHTO Classification	A-3	ASTM D 3283
Granulometry		
Clay (%)	0	ASTM D 422-90
Silt (%)	1.56	ASTM D 422-90
Sand (%)	98.4	ASTM D 422-90
Gravel (%)	0	ASTM D 422-90
Compaction Characteristic		
OMC, wopt (%)	7.15	ASTM D 698-12
MDD, γdmax	1.352	ASTM D 698-12
CBR (%)	7.607	ASTM D 1883

2. CEMENT CONTENT

In this study, Ordinary Portland Cement (OPC) Type I, widely recognized for its extensive use in various construction projects, was selected. To thoroughly analyze and understand the complex chemical composition of the cement, comprehensive XRF testing was conducted. The results of this analysis have been meticulously documented and are presented in Table 2.

The chemical composition of OPC Type I is outlined in detail, highlighting key components essential to its properties and performance. The high CaO (lime) content of 80.87% suggests a strong potential for forming calcium silicate hydrate (CSH), the primary component responsible for the cement's mechanical strength [20]. The SiO_2 content, at 7.8%, plays a crucial role in the formation of calcium silicate phases, which are vital for the cement's strength and durability [21]. Additionally, Al_2O_3 (aluminum oxide) at 1.6% is noted for accelerating the setting reaction, thereby contributing to the early strength of the cement [20], while Fe_2O_3 (iron oxide) at 5.86% plays a role in forming calcium ferrite, which influences both the strength and color of the cement [21]. The low or undetected MgO content suggests a reduced potential for unwanted expansion, which could lead to CTS cracking

[22]. The SO3 content of 2% ensures that adequate gypsum is present to control the cement's setting time. The low alkali content (K2O at 0.53% and Na2O undetected) minimizes the risk of alkali-silica reactions (ASR), which can cause cracking in CTS. Trace elements such as TiO2, V2O5, and others, although present in minimal amounts, generally do not significantly impact the main properties of the cement, though they may affect the color and some minor chemical characteristics [20], [21].

Table 2. The content of Ordinary Portland Cement (OPC) Type 1

Coumpound	Conc	Unit
MgO	0	%
Al_2O_3	1.6	%
SiO_2	7.8	%
P_2O_5	0.3	%
SO3	2	%
K2O	0.53	%
CaO	80.87	%
TiO2	0.35	%
V2O5	0.03	%
MnO	0.19	%
Fe2O3	5.86	%
CuO	0.063	%
ZnO	0.02	%
SrO	0.074	%
ZrO2	0.02	%
BaO	0.1	%
HgO	0.02	%
PbO	0.13	%
Na2O	No Intensity	

B. UNCONFINED COMPRESSION TEST

In this study, four cylindrical samples of 10x20 cm, as shown in Figure 1, were utilized with cement percentages of 6%, 8%, 10%, and 12% of the total dry sand weight. These percentages are based on the guidelines provided by the American Concrete Institute (ACI) No. 230, 2009 [23], which specifies that for SP-type soil, cement content can range from 7% to 11% of the total dry sand weight, as outlined in Table 3.

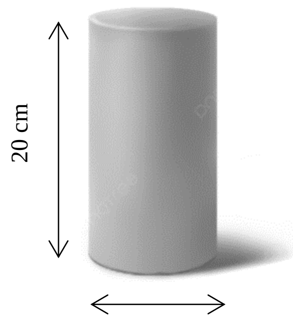

Figure 1 Sample of CTS for UCS Test

Table 3. Typical cement requirements for various soil types (American Concrete Institute, 2009) [23]

AASHTO soil classification	ASTM soil classification	Typical range of cement requirement*, percent by weight	Typical cement content for moisture-density test (ASTM D558), percent by weight	Typical cement contents for durability test (ASTM D559 and 560), percent by weight
A-1-a	GW, GP, GM, SW, SP, SM	3 to 5	5	3-5-7
A-1-b	GW, GP, GM, SW, SP, SM	5 to 8	6	4-6-8
A-2	GM, GC, SM, SC	5 to 9	7	5-7-9
A-3	SP	7 to 11	9	7-9-11
A-4	CL, ML	7 to 12	10	8-10-12
A-5	ML, MH, CH	8 to 13	10	8-10-12
A-6	CL, CH	9 to 15	12	10-12-14
A-7	MH, CH	10 to 16	13	11-13-15

*Does not include organic or poorly reacting soils. Also, additional cement may be required for severe exposure conditions such as slope protection

In the mixing de sign process, the water content for the natural sand used was determined from the results of the Standard Proctor Test, with an Optimum Moisture Content (OMC, wopt) of 7.150%, as shown in Figure 2. In addition to its role in the sand, water is also crucial for the activation and hydration of the cement, requiring an appropriate water-cement ratio for cement-treated sand. According to [24] the optimum w/c ratio for cement-treated sand is 0.33. The initial mix design is presented Table 4.

