Unconfined Compressive Strength and Water Stability Behavior of a Soil Treated with a Non-traditional Stabilizer.

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Abstract:

The main objective of this study was to analyze the unconfined 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) according to the USCS classification or Group A-7-5 according to the 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 effective 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 days. For this purpose, the specimens molded with only 3% and 15% cement served as comparison samples. Based on these 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 kgf/cm² at 7 days and 5.38, 3.15, and 3.09 kgf/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. 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, such as strength, volumetric stability, and water stability[1], [2], [3]. These deficiencies render the soil inadequate for supporting vehicular traffic loads and contribute to accelerated deterioration, often exacerbated by environmental factors such as adverse weather. 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, soil characteristics can be enhanced to meet the requirements for 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 (e.g., cement, lime, and fly ash) 2) Byproduct stabilizers also utilize pozzolanic reactions and cation exchange as primary mechanisms for stabilizing soils. Examples include lime, kiln dust, and cement kiln dust. 3) Non-traditional stabilizers, including ionic, enzyme, lignosulfonate, salt, petroleum resin, polymer, and tree resins, exhibit significant variations in their stabilization mechanisms. The primary mechanisms involve cation exchange, flocculation, reduction in affinity for water, coating of soil particles, physical bonding of particles, and compaction [7].

Non-traditional soil stabilizers are being promoted as cost-effective substitutes for traditional stabilizers. They exhibit a wide range of compositions and interactions with soil. Soil stabilization is a viable alternative for rural road construction and conservation[8]. However, some of these additives are effective only under specific conditions. Careful laboratory evaluations are important to select suitable non-traditional 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 was evaluated. To select different percentage combinations of additives, a procedure to assess the water stability of the stabilized soil was implemented.

Materials and Methodology

Soil characterization

Soils with various characteristics are found in Cali, Colombia. One of the prevalent soil types is high-plasticity silt, classified as MH in the Unified Soil Classification System (USCS). This soil is susceptible to strength loss when saturated with water, which can potentially damage road infrastructure. Therefore, in this study, areas in Cali that contained this soil type were identified for sample extraction, sampling, and analysis. Microzoning investigations indicate that this area is characterized by 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
USCS Soil Classification	MH
AASHTO 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 is available in liquid or solid forms, is colorless or white, and is soluble in water. Table 2 presents the product information provided by distributors.

Table 2: Product Information: Sodium silicate.

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 Portland Cement

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

Sodium Hydroxide.

NaOH, also known as caustic soda, is primarily used as an alkaline activator. It was added in the form of flakes with a purity of 90%. The provided product information indicated 98% NaOH, 0.25% sodium carbonate, and a Total Alkalinity (Na2O) of 76.18% m/m.

Mix proportions

The process for determining the additive percentages involved creating small test specimens compacted using the optimal moisture content and maximum dry density of the natural soil as a reference. Figure 1 illustrates the procedure used to estimate the percentages for the unconfined compressive strength tests.

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 contents (6%, 8%, and 10%), and four different amounts of sodium hydroxide contents (0%, 0.5%, 1.5%, and 3.0%). Three specimens were prepared for each dosage and testing condition (without immersion, with immersion, and with capillary absorption) at curing ages of 7 and 28 days. The specimens were compacted to the maximum dry density (MDD) and optimal moisture content (OMC) determined in a previous standard compaction test.

