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Original Article

Stabilization of Clay Soils for Andean Roads Using Microsilica: Evaluation of Mechanical Performance

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Abstract *- Soil types are very important for the foundations of civil engineering projects. They are used a lot in highways, buildings, bridges, and dams, and they make sure that the whole infrastructure stays stable for its whole life. The current study examines the stabilization of clayey soils for the Andean roads (Qhapaq Ñan) situated in the Huancan district, Huancayo province, within the department of Junín, through the incorporation of microsilica in varying dosages. This study investigates the impact of incorporating 2%, 4%, 6%, and 8% Microsilica (MS) on the physical and mechanical properties of clay soil, utilizing tests in accordance with ASTM and AASHTO standards, including Atterberg Limits, Modified Proctor, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS). The results show that the soil's liquid limit tends to go up to a dose of 4% MS, which is because it can hold more moisture; this obeys the retention capacity of humidity. The soil's mechanical property values also improved, especially when 6% MS was added. The results were 22.01% for CBR and 7.03 kg/cm² for unconfined compressive strength, which are good values for road subgrade. It is concluded that the incorporation of microsilica stabilizes clayey soil for Andean roads, increasing the strength and compaction of the subgrade and providing indicators of gradual soil improvement using up to a 6% MS dose; however, this dosage should be limited to no more than 6% MS due to secondary effects such as internal particle dryness and lack of homogeneity in the mix.*

Keywords *- Clay Soil, Microsilica, Soil Stabilization, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS).*

1. Introduction

One of the most important components in road infrastructure is the subgrade level, since it has the quality of soil variability condition; it affects the pavement layer and its subsequent deterioration. Among them, the pavement performance depends, to a great extent, on the quality of the subgrade soil. Deficiencies in resistance, stability, and bearing capacity tend to intensify under repetitive loads and humidity variations; this triggers the apparition of premature failure. This condition is frequent in low-quality soil, which is the reason why it is employed as a strategy with the purpose of improving the mechanical behavior. Traditional stabilization through the employment of lime and cement has been demonstrated to be effective.

Nonetheless, its application can involve high economic costs and a significant environmental impact. In response to this problem, the interest in sustainable alternatives based on the leverage of industrial sub-products has increased, since these sub-products permit enhancing the soil, and simultaneously, reduce the environmental impacts [1, 2]. For example, making Portland cement has a large carbon footprint because it uses a lot of energy and decarbonizes calcium carbonate during the process of manufacturing clinker. Figure 1 shows that cement production releases about 800 to 900 kg of CO_2 equivalent per ton of material. This justifies the increasing search for alternatives with less environmental impact. The use of conventional stabilizers of expansive soils, like lime and Portland cement, has a high carbon footprint (1.0 to 1.8 t CO_2/t), with the emissions of Portland cement being approximately 0.834 t CO_2/t and those of natural pozzolana and alkali-activated cements being lower (0.140–0.150 t CO_2/t) [4].

The microsilica or silica fume is a byproduct of a manufacturing process, which can be used as a supplementary cementing material in soil-cement mixtures to decrease the use of Portland cement production and to have positive impacts on the Environment, such as reducing CO_2 emissions [4]. It is a byproduct of the silicon and ferrosilicon industry and is a more environmentally sustainable alternative than the use of cement for soil stabilization, as the use of microsilica can lead to reductions between 40% and 50% in carbon emissions while keeping the same soil strength improvement benefits as cement. [5].

Among the materials, microsilica or silica fume stands out due to its high fineness and its pozzolanic nature. Experimental studies report improvements in compaction and significant increments in the resistance of the CBR index in stabilized soil with this material, mainly in fine soil with low bearing capacity [6, 7]. Likewise, it has been noted that the additives based on silica densify the internal structure of the soil and reduce its porosity, which translates into a better mechanical performance [8, 9].

Nevertheless, the possible evidence concentrates, in the majority, on clayey soils. Consequently, a knowledge gap persists with respect to the use of microsilica in clayey soils employed as subgrade, particularly in the area related to the optimal dosage and its mechanical response under service conditions.

In this context, this current research aimed to evaluate the effectiveness of employing microlisca as a stabilizing agent in a specific clayey soil used as a vial subgrade, analyzing the densification ranges and their influence on the relevant physical and mechanical parameters for pavements [10, 11].

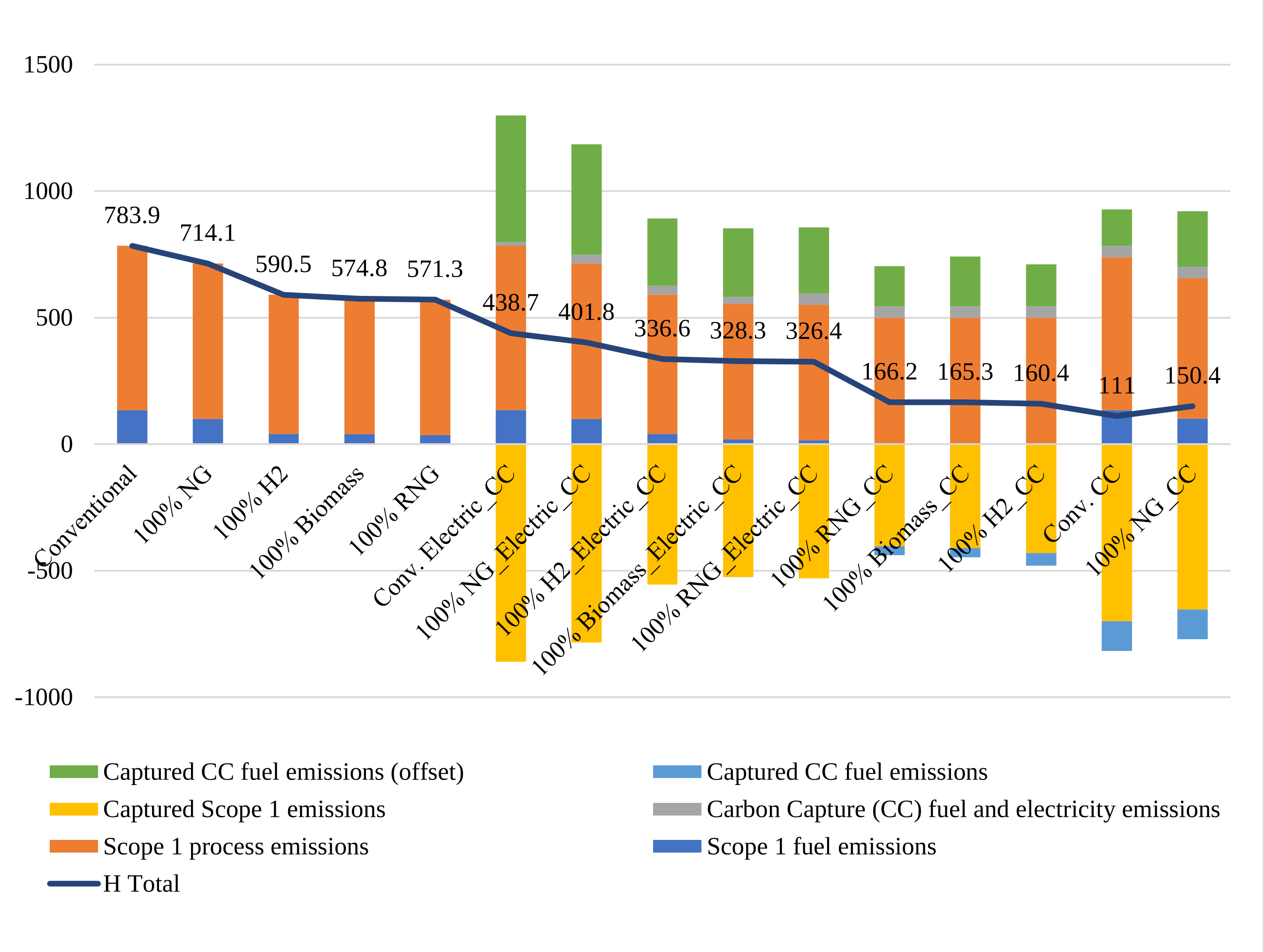

Fig. 1 Greenhouse gas emissions associated with Portland cement production, expressed in kg CO_2eq per ton of cement [3]

With the aim to attain this objective, an experimental methodology was proposed, which contemplates the characterization of natural clayey soil and its stabilization with different microlosica content. The performance of the material is evaluated through Proctor, CBR, and Unconfined Compressive Strength (UCS) normalized tests, following applied approaches in research of the same line of investigation [12].

The importance of this study lies in the generation of applicable experimental information on road Works, oriented to improve the mechanical behavior and subgrade soil durability. Besides, the results provide technical criteria for the use of microlisica, considering its potential in the optimization of the soil performance and the reduction of the environmental impact associated with conventional geotechnical engineering [13, 14].

