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The Effect of Curing Temperature and Rice Husk Ash Addition on the Behaviour of Sulfate-Rich Clay after Lime Stabilization

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Abstract**—**In the western region of Paraguay, the poor condition of the roads has negatively affected the development of this zone, where the absence of petrous material has led engineers to opt for the stabilization of soils with lime or cement as the main structure for bases and subbases of these roads. In several areas of this region, high sulfate contents have been found both in groundwater and in soils, which, when reacted with lime or cement, generate a new problem instead of solving it. On the other hand, the use of industrial waste as granulated slag and fly ash proved to be a sustainable practice widely used in the manufacture of cement, and now also, in the stabilization of soils worldwide. Works related to soils containing sulfates stabilized either with granulated slag or fly ash and lime shown a good performance in their mechanical behaviour. This research seeks to evaluate the mechanical behaviour of soils with high contents of sulfates stabilized with lime by curing them both, at the normalized temperature (23 ± 2 °C) and at 40 ± 2 °C. Moreover, it attempts to asses if the addition of rice husk ash has a positive influence on the new geomaterial. The 40 ± 2 °C curing temperature was selected trying to simulate the average local temperature in summer and part of spring session whereas rice husk ash is an affordable waste produced in the region. An extensive experimental work, which includes unconfined compression, durability and free swell tests were carried out considering different dry unit weights, lime content and the addition of 20% of rice husk ash. The results showed that the addition of rice husk ash increases the resistance and durability of the material and decreases the expansion of this, moreover, the specimens cured at a temperature of 40 ± 2 °C showed higher resistance, better durability and lower expansion compared to those cured at the normalized temperature of 23 ± 2 °C.

Keywords**—**Durability, expansion, lime stabilization, rice husk ash, sulfate rich soils.

I. Introduction

TYPICAL calcium-based stabilizers such as lime and Portland cement have long been used in a wide variety of soils in order to improve their mechanical properties. However, several studies have shown that the use of these stabilizers in soils containing sulphates can lead to a new problem instead of mitigating it [1]-[5].

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In [6], it was established that a mineral named ettringite was formed as a result of clay-lime-water-sulfate reactions, and its formation was responsible for the degradation of a stabilized soil, this result was subsequently confirmed independently by [7].

When the soil and/or groundwater contain sulfates in solution, in the presence of lime that can be combined with the alumina released from the clay, ettringite is formed. Below about 15 °C and assuming the presence of soluble carbonates in the system, ettringite can be transformed into thaumasite. Both minerals are highly expansive when exposed to water [8]. According to [9], this is the case of some soils of the western region of the Paraguayan Chaco where the formation of ettringite was verified by X-ray diffractometry and scanning electron microscopy images (Fig. 1).

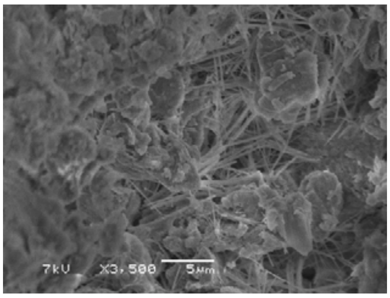

Fig. 1 Microstructural observation of ettringite in a lime stabilized soil from the Paraguayan Chaco [9]

The use of industrial by-products (fly ash, granulated slags, rice husk ash, among others) as additions or aggregates in construction materials is a sustainable practice that is being increasingly used [10]. The incorporation of pozzolans as fly ashes together with lime in the improvement of geomaterials was studied by several authors such as [10]-[12]. In [9], soils from the Paraguayan Chaco containing 14,000 ppm of soluble sulfates were improved using fly ash and lime.

This work seeks to demonstrate the problems of stabilizing sulfated soils with lime, as well as research new alternatives as the use of rice husk ash, which could be a viable alternative in the construction of stabilized bases and subbases.

