Unconfined Compressive Strength and Water Stability Behavior of a Soil Treated with a nontraditional stabilizer.

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Abstract:

The main objective of this study was to analyze the compressive strength behavior of fine soil stabilized with a mixture of sodium silicate, sodium hydroxide, and cement. The soil was classified as high-plasticity silt–MH (USCS classification) or Group A 7-5 (AASHTO classification). Proctor standard tests were performed to determine the maximum dry density and optimum moisture content of the natural soil. A series of test specimens was prepared to estimate the ranges for each stabilizer by assessing the sample integrity after 4 h of water immersion. Compression tests were conducted on samples with selected dosages at curing ages of 7 and 28 d. For this purpose, the specimens were molded with only 3 % and 15 % cement, which served as the comparison samples. Based on the previous results, the specimens were treated with various dosages of sodium silicate, sodium hydroxide, and cement: 4 % cement, 3 % sodium hydroxide, and three different concentrations of sodium silicate (6 %, 8 %, and 10 %). Compression tests were conducted under three conditions: without water immersion, with water immersion, and with capillary absorption. The specimens treated with 8 % sodium silicate showed the best performance under all three conditions, achieving compressive strength values of 3.74, 2.06, and 2.07 kg/cm² at 7 days and 5.38, 3.15, and 3.09 kg/cm² at 28 days of curing, respectively.

Keywords: Soil stabilization, chemical stabilization, sodium silicate, Cement, Compressive strength.

Introduction

Soils exhibit different behaviors, depending on their physical and mechanical properties. In some cases, their natural conditions render them unsuitable for construction purposes. This issue is particularly relevant in road projects, especially in the construction of rural roads, where significant challenges often arise owing to the physical and mechanical properties of in situ soil physical and mechanical properties, such as strength, volumetric stability, and water stability[1], [2], [3]. These deficiencies make the soil inadequate for supporting the loads generated by vehicular traffic and contribute to accelerated deterioration, which is frequently exacerbated by environmental factors, such as adverse weather conditions. In these situations, the need to implement soil improvement techniques such as chemical soil stabilization is evident[4]. This technique has extensive applications in road construction because, through the incorporation of various chemical compounds, it is possible to enhance the soil characteristics to meet the necessary requirements to achieve the desired performance in a road project[5].

The compounds used for soil stabilization are classified into three categories[6]: 1) Traditional stabilizers, which generally use pozzolanic reactions and cation exchange processes to stabilize soils, such as cement, lime, and fly ash. 2) Byproduct stabilizers, such as traditional stabilizers utilize pozzolanic reactions and cation exchange as the primary mechanisms for stabilizing soils. Examples include lime, kiln dust, and cement kiln dust. 3) Nontraditional stabilizers, including ionic, enzyme, lignosulfonate, salt, petroleum resin, polymer, and tree resins, exhibit significant variations in their stabilization mechanisms. The primary mechanism involves cation exchange, flocculation, reduction of the affinity for water, coating of soil particles, physical bonding of the particles, and compaction [7].

Nontraditional soil stabilizers are being promoted as cost-effective substitutes for traditional stabilizers[7].They exhibit a wide range of compositions and interactions with soil. Soil stabilization is a good alternative for rural road construction and conservation[8]. Nevertheless, some of these additives are only effective under specific conditions. It is important to perform careful laboratory evaluations to select suitable nontraditional additives for a specific project.

The water stability of stabilized soils is a key factor in these types of projects[9]. In this study, the unconfined compressive strength of fine soil treated with different combinations of Ordinary Portland Cement (OPC), sodium silicate, and sodium hydroxide were evaluated. To select different percentage combinations of additives, a procedure to achieve water stability of the stabilized soil was implemented.