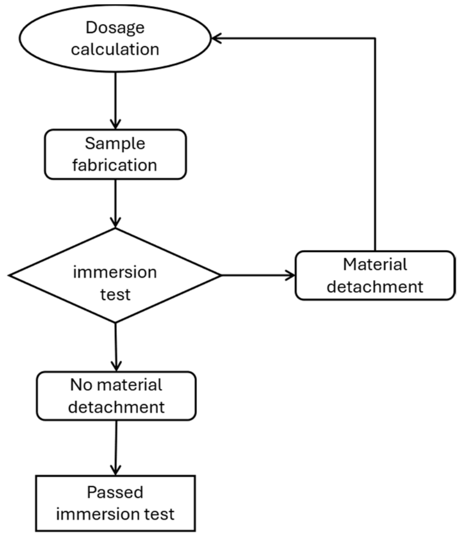

Figure 1 Dosage selection procedure

Approximately 1500 g of air-dried material was required to mold 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 of a control sample dried in an oven for 24 h. 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 each specimen maintained its shape after 4 h (240 min) of immersion in water. Thus, if a specimen did not detach before reaching the threshold time, the test was considered passed; otherwise, the sample was considered to have failed the test.

Table 3 Study Dosage Analysis

Dosages			Time [min]	Result
Sodium Silicate % %	Cement %	NaOH %		
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 strength tests. Additionally, to establish a comparison parameter, two percentages using only cement (4% and 15%, representing low and high dosages, respectively) were selected as standard samples.

Results and Discussion

Soil Gradation.

The soil particle size distribution curve is presented in Figure 2. Specifically, 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 material. According to the granulometric analysis using the hydrometer method, 49% was determined to be silt (sizes between 75 and 5 µm) and 45% was clay (sizes smaller than 5 µm).

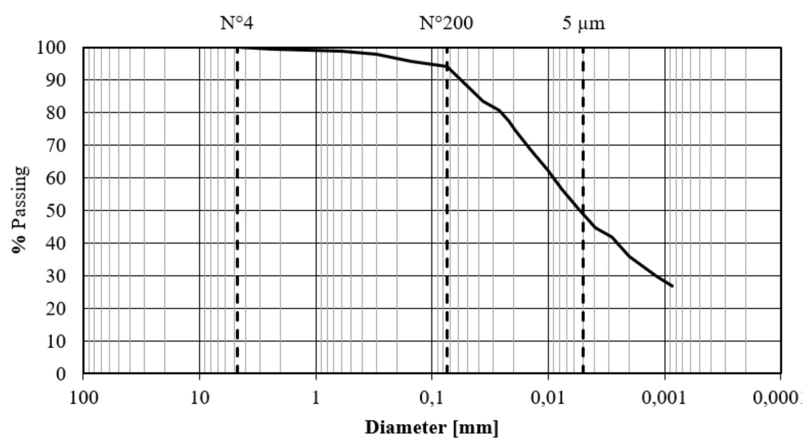

Figure 2 Particle size distribution of the soil under study.

Chemical Characteristics of the Natural Soil

Table 4 shows the different percentages of chemical compounds present in the soil. Notably, a high percentage of aluminum silicates (73.59%) was observed, primarily consisting of 48.13% silica and 25.46% aluminum relative to the total sample weight. Silica and alumina are important elements for soil stabilization due to 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 its suitability for various 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 of natural soil. Conversely, for low percentages, the density was lower than that of natural soil. A clear increase was observed for 8% and 10% sodium silicate, along with a decrease in the optimal moisture content (Figure 3).

Table 5 Moisture–Density Relationships

Dosage	**Density**	**W Optimum**
	[g/cm^3]	[%]
Natural soil	1.352	31
SS6 - C4 - H3	1.297	34
SS8 - C4 - H3	1.372	31
SS10 - C4 - H3	1.386	28