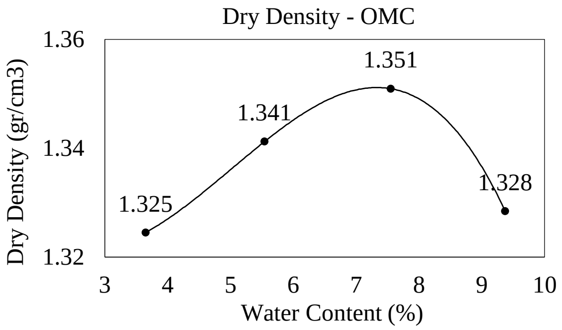

Figure 2 OMC of natural sand.

Table 4. Materials proportions of Cement Treated Sand

Code	W/C	OMC Sand	Materials by weight (%)			
			Cement	Sand	Water	
					OMC	W/C
SO_6	0.33	7.15%	86.86	5.21	6.21	1.72
SO_8	0.33	7.15%	84.90	6.79	6.07	2.24
SO_10	0.33	7.15%	83.02	8.30	5.94	2.74
SO_12	0.33	7.15%	81.23	9.75	5.81	3.22

* OMC Sand from total weight of sand
*For example, the test specimen SO_6 signifies S for Sand, O for Ordinary Portland Cement (OPC), and 6 indicating the percentage of cement used.

Figure 3 UTM TORSEE 200 tF Mechine

Based on Table 4, which outlines the material proportions for CTS, cylindrical test samples measuring 100 x 200 mm were prepared using steel molds. The materials were first prepared according to the proportions specified in the mix design plan. The sand and cement were mixed until homogeneous, after which water was gradually added and thoroughly mixed until fully combined. The mixture was then placed into the cylindrical mold in five layers, with each layer being compacted 25 times. After compaction, the surface of each sample was carefully leveled. Upon completion of the compaction process, the samples were left undisturbed for 24 hours, remaining within the mold and wrapped in plastic to ensure airtight conditions. The samples were then removed from the mold, wrapped in plastic wrap, and stored at room temperature for 7 days to undergo curing.

Following the curing process, compressive strength testing of the CTS was performed using a compressive testing machine located in the Civil Engineering Concrete Laboratory at ITS. The UTM TORSEE 200 TF was employed as the testing device, as shown in Figure 3. The compressive strength test for the CTS cylinders measuring 10 x 20 cm was conducted by positioning the cylinder under the loading apparatus, as depicted in Figure 4.

(a) (b)

Figure 4 CTS on UTM Mechine.

The test continued until the CTS cracked, with the maximum compressive strength displayed on the UTM TORSEE monitor. The compressive strength of the concrete was calculated using the formula specified in SNI 03-2834-2018 as follows:

$$f'_c = \frac{P}{A}$$

Where f'_c (compressive strength) is the value of the concrete's compressive strength in Mega Pascals (MPa), P is the maximum load applied during the laboratory test on the CTS cylinder, measured in Newtons (N), and A is the cross-sectional area of the tested CTS cylinder, measured in square meters (m²). The results of the CTS compressive strength test using the UTM TORSEE 200 TF indicated the pressure generated (kgf) divided by the cross-sectional area of the cylinder.

The UCS test on CTS was conducted to obtain optimal results from the various cement percentages specified in Table 4, which were then applied to the CTS samples. According to ACI guidelines outlined in Table 5

Table , for the type of soil classified as poorly graded sand (SP) A-3, which is the focus of this study, the minimum compressive strength at 7 days was set at 300 psi (2.07 MPa), while the expected maximum value was 600 psi (4.14 MPa), aligning with the planned strength.