2. Methodology and Materials

The study site was located on one of the Andean roads in the Huancán district, Huancayo province, Junín department, as shown in Figure 2, specifically along La Esperanza Avenue and its surroundings. The road is 510 ml and 8 to 12 meters wide (Figure 3). The roads are not paved, do not have sidewalks, and the surface is made of loose aggregate material. This layer is made of clay and is called the subgrade-Figure 2. The study site is located in Huancán-Huancayo-Junín.

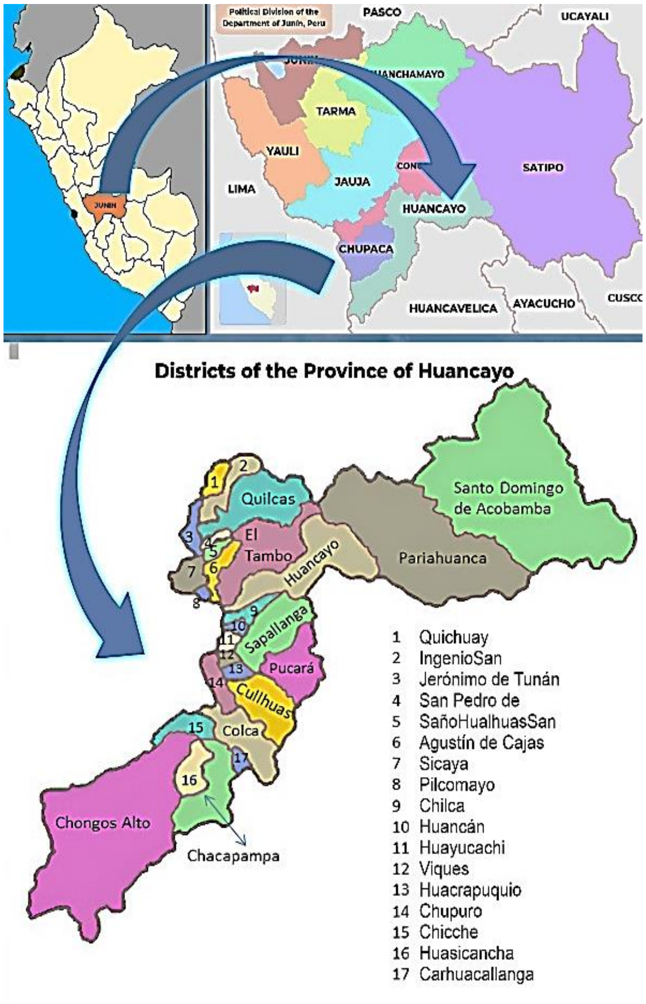

Fig. 1 **Location of the study site: Huancán Huancayo-Junín**

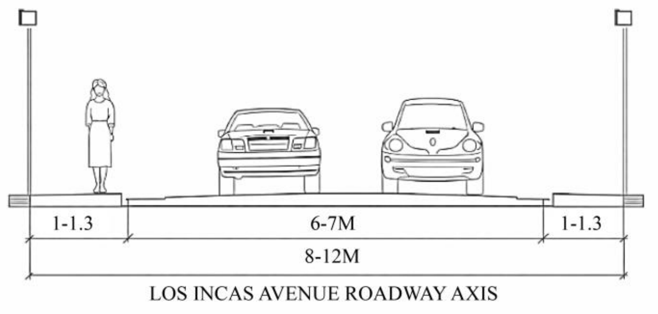

Fig. 2 Section of the Andean Road located in the Huancán district

In the research about its location, soil stabilization with less polluting additives to the Environment was proposed, since in high-Andean zones, the soil is used not only for building structures, but also for agricultural uses, and is an economic resource for the families living in these zones. Agriculture is a key socio-productive and economic axis in high-Andean regions, as it connects crop cultivation with livestock and traditional irrigation techniques and terraces [15]. The subgrade (road infrastructure component) is in contact with agricultural areas through water filtering. In high-Andean zones, hailstorms and snowfall events bring extreme rains or water accumulation, and these are responsible for filtering water into the subsoil, which brings components that change the composition of the soil itself. Carbon emissions are lowered by 8.74 times and 7.44 times relative to the carbon footprint of lime and cement, respectively, due to the carriage of harmful products such as lime and cement that have a high carbon footprint relative to other materials [16].

Water infiltration in subsoil also has a significant influence on water regulation in high Andean zones, where infiltrated water is temporarily stored in the subsoil and eventually fed to the flow of springs or flows during the dry season [17].

The following Table 1 demonstrates that traditional stabilisers for expansive soils, such as cement and lime, have a high carbon footprint in comparison to other alternative materials. The authors note that there are sustainable alternatives to soil improvement, e.g., use of materials with lower carbon emission, like natural pozzolanic materials and geopolymers [4].

Table 1. Stabilization of Clay Soil regarding its environmental impact [4]

Clay or Expansive Soil	Portland Cement	Very High	Its production generates a high carbon footprint and is one of the traditional stabilizers with the greatest environmental impact.
	Hydrated lime / Quicklime	High	Improves plasticity and strength, but its manufacture also involves calcination, energy consumption, and emissions.
	Lime + microsilica	Medium	Partially reduces dependence on cement and improves strength through pozzolanic reaction.
	Fly ash	Low	An industrial waste usable as a pozzolanic material; it can replace cement in stabilization.
	Natural pozzolana / Geopolymers	Low to Very Low	These are alternatives with lower environmental impact than traditional stabilizers.

2.1. Materials Used

2.1.1. Study Clay Soil

The evaluated clay soil from the Huancán district was obtained by extracting undisturbed material at a depth of approximately 0.5–1.5 m, corresponding to the representative subgrade stratum. We put the collected material in airtight containers and sealed bags to keep it from getting wet or dirty. Then we took it to the lab to be conditioned and treated.

The soil is intended to be used as road subgrade; therefore, its characterization and stabilization were focused on measuring changes in its compactness (OMC and MDD) and mechanical performance (CBR and UCS) under conditions that are compatible with pavement use.

In Figure 4, the location of the road can be appreciated. The needed quantity of soil for this current investigation is extracted from 3 points associated with different trial pits. Afterwards, humidity, specific weight, material washing through the N°200 mesh, granulometric analysis, and consistency limit tests were performed; meanwhile, for the Proctor test, 4 points were utilized for determining the compaction curve. For the CDR test, 3 models of each trial pit were prepared. Consequently, approximately 400 kg of the altered sample was collected, in which the humidity and the waste present in the tests were considered. Regarding the characterization that was obtained from the clayey soil extracted from the trial pit 1, representing the control sample: First, the standard granulometric analysis was performed, where more than 50% of the particles passed the mesh N°200 (fine grain), thus, the material finer than the N°200 sieve was determined by employing the hydrometer analysis. This passing percentage of the N°200 sieve was 74.31 % (Figure 5), classified as a soil of type CL (Low plasticity clay) according to SUCS (Table 2)