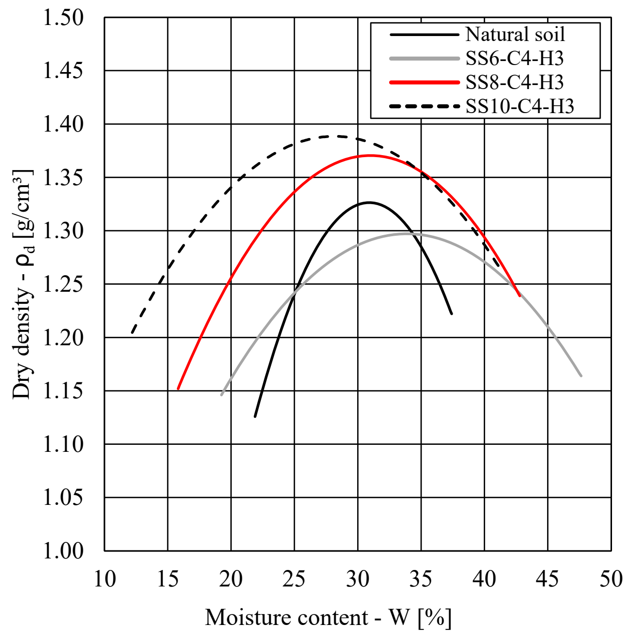

Figure 3 Moisture-density relationship

Consistency Limits of Stabilized Soil

Table 6 presents a clear relationship between the added amount of sodium silicate and the liquid and plastic limits of the soil. A slight increase in the liquid limit was observed as the sodium silicate content increased. Regarding the plastic limit, smaller values were obtained for SS6-C4-H3 (28) compared to natural soil (34). For the SS8-C4-H3 and SS10-C4-H3 dosages, the plastic limit increased to 31 and remained constant for these two dosages. For the plasticity index, a clear increase was observed compared to the value obtained for natural soil. This may be due to an initial state induced by sodium silicate, a viscous liquid that does not fully react and induces plastic behavior in the soil. This behavior may not remain constant over time as the chemical reactions progress.

Table 6 Consistency limits of the 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

Compressive Strength

Figure 4 shows the unconfined compressive strength results at 7 days for compacted soil specimens with three different dosages (SS6-C4-H3, SS8-C4-H3, and SS10-C4-H3) under the three testing conditions. The dashed line represents the average strength (2.01 kgf/cm^2) achieved by compacted samples of natural soil without immersion, serving as the reference for evaluating the dosage behavior. The specimens not subjected to immersion exceeded the reference threshold, with values of 3.40, 3.74, and 3.49 kgf/cm^2 for soils treated with SS6-

C4-H3, SS8-C4-H3, and SS10-C4-H3, respectively. This represents an average strength increase of 1.53 kgf/cm^2. However, when comparing strength development among the dosages, a trend was identified in which the SS8-C4-H3 dosage exhibited the best performance. Evaluating the strength difference in this state revealed only a 9% increase when the sodium silicate percentage was varied from 6% to 8%; conversely, when varied from 8% to 10%, a decrease of 6.68% was recorded. For the SS8-C4-H3 dosage, strengths obtained under testing conditions involving prior immersion for 4 h and capillary absorption for 12 h were similar to those of natural soil samples tested without immersion. This evidence shows that incorporating sodium silicate as a stabilizing agent positively affects the soil, improving its performance under saturated conditions at an early age.