Then, the mixture is poured into a steel cylinder mold in 5 layers, with each layer compacted 25 times. The cast specimens are left at room temperature for 24 hours. Subsequently, the samples are wrapped in plastic wrap and placed in a container at approximately 26°C for curing. Compression tests are conducted following ASTM 1633 standards. The requirement for soaking the samples in water for 4 hours before testing is disregarded due to potential sample damage by water. Compression strength testing is performed within a short period, specifically when the samples are 7 days old. The Unconfined Compressive Strength (UCS) values for Cement Treated mixtures are obtained by testing cylindrical specimens measuring 100 mm in diameter and 200 mm in height (with a length-to-diameter ratio of approximately 2.00). According to ACI 2009, the unconfined compressive strength requirements for cement treated mixtures after 7 days of curing must meet the criteria specified in Table 5

Table 5. Ranges of unconfined compressive strengths of cement treated soil (American Concrete Institute, 2009)

Soil Type	Soaked compressive strength, *psi	
	7-day	28-day
Sandy soil and gravelly soils: AASHTO Groups A-1, A-2, A-3 Unified Groups GW, GC, GP, GM, SW, SC, SP, SM	300 to 600	400 to 1000
Silty soils: AASHTO Groups A-4 and A-5 Unified Groups ML and CL	250 to 500	300 to 900
Clayey soils: AASHTO Groups A-6 and A-7 Unified Groups MH and CH	200 to 400	250 to 600

*Specimens moist-cured 7 or 28 day, Note : 1 psi = 0.0069 Mpa

C. CALIFORNIA BEARING RATIO (CBR) TEST

In this test, five cylindrical specimens measuring 15.3 x 17.7 cm were prepared and kept within the mold, as illustrated in Figure 5. The mixing procedure closely followed that used for the preparation of specimens in the Unconfined Compression Strength (UCS) test. The mixture was placed into the mold in three layers, with each layer compacted 56 times. After compaction, the surface of the specimen was carefully leveled, covered with filter paper, and then fully submerged in water for four days.

Figure 5 California Bearing Ratio Test

The mix design used for the test samples is shown in Table 6. After being removed from immersion, the samples were drained, and the CBR test was performed in accordance with ASTM D-1883.

Table 6. Materials proportions of CBR test

Code	W/C	OMC Natural Sand	Materials by weight (%)			
			Cement	Sand	Water	
					OMC	W/C
SO_0	0.33	7.15%	-	93.33	6.67	-
SO_6	0.33	7.15%	86.86	5.21	6.21	1.72
SO_8	0.33	7.15%	84.90	6.79	6.07	2.24
SO_10	0.33	7.15%	83.02	8.30	5.94	2.74
SO_12	0.33	7.15%	81.23	9.75	5.81	3.22

Following the completion of the CBR test, the CBR value was calculated using the equation provided in ASTM D-1883 as follows:

$$CBR = \left(\frac{P}{P_{standard}}\right) \times 10\%$$

Where P is the load applied to the test specimen for a specific penetration (kg), and $P_{standard}$ is the standard load corresponding to the same penetration (kg). Based on the CBR value obtained, the soil classification level, as provided in Table 7, was determined.

Table 7. Percentage of CBR Values for Subgrade, Subbase, and Base Layers

CBR(%)	Level	Objective
0-3	Very poor	Subgrade
3-7	Poor to fair	Subgrade
7-20	Fair	Subbase
20-50	Good	Base or Subbase
>50	Excellent	Base or Subbase

Sources: Bowles, 1996 [25]

The CBR test was employed to determine the optimum cement content, ensuring that the required compressive strength and adequate load-bearing capacity of the CTS were achieved. The CBR value was used to verify that sufficient structural support was provided by the varying cement content for highway applications. Relevant field conditions were simulated in this test, allowing the results to be used as a reference for roadway construction planning.

EXPERIMENT RESULTS AND DISCUSSIONS

A. THE INFLUENCE OF CEMENT ON COMPRESSIVE STRENGTH

Various cement percentages were utilized to evaluate the optimal composition for achieving maximum strength. The results of the UCS tests for Cement Treated Sand (CTS) with four different cement contents (6%, 8%, 10%, and 12%) are presented in Table 8. This data provides valuable insights into the performance of CTS under varying cement content when subjected to loading.

Table 8. The compressive strength results of Cement Treated Sand

Code	Load (kN)	Stress (MPa)	Displacement (mm)	Strain -
SO_6	5.21	0.66	2.15	0.0110
SO_8	14.49	1.84	1.84	0.0092
SO_10	23.09	2.94	1.46	0.0073
SO_12	30.02	3.82	1.37	0.0069

