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Soil Stabilization with Rice Husk Ash

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Abstract

Rice husk ash (RHA) is a by-product of rice milling. Its use as a soil stabilizer is an alternative to the final disposition with environmental benefit. Because RHA is not self-cementitious, a hydraulic binder such as lime must be added to form cements to improve the soil strength. Researches on stabilization by applying RHA and lime combinations were conducted in sandy soils. RHA of no-controlled rice husk incineration in conventional ovens and of laboratory burning at controlled temperatures were used. The alkaline reactivity of the RHA was studied through X-ray diffractometry analysis and loss on ignition tests. The formation of cementitious compounds was observed in mixtures of soil with different RHA and lime contents. Unconfined compression strength tests were conducted on soils treated with RHA and lime. Results show strength improvements for all RHA and lime contents and time periods studied, and all materials produced can be defined as modified rather than stabilized. Improvement of sandy soils with RHA is an alternative to the final disposition with environmental, social and economic benefits.

Keywords: rice husk ash, waste valuation, soil stabilization, alkaline reactivity, mechanical behaviour

1. Introduction

Rice husk is a by-product of the rice milling. About 100 millions of tons of husk per year are produced worldwide [1]. The husk is not suitable as animal feed because of its abrasive character and almost negligible digestible protein content [2], its high ash and lignin contents make it unsuitable as a raw material for paper manufacturing [3].

In order to reduce such volume of waste, rice husk is burned either in open heaps or as a fuel in ovens for rice drying, power generation, etc. The burning volatilizes the organic compounds and water of the rice husk, and about 20% of the mass remains as rice husk ash (RHA)

[2, 4–9]. If all rice husks had been burned, it would annually produce about 20 millions of tons of RHA worldwide. To value this residue is an alternative to its final disposition with environmental benefit.

Pozzolanas are siliceous and/or aluminous materials, which in themselves possess little or no cementing properties, but chemically react with calcium hydroxide, such as lime, to form compounds possessing cementitious properties [10]. The RHA contains around 90% of silica [4, 5], which is the highest concentration of all plant residues [2]. Based upon this, RHA has been used to improve properties of soil either when added alone or when mixed with a hydraulic activator such as the cement and lime [1, 6–8, 11–16]. Soil stabilization by the addition of RHA and lime is particularly attractive for road pavements because it leads to cheaper construction and lesser disposal costs, reduces environmental damage and preserves the most highly qualified materials for priority uses [7, 8].

The effect of the addition of RHA alone on the plasticity, unconfined compression strength (UCS) and California Bearing Ratio (CBR) of a lateritic soil with 45% passing the #200 sieve (75 μm), was studied by Rahman [11]. Results showed increases of UCS and CBR in 1 day with increase in RHA up to 20 and 18%, respectively, after which they started to decrease. Similarly, Alhassan [14] observed increasing of CBR with 6-day and 1-day soaking and without soaking when a clayey soil was stabilized with RHA up to 6 and 12%, respectively.

Generally, RHA cannot be used alone in soil stabilization because of its lack of cementitious properties [7, 8]. Development of UCS has been observed when clayey, clayey sandy, silty clayey and silty sandy soils were treated with RHA and lime or cement [1, 7, 8, 12, 13]. In the case of cement, it was observed that little or insignificant increases of UCS in lateritic and clayey soils stabilized with RHA and cement with respect to its increase when they were treated with cement alone [6, 12]. For a given lime or cement content there is an optimum value of RHA content which corresponds to the maximum UCS, which varies depending on the type of soil, ash characteristics, hydraulic activator and curing time [1, 7, 8]. Alhassan [15] attributes the UCS decreasing after this optimum value to the excess RHA that could not be utilized for the alkaline reactions. Also, he shows that addition of RHA in clayey soil-lime specimens further increased the UCS at specified lime content. This increment was rapid between 0 and 4% RHA content but decreased in rate from 6 to 8% RHA content at specified curing period.