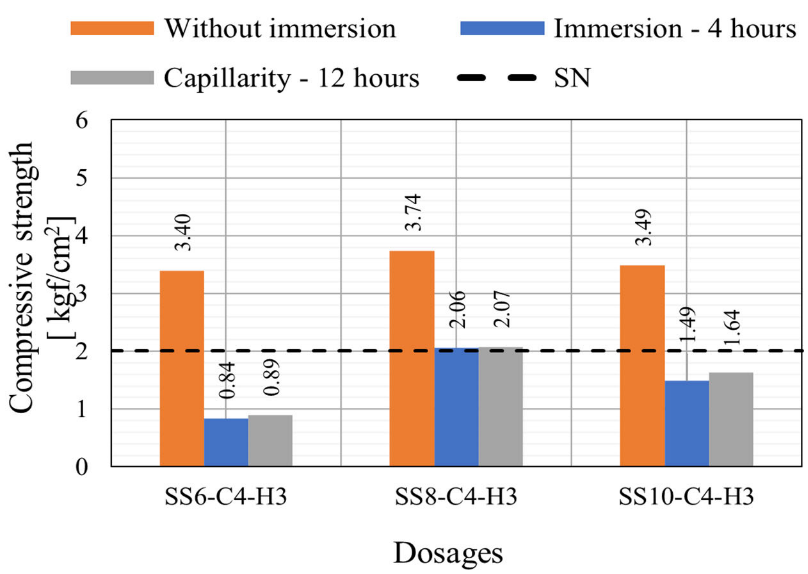

Figure 4 Unconfined compressive strength after 7 days of curing

Similar to the previous analysis, Figure 5 shows the compressive strength at 28 days of curing. The same trend observed for the specimens after 7 days of curing was evident, with the best result obtained for the SS8-C4-H3 sample. Additionally, the SS6-C4-H3 mixture developed slightly higher strengths for specimens subjected to 4 h of immersion than for those subjected to capillarity for 12 h, with an increase of 1.01 kgf/cm². For the SS10-C4-H3 dosage, specimens subjected to 4 h of immersion developed higher strengths than those subjected to 12 h of capillarity, with an increase of 0.76 kgf/cm^2.

The behavior of the different dosages at both curing ages shows a clear trend of increasing strength from 7 to 28 days for all three testing conditions. Notably, the specimens tested without immersion showed a greater increase in strength than the other two testing states. Overall, a homogeneous increase in strength was observed for the three dosages under different testing conditions from one curing age to the next. For a sodium silicate content of 6% (SS6-C4-H3) under immersion and capillarity conditions, the strength generated at 7 days of curing was lower than that of the natural soil without immersion.

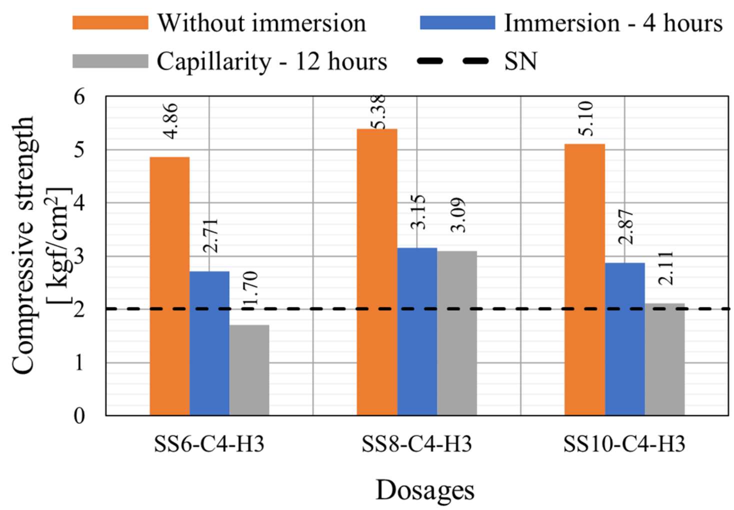

Figure 5 Unconfined compressive strength after 28 days of curing

Specimens treated with this value only reached an average of 0.86 kgf/cm^2, which is approximately less than half of the strength generated by the natural soil. Conversely, with the 8% sodium silicate dosage, approximately 100% of the natural soil strength was achieved under the same conditions at 7 days of curing, with strengths of 2.06 and 2.07 kgf/cm^2 for immersion and capillary absorption conditions, respectively. This indicates that values below 8% silicate generate low strength at early curing ages. At a dosage of 10% sodium silicate (SS10-C4-H3), under immersion and capillarity conditions, after 7 days of curing, the strength did not increase beyond 78% of the natural soil strength.

Regarding strength development at 28 days, in addition to the aforementioned conditions, it is evident that the non-immersion condition exhibited the greatest strength increase for all three dosages at both curing ages, compared to the other two conditions. Overall, comparing the strength achieved by the soil in its natural state, (2.01 kgf/cm^2) with strengths of 3.40, 3.74, and 3.49 kgf/cm^2 at 7 days and 4.89, 5.38, and 5.10 kgf/cm^2 at 28 days, specimens tested without immersion generated average increases of 1.53 kgf/cm^2 and 3.11 kgf/cm^2 for 7 and 28 days of curing, respectively.