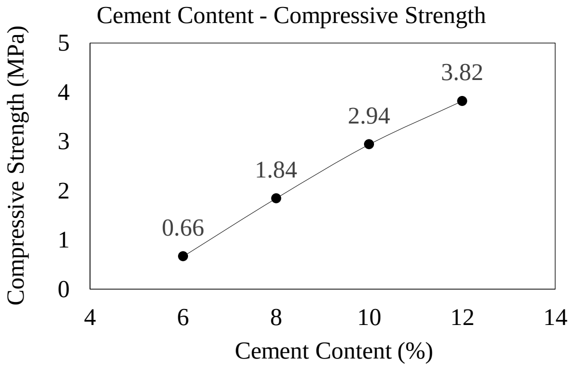

Figure 6 Graphic Compressive Strength vs Cement Content

According to Table 8 and Figure 6 the compressive strength test results for cement-treated sand with 6%, 8%, 10%, and 12% of the total dry sand weight using a UTM machine are shown. The results indicate increases in compressive strength of 1.18 MPa, 1.1 MPa, and 0.88 MPa respectively for each cement percentage. Therefore, the optimal cement percentage in this study is 10% because the increase remains significant compared to lower cement percentages. Although 12% cement content provides higher compressive strength, the increase is no longer significant. Cement-treated sand with 10% cement content achieves a compressive strength of 2.94 MPa at 7 days, meeting the standards outlined by ACI as listed in Table 5.

B. THE INFLUENCE OF CEMENT ON DUCTILITY

Increasing the cement percentage in cement-treated sand can cause the sample to become more brittle and less ductile, as illustrated in Figure 7 and Table 8.

It is evident that higher cement content results in higher compressive strength. However, this also leads to lower strain values, with higher cement content producing smaller peak strain values, indicating brittle behavior. Excessive brittleness may result in surface cracking, allowing moisture to penetrate the main road layers and sub-elements. Consequently, there is a decrease in road strength and durability, ultimately affecting structural performance and service life. Therefore, it is recommended to use cement proportions that offer adequate strength and durability at an affordable cost, with minimal cracking. Adhering to recommended cement usage proportions in cement-treated materials based on the soil type used can help anticipate excessive brittleness. As discussed earlier, the optimal cement content in this study is 10%, as indicated in Table 3, which specifies that for SP A3 soil type, cement content ranging from 7% to 11% of the total dry sand weight is suitable.

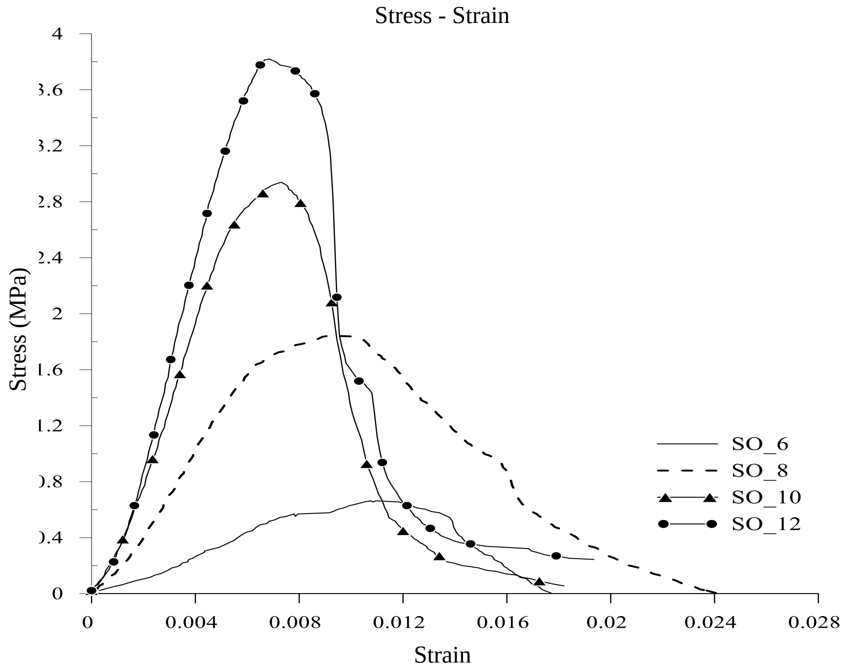

Figure 7 Stress-Strain Graph Cement Treated Sand

C. THE INFLUENCE OF CEMENT ON SOIL BEARING CAPACITY

The California Bearing Ratio (CBR) test was conducted in this study to evaluate the soil bearing capacity resulting from various cement content variations, with a total of five test samples. The cement contents used in this test were 6%, 8%, 10%, and 12%, as presented in Table 6. The soil bearing capacity values corresponding to each cement content can be observed in Table 9.. It was observed that natural sand without cement yielded a bearing capacity value of 7.607%. According to the classification in Table 7, this sand falls within the "fair" category, with a range of 7-20%. This category indicates that the sand can be used as a subbase layer, although additional stabilization is required to enhance its bearing capacity for supporting greater loads, thus necessitating stabilization with cement, referred to as Cement Treated Sand (CTS).