II. Experimental Program

A. Methods

First, soil and rice husk ash (RHA) properties were determined. Then the quantities of unconfined compression, durability and expansion tests of both, blends without RHA and containing 20% of RHA were defined. Three percentages of lime were studied (5%, 8% and 11%) and three dry unit weights (γ_d). Values of γ varied from 16 kN/m³ to 18 kN/m³ with moisture content of 15% in soil-lime mixtures and from 12.5 kN/m³ to 13.5 kN/m³ with moisture content of 29% in soil-RHA-cal mixtures (Fig. 2). In unconfined compression tests as well as durability and expansion tests, the specimens were cured for 7 and 28 days at 23±2 °C and at 40±2 °C in order to simulate the high temperatures usually found in the region.

B. Materials

Physical and chemical characterization of the soil is shown in Table I. The soil used was extracted from the western region of Paraguay (Paraguayan Chaco), specifically from the city of Filadelfia.

TABLE I
SOIL PHYSICAL AND CHEMICAL CHARACTERIZATION

Properties	Values	Standards
Liquid limit	42.40	ASTM D4318
Plastic limit	21.10	ASTM D4318
Plasticity index	21.30	ASTM D4318
Specific gravity	26.10 kN/m³	ASTM D854
% Pass sieve #200	92%	ASTM D6913
Dispersivity (Pinhole test)	ND3 (Lightly dispersive)	ASTM D4647
Dispersivity (Sodium Absorption Ratio)	No dispersive area	Sherard [13]
Soluble sulfates	6100 ppm	ASTM C1580/ SMEWW
USCS class	CL	ASTM D2487
AASHTO class	A-7-5	ASTM D3282

Proctor compaction tests were carried out under standard and modified energies for both soil-lime and soil-RHA-lime mixtures according to ASTM D698 and ASTM D1557 (Fig. 2). Optimum moistures for the modified energy of both, lime-soil and lime-RHA-soil were selected and three different γ_d in order to evaluate the effect of varying them.

The lime used was calcitic hydrated lime and the added contents (5%, 8% and 11%) were selected considering the experience of other works [16], [9] and that a minimum of 4% was obtained by the "initial lime consumption" method.

Chemical tests were performed on RHA samples in order to quantify oxides present on them (Table II).

The addition of 20% RHA was determined based on other work experiences [10], [14] and [15] and was calculated in relation to the γ_d of the material (lime-soil). The added RHA was previously ground until passing #200 sieve.

Distilled water was used in the preparation of the specimens. As the amount of soluble sulfate in the soil extracted to this work is 6,100 ppm, sodium and calcium sulfates were added in the water in powder form to obtain 20,000 ppm (2%). This practice was based on experiences such as [17] and was applied in order to study high-sulfate levels reactions considering that in the region have been found soils with up to 40,000 ppm but the amount of these is variable in time (by water transport or vegetation absorption). In addition, in road construction, the use groundwater which has high sulfate contents is common due to the scarcity surface water resources in the region. The proportions of sulfates used were based on the amounts found by [9] in soils studied from the same area.

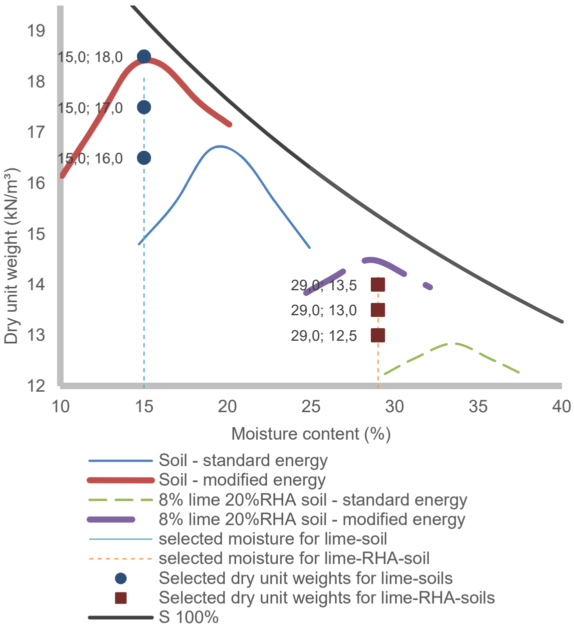

Fig. 2 Compaction test results for lime-soil and lime-RHA-soil

TABLE II
RHA CHEMICAL CHARACTERIZATION

Compound	Standard	Content (%)
Calcium oxide CaO	ASTM D4326	0.83
Silica oxide SiO_2		84
Aluminum oxide Al_2O_3		0.13
Iron oxide Fe_2O_3		0.027