Basha et al. [8] found that a lesser amount of cement is required to achieve a given strength as compared to cement-stabilized silty sandy soil when RHA is added. Since cement is more costly than RHA, this results in lower construction cost. Ali et al. [7], evaluating the effectiveness in the improvement of a clayey sandy soil with RHA, showing that lime is a more effective stabilizing agent than cement.

The aim of this chapter is to summarize experiences conducted in Uruguay to use soils improved with RHA and lime as pavement materials of low-volume roads [17–20]. First, a background of the state of the art of soil stabilization and, particularly, with RHA is performed. It is presented as results of mineralogical and reactivity characterizations of RHA with different burning processes, and unconfined compression strength improvement of different soils

treated with mixtures of these ashes and lime. The results are analysed taking into account the accumulated worldwide experience, from which general conclusions are drawn.

2. Background

2.1. Soil improvement

Soils are the most widely used materials in civil engineering works, particularly in pavements. However, the properties of local soils are not suitable for the requirements of particular structures. In these cases, improving soil properties is an attractive alternative. There are essentially two forms of improvement: modification and stabilization [1, 21]. When physical properties of soil, such as plasticity, texture, volumetric stability, hydraulic conductivity and workability are improved, it is named modification, and stabilization when a significant level of long-term strength gain and durability are developed. Modification can produce important strength improvement.

Different criteria have been proposed to define whether the soil treated is modified or stabilized. Thompson [22, 23] established an optimum content of lime to stabilize the soil one which produces a UCS of 345 kPa with 28-day cured at room temperature or 48 h at 49.5°C. The criterion has been extended to soil stabilization with ashes and lime. The National Association of Australian State Road Authorities (NAASRA) divides lime-treated materials as modified and stabilized according to their fundamental behaviour under applied loadings [24]. Modified materials are used and evaluated in the same manner as conventional unbound flexible pavement while stabilized materials have a sufficiently enhanced elastic modulus and tensile strength to have a practical application in stiffening the pavement. Austroads suggests for lime modification of pavement layers 28-day UCS values between 0.5 MPa and 1.5 MPa, and for lime stabilization UCS greater than 1.5 MPa [24]. For lime stabilization, the use of pH testing together with 28-day UCS testing is recommended to establish the optimum lime content of a material, however, no mention is made on the strength to produce a lime-modified material.

The strength requirements for using lime-stabilized materials as structural layers in pavement systems vary considerably from agency to agency [21]. Thompson [23] defined a lime-soil mixture as acceptable for a structural base if the UCS exceeded about 1050 kPa while some transport agencies of USA require minimal UCS values for sub-base and base layers between 700 kPa and 1400 kPa [21].

The soil stabilization using ashes is explained by the pozzolanic reactions. When the lime ($\text{Ca}(\text{OH})_2$) is mixed with RHA, in the presence of water, it releases calcium ions (Ca^{++}) and the pH of the medium increases above 12.4 [25]. In this high basic environment, the silicates and aluminates dissolve from the ash and react with the Ca^{++} to form calcium silicate hydrate (CSH) [2, 7, 8, 26]. In the case of mixture of cement and RHA, the silica reacts with the extra lime in the cement which in some cases can be as high as 60% [2]. Following James and Rao [27] the silicates formed are of the kind CSHI and CSHII, according to Eq. (1).



Where



These products of the pozzolanic reactions are primarily gels that cover and bond the soil grains causing the strength gain [7, 27, 28]. The gels slowly crystallize turning into well-defined CHS, which results in a further enhancement in strength. Pozzolanic reactions begin quickly, a few hours after adding the water to the mixture, and can continue for a very long period of time, even many years, as long as enough lime, silica and water are present and the pH remains high [21]. Ali et al. [7] show X-ray diffractograms (XRD) of mixtures of clayey sandy soil with RHA and lime cured for 7, 28 and 90 days. New peaks of calcium aluminate hydrate (CAH) and CSH appear after 7 days and continue to form after 28 and 90 days, while peaks of lime disappear at 28 days. These slow reactions cause a long-term strength gain of soils.

