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Mechanical properties of a soil improved with recycled demolition concrete for the construction of shallow foundations

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Abstract. To achieve a satisfactory level of safety and stability in the construction of structures in weak soils, one of the best solutions may be soil improvement, the recycling and reuse of construction and demolition materials results in the preservation of natural resources and the reduction of environmental pollution. Therefore, this experimental study proposes to evaluate the mechanical properties of soil for surface foundations incorporating recycled demolition material. The mechanical behavior of a clayey soil improved with recycled concrete from demolition (CRD) was analyzed by means of a series of compaction tests, unconfined compression of soil specimens and direct shear in mixtures with 10 %, 15 %, 20 % and 25 % CRD by weight. As a result, the highest compressive strength of the soil is obtained with 16.67 % CRD according to UCS tests; and an improvement in cohesion and friction angle for all CRD percentages. Thus, it can be demonstrated that CRD has a positive influence on the mechanical properties of a soil with clayey characteristics.

Keywords: mechanical properties, shallow foundations, recycled demolition material, soil improvement, unconfined compression of soil specimens, direct shear.

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Introduction

To perform different construction works, soil is one of the most important components [1]. Soils used for foundations are the most affected when dealing with loose soils with low shear strength [2], a structure transfers the load to the soil through the foundations at a depth of approximately two to three times its width [3] so avoiding the replacement of these by high quality raw materials [4], finding the suitable materials to treat reinforcement layers for footings in soils with unfavorable bearing capacity [5] and that the generated costs are affordable is one of the purposes of geotechnical engineering [6].

Due to the abundance of construction and renovation of urban buildings in developing and developed countries, there is an increase in the amount of construction and demolition waste [7], this inevitably leads to an increase in the proliferation of construction and demolition waste [8] coupled with the decrease in landfill capacity and the increased difficulty in identifying aggregate quarries [9] the implementation of the reuse of these wastes in civil construction should be developed to mitigate environmental problems [10].

Soils that include loose sands, soft clays, and organics are not suitable for construction projects because they do not possess valuable physical properties for their application [3, 11].

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A clayey soil tends to have low shear strength which is further reduced by wetting [12, 13], and a high expansive potential [14] contracting significantly if it dries out and expanding if it absorbs moisture which puts a lot of pressure on the substructure [15], added to this is the heterogeneous condition of these soils at the base of a building and their uneven compression due to poor compaction resulting in variable settlement of the foundation and its subsequent destruction [16, 17]. Therefore, stabilization is often required prior to the construction of civil infrastructures [18] by methods that are economical and environmentally friendly [19].

When we talk about soil improvement, there is a wide range of materials and methods to perform it. R&D materials are those from the construction, rehabilitation and demolition of any type of construction site, whether public or private [20, 21]. The three main demolition waste materials are crushed brick, recycled concrete aggregate (RCA), and reclaimed asphalt pavement [22].

A wide range of soil improvement methods have been developed to support shallow foundations, one of these methods is the in-situ mixing of recycled demolition materials. On a laboratory scale the influence of recycled concrete demolition material (CRD) on the behavior of clayey soils has been studied by several authors concluding that, the addition of this material in a proportion of 22% [23] and 15% [7] results in an increase of the unconfined compressive strength (UCS), permeability coefficient and CBR, as well as the reduction to zero of the free heave; [24] agrees that the optimum percentage of CRD to achieve improvements in the soil is 22%, but this author also compares the results with those obtained by fly ash and lime, concluding that the UCS at 28 days of fly ash is higher than that obtained by CRD waste and the highest CBR is obtained by using lime in the sample, where he states that lime is the best stabilizer to be used as subgrade, but C&D waste is more economical when it is required to have earlier resistances.

The influence of demolition recycled material (R&D) consisting of crushed floor concrete and bricks was also studied, presenting an increase in UCS value and soil shear strength (CBR) by 4 and 4.5 times respectively compared to an untreated soil by adding 20 % of (R&D), as well as, reducing swelling and swelling pressure of the stabilized soil by 80 % [25, 26].

Studies have also been done on the mechanical behavior of soils incorporating different types of reusable materials such as expanded polystyrene (EPS) where the lateral thrust coefficient (k0) was analyzed with the oedometer test at percentages of 0 %, 0.25 %, 0.5 % and 1% EPS by weight, concluding that, as EPS beads are highly deformable, the application of overburden pressure compressed the soft particles, leading to an increase in k_0 [27]; the permeability of the EPS - soil aggregate composite decreases with increasing dry unit weight, where wet compaction of the optimum moisture content contributes to a further increase in permeability variation [28], the influence of EPS bead inclusion on the strength properties of poorly graded stabilized sands was also evaluated [29].