C. Molding and Curing of Specimens

For unconfined compression tests (UCS), 50 mm diameter and 100 mm height cylindrical specimens were used. The soil was mixed with CCA and lime until a uniform consistency was observed. The water-sulphate solution was added, continuing the mixing process to create a homogeneous paste. The mixture was compacted statically in three layers inside a metal mold of 50 mm diameter. The specimens were sealed in plastic bags in order to avoid possible moisture losses and were placed in curing chambers at 23 ± 2 °C and at 40 ± 2 °C for 7 and 28 days.

For expansion tests, metal molds were used that allowed the fabrication of 54 mm diameter and 28 mm height specimens. The mixture of the materials followed the same procedure mentioned above and was compacted in a single layer and then immediately immersed in distilled water at 23±2 °C and at 40 ± 2 °C for 20 days.

For durability tests, 100 mm in diameter and 127.3 mm in height cylindrical specimens were compacted, followed the same procedure mentioned above, sealed in plastic bags and placed in curing chambers at 23±2 °C and at 40±2 °C for 7 days.

D. Unconfined Compression Tests

Before carrying out compression tests, the specimens were immersed in water for a period of 24 hours to ensure saturation and minimize suction effects [8]. The temperature of the water tank was controlled at 23±2 ºC. Immediately before the test, the specimens were removed from the water tank and dried superficially. The unconfined compression tests were carried out following the ASTM D5102 standard.

E. Swelling Tests

The swelling tests were carried out in fabricated metallic molds (Fig. 3) following a similar scheme of oedometer cells and in accordance with ASTM D 4546.

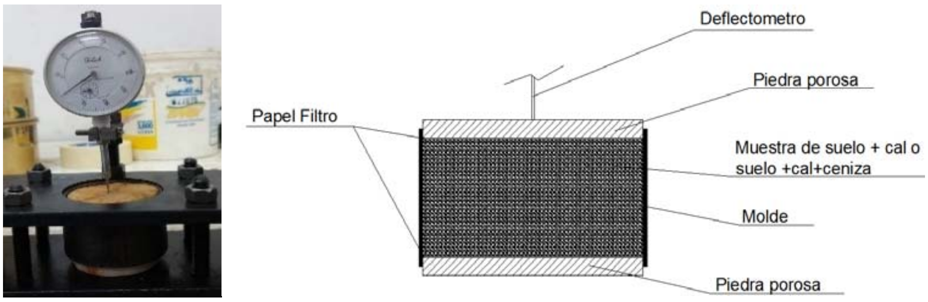

Fig. 3 Uni-dimensional swelling test scheme

The apparatus keeps the material confined allowing only axial movement, and a fixed deflectometer is able to measure deformations. The apparatus is immersed in water at 23 ± 2 °C and at 40±2 °C until the top is covered.

F. Durability Tests

Durability tests of compacted lime-soil and lime-RHA-soil blends after wetting-drying cycles were carried out in accordance with ASTM D559. The method aims to determine the mass loss throughout 12 wet-dry cycles. After the 7 days curing period is completed, every cycle starts by immerging the specimen in water for 5h at 23±2 °C. After stove-drying for 42h at 71±2 °C, specimen is finally brushed 18 to 20 times around its circumference and 4 times on the top and bottom surfaces, by using a force of 14 N.