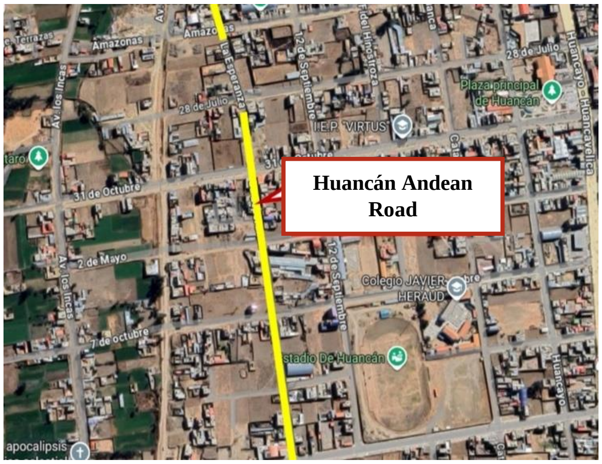

Fig. 3 **View of the Andean Road location in the Huancán district**

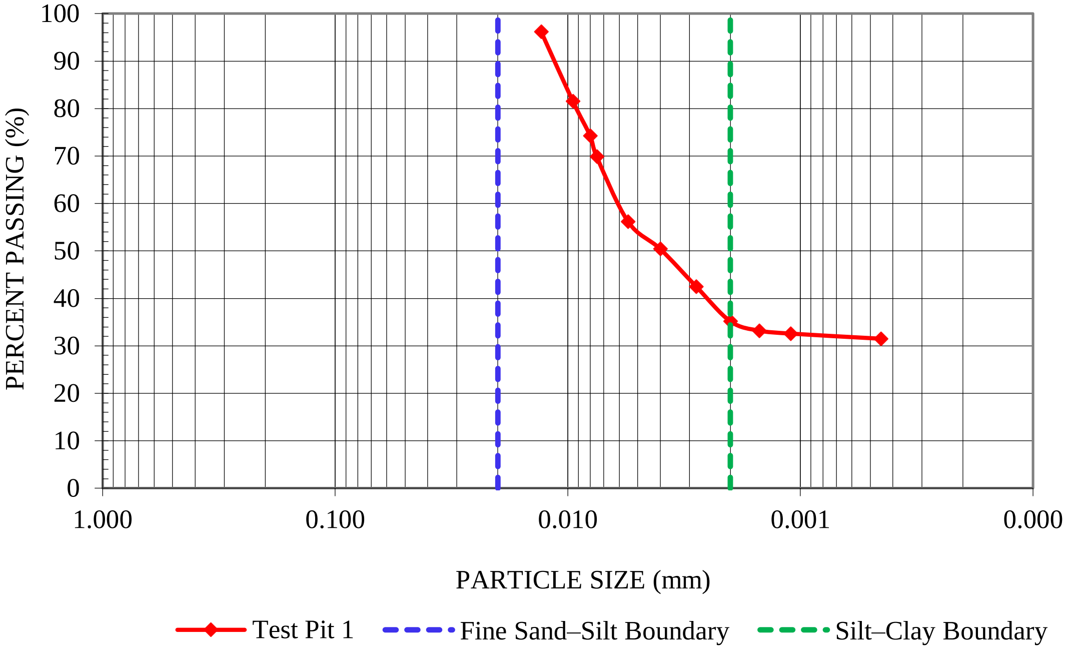

Fig. 4 **Grain size curve of the soil associated with the trial pit**

Table 2. USCS classification of each trial pit.

Sample	LL	L.P.	I.P	SUCS Classification
Trial pit 1	24.17	11.86	12.31	CL
Trial pit 2	23.95	10.21	13.74	CL
Trial pit 3	23.84	11.93	11.91	CL

2.1.2. Microsilica (Silica Fume)

Microsilica, also known as silica fume, is an industrial byproduct that is generated during the production process of silicon metal and ferrosilicon alloys in electric arc furnaces. It is mainly composed of amorphous silicon dioxide, and it is characterized by its extreme fineness. According to the definition of the American Concrete Institute (ACI), silica fume is a non-crystalline silica that is very fine and is produced as a byproduct of those industrial processes, and can present pozzolanic and cementing properties as well [18]. The main physical and functional properties of the employed microsilica are summarized in Figure 6, which presents the morphological, density, and physical state properties.

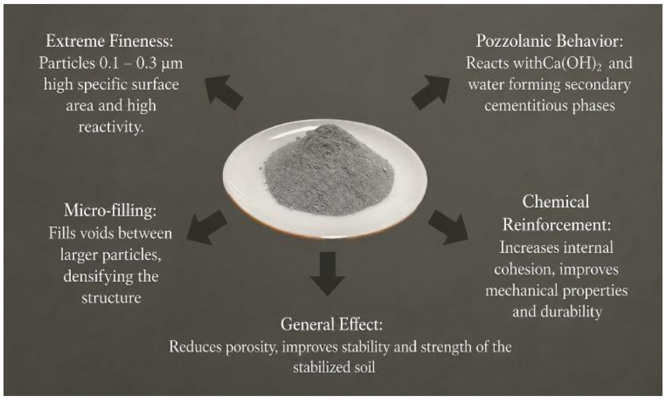

Fig. 5 Physical and functional properties of microsilica.

With the objective of complementing the description of microsilica and facilitating the comparison with other stabilizing materials. In Table 3 are presented the most relevant technical and physical properties.

Table 3. Physical and chemical properties of microsilica [18]

TECHNICAL PROPERTIES	
State	Amorphous – Sub – micron powder
Color	Gray powder
Specific Gravity	2.10 to 2.40
Solubility	Insoluble
Bulk Density - Densified	600 to 650 kg/m³
Bulk Density - Undensified “as produced.”	300 to 350 kg/m³

2.2. Experimental Design

2.2.1. Microsilica Dosage

The percentages of microsilica were selected based on the reported ranges in the literature for fine soils stabilization [19]. This current investigation adapts those ranges for their application in clayey soil, evaluating their effect on the behavior of the material in Table 4.

For the research, the dosage was prudent and optimal according to the quality of the soil and the additive, and the dosages are obtained by collecting background data, which are dependent on the components of the stabilizing material. Recent research with the use of high-efficiency additives, such as nanochemicals, biopolymers, and fibers, has shown the best improvements with the lowest percentages (close to 1%–2.5%) [20]. Higher ranges were obtained with mineral wastes or mineral waste materials, including recycled glass powder, limestone waste, ash, and cementing mixtures, where the content of wastes ranged, in research, from 3% to 20% [21].

Based on the results of the background information, the proposed dosages for the research are 2%, 4%, 6%, and 8%, which are within a reasonable range, allowing the study of the behavior of microsilica from a low increment to an intermediate increment while maintaining the soil structure and ensuring its technical and economic efficiency.

Table 4. Nomenclature and microsilica dosage evaluated.

Mix Code	**Microsilica Content (% of dry soil weight)**	**Description**
MS-2	2 %	Low dosage
MS-4	4 %	Intermediate dosage
MS-6	6 %	High dosage
MS-8	8 %	Elevated dosage

2.2.2. Preparation of Soil–Microsilica Mixtures

The preparation of the soil-microsilica mixtures was carried out following the systematic procedure similar to the one employed in previous studies about stabilization in soils with sustainable materials (Figure 7). That procedure included the preparation and sieving of the soil, the components weighing, the dry mixture of the soil with microsilica, the controlled addition of water, and the humidity homogenization until a uniform mixture was reached. In cases where the humidity or the homogeneity did not comply with the established criteria, the necessary settings were performed before the final conditioning of the samples for the corresponding tests.

Fig. 6 Huancan clay soil and microsilica

This process is represented in a scheme in Figure 8, where the rectangles indicate the performed actions and the diamonds show the decisions or quality control applied during the preparation of the mixtures.

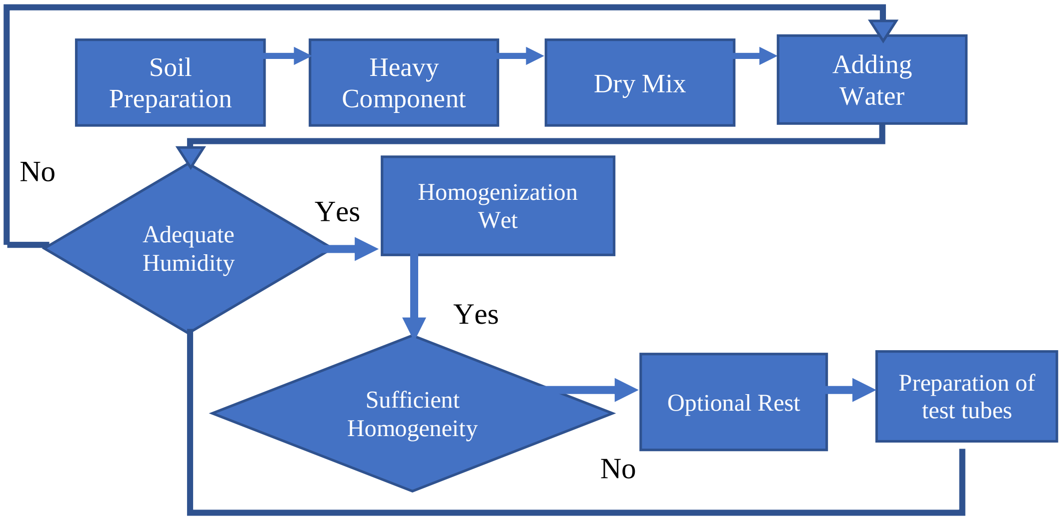

Fig. 7 Flowchart of the soil-microsilica mixture preparation process

2.2.3. Sample Curing

The specimens compacted at the optimum humidity (Proctor) were sealed (plastic or hermetic bags) with the aim of avoiding the loss of humidity and were cured in a humid environment between 20-25 °C. Ages in the range of 7, 14, and 28 days were considered (day 0 = molding). For each dosage, independent specimens were prepared and classified by their age. Once the programmed time was reached, the specimens were tested immediately, and this can be observed in Table 5. The section of the ages corresponds to the progressive development of the pozzolanic reaction associated with the microsilica and the gradual gain in strength.

Table 5. Curing schedule and applied tests.

Stage	Age (days)	Test(s)	Purpose
Characterization/ compaction	0	Proctor	Obtain OMC and MDD for molding
Mechanical evaluation (curing)	7	UCS, CBR	Early response
Mechanical evaluation (curing)	14	UCS, CBR	Intermediate evolution
Mechanical evaluation (curing)	28	UCS, CBR	Reference response

3. Experimental Program and Testing Methodology

3.1. Mix Proportions

In this research, specific microsilica proportions were utilized for the analysis of four mixture configurations. A total of 225 specimens were tested in order to analyze their mechanical and physical properties, including the consistency limits, humidity content, and the subgrade bearing capacity, according to the norms NTP 339.129 [22], NTP 339.141 [23], NTP 339.145 [24] y NTP 339.167 [25], respectively.