Ali et al. [7] showed that addition of RHA-lime to a clayey sandy soil produces higher initial rate of UCS development. 6 and 9% RHA contents give an average increase in strength of 35 and 49% as the curing time increased from 7 to 28 days at 30°C. The rate of UCS development reduces at the later stages. The dependence of strength development on curing provides a considerable factor of safety for designs based on say 7-, 28- or 56-day strength [7]. UCS increases can be observed between 1 day and 7 day when both lime and cement were used to improve lateritic soil treated with RHA [11] and up to 28 days in a clayey soil stabilized with RHA and cement [12].

The enhancement of UCS development by adding RHA is influenced by the temperature [7]. As the temperature increases, the rate of strength development is intensified, due to the crystallization of cementing minerals is accelerated. Ali et al. [7] observed a significantly higher rate of UCS development in specimens of clayey sandy soil stabilized with 612 and 18% RHA and 6 and 9% lime cured during 28 days at 60°C with respect to similar specimens cured with the same time but at 30°C.

2.2. Rice husk ash reactivity

The properties of RHA depend greatly on whether the husks have undergone complete destructive combustion or have only been partially burnt [4]. Houston [4] classified RHA into high-carbon char (black), low-carbon (grey) ash and (3) carbon-free (pink or white) ash. Colour changes are associated with the completeness of the combustion process as well as structural transformation of the silica in the ash [2]. XRD studies have shown that pink ash consists essentially of tridymite and cristobalite [4], the high-temperature crystalline forms of silica. There is little if any quartz, the low-temperature crystalline form of silica. At low-combustion temperatures considerable amorphous silica remains, giving black and grey ash. Also, white colour is an indication of complete oxidation of the carbon in the ash [2].

The characteristic of the ash depends on temperature, burning time, cooling time and burning type [3, 8]. The type of ash suitable for pozzolanic activity is amorphous rather than crystallized [2]. The structural transformations of the silica affect the ash reactivity since the larger surface area of the silica the greater the extent of the chemical reactions with the

$\text{Ca}(\text{OH})_2$ [2, 6]. Incineration of rice husk in the temperature range of 550–700°C is generally found to produce amorphous silica in the ash while temperatures in excess of 900°C produce unwanted crystallized forms [2]. However, Smith and Kamwanja [29] have reported that temperatures of about 800°C maintained for 12 h give small proportions of crystallized silica. Mehta [3] established that a highly reactive ash can be produced by maintaining the combustion temperature below 500°C under oxidizing conditions for relatively prolonged period or up to 680°C provided the high temperature exposure was less than one minute. Prolonged heating above this temperature may cause the material to convert (at least in part) to crystalline silica. Yeoh et al. [30] report that silica in RHA can remain in amorphous form at combustion temperatures of up to 900°C if the combustion time is less than 1 h, whereas crystalline silica is produced at 1000°C with combustion time more than 5 min. Other reports claim that crystallization of silica can take place at temperatures as low as 600, 500 or even at 350°C with 15 h of exposure [31].

Technologies of ash production vary from open-heap burning to specially designed incinerators. When the rice husk is burned in open-heap or conventional oven, crystalline ash with low reactivity produced, while when it is incinerated in an oven with controlled temperatures, the residue is a highly reactive white ash [3]. The rice husk incinerated in oven at controlled temperature conditions between 800–900°C verified a high reactivity of the ash in comparison with the ash resulting of the open-heap burning. RHA from burning in heaps and oven-dried at 60°C showed a much scattered XRD with peaks of quartz and tridymite [7].

The carbon content of RHA influences the stabilization process, retarding the reactions and producing low increases of strength. The avidity of carbon by calcium ions interfere the reactions between Ca^{++} and silica [32]. According to these authors, lime stabilization of soils with 6% of carbon is economically impracticable. Remaining carbon content less than 3% have been measured in a RHA obtained by burning in a simple combustion chamber at 800°C [11] and in heaps and oven-dried at 60°C [7].