The incorporation of fly ash into soil was studied, concluding that geopolymerization converts clay soil into a non-plastic silt-like material due to the fact that the clay particles are covered by geopolymer gels, thus forming coagulated particles with considerably less likelihood of swelling, consolidation and drying shrinkage [30]; results also indicate that a fly ash-based geopolymer could be a simple solution to increase the sorption and metal removal capacity of local clay to mitigate potential contaminants due to leachate penetration into the soil [31].

Likewise, an attempt was made to examine the effect of lime-zeolite stabilization on the behavior of a natural soil the size of a low plasticity silt, by performing standard compaction tests, as well as unconfined compression experiments specimens were subjected to consecutive cycles of freezing and thawing showed a significant improvement in the mechanical performance of the treated soil in terms of strength and durability [32].

A study was conducted with direct shear tests on a rubber-sand composite along a nonwoven geotextile layer, demonstrating that the addition of 40 % granulated rubber to pure sand caused an approximately 50 % reduction in the maximum mobilized interface shear stress as loading cycles progressed [33].

In addition, literature reviews have been conducted: on cementitious composites, common unconventional stabilizers, reinforcing fibrous inclusions, and the simultaneous use of a stabilizer and a reinforcing agent where the most prominent studies are detailed and laid out in a logical sequence to present the most practical mixtures used for soil stabilization purposes [34]; also, the effects of EPS incorporation in different types of mixtures were investigated by reviewing the most prominent studies on EPS beads and blocks subjected to static and cyclic loading, the study proposes some essential practical issues to be followed for future research that are lacking in the current literature [35].

Therefore, the objective of this research is to evaluate the mechanical properties of a soil with clayey characteristics by adding 10 %, 15 %, 20 % and 25 % by weight of recycled concrete from demolition; subjecting it to unconfined compressive strength tests UCS and direct shear to verify the mechanical behavior of the soil in parameters of shear strength, cohesion, and friction angle in the construction of shallow foundations.

Methods

Materials used. Figure 1 shows the flow diagram of the processes followed for the development of this research, from the location of the land to obtain the soil samples and the collection of the CRD samples, their crushing process and the laboratory tests performed.

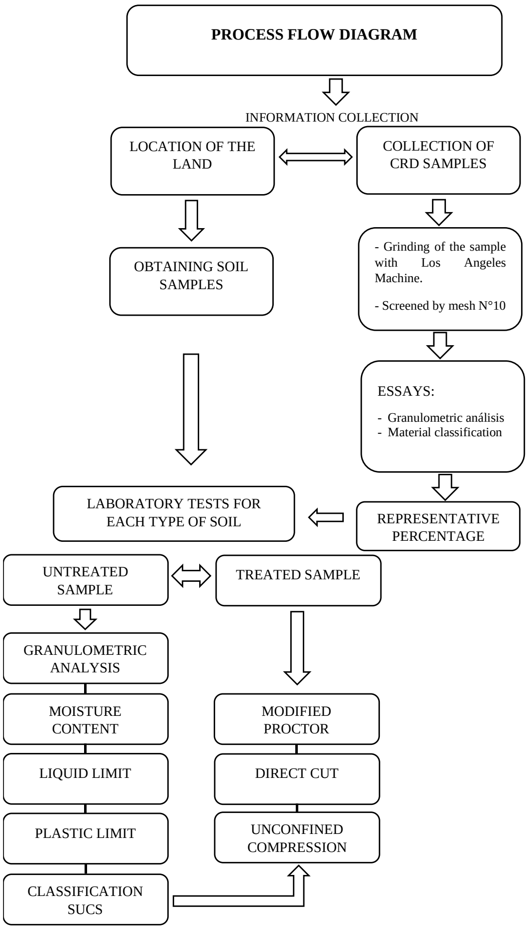

Fig. 1. Process flow diagram

Soil. Soil samples were collected through 9 soil pits in the locality of Ferreñafe, Lambayeque, Peru with a depth of 1.50 meters to avoid the presence of vegetation and loose soils. The representative clay samples were collected in polyethylene bags in order to avoid any variation in moisture content. The geotechnical properties of the soil are given in Table 1.

