Improvement of access roads to agricultural areas using sediments from the clarification of irrigation water and industrial waste

Cinthya Alvarado, MSc[1], Alfredo Guerra, BS[2], Iván Vásquez Alfaro, BS[3], Hernán Alvarado-Quintana, PhD[4]
[1]Universidad Privada del Norte, Perú, cinthya.alvarado@upn.edu.pe
[2]Universidad Nacional de Trujillo, Perú, alfred.t.castel@gmail.com
[3]Universidad Nacional de Trujillo, Perú, ivasqueza@unitru.edu.pe
[4]Universidad Nacional de Trujillo, Perú, halvarado@unitru.edu.pe

Abstract*– This research evaluates the effect of the addition of sediments from irrigation water clarification, rice husk ash (CCA), and calcareous scallop residue (RCCA) in the stabilization of sandy soils to improve access roads to agricultural areas. For this, the physical properties, microstructures, and phase analysis were determined by hydrometry, scanning electron microscopy, and X-ray diffraction respectively. Five soil-sediment mixtures were evaluated at different percentages by means of the California Bearing Ratio (CBR) test. Then, to determine the best dosage of stabilizers on the best mixture obtained previously, 4 samples were tested at different proportions of CCA and RCCA by means of the CBR and triaxial compressive strength tests. The results showed that the mixture of 60% soil - 40% sediment presents an increase in the CBR index of 42 compared to the natural soil (CBR of 6) and this mixture reaches a CBR index of 94 when 6% CCA and 1.5% RCCA are added. In addition, according to the Triaxial test, an undrained cohesion of 796.33 kPa was obtained. Finally, it is concluded that the soil-sediment combination showed an increase of 57% in its support capacity when mixed with minimum percentages of CCA and RCCA, an increase in stiffness and undrained cohesion was also observed. The physical-chemical stabilization presented was applied in the design of the thickness of the rolling layer of the access roads to agricultural areas incorporated by the Chavimochic Project.

***Keywords*-- Stabilization, improvement of soils, sandy soils, sediments, industrial waste.**

I. INTRODUCTION

In recent decades in the northern region of Peru, large irrigation projects have been carried out, such as Chira-Piura, Jequetepeque-Zaña, Chavimochic, and Olmos, which have made it possible to enable immense agricultural areas in areas that were previously desert and have become extensive cultivation fields for agro-export, driven by agro-industrial investment. However, they are currently interconnected by a precarious road system, since they are impassable roads (Figure 1). Along these roads, the sandy soils are mechanically unstable, due to their low support capacity and the lack of a binding material that binds their particles, these problems make it difficult for vehicles to access the cultivation areas.

On the other hand, because the irrigation of these agricultural fields is technicized (drip, sprinkler, or pivot), the agro-industrial companies that work in the fields of the aforementioned irrigation projects, find themselves in the need to clarify their irrigation waters. This generates the storage of tens of thousands of cubic meters of sediment per sedimentation well annually, which in the critical months of rain in the mountains of our country causes the collapse of these structures [1]. The excessive accumulation of these sediments, consisting mainly of fine sand, silt, and clay, generates negative impacts on the environment, so it is proposed to use them in combination with the sandy soil of the area as material for paving access roads to the areas of cultivation.

Fig. 1 Sandy soils on the access roads to the agricultural fields of Virú

Digital Object Identifier (DOI):
http://dx.doi.org/10.18687/LACCEI2022.1.1.381
ISBN: 978-628-95207-0-5 **ISSN:** 2414-6390

Desert sands are materials with low bearing capacity, strength, and stiffness, and the high porosity of this type of soil causes excessive settlement and serious damage to roads and highways [2]. Likewise, due to its particle size, the sand has low compactness, with a large volume of voids between the particles and its deformation capacity is very high [3].

The stabilization of sandy soils has now become a trend and several stabilization alternatives have been tried in recent years. Mixing desert sands with other materials such as natural clays, bentonite, cement kiln dust, and incinerator ash was found to improve the properties of the sand so that it can be used to support structures and roads [4]. Stabilization results of fine sand with industrial by-products, such as granulated blast furnace slag, low calcium fly ash, and metakaolin were reported by reference [5].

On the other hand, in the La Libertad region, Peru, there are companies dedicated to the production of bricks that have been using rice husks as fuel in the burners of the Hoffman Furnaces, accumulating large amounts of ash that cause a high environmental impact. Rice husk ash (CCA) is a residue obtained from its combustion process that has pozzolanic properties when obtained under controlled conditions. Each ton of rice produces approximately 200 kg of husk, of which approx. 40 kg of ash after combustion [6], with a silica content of more than 90% [7], which combines with lime to form hydrated calcium silicates, a binder that gives resistance and stability to the soils.

Additionally, along the Peruvian coast, there is a business activity oriented to the processing and export of the edible part of fan shells whose calcareous residues (the shells) are being dumped on vacant land and close to the processing plants of this mollusk, also causing high environmental pollution.