The configuration included a partial substitution with microsilica in the following proportions 2 %, 4 %, 6% y 8 %. The details of the proportions utilized in each configuration are presented in Table 6.

Table 6. Nomenclatures used for the mix proportions.

Replacement Proportion (%)	Nomenclature
Clay Soil	SA
Microsilica Replacement	**Nomenclature**
2%	2 MS
4%	4 MS
6%	6 MS
8%	8 MS
Clay Soil and Microsilica Combination	**Nomenclature**
98% Clay Soil + 2% Microsilica	98 SA + 2 MS
96% Clay Soil + 4% Microsilica	96 SA + 4 MS
94% Clay Soil + 6% Microsilica	94 SA + 6 MS
92% Clay Soil + 8% Microsilica	92 SA + 8 MS

3.2. Moisture Content

The test to determine the moisture content in the Andean Huancan soil through direct heating was performed according to the guideline NTP 339.129 [22], whose aim is to determine the water content in the soil by drying the humid sample. For this objective, humid samples were weighted according to each configuration of the mix in different proportions.

Subsequently, the samples were placed in the furnace at a controlled temperature of 105 °C until reaching a constant weight. This process guaranteed the total elimination of the samples, as shown in Figure 9.

Fig. 8 Water reduction in soil samples by heat

Once dry, the samples were weighed again with the purpose of obtaining the dry weight of each of them. From this data, the moisture content was calculated by using the formula below.

$$\omega(\%) = \frac{M_{CWS} - M_{CS}}{M_{CS} - M_C} x100 = \frac{M_W}{M_S} x100 \qquad (1)$$

Where: "$\omega(\%)$"Is the moisture content, "M_{CWS}" is the recipient mass plus the wet sample (gr), "M_{CS}" is the recipient mass plus the oven-dry sample (gr), "M_C" is the recipient mass (gr), "M_W" is the water mass (gr), "M_S" is the mass of the solid particles (gr).

3.3. Consistency Limits

The tests for Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) were executed according to the guideline NTP 339.129 [22]. The test for Liquid Limit (LL) determines the water content at which the soil changes from a plastic state to a liquid one. For this purpose, a natural soil sample is placed with a specific content of water in a brass cup, and a standard cone is dropped in the soil with the aim of measuring the number of blows required for closing the 12,7mm groove. In this way, the liquid limit is determined. For the Huancan soil sample, the microsilica is added in variable proportions (2 %, 4 %, 6 % y 8 %), replacing an equivalent percentage of soil. Modified and natural soil samples were analyzed, employing the same procedure, registering the number of blows and the weights of the dry and wet samples. The Plastic Limit (PL) measures the water content at which the soil goes from a plastic state to a semisolid state-rolling a thread of soil until its moisture content is reduced and forms a filament of approximately 3,2 mm in diameter (1/8 inch). Afterwards, this sample is dried in the furnace. The moisture content is reported as the plastic limit. The plasticity index was calculated as the result of the difference between the liquid limit and the plastic limit. The plasticity index is calculated as indicated below:

$$PI = LL - LP \qquad (2)$$

Where: "PI" is the plasticity index, "LL" is the liquid limit, and "PL" is the plastic limit.

3.4. Modified Proctor Compaction Test

The soil compaction test in the laboratory through the modified Proctor approach followed the guidelines of the norm NTP 339.141 [24] as shown in the Figure 10, that defines the approach applying an energy of 2700 kN·m/m³ (56 000 ft-lbf/ft³) for evaluating the characteristics of soil comparison, specifically, the Maximum Dry Density (MDD) and the Optimum Moisture Content (OMC). The modified proctor test consisted of compacting the soil in a mold with a hammer of 4,54 kg, applying 25 blows per layer in three layers, increasing the water content by 3 % per test. For the soil sample, the microsilica was added in the following proportions 2 %, 4 %, 6 % y 8 %, replacing the soil percentages, and it was tried in the same conditions as in natural soil, with all the registered data of the weights in the datasheet.

Fig. 9 Modified Proctor compaction and equipment during execution

The proctor test was performed according to the standard NTP 339.127 [26], with the objective of determining the Optimal Moisture (OMC) and the Maximum Dry Density (MDD), utilized in the molding of the specimens for the mechanical tests.

$$p_m = \frac{1000x(M_t + M_{md})}{V} \qquad (3)$$

Where: "p_m" is the wet density of the compacted sample (Mg/m³), "M_t" is the mass of the wet sample and the mold (kg), "M_{md}" is the compaction mold mass (kg), "V" is the volume of the compaction mold (m3)

$$\rho_d = \frac{\rho}{1+\omega/100} \quad (4)$$

Where: "ρ_d" is the dry density of the compacted sample (Mg/m³), "ω" is the water content (%)

3.5. California Bearing Ratio (CBR) Test

The CBR test was executed following the guidelines of the norm NTP 339.145 [24]. This trial approach is utilized mainly for the evaluation of the strength of cohesive materials with a maximum particle size of 19.0 mm (3/4 inch).

The procedure of the performed tests started with the preparation of 4 specimens for each mix configuration. Subsequently, the specimen is submerged completely in water for 4 days in order to simulate the moisture conditions. After the periodic curing process of 7, 14, and 28 days, the specimen is placed along with the CBR test equipment, as shown in Figure 11.

Fig. 10 Preparation of samples for CBR testing

3.6. Unconfined Compressive Strength (UCS) Test

The Unconfined Compressive Strength test (UCS) of the soil is performed following the described instructions in the standard NTP 339.167 [25]. This test determines the compressive strength of the soil samples without lateral confinement, which provides a quick evaluation of the soil stability. For the tests, a deformation speed of 1 mm/min was applied with the objective of evaluating the strength differences between the soil treated with microsilica. The samples were prepared with 2%, 4%, 6% y 8% of each addition, were modeled in cylindrical forms (height-diameter index of 2:1), were sealed in plastic bags to retain moisture, and were cured at 20 °C for 7, 14 y 28 days. After the curing process, the samples were subjected to axial loading until failure, and the maximum load was recorded to determine the UCS values.

$$q_\mu = \frac{P_{max}}{A_0} \quad (5)$$

Where: q_μ is the unconfined compressive strength (MPa, kg/cm² or kPa), P_{max} is the maximum load and A_0 is the initial cross-sectional area. The UCS allows the comparison of the mechanical performance among dosages and curing ages [27].

3.7. Data Analysis Procedure

The experimental data were organized by the test conditions (clay soil and stabilized mixes), microsilica dosage, and curing age. For each variable of answer (OMC, MDD, CBR y UCS), the descriptive statistics: average and standard deviation, were calculated from the available replicates. The performance comparison between the dosages was executed through the variation analysis of each property with the microsilica content, and when it corresponded, with the curing time. Additionally, the improvement with respect to the natural soil was quantified by using the percentage increment:

$$\%\Delta X = \frac{X_{est} - X_{nat}}{X_{nat}} x100 \quad (6)$$

Where X_{est} corresponds to the value of the stabilized soil and X_{nat} corresponds to the natural soil (clay soil). The dosage with better performance was identified from the biggest increment in the CDR and or the UCS, considering the CDR index as the representative parameter of the bearing capacity of the subgrade, confirming the criteria of the already established pavement design in AASHTO Guide for Design of Pavement Structures (1993), and keeping the parameters of compatible compaction with its practical application [28].

4. Results and Discussions

4.1. Atterberg Limits

Table 7 presents the Atterberg limit results for each specimen, and in Figure 12, the average values of these limits are indicated, and as can be observed, the control soil presents an LL of 23,99 %, an L.P. of 11,33 %, and an I.P. of 12,65 %. These outcomes demonstrate that the soil possesses a significant compressibility (higher LL) and is susceptible to volume changes (higher I.P.). Hence, the subgrade level needs stabilization [19].

In the case of the soil with Microsilica (MS) added, both the LL and the L.P. have an increasing trend as the MS content increases; the LL increases up to 23.6%, as shown in Figure 12. The microsilica possesses a superficial area that is extremely high due to the size of its fine particles, increasing the general superficial area of the soil when it is incorporated into the soil, and its water retention capacity improves as well, which leads to an increase in the LL [29]. A particular case, when the microsilica level is 6%, fills the voids and strengthens the links among particles, increasing the L/P/ and the water retention. On the other hand, when employing the MS of 8%, the clayey minerals experience a more intense pozzolanic reaction, although strengthening the bonds, triggering a reduction in the soil capacity for retaining water, which reduces the L.P.