Materials and Methodology

Soil characterization

Soils with various characteristics have been found in Cali, Colombia. One of the prevalent soil types is high-plasticity silt, classified as MH according to the Unified Soil Classification System (SUCS). This soil is susceptible to loss of strength when saturated with water, which can potentially lead to damage to road infrastructure. Therefore, in the context of the current research, the decision was made to identify some areas in Cali where this type of soil can be found for sample extraction, sampling, and study. Microzoning investigations indicate that this area is characterized by the presence of a surface layer of fine soils, primarily composed of inorganic high-plasticity silts (MH) and inorganic high-plasticity clays (CH)[10]. Table 1 lists the characteristics of the soils studied.

Table 1. Soil Characteristics.

Characteristic	Value
Color	Ocher
SUCS Soil Classification	MH
AASTHO Soil Classification	A 7-5
% passing sieve No. 200.	94.04
% Silt	49
% Clay	45
Liquid Limit	62
Plastic Limit	34
Plasticity Index	28
Specific Gravity	2.706
% Organic Matter	1.15

Stabilizing materials

Sodium silicate

Sodium silicate, also known as soluble glass, has the chemical formula, $Na2SiO3$. It can be found in liquid or solid forms, is colorless or white, and is soluble in water. Table 6 presents the product information provided by the distributors.

Table 2: Product information: Sodium silicate.

Product information	
Color	grayish
alkalinity	Minimum 11%
PH	12.89
Silica Content:	Min 28.95% - Max 33.35%
Density	Min 46.0 °Be - Max 48 °Be
Texture	Fluid
Total Solids	41% - 44%
Specific Gravity	1.465 g/cc - 1.485 g/cc
Presentation.	Liquid
Ratio Na2: Si02	2.6 - 2.8
Measurement Temperature.	19.5 °C - 20.5 °C

Ordinary Porland Cement

General-purpose gray cement was used, which, as established by the manufacturer, complies with the specifications of the Colombian Technical Standard NTC 121 (Standard ASTM C 150).

Sodium Hydroxide.

NaOH, also known as Caustic Soda, is primarily used as an alkaline activator and has the chemical formula NaOH. It was added in the form of flakes, with a purity of 90 %. The provided product information indicated that 98 % NaOH, 0.25 % Sodium Carbonate, and Total Alkalinity (Na2O) of 76.18 %m/m.

Mix proportions

The process used to determine the percentage of additives involved the creation of small test specimens that were compacted using the optimal moisture content and the maximum dry density of the soil in its natural state as a reference. Figure 1 illustrates the procedure used to estimate the percentages of the unconfined compressive strength tests.

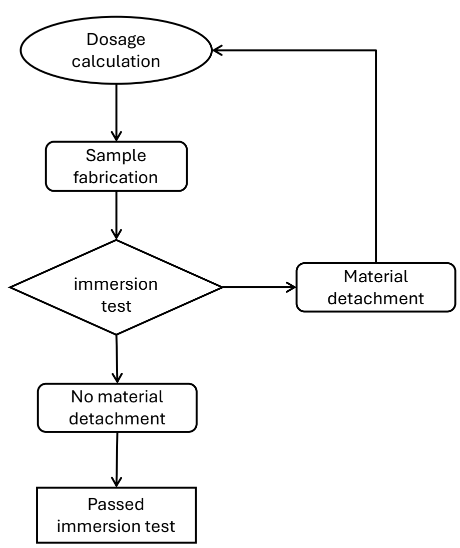

Figure 1 Dosage selection procedure

The dosage selection was based on water stability. Small test specimens (50 mm in diameter and 60 mm in height) were prepared using soil with various cement contents (3, 4, and 5 %), three different amounts of sodium silicate (6, 8, and 10 %), and four different amounts of sodium hydroxide (0, 0.5, 1.5, and 3.0 %). Three specimens were prepared for each dosage for each testing condition (without immersion, with immersion, and with capillary absorption) at curing ages of 7 d and 28 d. The specimens were compacted to the maximum dry density (MDD) and optimal moisture content (OMC) as determined in a previous standard compaction test.