For this reason, this research proposes the ecological alternative of taking advantage of the sediments and industrial waste of the region to enable new access roads in an economic and sustainable way.

Finally, the following objectives were set:

• Determine the optimal mix between sandy soil and cohesive sediment that improves its properties according to the CBR and Atterberg Limits tests.

• Evaluate the influence of the dosage of the CCA and RCCA stabilizers on the CBR and the triaxial compressive strength of the soil-sediment mixtures.

• Estimate the thickness of the wearing course from the NAASRA Method in the agricultural roads of the Chavimochic Project, Peru.

To meet these objectives, the research was developed in two stages: first, to determine the best percentage of sediment on the sandy soil and then to evaluate the best dosage of stabilizers based on industrial waste on the soil-sediment mixture.

II. MATERIAL AND METHODS

A. *Material*

1) Soil: Soil samples were collected in the Virú district of the department of La Libertad, Peru. This corresponds to a sandy soil free of organic matter whose natural humidity is 1.01% (ASTM D-2216). The percentage that passed sieve N°4 (T4) and sieve N°200 (T200) was 100% and 0.64%, respectively (ASTM D-422). Its fineness modulus was 1.51. According to the unified soil classification system (SUCS), it is called SP. It is a poorly graded sandy soil with a plasticity index equal to zero; its organoleptic characteristics are similar to the fine aggregate used in construction. Table I highlights its main characteristics.

TABLE I
SOIL PROPERTIES

Granulometry	Gravel	Sand	Fines
	0%	99.36%	0.64%
Classification	SUCS	AASHTO	Cu
	SP	A-3 (0)	2.3
Physical Properties	Specific Gravity	Plastic Index	Cc
	2.62	0	0.9

Figure 2 illustrates the granulometric distribution of the soil particles under study, defined on the abscissa by the particle size expressed in millimeters, while the corresponding percentage that passes said sieve opening is expressed on the ordinate, outlined by the line of red color; the gradation of a well-graded soil drawn on the blue line is also attached. Regarding the granulometric classification, the relative proportion of the different particles, we have that the soil is made up of 99.4% sand, just 0.6% silt, and/or clay, subtracting 0% gravel, expressed based on the dry weight of the soil.

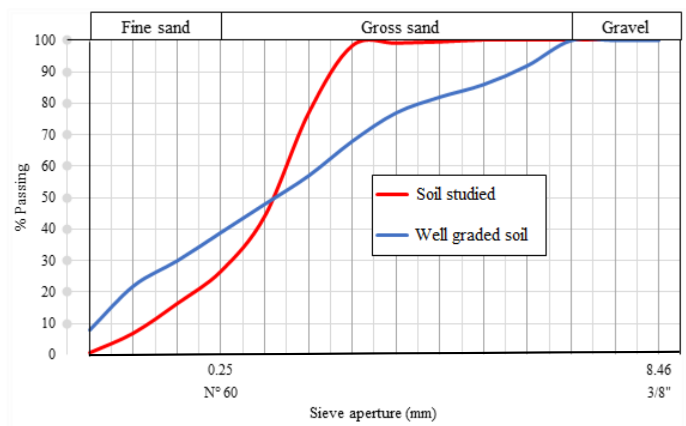

Fig. 2 Particle size curve of the soil under study compared to a well-graded soil.

2) Sediment: The sediment was collected from the irrigation water clarification pond of the company AguaLima SAC, located in Virú, Department of La Libertad, Peru. It was dried in an oven at 110 °C and sieved with mesh No. 50, its natural humidity being 1.90%.

The sediment was then characterized by sieve granulometric analysis and hydrometry (ASTM D-422 Standard), obtaining that it is composed of 67% silt (between 0.002 and 0.06 mm) and 28.5% clay (<0.002 mm). Figure 3 shows its complete granulometric curve. Likewise, it was determined through laboratory tests that the sediment has a specific gravity of 2.74, a dry density of 1.84 g/cm^3, a LL of 36.0, and an LP of 24.2.

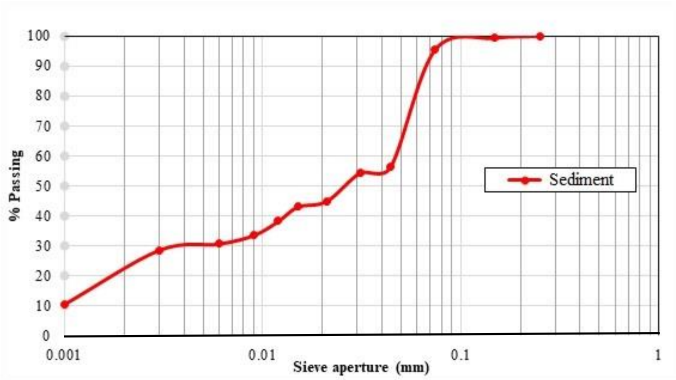

Fig. 3 Granulometry curve of the sediment.