Table 9 CBR test results of Cement Treated Sand

Code	CBR (%)
SO_0	7.61
SO_6	19.42
SO_8	26.06
SO_10	30.79
SO_12	38.48

The addition of 6% cement increased the bearing capacity to 19.42%. Although this increase remains within the "fair" category, the sand-cement mixture at this percentage still offers a more stable subbase layer compared to natural sand without cement. Higher cement contents of 8%, 10%, and 12% resulted in significant increases in bearing capacity, reaching 26.06%, 30.79%, and 38.48%, respectively. At these percentages, the bearing capacity values fall within the "good" category. The "good" category signifies that the sand-cement mixture at these cement contents possesses sufficient strength for use as both base and subbase layers.

Overall, this analysis demonstrates that increasing the cement content in the sand mixture significantly enhances the bearing capacity. This improvement enhances the quality and bearing capacity of the sand, allowing it to meet the technical requirements for use in road construction with higher loads. The selection of a 10% cement variation as the optimal mixture for Cement Treated Sand (CTS) with SP A-3 soil type was based on analysis results showing that, at 10% cement content, the bearing capacity reached 30.79%, which falls within the "good" category. This indicates that the mixture has sufficient strength and stability to support higher road loads.

CONCLUSIONS

This study examined the mechanical behavior of Cement Treated Sand (CTS) with cement contents of 6%, 8%, 10%, and 12%, using Ordinary Portland Cement (OPC) as the stabilizing agent. Laboratory tests, including Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR), were conducted to determine the optimal mixture based on strength and bearing capacity.

The findings show that 10% cement provides the most effective performance, consistent with ACI (2009), which recommends 7–11% for S–P soils. The UCS value of 2.94 MPa satisfies ACI 230-2009 requirements, while the CBR value of 30.79% classifies the mixture as "good," confirming its suitability for base and subbase layers. The increase in brittleness at higher cement contents further emphasizes the need to follow recommended limits to maintain adequate performance and durability.

This study was limited to laboratory-scale testing with a single sand type (SP–A3) and a short curing period. Future research should examine long-term durability, environmental resistance, and field performance under varying climatic and loading conditions to provide a more comprehensive understanding of CTS behavior.

REFERENCES

[1] N. A. Al-Saray, Q. S. Shafiqu, and M. A. Ibrahim, "Improvement of strength characteristics for sandy soils by polypropylene fibers (PPF)," *J. Phys. Conf. Ser.*, vol. 1895, no. 1, 2021, doi: 10.1088/1742-6596/1895/1/012016.

[2] A. Salunkhe, V. Sre Adethya, R. Gobinath, J. Hari Prasanth, and S. Karthikeyan, "Shear behaviour of cement treated sand," *Mater. Today Proc.*, vol. 68, pp. 1266–1272, 2022, doi: 10.1016/j.matpr.2022.06.077.

[3] K. A. Tariq and T. Maki, "Mechanical behaviour of cement-treated sand," *Constr. Build. Mater.*, vol. 58, pp. 54–63, 2014, doi: 10.1016/j.conbuildmat.2014.02.017.

[4] X. Wei and T. Ku, "New design chart for geotechnical ground improvement: characterizing cement-stabilized sand," *Acta Geotech.*, vol. 15, no. 4, pp. 999–1011, 2020, doi: 10.1007/s11440-019-00838-2.

[5] T. Namikawa, S. Hiyama, Y. Ando, and T. Shibata, "Failure behavior of cement-treated soil under triaxial tension conditions," *Soils Found.*, vol. 57, no. 5, pp. 815–827, 2017, doi: 10.1016/j.sandf.2017.08.011.

[6] B. G. E. Halsted, D. R. Luhr, and W. S. Adaska, "Guide to Cement-Treated Base (CTB) Guide to Cement-Treated Base (CTB)".

[7] H. Hara, K. Ikeda, and N. Yoshimoto, "Strength reduction mechanism of cement-treated soil under seawater environment," *Soils Found.*, vol. 64, no. 1, p. 101425, 2024, doi: 10.1016/j.sandf.2024.101425.