Table 7. Atterberg Limits

Description				**Atterberg Limit**		
Item	Code	Group Code	Description	LL.	L.P.	I.P.
N	Clay Soil [CS]					
1	N01	Control soil	[SA] 100%	24.17	11.86	12.31
2	N02	Control soil	[SA] 100%	23.95	10.21	13.74
3	N03	Control soil	[SA] 100%	23.84	11.93	11.91
R	Clay Soil [CS] + Microsilica [MS]					
4	R01.1	MS 2%	[SA] 98% + [MS] 2%	26.34	14.84	11.50
5	R01.2	MS 2%	[SA] 98% + [MS] 2%	26.01	15.73	10.28
6	R01.3	MS 2%	[SA] 98% + [MS] 2%	26.42	16.65	9.77
7	R02.1	MS 4%	[SA] 96% + [MS] 4%	31.01	22.36	8.65
8	R02.2	MS 4%	[SA] 96% + [MS] 4%	30.74	23.45	7.29
9	R02.3	MS 4%	[SA] 96% + [MS] 4%	30.53	20.40	10.13
10	R03.1	MS 6%	[SA] 94% + [MS] 6%	28.59	22.55	6.04
11	R03.2	MS 6%	[SA] 94% + [MS] 6%	29.60	23.47	6.13
12	R03.3	MS 6%	[SA] 94% + [MS] 6%	29.20	24.03	5.17
13	R04.1	MS 8%	[SA] 92% + [MS] 8%	31.12	20.82	10.30
14	R04.2	MS 8%	[SA] 92% + [MS] 8%	30.89	21.75	9.14
15	R04.3	MS 8%	[SA] 92% + [MS] 8%	32.15	22.35	9.80

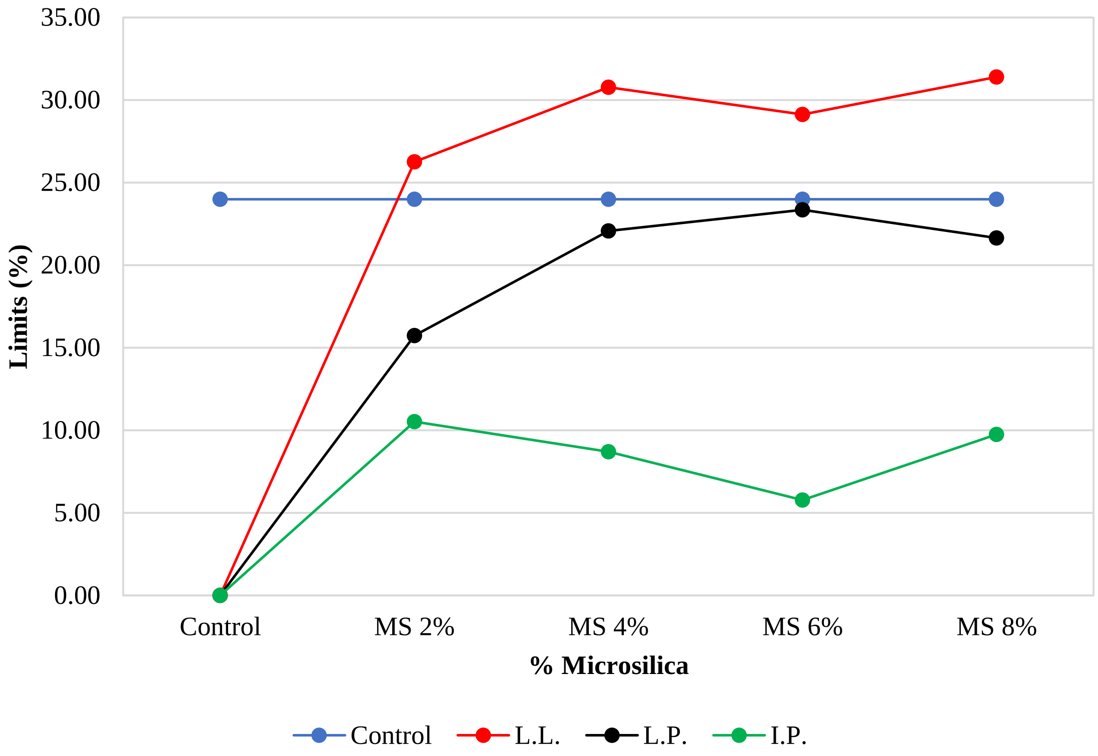

Fig. 11 Variation of Atterberg Limits of Huancán soil with microsilica addition

Conversely, the Plasticity Index (I.P.) is reduced as long as the MS increases up to a dosage of 6%, and with the addition of MS of 8%, the soil becomes more plastic. On the other hand, with a microsilica content between 2% - 6%, the I.P. decreases as the flocculation and agglomeration of clay particles reduce the plasticity [30]. The fine silica particles are absorbed in the clay Surface, which limits the water retention and reduces the gap between LL and L.P. This plasticity index increases with an MS of 8% because an excess of fine particles improves water retention, slows the pozzolanic processes, and raises the plasticity significantly. The strongest pozzolanic reactions were the ones with 6% of microsilica, which makes L.P. mode adequate, enhancing cementation and the particle aggregation while reducing the soil plasticity and stabilizing it as a subgrade layer [30].

Figure 13 illustrates the average of the Maximum Dry Density (MDD) of clay soil related to the Optimal Moisture Content (OMC), in which the control sample showed a value of MDD of 1.85 gr/cm³ with an OMC of 11.41 %. The MS addition between 2 and 6% originates an increment in the MDD and the OMC, reaching MDD values of up to 1.91 gr/cm³ and OMC 13.43 %. The MDD increase is attributed to the fine nature of the microsilica, that fills voids between the soil particles, which leads to a more dense disposition of particles, which can increment the cohesion forces among the soil particles, altering, in this way, the natural structure of the soil, resulting in an stabilization potential and soil compaction [31], besides, this raise occurs mainly due to the less specific gravity of microsilica tan the soil particles, which makes the soil and additive mix more compact and stable [31].

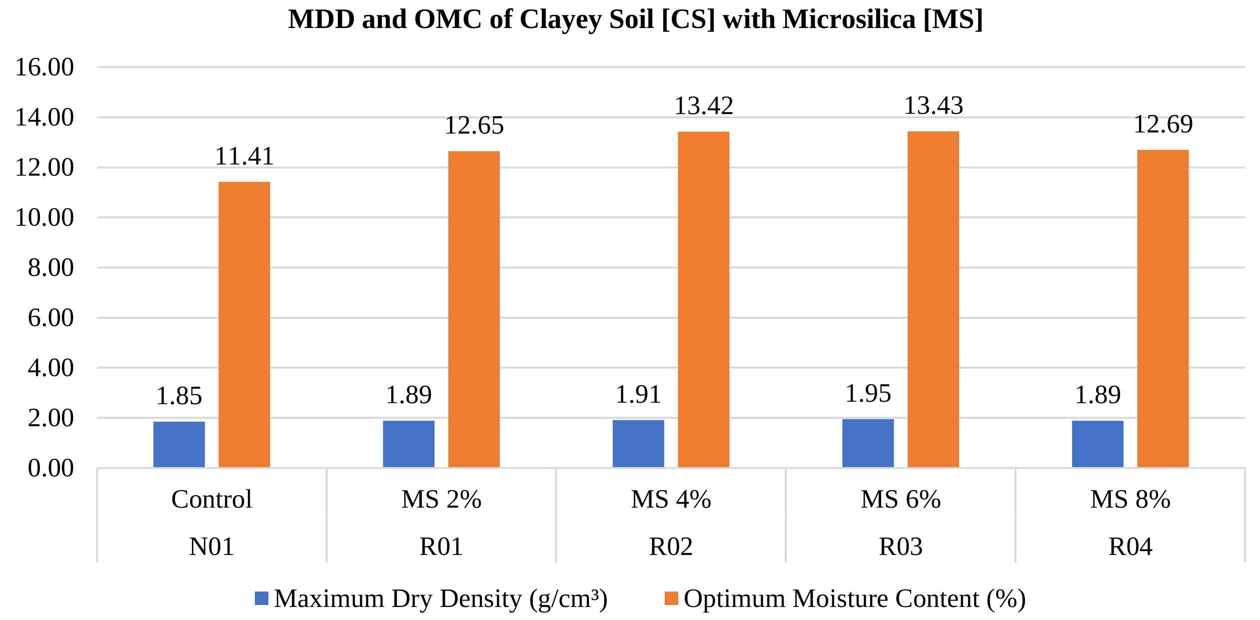

Fig. 12 MDD and OMC obtained from microsilica addition in the soil

4.2. Dry Density

On the other hand, the dosage of 8% of MS, the MDD reduces in the same way of the OMC, which shows a reduction in comparison with the MS of 6%, as shown in Figure 13., this effect occurs once surpassing the pozzolanic reaction of the stabilizing soil, when the MS excess and the stable reaction of the flocs are added, the permeability of the clay component is notably reduced, triggering moisture restrictions in the internal layer of the clay matrix, altering the biggest superficial layer of humidity in the stabilizing soil.