The phases of the sediment were identified using a Rigaku diffractometer, model Miniflex 600, where it is observed that the main phases are quartz, muscovite, and kaolinite as shown in Figure 4.

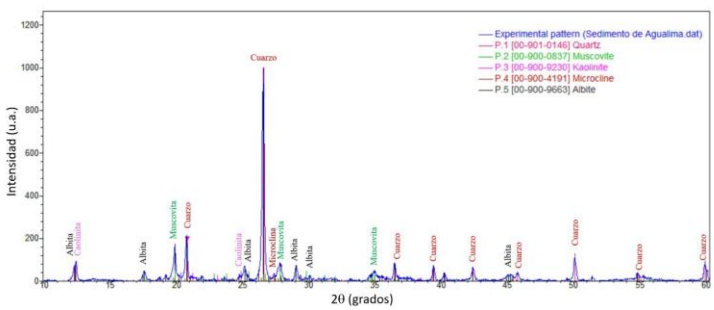

Fig. 4 X-ray diffraction of the sediment

The atomic adsorption analysis performed on the sediment used determined its mineralogical composition, revealing that it is predominantly composed of quartz, which is a crystalline phase of silica. The result is shown in Table II.

TABLE II
MINERALOGICAL COMPOSITION OF THE SEDIMENT

Mineral	Fórmula	Cantidad (%)
Quartz	SiO_2	70.72
Muscovite	(K,Na)(Al, Mg, Fe)$_2$	6.82
Kaolinite	$Al_2Si_2O_5(OH)_4$	5.85
Microline	K $AlSi_3O_8$	4.08
Albite	(Na,Ca) (Si, Al)$_4O_8$	3.46
Pyrophyllite	$Al_2Si_4O_{10}$ $(OH)_2$	3.31
Andalusian	$Al_2(SiO_4)O$	1.91
Others	-	4.05

3) Calcareous scallop residue (RCCA): The RCCA was collected from the company Acuapesca of Casma, Department of Ancash. It was crushed in a ball mill for 6 hours, then it was calcined at 900°C for 2 hours to transform it into calcium oxide (CaO) and finally, it was sieved through mesh N° 50.

The chemical composition of RCCA was 96.57% calcium carbonate ($CaCO_3$) and calcined was 99% CaO. Figure 5 shows its microstructure obtained by scanning electron microscopy (SEM) of the uncalcined and calcined RCCA.

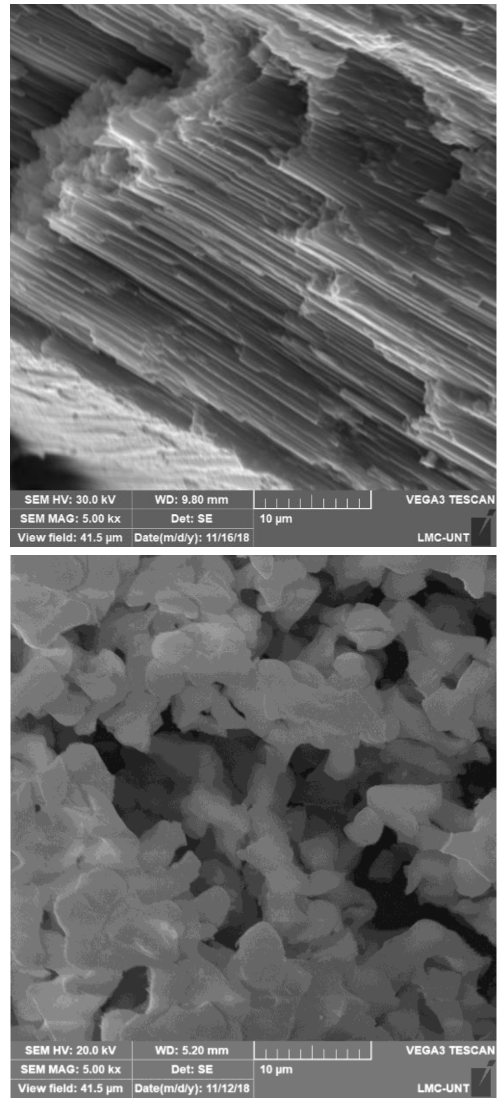

Fig. 5 Microstructure obtained by scanning electron microscopy of (a) uncalcined RCCA, and (b) RCCA calcined at 900°C for 2 hours.

4) Rice Hush Ash (CCA): The CCA was collected from the Hoffman kilns of the company Strong Bricks of Poroto, Department of La Libertad - Perú. It was sieved with N°50 mesh and then ground in a ball mill for 6 hours.