III. Results

A. Effects of Curing Temperature

Fig. 4 shows UCS results of lime stabilized sulfated (20.000ppm) soil after 7 curing days at 23 °C and at 40 °C. Each result is the average of three specimens tested. As can be observed, all the specimens cured at 23 °C for 7 days did not show strength since they did not support 24 hs water immersion. Also, specimens cured at 40 °C, containing 5% of lime and γ_d of 16 kN/m³ and 17 kN/m³ did not show strength. The remaining specimens cured at 40 °C showed an increase in UCS with the increase in the amount of lime and γ_d.

Fig. 5 shows UCS results after 28 days of curing at 23 °C and at 40 °C. In this case, it can also be observed apparently null and marginal strengths when specimens were cured at 23 °C while those cured at 40 °C showed high strengths from 1,000 to approximately 5000 kPa.

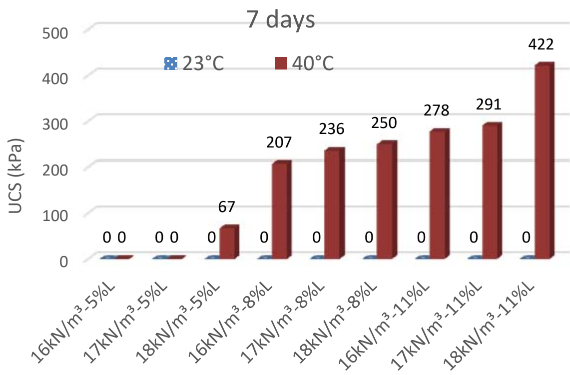

Fig. 4 UCS lime-soil strength values in 7 days of curing at 23 °C and 40 °C (20.000 ppm of sulfates)

Fig 6 shows swell test results on lime-soil mixtures at both 23 °C and 40 °C. At 23 °C, lime-soil samples showed important expansions from approximately 30% to 50% while at 40 °C expansions decreased, observing values of 10% to 30%.

In the case of durability tests, the specimens cured at 23°C were not capable of resisting the first 4hs immersion in water whereas those cured at 40°C only reached the second cycle of the test.

The positive effect of curing lime-soil mixtures at a higher temperature, increasing strength and decreasing expansion on the geomaterial is notable. This effect can be attributed to the fact that high temperatures act as catalysts for lime-water-clayminerals pozzolanic reactions [18] while decreasing the solubility of the sulphates of the system [19] avoiding in a certain amount the lime-water-sulfates-clayminerals reactions that are responsible for the formation of ettringite. Nonetheless, this effect is not remarkable in durability tests, where, despite the minimum improvement showed by curing the blends at 40 °C, this is not enough to consider them as subbase or base pavement material. It is important to highlight that durability tests can be considered as dynamic test where the external agent is the moisture variation trying to imitate severe environmental conditions [20].

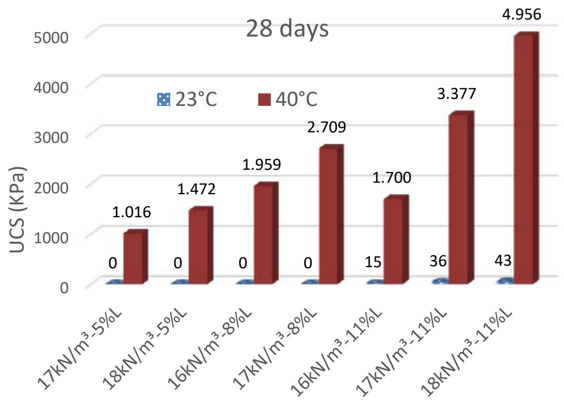

Fig. 5 UCS lime-soil strength values in 28 days of curing at 23°C and 40°C (20.000ppm of sulfates)