Conclusions

This study assessed the unconfined compressive strength of soil stabilized using a non-traditional stabilizer. This study employed a methodological approach centered on laboratory experiments to evaluate water stability, specifically the remaining resistance after immersion and capillary soaking tests.

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

Through the preparation of test specimens subjected to water immersion, it was determined that the dosages enabling samples to maintain their integrity under water (i.e., water stability) were 6%, 8%, and 10% for sodium silicate and 3%, 4%, and 5% for cement, respectively, along 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 was experimentally determined at the established test dosages through laboratory tests under soaked conditions. The unconfined compressive strength results for soil samples dosed with sodium silicate, sodium hydroxide, and cement reflected an increase in soaked strength as the curing time increased from 7 to 28 days, which significantly exceeded the strength of natural dry soil.

The compressive strength results for the soil samples treated with sodium silicate, sodium hydroxide, and cement showed an increase in strength as the curing time increased from 7 to 28 days under 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. These reactions are responsible for generating silica gel, which facilitates bonding between particles.

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 either equaled or exceeded the values achieved by the samples tested with compacted natural soil.

References

[1] F. G. Bell, “Bell, Fred G. "Lime stabilization of clay minerals and soils." *Engineering geology* 42.4 (1996): 223-237. DOI: https://doi.org/10.1016/0013-7952(96)00028-2

[2] T. M. Petry, F. Asce, and D. N. Little, “Review of Stabilization of Clays and Expansive Soils in Pavements and Lightly Loaded Structures-History, Practice, and Future,” 2002, DOI: https://doi.org/10.1061/(ASCE)0899-1561(2002)14:6(447).

[3] Y. Wang, H. Zhang, and Z. Zhang, “Experimental study on mechanics and water stability of high liquid limit soil stabilized by compound stabilizer: A sustainable construction perspective,” *Sustainability (Switzerland)*, vol. 13, no. 10, 2021, DOI: https://doi.org/10.3390/su13105681

[4] “TM. Army. Soil stabilization for pavements”.(1994).

[5] S. M. Lim, D. C. Wijeyesekera, A. J. M. S. Lim, and I. B. H. Bakar, “Critical Review of Innovative Soil Road Stabilization Techniques,” *International Journal of Engineering and Technology Research*, vol. 3, no. 5, 2014.

[6] D. N. Little and S. Nair, “Recommended Practice for Stabilization of Subgrade Soils and Base Materials National Cooperative Highway Research Program.”

[7] J. S. Tingle, J. K. Newman, S. L. Larson, C. A. Weiss, and J. F. Rushing, “Stabilization mechanisms of nontraditional additives,” *Transp Res Rec*, vol. 2, no. 1989, pp. 59–67, 2007, doi: 10.3141/1989-49.

[8] P. Lindh and P. Lemenkova, “Effects of GGBS and Fly Ash in Binders on Soil Stabilization for Road Construction,” *Romanian Journal of Transport Infrastructure*, vol. 11, no. 2, 2022, DOI: https://doi.org/10.2478/rjti-2022-0010

[9] R. Y. Patil and M. S. Ranadive, “Design and development of methodology for construction of thin white topping for rural roads in India,” *Innovative Infrastructure Solutions*, vol. 7, no. 4, 2022, DOI: https://doi.org/10.1007/s41062-022-00762-7

[10] Colombian Geological Service, “Report 4: Investigations and Geotechnical Zoning of the City of Santiago de Cali,” 2005.

[11] A. A. Firoozi, C. Guney Olgun, A. A. Firoozi, and M. S. Baghini, “Fundamentals of soil stabilization,” *International Journal of Geo-Engineering*, vol. 8, no. 1, Dec. 2017, doi: 10.1186/s40703-017-0064-9. DOI: https://doi.org/10.1186/s40703-017-0064-9