3. Materials and methods

3.1. Rice husk ash

Four RHA from no-controlled burning were studied (RHAU). Three RHA from rice husk burned in conventional ovens to rice drying were collected in the rice mills of Arrozur (RHAA) in Villa Sara, Arrozal 33 (RHA33) in Vergara, both in Eastern Uruguay, and Demelfor (RHAD) in Artigas, northern Uruguay. The remaining no-controlled RHA is a result of the incineration in the furnaces of the power-generation plant of Galofer (RHAG), situated in Villa Sara.

RHA produced in laboratory at controlled temperature and time (RHAC) was also studied. Rice husk taken from Arrozur was incinerated in an oven at 500, 650, 800 and 900°C (RHA500, RHA650, RHA800 and RHA900) for 4 h and cooled at room temperature.

3.2. Soils

Four different sandy soils were used in the researches. The soil, classified according to the Unified Soil Classification System (USCS) as well-graded silty sand (SW-SM), collected in the Perez Bustos quarry, near Montevideo (PBS). The silty sand (SM) from a quarry located in Vergara (VS) and a poorly graded sand (SP) taken from Villa Passano (VPS), both in eastern Uruguay. The reddish poorly graded silty sand (SW-SM) from the Sandstone quarry, near Artigas (SS), northern Uruguay. **Table 1** shows the properties and classification of the soils. The fine content (grain-size passing the #200 sieve) is similar in PBS, VS and SS (less than 7%), while VPS has about 17% of fines. All the soils have plasticity index equal to zero ($IP = 0$), that is the soils are not plastic.

3.3. Lime

A commercial hydrated lime (L), mark Bulldog, produced by the Oriental de Minerales Company of Uruguay was used in the stabilization of PBS and SS. It is a calcium lime with 66% of calcium oxide (CaO), 5% of magnesium oxide (MgO) and other elements like silica and ferric oxide. The lime is fine with 100% passing the #10 sieve and 93% passing the #200 sieve, whereas 91% was greater than 2 mm.

The VPS and VS were treated with a residual quicklime (RL) from Cementos del Plata Plant. This lime does not accomplish the requirements for its use as chimney filter and it is a calcium lime with CaO varying between 70 and 93%, a maximum MgO of 8% and ferric oxide (Fe_2O_3) between 0.5 and 4.5%.

3.4. X-ray diffraction

X-ray diffraction analyses were performed on the residual RHA from the no-controlled burning in the Arrozur Mill (RHAA), RHA of controlled incineration (RHA500, RHA650, RHA800 and RHA900), PBS, mixtures of PBS with 15 and 20% RHAA and 5 and 10% lime cured for 28 days (PBS-15RHAA-5L, PBS-20RHAA-5L, PBS-20RHAA-10L), and mixtures of PBS with 15% RHA650 or RHA800 and 5% lime with 28 days (PBS-15RHA650-5L, PBS-15RHA800-5L). A dusty diffractometer with $CuK\alpha$ radiation and wavelength of 1.5418 \AA was used. The samples were obtained from the specimens for the UCS tests once these were completed and they were milled in mortar before analysis to have a grain size less than 0.075 mm.

Property	Perez Bustos (PBS)	Vergara (VS)	Villa Passano (VPS)	Sandstone (SS)
Passing #4 (4.76 mm)	98.6	100.0	99.8	99.8
Passing #10 (2 mm)	89.6	99.9	91.6	99.6
Passing #40 (0.42 mm)	26.1	41.0	13.8	77.6
Passing #200 (0.074 mm)	6.5	16.9	3.6	6.2
USCS Classification	SW-SM	SM	SP	SP-SM

Table 1. Physical properties and classification of soils.