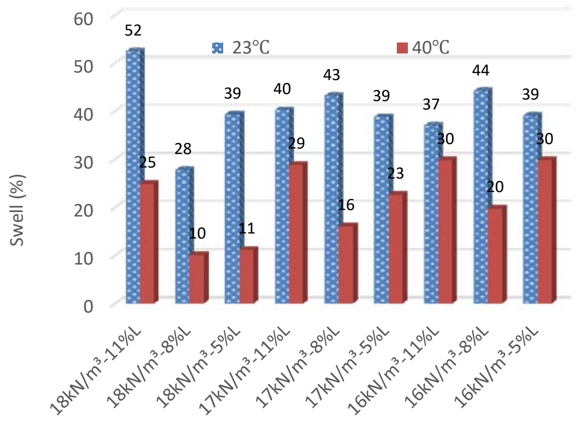

Fig. 6 Swell values of lime-soil blends after 20 days immersion at 23°C and 40°C (20.000ppm of sulfates)

B. Effect of RHA Addition

Figs. 7 and 8 illustrates the effect of adding 20% of RHA in lime-soils blends. In this case, all the specimens showed UCS after 7 days of curing at 23 °C, unlike those without RHA which did not show UCS at all (Fig. 4). Moreover, after 7 days curing at 40 °C, the soil-RHA-ash blends showed better UCS (approximately 4 times higher) compared to soil-lime blends. Additionally, after 28 days curing at 23 °C, the addition of RHA showed better UCS in comparison to soil-lime blends. However, after 28 days curing at 40 °C, no significative differences between soil-lime and soil-RHA-lime UCS were observed, and soil-lime blends under the same conditions showed a UCS. This may occur because the amount of RHA used was greater than the optimum, and residues of RHA did not generate puzzolanic reactions with lime and only weakened the geomaterial, because, it is important to emphasize that the addition of RHA markedly decreases the γ_d of the blends (Fig. 2).

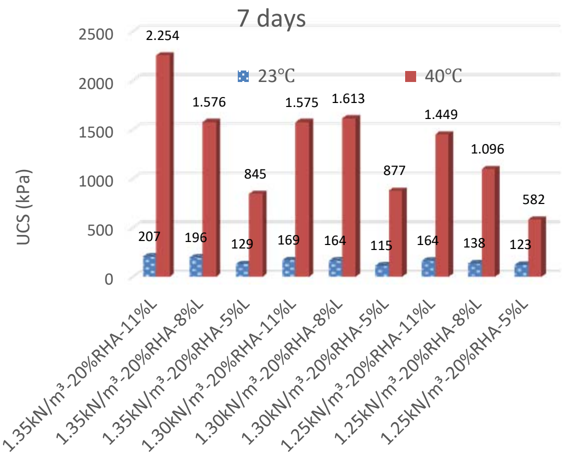

Fig. 7 UCS lime-RHA-soil strength values in 7 days of curing at 23°C and 40°C (20.000ppm of sulfates)

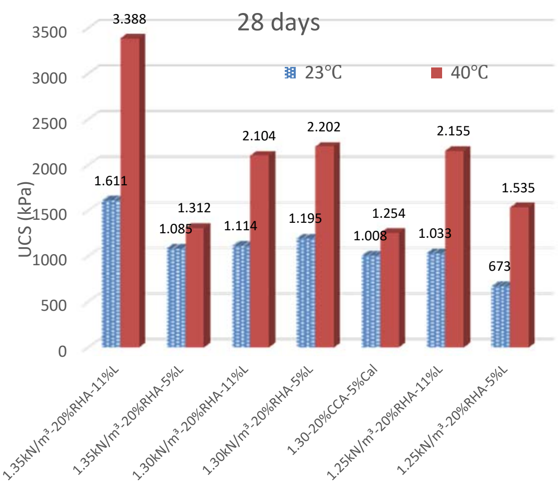

Fig. 8 UCS lime-RHA-soil strength values in 28 days of curing at 23°C and 40°C (20.000ppm of sulfates)

Regarding the volumetric stability of the material, in Fig. 7 a significant decrease in swelling adding 20% of RHA to soil-lime blends can be observed. In specimens cured at 23 °C, swelling was reduced from a range of 30% to 50% to a range of 11% to 24%, whereas in specimens cured at 40 °C, a reduction of swelling from a range of 10% to 30% to a range of 9% to 10% was observed.