TABLE III
ATOMIC ABSORPTION SPECTROSCOPY OF CCA

Compound	CCA
SiO_2	94.1
Al_2O_3	0.12
Fe_2O_3	0.91
CaO	0.55
MgO	0.95
K_2O	2.1
Na_2O	0.11
Loss to fire (900°C)	4.29

Subsequently, an Atomic Absorption Spectroscopy analysis was carried out, obtaining that its main component is silica (see Table III). On the other hand, Figure 6 shows the SEM microstructure of CCA in which average particle size of fewer than 3 µm can be seen, and Figure 7 shows the X-Ray Diffraction analysis where it can be seen that the CCA is composed mainly of the amorphous phase of silica represented by the noise at the base of the spectrum and by the crystalline phases of quartz and cristobalite in smaller quantities.

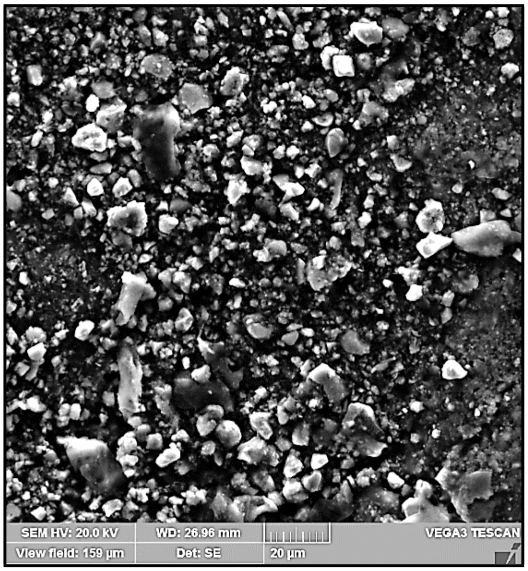

Fig. 6 Microstructure obtained by scanning electron microscopy of CCA

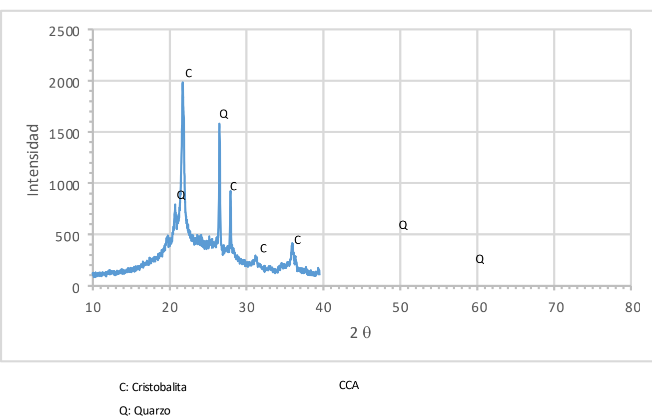

Fig. 7 X-Ray Diffraction of CCA

B. Methods

1) Experimental design: To define the best soil-sediment combination, a total of 15 specimens were evaluated with the following dosages: 0%, 20%, 30%, 40%, and 50% sediment, at a rate of 3 replicates per dosage. Atterberg limits and CBR test were performed to determine the optimal percentage, after which the triaxial compression test was performed on the sample that obtained the best result. The coding used for this design is shown in Table IV.

TABLE IV
EXPERIMENTAL DESIGN SOIL - SEDIMENT

	Sediment				
	0%	20%	30%	40%	50%
Soil	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}

To determine the best dosage of stabilizers (CCA and RCCA), a total of 12 samples were evaluated, where both additions were combined at different proportions, through their CBR index. Similarly, the sample that obtained the best result was tested for triaxial compression. Stabilizers were not evaluated separately because CCA only acts as a pozzolan if calcium hydroxide is present, which is provided by RCCA. Table V shows the coding used.

TABLE V
EXPERIMENTAL DESIGN OPTIMUM MIXTURE SOIL - SEDIMENT + RCCA + CCA.

Soil + % Optimal sediment		RCCA	
		1.5%	3%
CCA	3%	B_{11}	B_{12}
	6%	B_{21}	B_{22}

2) Design of wearing course by the NAASRA method: For dimensioning the thickness of the pavement layer, the NAASRA method was used, [National Association of Australian State Road Authorities (today AUSTROADS)], which relates to the soil support value (CBR) and the load acting on the pavement, expressed in the number of repetitions of equivalent axes:

$$e = [219 - 211 \text{ x } (\log_{10} CBR) + 58 \text{ x } (\log_{10} CBR)^2] \text{ x } \log_{10}(N_{rep} / 120)$$

Where: e = thickness of the pavement layer in mm, CBR = CBR value of the subgrade and N_{rep} = number of repetitions of equivalent axes for the design lane.

III. RESULTS AND DISCUSSION

A. Modified proctor test

Modified proctor tests were carried out according to ASTM D-1557 Standard on sandy soil with different percentages of sediment, determining the maximum dry density (γ) and the optimum compaction moisture (H). Figure 8 shows a linear correlation between the amount of sediment and maximum compaction moisture. The results are summarized in Table VI.