Table 1. Physical properties of soil

		MOISTURE CONTENT (%)	LIMITS OF ATTERBERG			GRANULOMETRY				CLASS. USCS	γ_{max} g/cm^3	OCH %
POINT	DEPTH		LL (%)	LP (%)	IP (%)	% PASS N°4	% PASS N°10	% PASS N°40	% PASS N°200			
C1	1.5 m	26.29	22.07	17.40	4.17	100.0	99.5	86.4	17.8	SC-SM	1.973	9.44
C2	1.5 m	15.09	22.16	16.94	5.22	100.0	99.5	93.8	22.7	SC-SM	1.978	9.08
C3	1.5 m	21.98	41.96	23.23	18.74	100.0	99.2	96.7	35.1	SC	2.018	10.44
C4	1.5 m	21.83	29.98	16.43	13.56	100.0	98.7	94.0	66.2	CL	1.930	13.06
C5	1.5 m	18.22	49.46	20.82	28.64	100.0	99.0	96.6	51.7	CL	1.981	10.34
C6	1.5 m	15.11	38.64	17.11	21.53	100.0	99.2	95.0	53.1	CL	1.968	10.71
C7	1.5 m	18.99	44.71	16.35	28.35	99.9	98.4	94.2	60.0	CL	2.010	11.38
C8	1.5 m	21.57	44.16	15.90	28.26	100.0	98.5	92.8	62.4	CL	2.016	11.40
C9	1.5 m	19.49	52.59	23.19	29.40	100.0	99.6	94.2	74.4	CH	1.896	14.37

Recycled demolition material. The CRD material consisted of concrete rubble obtained from demolition activities of sidewalks, columns of a building under renovation and laboratory cores.

Due to the large size of these blocks and that they cannot be directly implemented in experimental studies because of the small/medium scale of the laboratory equipment, the chosen CRD material was dried, crushed and filtered through a 2 mm No. 10 sieve and kept in air-tied polyethylene bags at a controlled temperature. The crushing process was carried out in the Los Angeles Abrasion Machine, in a time span of 15 min per sample. The physical properties of the residues are presented in Table 2.

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Table 2. Physical properties of CRD

Characteristic	**Worth**
Uniformity coefficient, Cu	1.4
Curvature coefficient, Cc	0.9
Classification according to USCS	SP

Experimental work

A series of laboratory tests were performed consisting of Modified Proctor, Unconfined Compressive Strength USC and Direct Shear testing on natural soil and recycled concrete demolition waste at (10 %, 15 %, 20 %, 25 %). Sample preparation and laboratory testing were performed in accordance with the appropriate ASTM standards.

Compaction Testing. Modified Proctor compaction tests (ASTM D-1557) were performed to determine optimum moisture content (OCH) and maximum dry density (MDS). The soil and composite mixtures were thoroughly mixed for 12 hours prior to compaction. First, compaction tests were performed to determine the compaction characteristics of the unstabilized soil. Subsequently, tests were conducted on the composite mixtures consisting of soil plus CRD in all their percentages under study. A soil sample weighing 2.5 kg was taken and passed through a 4.75 mm No. 4 sieve to perform the compaction test in a modified Proctor mold of 943 cm^3 capacity. The water is then added to the soil and mixed thoroughly without the formation of lumps. This sample is divided into 5 equal parts, poured into standard mold in five layers and compacted by applying 25 blows per layer using a modified rammer weight of 44.48 N weight dropped from a height of 47.52 cm.

Shredded from RDC **Physical characterization of the soil** **Compaction tests**

Specimen Compaction **Test of UCS** **Direct Shear Tests**

Fig. 2. Materials used and experimental work

Unconfined compressive strength tests. Unconfined compressive strength tests (ASTM D-2166) were performed on 41 mm diameter and 88 mm high cylindrical specimens at optimum moisture content, compacted to maximum dry density. The specimens were prepared by compacting them by simulating the Modified Proctor dynamic compaction energy in five equal layers in the standard 99.99 cm^3 mold by applying 19 blows per layer using a rammer weight of 17.18 N dropped from a height of 16 cm. Three specimens were made per sample, and these were cured by keeping them in plastic bags to prevent moisture loss and tested at 24 hours. The UCS was determined as the average of values. UCS tests were performed on the specimens at a strain rate of 1.68 mm/min. Stress and strain values were recorded, and a graph was plotted between in stress as the ordinate and strain as the abscissa.