3.5. Loss on ignition

The organic matter content of all RHAU and RHAC was evaluated by loss on ignition tests, following the ASTM standard D7348. Samples of the RHAU were initially weighed and then subjected to a controlled temperature of 550°C during 3 h into a muffle. Because the RHAU were produced with temperatures similar or greater than 550°C, a temperature of 1000°C was adopted for tests. Thereafter, the samples were weighed after cooling at room temperature. The carbon content is the ratio between the final and initial weights of the samples.

3.6. Compaction tests

Standard Proctor compaction tests according to AASHTO Standard T99 were carried out to determine the maximum dry unit weight (MDUW) and the optimum moisture content (OMC) of the PBS and materials of PBS treated with 20% of RHAA (PBS-20RHAA-10L) by dry weight of soil and 10% of lime by dry weight of soil. Modified Proctor compaction tests were conducted in accordance to AASHTO T180 on soils and soil-RHA-lime materials.

The soils, RHA and lime were previously manually mixed in dry and thereafter various moisture contents were added and homogenized by manual mixing. The compaction was carried out immediately or 1 h after water mixing.

3.7. Unconfined compression strength tests

UCS tests of the soils and the soils stabilized with different RHA and lime contents and for different time periods were carried out following the AASHTO Standard T208. Cylindrical specimens, 3.72 cm in diameter and 7.65 cm in high were compacted into a metallic mould by kneading system at MDD and OMC of the corresponding standard or modified Proctor compaction test. The soil-RHA-lime specimens were compacted immediately or 1 h after water mixing and thereafter they were enveloped in polyvinyl film and stored in a moisture chamber at room temperature for the corresponding curing time. Finally, the specimens were tested in a triaxial load press up to failure.

4. Results and discussion

4.1. Mineralogical composition of rice husk ash

XRD analyses of RHA from Arrozur (RHAA) and RHA from laboratory-controlled incineration (RHA500, RHA650, RHA800, RHA900) are given in **Figure 1**, where they have been dislocated in the intensity axle for better viewing. Peaks in the diffraction angles (2θ) of 21.96, 31.42, and 36.35° are observed in the XRD of the RHAA, which are characteristics of cristobalite, a high-temperature crystalline form of silica [4]. The rice husk is burned in conventional ovens in the Arrozur Mill producing a crystalline ash with low reactivity [3]. Peak of carbon is also identified in RHAA at 2θ of 26,62°, which is indication of crystallization of part of the organic of the husk during the burning.

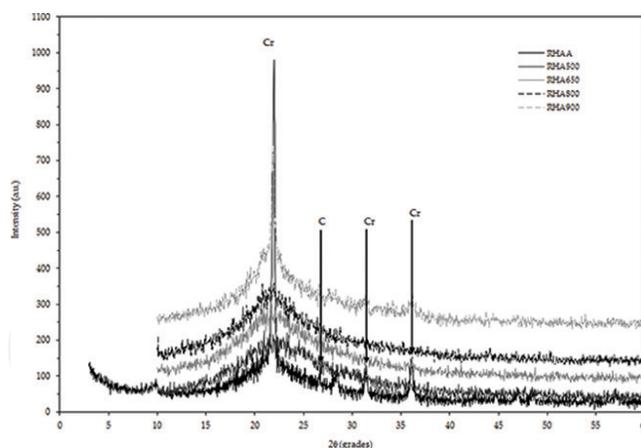


Figure 1. X-ray diffractograms of residual RHA from Arrozur and laboratory-controlled incinerating RHA. Cr: cristobalite; C: carbon.

XRD of RHA500, RHA650, and RHA800 are similar and show amorphous shape, without well-defined peaks, indicating that the silica in these ashes is amorphous rather than crystalline. The XRD of RHA900 presents peaks of cristobalite similar to that of the no-controlled burning ash. An upper limit of controlled temperature to secure RHA with considerable amorphous silica would be about 800°C, if it is maintained for 4 h, beyond which they would lead to ashes with silica mostly crystallized.