The result found explains that the sediment, being a fine material, has a higher specific surface area, therefore it requires more water to achieve an optimal rearrangement of its particles in the interstices of the granular soil studied.

For sample A14, the maximum dry unit weight is 19.6 kN/m³ and an optimum compaction humidity of 9.2%.

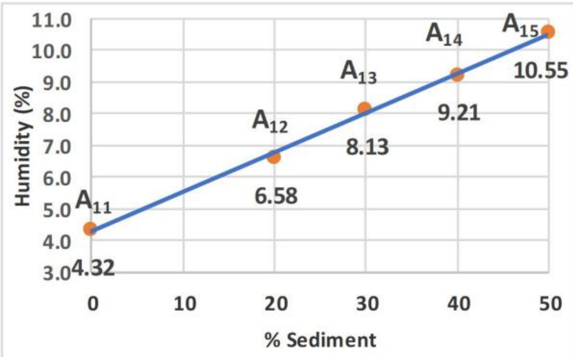

Fig. 8 Maximum compaction moisture, soil-sediment specimens

B. Granulometry

Below is the granulometric distribution of mixture A14, the procedure applied was the method of sieving and sedimentation as indicated by the standard. Figure 9 shows that coarse particles have a uniform diameter, while fine-grained particles have a graded distribution.

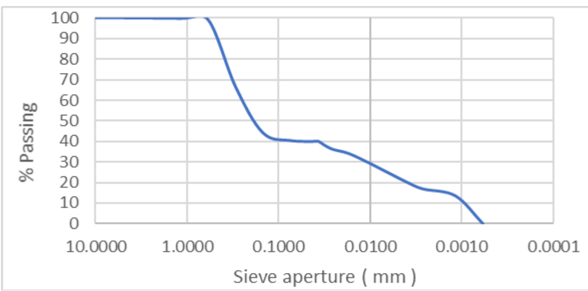

Fig. 9 Particle size curve sample A_{14}

C. Atterberg limits

The liquid limit (LL), the plastic limit (LP), and the plasticity index (IP) of sample A14 (60% soil - 40% sediment) were determined according to the ASTM D-4318 standard, obtaining values of 17%, 9%, and 8% respectively, complying with the quality requirements demanded by the MTC, which is for the LL of 35% maximum.

D. CBR

The CBR tests were carried out according to the ASTM D-1883 Standard, using a 50 kN capacity Humboldt HM-3000.3F press. Table VI shows the CBR results of the different compacted soil-sediment mixtures at optimum moisture conditions and cured for 4 days.

TABLE VI
CBR INDEX FOR SOIL-SEDIMENT SAMPLES

Muestra	γ_w [Tn/m³]	H [%]	CBR [%]
A_{11} (Soil)	1.68	4.32%	6
A_{12} (Soil + 20% Sediment)	1.98	6.58%	15
A_{13} (Soil + 30% Sediment)	2.08	8.13%	29
A_{14} (Soil + 40% Sediment)	2.12	9.21%	42
A_{15} (Soil + 50% Sediment)	2.17	10.55%	30

Figure 10 (a) shows the relationship between the tension and piston penetration, for the CBR test on compacted soil-sediment mixtures. A more rigid behavior and a maximum value in the final tension are observed in sample A14 (60% SP - 40% Sediment). The behavior reflects that as the content of cohesive material (sediment) increases, the CBR index is higher, also observing that the soil-sediment mixture reaches a state of saturation when the amount of fine material is greater than 50% by weight of the natural soil, which is reflected in a decrease in the CBR index, due to the fact that the soil acquires high plasticity. Likewise, the CBR index found in the 60% soil – 40% sediment mixture meets the quality requirements demanded by the MTC for unpaved roads with low traffic volume, which is a minimum of 40%. In the same way, the volumetric expansion value was determined for sample A14, which was 0.69%, which represents an adequate value according to [8] for its use as a base in pavements, since it is less than 1%, these characteristics make the material resistant to atmospheric environments of variable humidity.