Shear strength tests. The shear strengths of the RCA clay mixtures were determined using the direct shear test method (ASTM D-3080). The conventional direct shear apparatus implemented consisted of a shear box that accommodates a 60 mm diameter soil sample with 22 mm depth. During vertical (normal) tension tests, it is applied mechanically using dead weights and a lever arm, while shear tension is exerted by a displacement-controlled motor. The displacement gauges have a resolution of 0.01 mm and 0.001 mm respectively, while shear force measurements are accurate to 0.05 kg.

Specimen fabrication, performed in three layers (each approximately 7-8 mm), is generally similar to that described for unconfined compression testing, i.e., each specimen is made at optimum moisture content compacted to maximum dry density; simulating modified Proctor compaction energy in a 67.85 cm^3 mold applying in this case 22 strokes per layer using a rammer weight of 17.18 N dropped from a height of 16 cm. The specimens are cut under vertical stresses of σ_n = 0.48, 1.12 and 1.61 kg/cm^2. After applying vertical tension, the specimen is gradually immersed in water and soaked for 24 h before cutting (the specimens had no prior curing). Throughout the soaking period, any settlement and compression of the sample is monitored. Soil samples were sheared at a constant rate of 1 mm / min up to the maximum horizontal displacement (u) of 6 mm. This rapid shear rate would significantly deny the samples the time required for drainage, and therefore conditions resembling an undrained shear would prevail.

Results and discussion

As a result of the experimental studies, the characteristics of unconfined compressive strength UCS and shear strength were determined; according to the USCS classification, the soils were grouped into 4 groups with similar physical characteristics.

Soil compaction tests. The Modified Proctor results are shown in Figure 3, these show a tendency to decrease both OCH and MDS as the percentage of CRD increases; OCH decreases due to the presence of coarser particles of CRD waste compared to those of soil, which results in reduced surface area and therefore a lower affinity for water [23], the decrease in MDS occurs because the specific gravity of CRD waste is lower than those of natural soil and also CRD aggregates present unreacted cement that flocculates with clay to provide less densification [25].

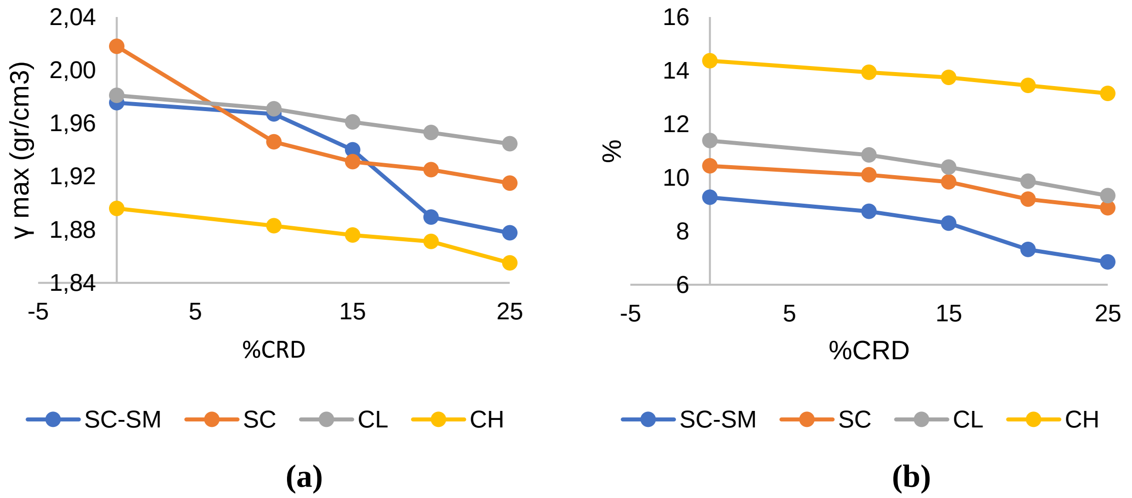


Fig. 3. Compaction test results: (a) maximum dry density, (b) optimum moisture content

Table 3. Preliminary laboratory results, Modified Proctor test

MODIFIED PROCTOR RESULTS FOR SOIL / CRD

CALICATA	CRD	MDS	OCH
	%	g/cm3	%
SC-SM	0	1.976	9.26
	10	1.967	8.74
	15	1.940	8.30
	20	1.890	7.31
	25	1.878	6.85
SC	0	2.018	10.44
	10	1.946	10.10
	15	1.931	9.84
	20	1.925	9.19
	25	1.915	8.87
CL	0	1.981	11.38
	10	1.971	10.84
	15	1.961	10.39
	20	1.953	9.87
	25	1.945	9.33
CH	0	1.896	14.37
	10	1.883	13.93
	15	1.876	13.74
	20	1.871	13.45
	25	1.855	13.15

Unconfined compressive strength tests. Figure 4 shows the behavior of the soil after incorporating CRD by weight in different percentages and subjecting it to compressive strength tests with 24 hours of curing in a humid chamber. In all the research points (test pits), an improvement in strength is observed with the addition of CRD. The average optimum CRD % is calculated by interpolating all the results of the 04 soil types.