[8] L. Miao, F. Wang, J. Han, W. Lv, and J. Li, "Properties and Applications of Cement-Treated Sand-Expanded Polystyrene Bead Lightweight Fill," *J. Mater. Civ. Eng.*, vol. 25, no. 1, pp. 86–93, 2013, doi: 10.1061/(asce)mt.1943-5533.0000556.

[9] S. Chuenjaidee, P. Jamsawang, P. Jongpradist, and X. Chen, "Flexural Performance of Cement-Treated Sand Reinforced with Geogrids for Use as Sub-Bases of Pavement and Railway Structures," *Materials (Basel).*, vol. 15, no. 8, 2022, doi: 10.3390/ma15082877.

[10] S. W. Moon, G. Vinoth, S. Subramanian, J. Kim, and T. Ku, "Effect of fine particles on strength and stiffness of cement treated sand," *Granul. Matter*, vol. 22, no. 1, pp. 1–13, 2020, doi: 10.1007/s10035-019-0975-6.

[11] A. A.-R. Rasha, M. A. Al-jumaili, and K. R. A.-Z. Ahlam, "Study of Cement Treated Base Agreagate Properties for Pavement Structure," *Int. J. Inf. Res. Rev.*, vol. 5, no. February, pp. 5093–5100, 2018.

[12] C. Sand, C. Types, and C. Temperatures, "Di ff erence in Strength Development between Cement-Treated Sand and Mortar with Various," 2020.

[13] G. Vinoth, S. W. Moon, J. Moon, and T. Ku, "Early strength development in cement-treated sand using low-carbon rapid-hardening cements," *Soils Found.*,

vol. 58, no. 5, pp. 1200–1211, 2018, doi: 10.1016/j.sandf.2018.07.001.
[14] L. S. Ho, K. Nakarai, Y. Ogawa, T. Sasaki, and M. Morioka, "Strength development of cement-treated soils: Effects of water content, carbonation, and pozzolanic reaction under drying curing condition," *Constr. Build. Mater.*, vol. 134, pp. 703–712, 2017, doi: 10.1016/j.conbuildmat.2016.12.065.
[15] Y. Amini and A. Hamidi, "Triaxial shear behavior of a cement-treated sand-gravel mixture," *J. Rock Mech. Geotech. Eng.*, vol. 6, no. 5, pp. 455–465, 2014, doi: 10.1016/j.jrmge.2014.07.006.
[16] J. Gu, H. Lyu, J. Yang, and C. Zeng, "Effects of cement content and curing period on geotechnical properties of cement-treated calcareous sands," *Transp. Geotech.*, vol. 33, no. January, p. 100732, 2022, doi: 10.1016/j.trgeo.2022.100732.
[17] A. Wassermann, A. Abdallah, and O. Cuisinier, "Impact of wetting and drying cycles on the mechanical behaviour of a cement-treated soil," *Transp. Geotech.*, vol. 36, no. April, p. 100804, 2022, doi: 10.1016/j.trgeo.2022.100804.
[18] ASTM, "Designation: D 2487 - 00: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)," *ASTM Int.*, vol. 04, pp. 1–12, 2000.
[19] V. N. Georgiannou, D. Ph, M. Konstadinou, D. Ph, and P. Triantafyllos, "Sand Behavior under Stress States Involving Principal Stress Rotation," vol. 144, no. 6, pp. 1–14, 2018, doi: 10.1061/(ASCE)GT.1943-5606.0001878.
[20] K. L. Scrivener, V. M. John, and E. M. Gartner, "Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry," *Cem. Concr. Res.*, vol. 114, no. March, pp. 2–26, 2018, doi: 10.1016/j.cemconres.2018.03.015.
[21] T. Zhu, X. Lu, and M. Dittrich, "Calcification on mortar by live and UV-killed biofilm-forming cyanobacterial Gloeocapsa PCC73106," *Constr. Build. Mater.*, vol. 146, pp. 43–53, 2017, doi: 10.1016/j.conbuildmat.2017.04.026.
[22] R. Das, R. Bandyopadhyay, and P. Pramanik, "Stereo-regulated Schiff base siloxane polymer coated QCM sensor for amine vapor detection," *Mater. Chem. Phys.*, vol. 226, no. January, pp. 214–219, 2019, doi: 10.1016/j.matchemphys.2019.01.023.
[23] ACI, *American Concrete Institute - Report on Soil Cement*, vol. 76, no. 7. 2009.
[24] I. I. Hadijah, *Cement Treated Base (CTB) sebagai Lapis Fondasi Atas*. 2022. [Online]. Available: www.sulur.co.id
[25] J. E. Bowles, *Foundation Analysis and Design*. 1996.