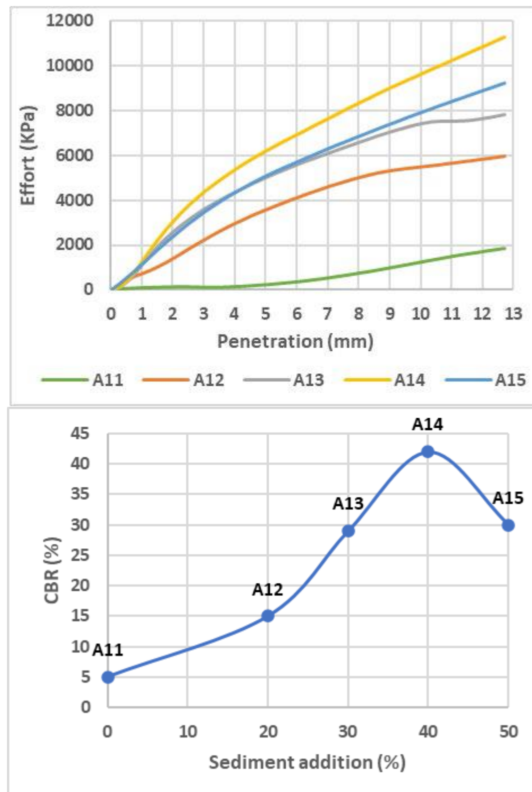

Fig. 10 [Soil-Sediment]: (a) Graph: Effort vs. Penetration (b) Graph: CBR vs. Percentage of sediment.

On the other hand, the records reported increases in the support capacity (CBR) of the soil-sediment when mixed with minimum percentages in addition to CCA and RCCA, exceeding in all cases the resistance required by the MTC for the design of a road. unpaved with low traffic volume which is a minimum of 40% CBR. It should be noted that the best dosage of stabilizers on the soil-sediment mixture was sample B21 (6% CCA and 1.5% RCCA), obtaining a high CBR value equal to 94, followed by sample B11 (3% CCA and 1.5% RCCA), this allows us to affirm that the mixtures with lower amounts of RCCA are those that reach higher CBR; and with the same RCCA, the CBR value increases with the dosage of CCA. These behaviors can be observed in Table VII and in 1 Figure 11 (a). The explanation is due to the fact that an excess of RCCA decreases the humidity of the mixtures and contributes to their swelling, which weakens their resistance. On the other hand, with an excess of CCA at low amounts of RCCA, its kinetics improves because the points of contact between the CCA and the RCCA increase, producing more conglomerating phases, thus increasing resistance. Similarly, specimen B21 presented a volumetric expansion of 0.58%, which represents a lower value than that obtained by the soil-sediment mixture without natural stabilizers, this is due to the cementing effect of CaO and SiO_2 from RCCA and CCA, respectively.

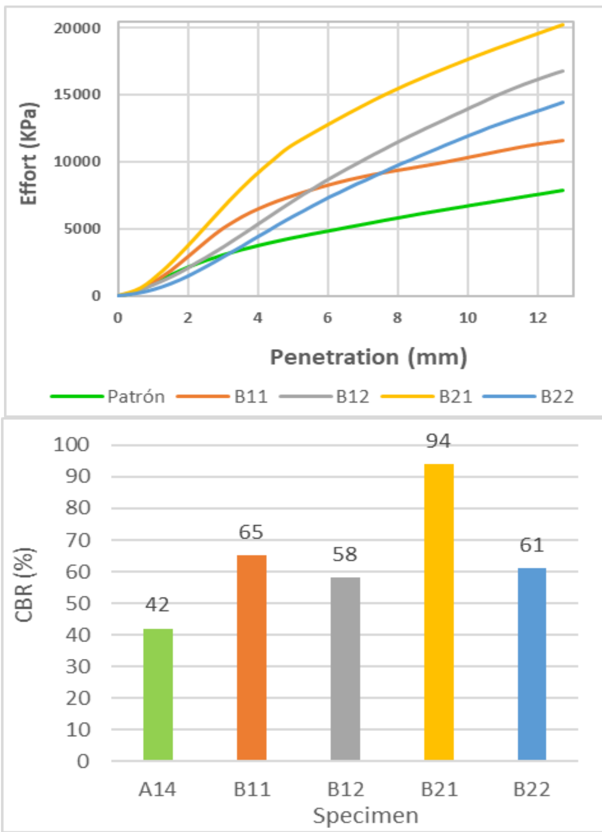

Fig. 11 [Soil/Sediment] + [CCA/ RCCA]: (a) Graph: Effort vs. Penetration (b) Graph: CBR vs. Chemically stabilized specimen.

TABLE VII
CBR INDEX (CCA - RCCA)

Specimen	γ_w [Tn/m^3]	Hum. [%]	CBR [N°]
A14 (Pattern)	2.12	9.05%	42
B11 (3% CCA y 1.5% RCCA)	1.99	8.69%	65
B12 (3% CCA y 3% RCCA)	2.05	8.49%	58
B21 (6% CCA y 1.5% RCCA)	2.00	9.71%	94
B22 (6% CCA y 3% RCCA)	2.05	8.60%	61

The high rise in CBR can be attributed to the fact that the soil has been chemically activated through the pozzolanic reaction of material rich in silica such as and material rich in calcium such as the residue of fan shells, several researchers have been confirming this type of verification with different residues rich in silicon with lime, cement and/or materials rich in calcium [9] – [12].