Approximately 1500 g of air-dried material was required to mold the three samples. The quantities of cement, sodium silicate, and sodium hydroxide required were estimated relative to the dry weight of the samples. This estimation was based on the moisture content obtained from a control sample that was dried in an oven for 24 h. It is worth mentioning that the calculations considered possible variations in soil moisture due to external factors such as ambient relative humidity.

Table 3 shows the different dosages tested for water stability along with the time during which each specimen maintained its shape after 4 h of water immersion (equivalent to 240 min). Thus, when the specimen did not detach before reaching the threshold time, the test was considered to have passed; otherwise, the sample was considered not to have passed the test.

Table 3 Study Dosage Analysis

Dosages		NaOH %	Time [min]	Result
Sodium Silicate % %	Cement %			
4	3	-	3	Not passed
6	3	-	5	Not passed
8	3	-	7	Not passed
				Not passed
4	3	0,5	10	Not passed
6	3	0,5	23	Not passed
8	3	0,5	50	Not passed
				Not passed
6	3	1,5	50	Not passed
8	4	1,5	65	Not passed
10	5	1,5	85	Not passed
6	3	3,0	240	Passed
8	4	3,0	240	Passed
10	5	3,0	240	Passed

Unconfined Compression Test

The doses with the best performance in the water stability test were selected for further investigation under unconfined compression. As shown in Table 3, only the dosages of sodium silicate (6, 8, and 10 %), cement (3, 4, and 5 %), and 3 % sodium hydroxide passed the water stability test. These values were selected for the soaked unconfined compressive tests. Additionally, to establish a comparison parameter with the aforementioned dosages, it was decided to select two percentages using only cement, one low and one high, at 4 % and 15 %, respectively, for use as standard samples.

Results and Discussion

Soil gradation.

The soil particle size distribution curve is shown in Figure 2. Here, 100 % of the soil passed through sieve No. 4, and 5.96 % of the material retained on sieve No. 200 corresponded to sand (distributed between sieves No. 8 and 200). Thus, 94.04 % of the material was fine, of which, according to the results of the granulometric analysis using the hydrometer method, percentages of 49 % for silts (sizes between 75 µm and 5 µm) and 45 % for lays smaller than 5 µm) were determined.

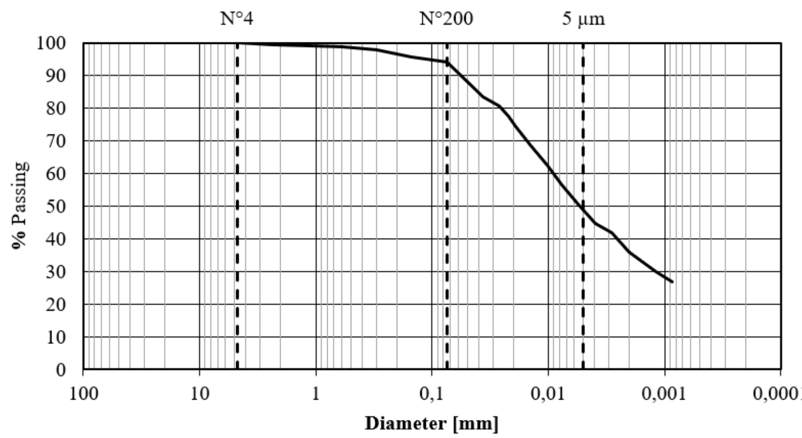

Figure 2 Particle size distribution of the soil under study.

Chemical characteristics of the natural

The different percentages of chemical compounds present in the soil are shown in Table 4. It is noteworthy that there was a high percentage of aluminum silicates at 73.59 %, primarily consisting of 48.13 % silica and 25.46 % aluminum, relative to the weight of the total sample. Silica and alumina are important elements for soil stabilization because of their capacity to bind soil particles, enhance soil structure, ensure chemical stability through reactions with other compounds, and contribute to soil reinforcement[11]. Their presence and chemical interactions profoundly influence soil properties and determine their suitability for a variety of engineering applications.