DRX of materials of PBS treated with residual RHA from Arrozur (RHAU) and lime and with RHA burned at controlled temperatures of 650 and 800°C (RHAC) and lime are depicted in **Figure 2**. Peaks of quartz, corresponding to the sandy soil, remain in all the DRX because it is a crystalline mineral that cannot react with the ash and lime.

The DRX of materials with RHAU (15 and 20%) and lime (5 and 10%) are similar. As was expected, peaks of cristobalite of the RHAU remain in those DRX. New peaks for 2θ of 24.37 and 35.75° of antigonite are present. This is a calcium aluminate silicate hydrate (CASH) which have been produced by the pozzolanic reactions between the Ca⁺⁺ the lime and the silica of the

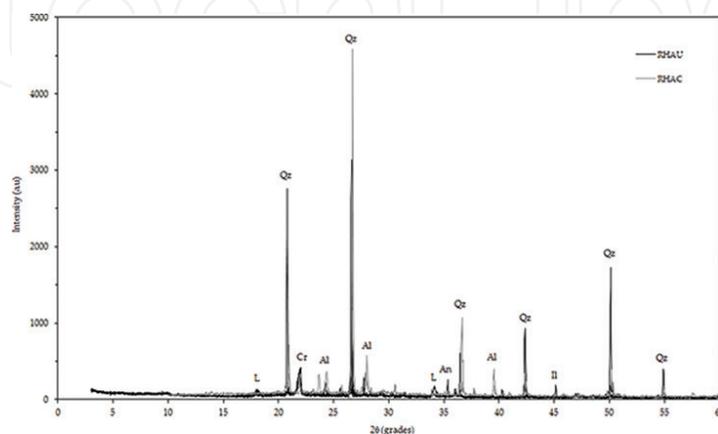


Figure 2. X-ray diffractograms of Perez Bustos soil treated with residual and controlled RHA and lime for 28 days. Qz: quartz; Il: illite; Cr: cristobalite; An: antigonite; L: lime; Al: albite.

ash. Despite the RHAU has mostly crystalline silica, it contains enough amorphous silica to react with the lime and form cementitious products. The peaks of lime mineral could be due to the exceeding lime that has not reacted before 28 days, because the alkaline reactions are slow.

New peaks of albite, a calcium aluminate silicate hydrate (CAH), are observed in both DRX of materials with RHAC, which demonstrates that reactions between the amorphous silica of these ashes and the Ca^{++} of the lime have taken place before 28 days. The similarity among the XDR shows that the pozzolanic reactivity of the RHA is quite independent of controlled incineration temperatures within the range of 650–800°C.

It is more difficult to identify the cementitious products in the DRX of the materials with RHAU than the DRX of the materials with RHAC. This would indicate that the reactivity of the RHAC is much greater than that of the RHAU, particularly within the controlled temperatures from 650 to 800°C. RHA percentages to obtain similar reactions are less in those produced at controlled temperature than in the residual ones. The use of RHA incinerated at controlled temperature within 650–800°C is a more efficient soil improving alternative.

4.2. Carbon content of the rice husk ashes

The mean values of loss on ignition of the four RHAU studied and of the RHA produced in the laboratory at temperatures during 4 h are presented in **Table 2**. All the RHAU are resultant of the husk burning in conventional ovens and are black in colour and remained mainly with this colour with white veining or tended to a grey colour. The carbonized part of the organic during the no-controlled incineration cannot be volatilized when the ash is again incinerated at 550°C for 4 h. However, the RHAU have different organic contents maybe due to the type of oven, temperature gradients inside them and incineration times. The RHAU from the Galofer Power Generation Plant (RHAG) has the least organic content, which coincides with that it is the most fine and free of impurities ash. Slightly higher organic content has the RHAU from the Arrozur Mill (RHAA). This mill and Galofer Plant are located in the same place and the burning process are almost similar. RHA 33 and RHAD present a considerable amount of no burned husk, which influences the greater organic content determined. In any case, the organic content of the RHAU is greater than that considered as suitable for soil stabilization [32]

Material	Temperature (°C)	Time (h)	Loss on ignition (%)
RHAA	550	3	18.6
RHAG	550	3	15.0
RHA33	550	3	34.1
RHAD	550	3	38.8
RHA500	1000	3	7.8
RHA650	1000	3	4.1
RHA800	1000	3	2.3
RHA900	1000	3	0.3

Table 2. Loss on ignition of the RHA.