Figure 14 shows the level of variation of the samples with the proposed DM dosage with respect to the standard sample for MDD, evidencing an increasing tolerance up to a dosage of 6 % DM in the OCM; however, when using a dosage of 8% DM the resistance capacity is lost reaching only as the 2% DM sample, the increase to the margin of 6% DM is attributed to the filling and better packing, however when it reaches 8% DM an overdosing occurs. This explains that at higher contents of micro silica, there are surfaces in the compaction layers without hydration, although there is optimum moisture for the ideal instantaneous compaction, but in time it does not hydrate the mixture leaving dry parts without hydration; in addition, on the other hand, the partial replacement of the soil by an ultrafine material of lower bulk density and the tendency to flocculate agglomerate decrease the efficiency of the rearrangement under compaction, resulting in lower MDD [32]. In addition, as expected, the use of MS requires an OCM of approximately 9.8 % as a minimum value to increase the MDD capacity with respect to the standard, as shown in Figure 15.

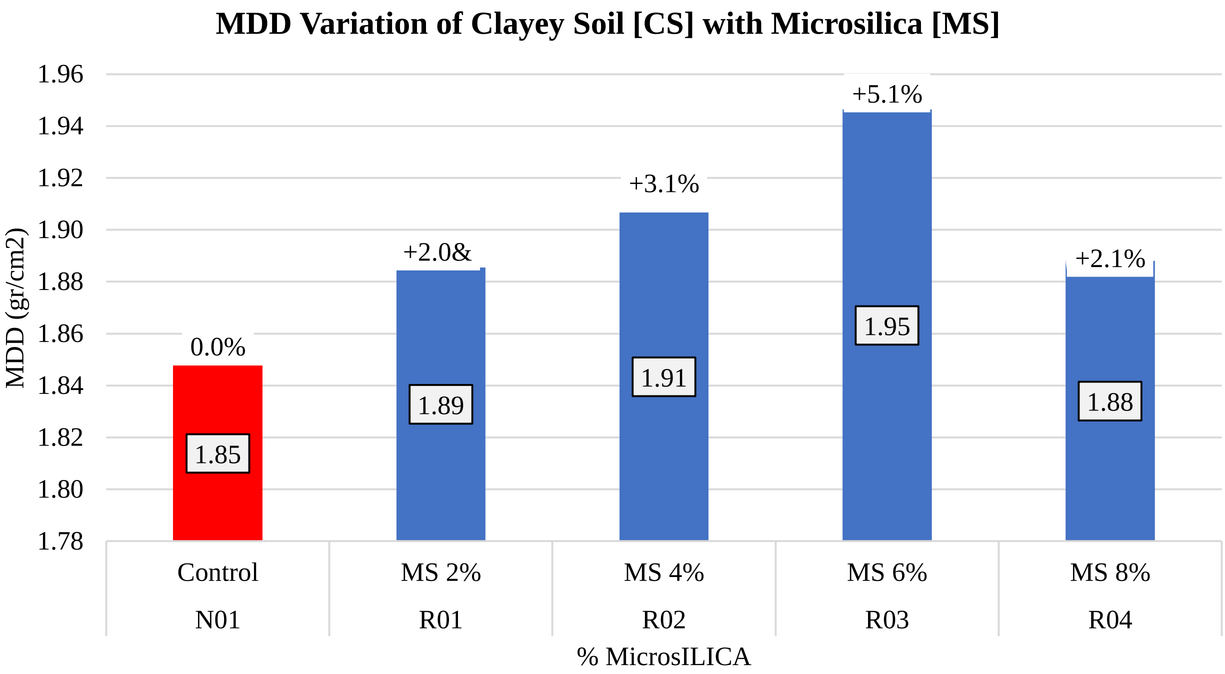

Fig. 13 Variation of average maximum dry density of clay soil with microsilica addition

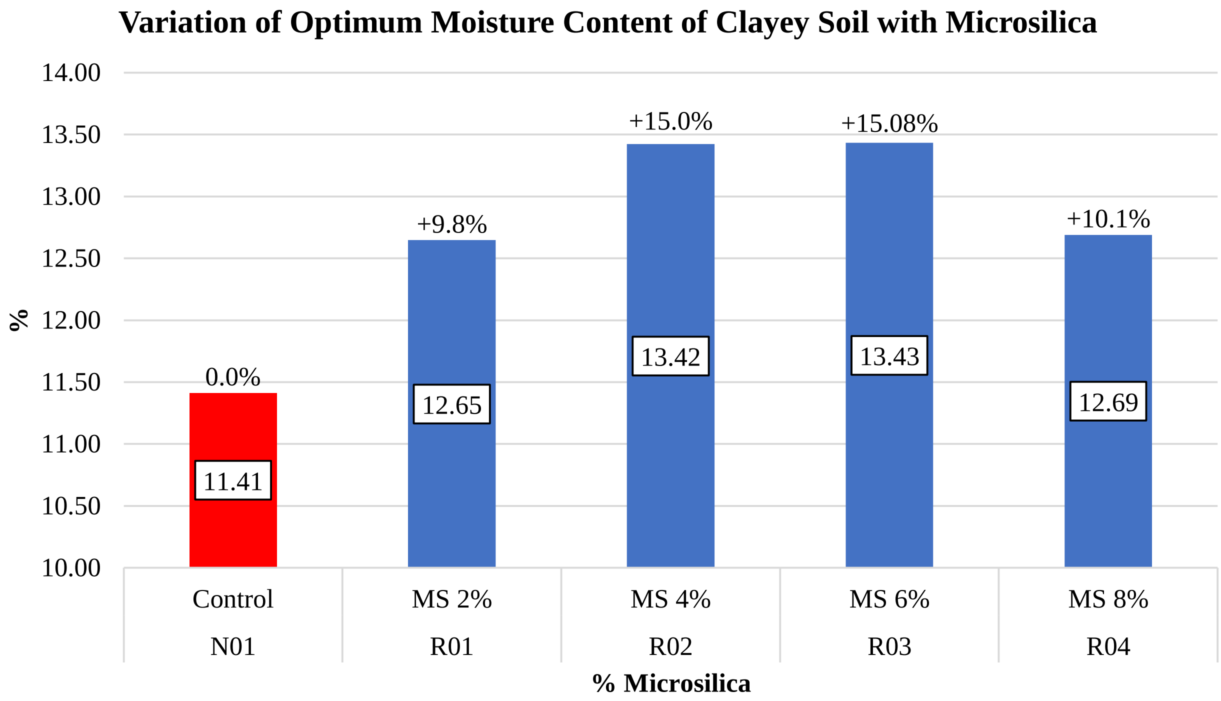

Fig. 14*:* **Variation of average optimum moisture of clay soil with microsilica addition**

4.3. CBR Test

Table 8 shows the variability parameters in the CBR tests for each category of trial pit. In which the values with less variability (standard deviation) were found in the control sample and the sample with MS of 6%. On the other hand, the samples with higher variability were found in the samples with MS of 2%, which can trigger a smooth CBR variation in average values.

Table 8. Variability parameters for each soil type in the samples

CBR at 100% and 95% for 0.1" y 0.2" Clay Soil [CS] + Microsilica [MS]						
Description		N01	R01	R02	R03	R04
Addition	Sample	Control	MS 2%	MS 4%	MS 6%	MS 8%
CBR at 100% of MDS for 0.1."	MEDIA	5.45	16.37	18.25	22.01	18.67
	MIN	4.51	14.92	16.61	21.62	17.84
	MAX	6.31	17.59	19.80	22.67	19.22
	EST.DEV.	0.903	1.351	1.597	0.577	0.731
CBR at 95% of MDS for 0.1."	MEDIA	4.31	15.37	17.05	21.20	16.84
	MIN	3.35	14.07	15.79	20.76	16.02
	MAX	5.29	16.84	18.17	21.83	18.46
	EST.DEV.	0.970	1.393	1.196	0.558	1.407
CBR at 100% of MDS for 0.2."	MEDIA	4.89	15.00	15.18	20.70	16.27
	MIN	4.19	14.35	14.42	20.34	15.36
	MAX	6.14	16.29	15.95	21.41	17.90
	EST.DEV.	1.083	1.120	0.765	0.612	1.409
CBR at 95% of MDS for 0.2."	MEDIA	4.48	13.97	14.01	19.72	14.67
	MIN	4.19	13.27	12.83	19.35	13.95
	MAX	5.07	14.84	15.23	20.37	15.46
	EST.DEV.	0.508	0.798	1.200	0.562	0.758