Table 4 Soil chemical composition

Name	compound	% by weight
Silicon	SiO_2	48.13
Aluminum	Al_2O_3	25.46
Iron	Fe_2O_3	20.86
Titanium	TiO_2	2.11
Magnesium	MgO	1.16
Calcium	CaO	0.88
Sodium	Na_2O	0.40
Manganese	MnO	0.25
Potassium	K_2O	0.21
Phosphorus	P_2O_5	0.14
Barium	Ba	0.12
Sulfur	SO_3	0.10
Vanadium	V	0.06
Chromium	Cr	0.03
Cobalt	Co	0.02

Copper	Cu	0.02
Zirconium	Zr	0.02
Zinc	Zn	0.02
Scandium	Sc	0.01

Characteristics of the treated soil

Three dosages that passed the water stability test were selected for further investigation: SS6–C4–H3, SS8–C4 –H3, and SS10–C4–H3, where C4 refers to 4 % cement, and H3 refers to 3 % sodium hydroxide. Similarly, SS6, SS8, and SS10 refer to 6, 8, and 10 % sodium silicate, respectively. As shown in Table 5, the overall density for high percentages of sodium silicate was greater than that obtained for the natural soil. Conversely, for low percentages, the density was lower than that of the natural soil. A clear increase was observed for 8 % and 10 % sodium silicate, along with a decrease in the optimal moisture content (Figure 3).

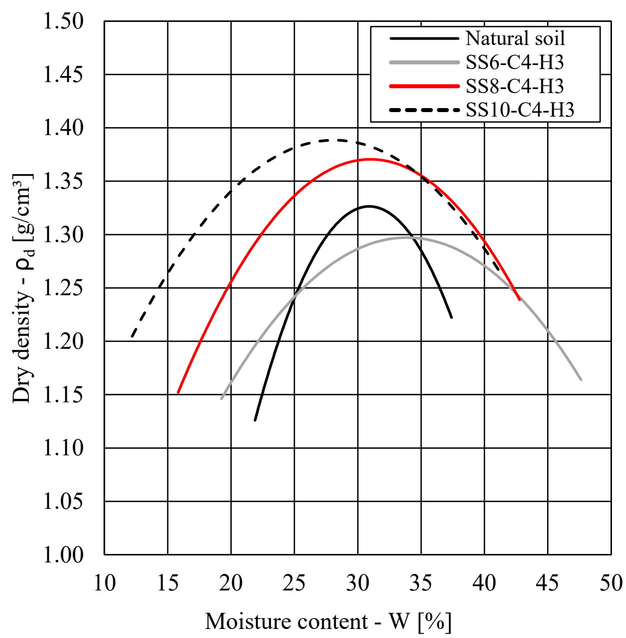

Figure 3 Moisture-density relationship

Table 5 Moisture–Density Relationships

Dosage	**Density**	**W Optimum**
	[g/cm³]	[%]
Natural soil	1.352	31
SS6 - C4 - H3	1.297	34
SS8 - C4 - H3	1.372	31
SS10 - C4 - H3	1.386	28

Consistency limits of stabilized soil

A clear relationship between the added amount of sodium silicate and the liquid and plastic limits is presented in Table 6. A slight increase in the liquid limit was observed as the sodium silicate content increased. Regarding the plastic limit, although smaller values were obtained for SS6-C4-H3 than for natural soil for all three dosages, a value of 28 was obtained for SS6-C4-H3, whereas for the SS8-C4-H3 and SS10-C4-H3 dosages, there was an increase in the plastic limit to a value of 31, which remained constant for these two dosages. For the plasticity index, a clear increase was observed compared with the value obtained for natural soil. This may be due to an initial state induced by sodium silicate, which is a viscous liquid that does not fully react and induces plastic behavior in the soil. This behavior may not remain constant over time as chemical reactions progress.

Table 6 Consistency limits of stabilized soil.