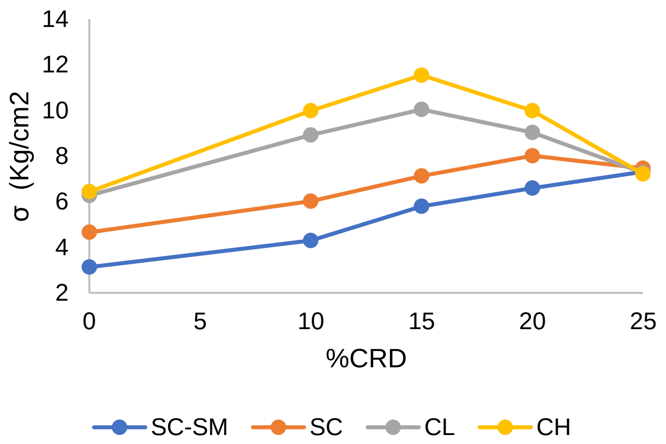


Fig. 4. Unconfined Compressive Strength Test Results

The Shapiro Wilk normality test presented a p-value of significance lower than 0.05 ($p=0.023<0.05$), for the variable percentage of recycled concrete from demolition (%), i.e. the normality assumption was not met, while the p-value was greater than 0.05 ($p=0.918>0.05$) for the variable Unconfined compressive strength (kg/cm²), complying with the normality assumption, therefore, the correlation was quantified with Spearman's correlation test, which presented a p-value of significance lower than 0.05 ($p=0.041<0.05$), rejecting the null hypothesis, showing that there is a significant relationship between both variables, likewise Spearman's correlation coefficient reached a positive value ($r_s=0.460$), that is, there is a low direct correlation between both variables.

According to Figure 5 the approximate dispersion equation which is:

$$\sigma = -119.06\%CRD^2 + 39.705\%CRD + 5.0079 \quad (1)$$

Deriving the equation with respect to the %CRD we obtain:

$$\sigma = -238.12\%CRD + 39.705 = 0 \quad (2)$$

And if the equation equals zero, the average optimal %CRD of the 4 soil types can be obtained: %CRD = 16.67 % y σ = 8.32 kg/cm^2.

From Figure 5, as a result, the average optimum percentage of CRD is 16.67 % reaching a compressive strength of 8.32 kg/cm^2, with higher percentages of CRD the compressive strength decreases progressively.