Figure 16 exhibits the values obtained from the CDR executed tests, where the values were obtained from the three trial pits. The control sample depicted an average of 4.5% for a CBR of 100% correspondent to the 0.1, and a CBR of 4.31 % - 100% of MDS, corresponding to the 0.2". In the samples with MS of 6%, 22.01% was obtained for a CBR-100% of MDS correspondent to the 0.1" and 21.20 % for a CBR - 95% of MDS correspondent to the 0.2". The rise of the CDR percentage results from the adequate puzzolonic mix among the mechanical components of the structure, which provides a higher deformation and volume change, adequate for the stabilization of the subgrade of the clay soil, within the prescribed parameters by current regulations [33]. On the other hand, the microsilica excess (over 9%) triggers difficulty during compaction, reducing confined packing of particles, and therefore, losing cohesion [19]

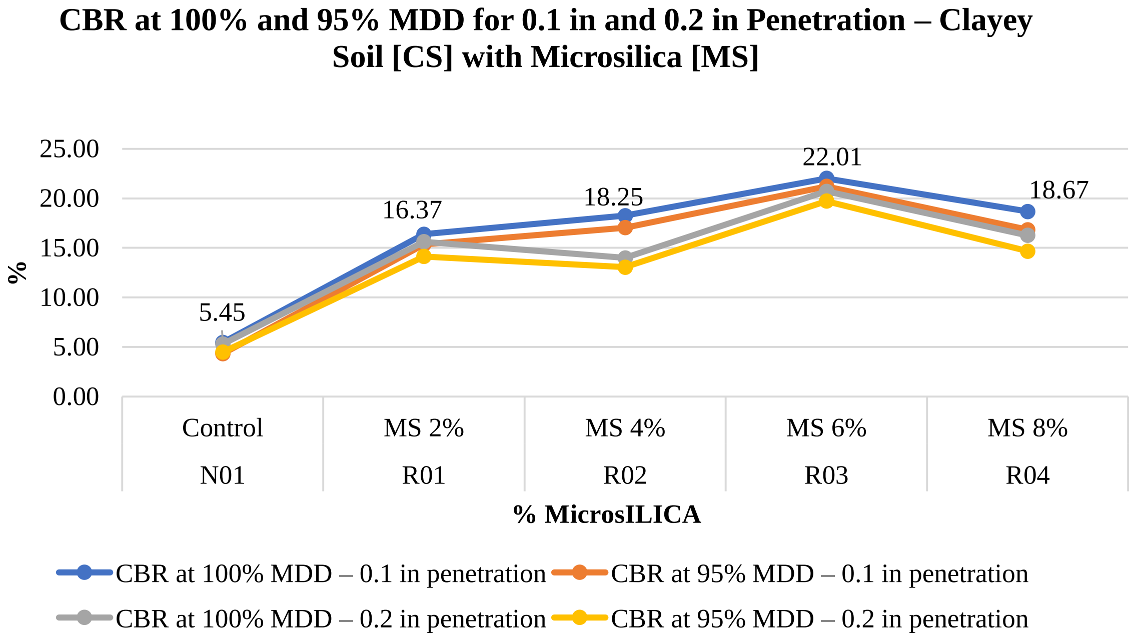

Fig. 15 CBR at 100% and 95% for 0.1" and 0.2" of the specimens

In Figure 16, the typical optimal dosage behavior is exhibited; the CBR of the control soil increases markedly from 2-6%, the microsilica is an extremely fine particle, which is why it can fill gaps. This feature favors a more dense distribution of the particles, and when there is chemical availability, the microsilica acts as a cementing element on a low scale due to its own calcium content in the clay that contributes to a more rigid matrix; this reflects higher CBR values. Recent studies with siliceous additives report an increase in the bearing capacity and improvements in the mechanical properties under ideal dosages [34].

4.4. Unconfined Compressive Strength (UCS)

Figure 17 shows the curing effect in the Unconfined Compressive Strength (UCS) of stabilized soil with MS, evaluated at 7, 14, and 28 days. The outcomes demonstrate an increment in the UCS with the addition of MS in the proposed dosages. Nonetheless, the control sample with the value of 1.85 Kg/cm2 in the 28 days is under the stabilization limit for subgrade soils. The highest UCS corresponds to 7.03 Kg/cm2, which was achieved with a sample of 6% of MS after 28 days of curing, as shown in Figure 15. Nevertheless, the prolonged curing time affects the UCS favorably, because Calcium Silicate Hydrate (CSH) gels formed during the pozzolanic reactions bind soil particles and reduce porosity. This situation translates to a positive strengthening in the soil matrix, specifically for the clay soil, raising the soil resistance to deformation and enhancing its compressive strength. Besides, microsilica contributes to the mitigation of negative effects of curing on the soil properties like expansion and contraction, which in the last instance involves an enhancement of the mechanical properties of the soil [35].

Additionally, this increment from 1.85 kg/cm2 to 7.03 kg/cm2 in the UCS utilizing an MS of 6% demonstrates that the addition of MS in the clayey soil increments the mechanical properties of the soil in a favorable manner for the application of road subgrade stabilization, besides reaching the adequate values according to the established pavement design criteria established in [36].

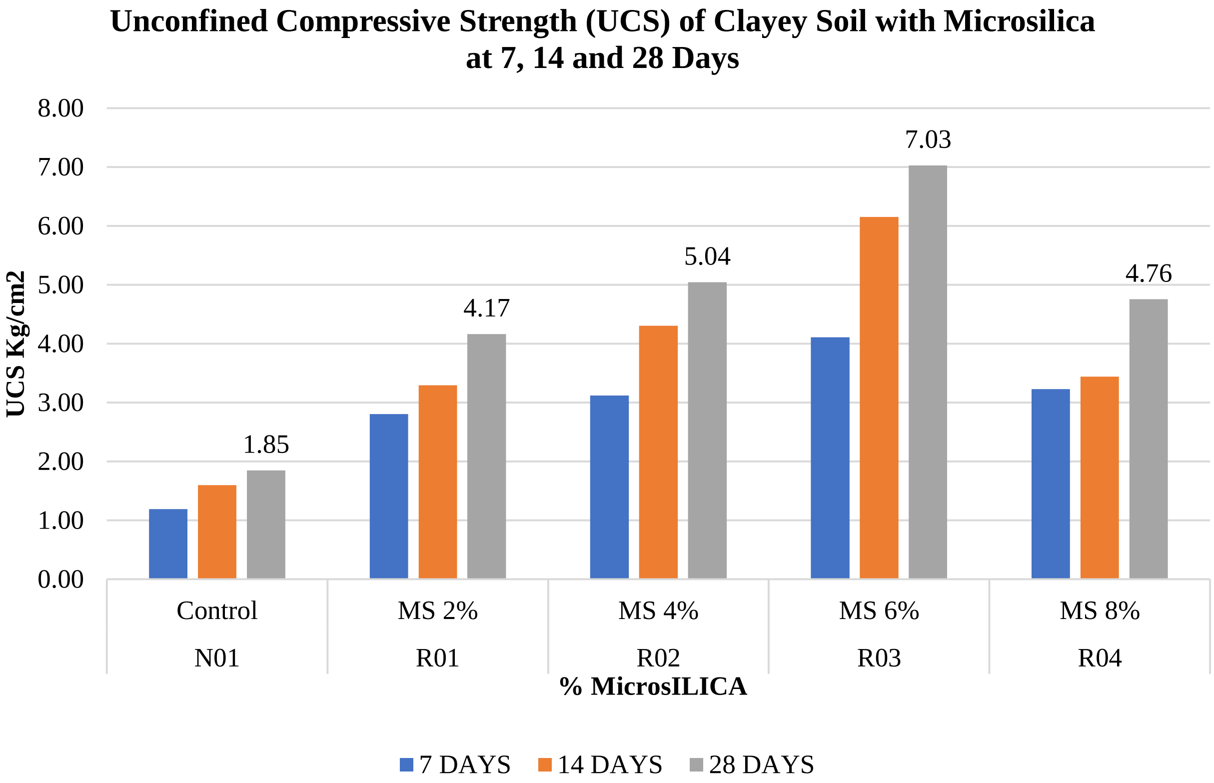

Fig. 16 Average compressive strength for ages of 7, 14, and 28 days

4.5. Treatment of Results

In Table 9, the results of the treatment are exhibited through the ANOVA test, which gave mechanical properties numbers with a value of <0.05 for all the tests. This indicates that the Null Hypothesis ($H0$) is rejected and the alternative hypothesis is accepted ($H1$). This last hypothesis mentions that there are changes in the mechanical properties among various treatments performed, essentially with the addition of 6% microsilica to the clay soil. Thus, the addition of microsilica improves the mechanical properties of the soil significantly with respect to the subgraded stabilization of the Andean road [35].