E. Triaxial

This test was carried out according to the ASTM D-2850 standard using a Humboldt triaxial test system with automatic pressure control operated on a 50 kN capacity HM-3000.3F frame. Three cylinders of 7cm diameter by 14 cm high were made and tested from the best soil-sediment mixture obtained in the CBR test (40% sediment - 60% soil) compacted at optimal moisture conditions and cured for 4 days at normal conditions. normal environments. They were tested at three confining pressures of 20, 40, and 80 kPa. The curves obtained from the triaxial compression test are shown in Figure 12. It was determined that the undrained cohesion value (Cu) is 771.67 kPa. It is observed that at higher confinement pressures, the maximum strength and stiffness increase up to a limit after which they decrease since yielding occurs due to plane slippage when overcoming the critical stress of the sediment that presents a laminar structure and because it also overcomes the cohesive forces. that hold the sand particles together, corroborated in the graph by the red curve presenting greater deformation than the blue curve.

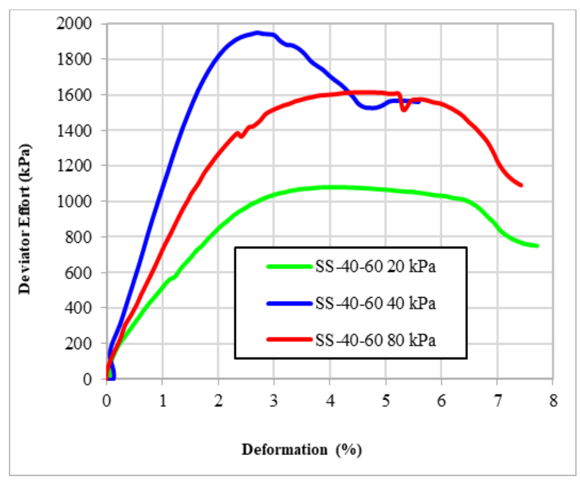

Fig. 12 UU triaxial compression test of sample A_{14}: Stress-Strain Curves

Shear strength parameters (Cu and σ_s) increase with the amount of sediment. A substantial gain in undrained soil cohesion was observed when mixed with 40% sediment. This condition also implies a gain in the angle of internal friction. The values found for the 60% soil - 40% sediment mixture compared to the other mixtures are good. The increase in undrained cohesion reflects that the sediment has agglomerating characteristics.

For the soil-sediment mixture with an optimal dosage of stabilizers with CBR of 94 (sample B_{21}), they were tested in the same way at three confinement pressures of 20, 40, and 80 kPa. The curves obtained from the triaxial compression test are shown in Figure 13. The results showed that the undrained cohesion for sample B_{21} was mixed with minimum percentages of natural additions increased to 796.33 kPa compared to sample A14 which reached a Cu equal to 771.67 kPa. It can be seen that the maximum resistance is 1818 kPa when the specimen is subjected to a confinement pressure of 40 kPa, at higher confinement pressures the maximum resistance increases but not the stiffness, in both cases, it is explained because when the CCA interacts and the RCCA, new crystals are generated in the form of needles [13] that, when the pressure increases, there is a greater interlocking between said crystals, which increases the resistance, keeping the rigidity almost constant, corroborated in the graph by having the three curves the same slope in the linear region and differing only in the maximum peak that they reach, since the greater the confining pressure, the greater the effort to unlock the crosslinking of the acicular crystals formed by the cementing reactions.

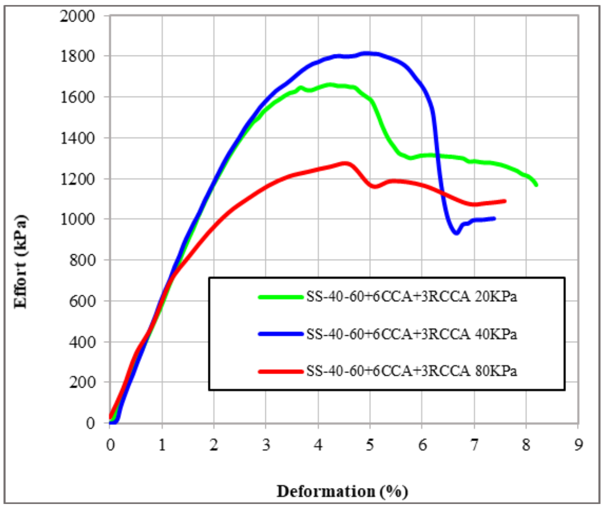

Fig. 13 UU triaxial test of sample B_{21} (SS 60-40 CCA RCCA 6-1.5): Stress-Strain Curves

F. *Design of wearing course by the NAASRA method.*

Knowing the CBR of the optimum soil-sediment mixture and stabilizing additions, it is possible to establish a convention that allows determining, based on practical considerations, the thickness of the wearing course using this design method, the results of which are summarized in Table VIII.