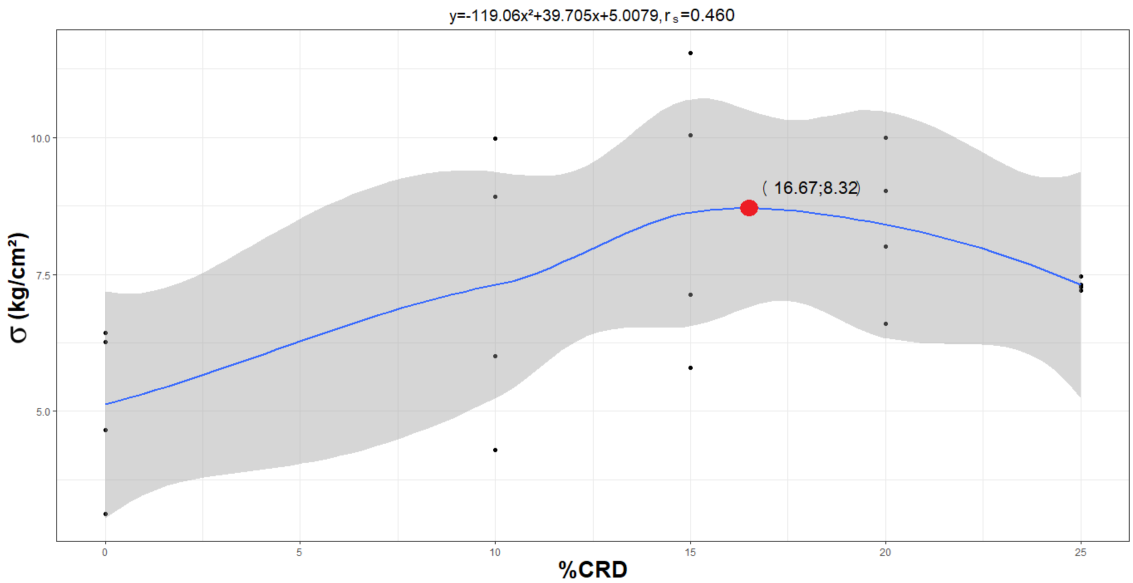
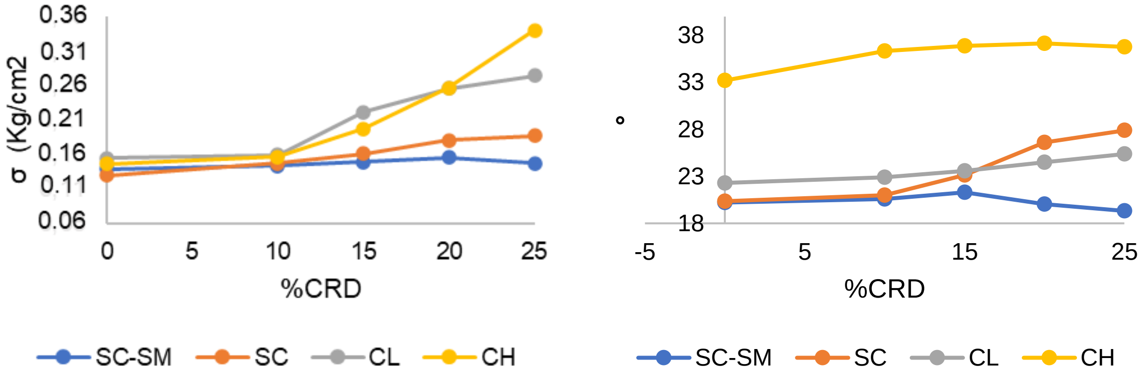


Fig. 5. Dispersion of the UCS test results and their respective approximate equations

On the other hand other authors, [23] argues that, in their research the addition of 22 % CRD increases the UCS to 1062 kPa, which was more than two and a half times that of the UCS of natural soil, with 22 % CRD the UCS increases to 1062 kPa, after the addition of 24 % CRD, the USC increases to 1012 KPa which is less than the UCS of the soil + 22 % composite CRD waste, therefore, he concluded that 22 % CRD can be considered as the optimum percentage for stabilization of that type of soil.

The researcher [25] considered 20 % CRD as the optimum percentage with a 4-fold increase over natural soil for a curing period of 28 days, at more days of curing the strength growth is marginal. [7] also analyzed the UCS strength of a clayey soil at different curing periods and sample percentages, having at 15 % CRD at 28 days of curing a compressive strength of 1567 KPa compared to UCS= 275 KPa for an unstabilized soil without any curing. These results are similar to the present investigation, which in this case the optimum percentage is 16.67 %, beyond this percentage the compressive strength of the soil decreases.

Shear strength tests. The results of the shear strength tests are shown in Figure 6. These results present an upward trend with a downward curve in some cases. For its part [7] argues that for RCA - natural clayey soil mixtures, the increase in %CRD results in dilatant behavior and higher shear strength as reflected in results with high cohesion and high peak internal friction angle, since, mixing RCA with clayey soils results in stronger, stiffer and less compressible mixtures that are particularly suitable for construction purposes as subbase / subgrade of road pavements.



(a) **(b)**

Figure 6. Shear strength test results: (a) Cohesion, (b) Internal friction angle

Conclusions

1. The physical tests of the soils defined the type of soil to which they belonged; there was no previous information on the type of soil in the sampling area; but after the pertinent analysis in the laboratory, SC-SM, SC, CL and CH soils were obtained according to the USCS classification.
2. By means of the Modified Proctor test, information was obtained for the subsequent elaboration of the compacted specimens according to their OCH and MDS; these results showed a tendency to reduce as a higher percentage of CRD was added to the sample.
3. According to the unconfined compressive strength test of cylinders of natural soil and soil improved with CRD, it was obtained through a dispersion analysis that the addition of this aggregate in a 16.67% by weight in a soil with clay properties presents the greatest improvements according to the UCS test.
4. For the RCA - natural soil mixtures, the increase in %CRD results in an increase in the angle of friction and cohesion with respect to the soil in its natural state.

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