Table 9. Treatment of results using the ANOVA test

ANOVA Clayey Soil [CS] + Microsilica [MS]				
ANOVA	Description	G.L.	F	P - valor
Maximum Dry Density	Between specimens	4	7.28	0.005156
	Within specimens	10		
	Total	14		
Optimum Moisture Content	Between specimens	4	4.85	0.019512
	Within specimens	10		
	Total	14		
CBR at 100% MDD for 0.1."	Between specimens	4	98.79	0.000000
	Within specimens	10		
	Total	14		
CBR at 95% MDD for 0.1."	Between specimens	4	91.12	0.000000
	Within specimens	10		
	Total	14		
CBR at 100% MDS for 02."	Between specimens	4	93.95	0.000000
	Within specimens	10		
	Total	14		
CBR at 95% MDS for 02."	Between specimens	4	141.58	0.000000
	Within specimens	10		
	Total	14		
7-Days UCS	Between specimens	4	17.53	0.000163
	Within specimens	10		
	Total	14		
14-Days UCS	Between specimens	4	50.15	0.000001
	Within specimens	10		
	Total	14		
28-Days UCS	Between specimens	4	48.88	0.000002
	Within specimens	10		
	Total	14		

4.6. Comparative Performance, Economic Sustainability, and Environment

Extensive testing under strict regulatory and quality requirements optimally generated the interaction of microsilica and clay soil, using a dosage percentage of the clay soil replaced by microsilica of 6%. When a sufficient amount of the improvement material was achieved, this parameter enabled us to compare the pollution produced by its incorporation in the soil with other stabilising agents (Table 10), and it was concluded that the microsilica was the least polluting of the different agents used to improve clay soils.

Table 10. Environmental Evidence regarding stabilization methods [37]

Stabilizing material	Environmental Impact regarding stabilization methods
Portland Cement	According to [38], cement manufacturing emits approximately. 0.95 t of CO_2 per ton of cement, and conventional cement is one of the main sources of environmental impact in cementitious mixtures.
Hydrated lime / Quicklime	According to [39], regarding the production of hydrated lime, the study reports a GWP of 0.94 kg CO_2-eq/kg of hydrated lime. Additionally, it indicates that changes in kiln fuel can reduce GWP by 9%, 18%, and 22% compared to the baseline scenario.
Fly ash	According to [38], the maximum replacement of clinker by secondary cementitious materials, including industrial byproducts such as fly ash, could have avoided up to 1.3 Gt CO_2-eq in 2018, equivalent to approximately. 44% of cement production emissions.
Microsilica / Silica fume	According to [43], the study evaluated geopolymer concrete with fly ash and microsilica. It reported that geopolymers have lower GWP than cement concrete, and that the activated fly ash–microsilica mixture without sodium silicate presented the lowest environmental impacts.

For expansive soils, it is reported that composite cement–microsilica stabilization increases the durability of expansive soils due to the formation of C–S–H gel, which maintains 84.4% of the original strength even after the wetting and drying cycle [41]. This is a beneficial interaction between soil-cement and microsilica; however, in terms of the use of both components, the environmental pollution resulting from the use of soil will not be reduced, so the research proposes to use microsilica alone.

In the study of expansive subgrade soils [42], the combination of micro silica and polypropylene fibres for its microphysical and mechanical behaviour in soil classified as a high-plasticity inorganic clay soil under freezing and thawing cycles, reaching maximum Unconfined Compressive Strength (UCS) values of 5003.51 kPa after 28 days of curing. In the research, in which only microsilica was used (without large amounts of other products that would change the characteristics of the soil), with appropriate doses without adding to the carbon footprint, we were able to achieve the value of 7.03 kg/cm² or 689.407 kPa after 28 days of curing.

Given the fact that components are, for the most part, industrially obtained, the research did not include an economic evaluation, although it is not absent from this factor. For this reason, the unit cost analysis through industrial or home production was carried out by making use of a unit price analysis. Costs were arranged with regard to material, labour, equipment, processing, waste, control, and collection. The unit price analysis involves a set of resources, including their units, unit costs, yields, and quantities, and each unit price will consist of such a set [43].

Table 11. Cost analysis by stabilizing material

Material	Main Material (S/)	Auxiliary inputs (S/)	Labor (S/)	Tools (S/)	Equipment (S/)	Control and storage (S/)	Total UPA Cost (S/ per t)
Lime	428.40	12.00	5.80	0.17	3.24	1.50	451.11
Cement	673.20	8.00	5.80	0.17	2.16	1.00	690.33
Fly ash	370.80	18.00	6.70	0.20	3.60	2.50	401.80
Microsilica	2,472.00	41.00	7.86	0.24	3.96	5.00	2,530.06

As we can observe in the following graph, obtaining microsilica in comparison with other stabilizing materials is not economically sustainable, as it is a process that demands more control, as shown in Table 11. Silica fume / microsilica as an additive in stabilized soft soils can be utilized as a recycled pozzolanic material for improvement of soft soils due to its high SiO_2 content, a high specific surface area, and the capacity to promote the formation of C-S-H gel, which fills voids [44]. The results of the researched parameters and compared values with the background information indicate that the stabilisation with mineral additives, industrial waste, biopolymer, and pozzolanic materials can result in a significant improvement of the mechanical properties of the subgrade soil. The research on clay soils using microsilica, for areas of the high Andean regions (Huancayo, Huancan area), obtained suitable and optimal improvement results from the interaction of both materials, due to the optimal dosage obtained. Based on [45], they tested contents of 2%, 4%, and 8% microsilica in expansive clay soils, and found that the more microsilica they added, the less swelling pressure, and the better the behavior of the soil for use in pavement subgrade. They concluded that the swelling pressure was decreased from 67.21 kPa to 34.02 kPa, which is a reduction of 49.38%, at 8% microsilica content. This supports the results from the research on the interaction of clay soil and microsilica at the optimum amount of 6% for both.

Concerning compressive strength, [42] used 8% microsilica and added 0.5% polypropylene fiber to the subgrade soil and obtained an appropriate value for compressive and tensile strength; thus, the ratio of 8% microsilica to 0.5% polypropylene fiber was found as an optimal ratio for subgrade soil stabilization and for practical application in the field. In relation to the results of the compressive strength test, it can be seen that the compressive strength obtained is 7.03 kg/cm², which is a representative improvement with an increase in strength of 386.263% compared to the control specimen with a strength of 1.85 kg/cm². This confirms the results of [46], where the kaolinitic soil stabilized with 6% microsilica and 6% silica fume was able to reach the optimum amount in terms of mechanical strength. With the addition of shell ash or lime, an increase was obtained from 15.51 kN/m² at 1 day of curing to 93.54 kN/m², 145.34 kN/m², and 189.75 kN/m² at 30 days for shell ash contents of 3%, 6%, and 9%, respectively. These are approximate percentage increases of 503%, 837%, and 1123% over the original value. These investigations help in demonstrating that when used independently, the microsilica has sufficient responses to external loads, but when combined with the increase of one such stabilizing material, it gives better responses to external loads in conjunction with the use of calcium-rich materials that promote the formation of cementing products and significantly increase the compressive strength of soil.

5. Conclusion

The conclusion synthesizes the key findings of this research, highlighting the influence of Microsilica (MS) and the Huancan Andean Clayey Soil (CS) in the enhancement of the mechanical properties of the soil. Specifically, the addition of MS significantly influenced the Liquid Limit (LL), the Plasticity Index (PI), and improves the Unconfined Compressive Strength (UCS) of the soil. From the performed experiments, the following conclusions were extracted:

- The addition of Microsilica (MS) increases the Liquid Limit (LL) of the clayey Andean soil and raises its Plastic Limit (PL), while the Plasticity Index (PI) decreased, acquiring its strength and compaction properties with the addition of 6% of microsilica, due to the pozzolanic reaction in the mix.
- The clayey Andean soil presented an initial Maximum Dry Density (MDD) of 1.85 gr/cm³ with An Optimal Dry Content (OMC) of 11,41 %. The addition of the MS increased the MDD to 1.95 gr/cm³, and diminished the OMC to 13,43 %, with the addition of 6% of microsilica. The MS fills the voids in the soil during the pozzolanic reaction, permitting the soil to acquire its cohesion and strength properties against moisture.
- The addition of microsilica increased the CBR values, especially in the CBR at 100% for 0.1", which reached a value of 22.01% with the addition of 6% of microsilica. This indicates a higher resistance to external forces with the addition of microsilica.
- In the analyzed soil, the UCS increased from 1.85 Kg/cm2 to 7.03 Kg/cm2 after the curing process and the addition of 6% microsilica, with a significant enhancement during the 28-day curing period, so the soil complies with the established criteria in respect to the parameters of road design of AASHTO.

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