TABLE VIII
CALCULATION OF THE THICKNESS OF THE WEARING COURSE BY THE NAASRA METHOD

NAASRA Method	IMDA (Total vehicles)	Heavy vehicles
Projected traffic	< 15	<5
EE repetition number (design lane)	2.0 x 104	
Shaft type	Single double wheel	
Design period (years)	5	
CBR Subgrade	6	
Thickness (cm) stabilized surface	20	

IV. CONCLUSION

It was determined that the optimal soil-sediment ratio was 60%-40% by weight, respectively, showing that the mixture acquired an adequate gradation that was reflected in a considerable increase in the CBR index of 42 compared to the natural soil (6), an IP of 8, an undrained cohesion of 771.67 kPa.

It was found that adding 1.5% RCCA and 6% CCA to the soil-sediment mixture (60%-40%), presents a maximum CBR index of 94 for the experimental design evaluated, the increase in support capacity shows that there were pozzolanic reactions between the amorphous silica of the CCA and the calcium ions of the RCCA, in addition, according to the Triaxial test, an undrained cohesion of 796.33 kPa was obtained, surpassing in both cases the soil sediment sample without additions.

Applying the equation of the NASSRA method, it was possible to estimate the thickness of the wearing course by 20 cm for the access roads to the cultivation areas enabled by the Chavimochic project, Peru.

REFERENCES

[1] P. Mendoza and H. Vizconde, "Influencia del tipo y dosificación de estabilizante sobre la resistencia a la compresión y el índice CBR en sedimentos no estabilizados, formados a partir de sedimentos del proyecto Chavimochic para la pavimentación de caminos rurales.", B.S. thesis, National University of Trujillo, Trujillo, 2008.

[2] P. Rabbani, Y. Daghigh, M. Reza Atrechian, M. Karimi and A. Tolooiyan, "The potential of lime and grand granulated blast furnace slag (GGBFS) mixture for stabilization of desert silty sands", *Journal of Civil Engineering Research*, vol. 2, n.° 6, pp. 108 - 119, december 2012, doi: 10.5923/j.jce.20120206.07

[3] C. Alvarado and A. Guerra, "Influencia de la adición de ceniza de cáscara de arroz activada alcalinamente sobre la estabilización ecológica de la mezcla de suelo - sedimento en la provincia de Virú", B.S. thesis, National University of Trujillo, Trujillo, 2018.

[4] Y. E. A. Mohamedzein, M. Y. Al-Aghbari y R. A. Taha, "Stabilization of desert sands using municipal solid waste incinerator ash", *Geotechnical and Geological Engineering*, vol. 24, n.º 6, pp. 1767–1780, diciembre de 2006. Accessed February 15, 2022, doi:10.1007/s10706-006-6806-7

[5] A. Buchwald y M. Schulz, "Alkali-activated binders by use of industrial by-products", *Cement and Concrete Research*, vol. 35, n.º 5, pp. 968–973, 2005.

[6] B. O. Juliano, *Rice: Chemistry and Technology.* 2ª ed. USA: American Association of Cereal Chemists, 1985.

[7] L. Ordoñez, "Reutilización de la ceniza de cáscara de arroz como material de construcción: Valoración y optimización de sus propiedades puzolánicas", Ph.D dissertation, Polytechnic University of Valencia, Valencia, 2007.

[8] C. Crespo, *Mecánica de suelos y cimentaciones*, 6a ed. Monterrey: Limusa, 2014.

[9] E. C. Mansaneira, N. Schwantes-Cezario, G. F. Barreto-Sandoval, and B. Martins-Toralles, "Ceniza de bagazo de caña de azúcar como material puzolánico," DYNA (Colombia), vol. 84, no. 201, pp. 163–171, 2017, doi: 10.15446/dyna.v84n201.61409.

[10]S. Horpibulsuk, C. Phetchuay, A. Chinkulkijniwat, and A. Cholaphatsorn, "Strength development in silty clay stabilized with calcium carbide residue and fly ash," Soils and Foundations, vol. 53, no. 4, pp. 477–486, 2013, doi: 10.1016/j.sandf.2013.06.001.

[11]A. Kumar and D. Gupta, "Behavior of cement-stabilized fiber-reinforced pond ash, rice husk ash-soil mixtures," Geotextiles and Geomembranes, vol. 44, no. 3, pp. 466–474, Jun. 2016, doi: 10.1016/j.geotexmem.2015.07.010.

[12]M. S. I. Zaini et al., "Effect of optimum utilization of silica fume and eggshell ash to the engineering properties of expansive soil," Journal of Materials Research and Technology, vol. 14, pp. 1401–1418, Sep. 2021, doi: 10.1016/j.jmrt.2021.07.023.

[13]Jiang, Huang, Ma, and Luo, "Analysis of Strength Development and Soil–Water Characteristics of Rice Husk Ash–Lime Stabilized Soft Soil," Materials, vol. 12, no. 23, p. 3873, Nov. 2019, doi: 10.3390/ma12233873.