Dosage	Ll	LP	IP
Natural soil	62	34	28
SS6 - C4 - H3	66	28	38
SS8 - C4 - H3	67	31	36
SS10 - C4 - H3	69	31	38

Resistencia a la compression

The results of the unconfined compressive strength at an age of 7 d for compacted soil specimens with three different dosages (SS6-C4-H3, SS8-C4-H3, and SS10-C4-H3) are shown in Figure 4 for the three testing conditions. The dashed line represents the average strength achieved by compacted samples of natural soil without immersion, which is 2.01 kgf/cm², serving as the reference for evaluating the behavior of the dosages. The specimens not subjected to immersion exceeded the reference threshold, with values of 3.40, 3.74, and 3.49 kgf/cm² for the soils treated with SS6-C4-H3, SS8-C4-H3, and SS10-C4-H3, respectively, representing an average strength increase of 1.53 kgf/cm². However, when comparing the strength development among the dosages, although a trend was identified where the SS8-C4-H3 dosage exhibited the best performance, evaluating the difference in strength in this state revealed only a 9 % increase when the sodium silicate percentage was varied from 6 % to 8 %; conversely, when it was varied from 8 % to 10 %, a decrease of 6.68 % was recorded. For the SS8-C4-H3 dosage, the strengths obtained under testing conditions involving prior immersion for 4 h and capillary absorption for 12 h were similar to those of the samples tested with soil in its natural state without immersion. This evidence shows that the incorporation of sodium silicate as a stabilizing agent has a positive effect on the soil, improving its performance under saturated conditions at an early age.

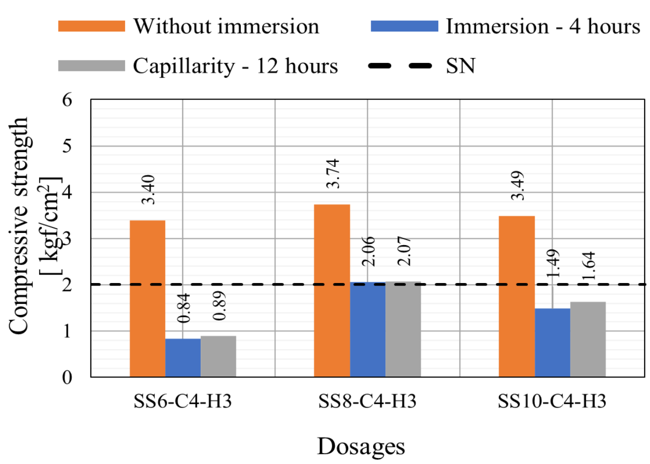

Figure 4 Unconfined compressive strength after 7 days of curing

As in the previous analysis, Figure 5 shows the compressive strength at 28 d of curing. The same trend was observed for the specimens after 7 d of curing, showing that the best result was obtained for the SS8-C4-H3 sample. Additionally, it was noted that the SS6-C4-H3 mixture developed slightly higher strengths for the specimens subjected to 4 h of immersion than those subjected to capillarity for 12 h, with an increase of 1.01 kgf/cm². For the strength values for the SS10-C4-H3 dosage, the specimens subjected to 4 hours of immersion developed higher strengths than did those subjected to 12 hours of capillarity, with an increase of 0.76 kgf/cm² in this case.