Durability tests show that the addition of 20% RHA improves the performance of the geomaterial in this aspect. In Fig. 10, it can be observed that most of the blends were capable of bearing 12 wetting-drying cycles. Three specimens cured at 23°C did not resist to 12 wetting-drying cycles whereas at 40 °C, all the specimens resisted. Accumulated loss of mass (ALM) after 12 wetting-drying cycles from 30% to

100% was observed in specimens cured at 23°C, whereas in specimens cured at 40°C, 18% to 30% of ALM after 12 cycles were observed.

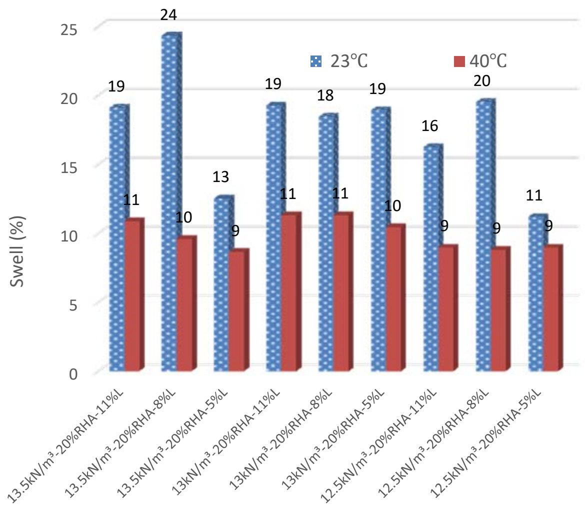

Fig. 9 Swell values of lime-RHA-soil blends after 20 days immersion at 23°C and 40°C (20.000ppm of sulfates)

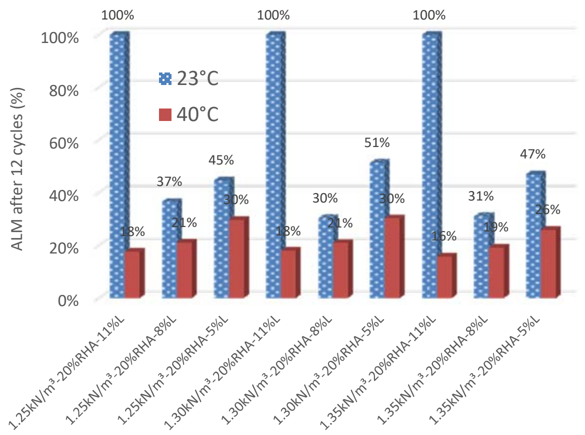

Fig. 10 Accumulated loss of mass after 12 wet-dry cycles for blends cured 7 days at 23°C and 40°C (20.000ppm of sulfates)

A positive effect of adding RHA in the stabilization of soils containing sulfates in terms of strength, durability and volumetric stability could be noted in the test results. According to [21], blends alkali activated with slags or fly ashes, generally show better sulfate attack resistance than Portland cement for example, but the mechanisms that control these improvements in a microstructural level are still not well understood.

IV. Conclusions

The acceleration of pozzolanic reactions together with the decrease in sulfate's solubility at high curing temperatures proved to have an important effect on the strength and the volumetric stability of soil-lime and soil-RHA-lime blends. Nevertheless, temperature effects on the durability of lime-soil blends showed marginal improvements, but, on the durability of lime-RHA-soil blends, highs temperature played an important role. It is important to take into account the positive effects of high temperatures when mixing and compacting stabilized rich sulfate soils in field.

The addition of rice husk ash influenced notably on a better performance of the geomaterial in terms of strength, durability and volumetric stability. The use of rice husk ash to stabilize these soils would be a sustainable, useful and economically feasible proposal, considering that in the region this is a waste without much value and discarded in the majority of cases.

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