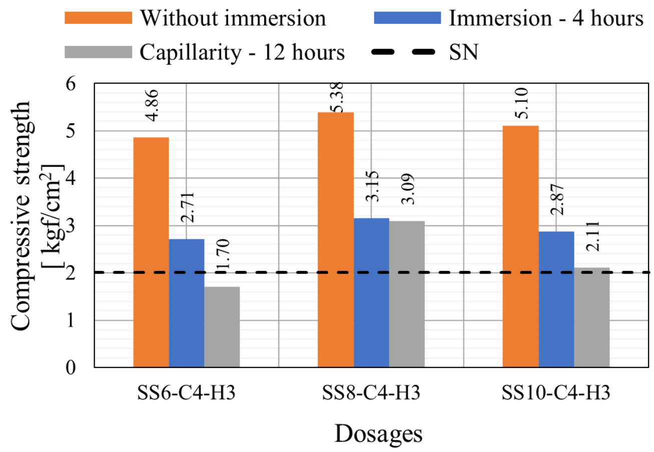

Figure 5 Unconfined compressive strength after 28 days of curing

The behavior of the different dosages at the two curing ages shows a clear trend of increasing strength from 7 to 28 d for the three testing conditions. It is noteworthy that the specimens tested without immersion showed a greater increase in strength compared with the other two testing states. Overall, a homogeneous increase in the strength of the three dosages under different testing conditions was observed from one curing age to another. It is noticeable that for a sodium silicate content of 6 % (SS6-C4-H3) under immersion and capillarity conditions, the strength generated at 7 days of curing is lower than the strength of the soil in its natural state without immersion, as specimens treated with this value only reached an average of 0.86 kgf/cm², approximately less than half of the strength generated by the natural soil. The opposite occurs with the dose of 8 % sodium silicate, where under the same conditions at 7 days of curing, approximately 100 % of the strength of the natural soil was achieved, with strengths of 2.06 and 2.07 kgf/cm² for the immersion and capillary absorption conditions, respectively, indicating that values below 8 % of silicate generate low strengths at early curing ages. At a dosage of 10 % sodium silicate (SS10-C4-H3), under immersion and capillarity conditions after 7 d of curing, the strength of the natural soil did not increase, reaching an average of 78 %.

Regarding the development of strength at 28 d, in addition to the aforementioned conditions, it is evident that the non-immersion condition, compared to the other two conditions, exhibited the greatest increase in strength for the three dosages at the two curing ages. Overall, comparing the strength achieved by the soil in its natural state, which was 2.01 kgf/cm², with strengths of 3.40, 3.74, and 3.49 kgf/cm² for 7 days and 4.89, 5.38, and 5.10 kgf/cm² for 28 days, the specimens tested without immersion generated average increases of 1.53 kgf/cm² and 3.11 kgf/cm² for 7 and 28 days of curing, respectively.

Conclusions

This study aims to assess the unconfined compressive strength of soil stabilized using a nontraditional stabilizer. This study employed a methodological approach centered on laboratory experiments to evaluate the water stability in terms of the remaining resistance after immersion and capillary soaking.

The soil characteristics of the city of Santiago de Cali (Colombia) were used in this study. It was classified using the Unified Soil Classification System (USCS) as high-plasticity silt (MH) and according to the AASHTO classification system as A 7-5.

Through the preparation of test specimens subjected to water immersion, it was determined that the dosages of additives enabling the samples to maintain their integrity under water (water stability) were 6 %, 8 %, and 10 % for sodium silicate and 3 %, 4 %, and 5 % for cement, respectively, with an alkaline activator (3 % sodium hydroxide). All percentages were based on the dry weight of the soil.

Based on the water stability results, the influence of the chemical compounds on the mechanical behavior of the soil at the established test dosages was experimentally determined through laboratory tests under soaked conditions. The results of unconfined compression strength for soil samples dosed with sodium silicate, sodium hydroxide, and cement reflect an increase in soaked strength as the curing time increases from 7 to 28 days, which significantly exceeds the strength of natural dry soil.

The compression strength results for the soil samples dosed with sodium silicate, sodium hydroxide, and cement reflect an increase in strength as the curing time increases from 7 to 28 d for all three test conditions (without immersion, with immersion, and with capillary absorption). This demonstrates that exposing the specimens to a controlled humidity environment positively influences the pozzolanic reactions occurring in the soil, which in turn are responsible for generating silica gel, which is responsible for the bonding between particles.

The action of the sodium silicate-cement mixture positively influenced the behavior of the specimens under critical conditions of water immersion and capillary absorption. This is reflected by the observation that for the SS8-C4 dosage at both curing ages, the compressive strengths achieved by the tested specimens under both conditions are equal to or exceed the values achieved by the samples tested with compacted natural soil.

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