The organic content of the RHA noticeably decreases when the incineration is temperature-controlled. For a relatively low controlled temperature of 500°C (RHA500), the loss on ignition was 7.8% meanwhile that of RHAA was 18.6%. The organic content almost linearly decreases with the increasing of the controlled temperature. The control of temperature and the incineration method are fundamental when the objective is to produce RHA with high pozzolanic reactivity. The organic content of RHA500 and RHA650 are relatively high for soil stabilization purposes while it can be considered as allowable for RHA800 [32]. A lower limit of controlled temperature to secure a RHA with an allowable organic content would be about above 650°C, if it is maintained for 4 h.

4.3. Compaction characteristics

The dry unit weight-moisture content relationship of PBS, PBS with 20% RHAA and 10% L (PBS-20RHAA-10L), SS, SS with 20% RHAD and 5% L (SS-20RHAD-5L), VPS, and VPS with 20% RHAG and 3% RL and 5% RL (VPS-20RHAG-3RL, VPS-20RHAG-5RL) are depicted in

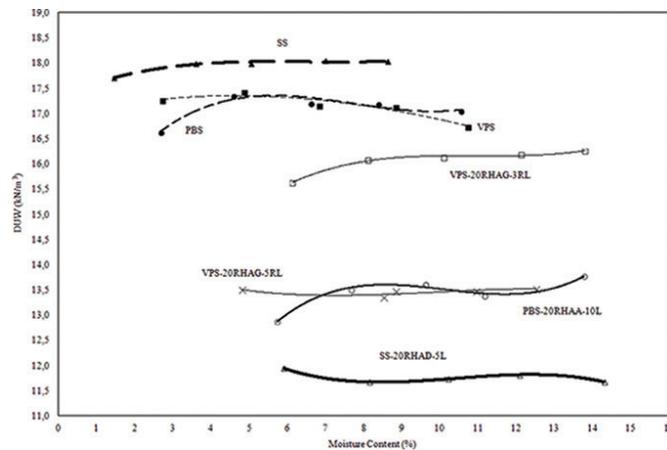


Figure 3. Dry unit weight-moisture content relationship of natural and stabilized Perez Bustos soil, Sandstone soil and Villa Passano soil.

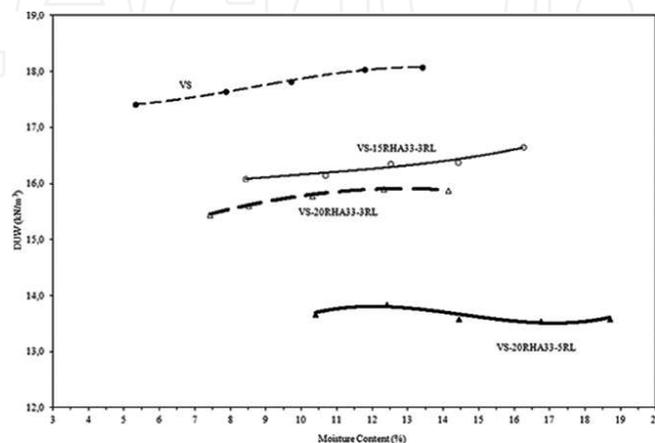


Figure 4. Dry unit weight-moisture content relationship of natural and stabilized Vergara soil.

Figure 3. Figure 4 shows the compaction curves of VS and VS with 15 and 20% RHA33 and 3 and 5% RL (VS-15RHA33-3RL, VS-20RHA33-3RL, VS-20RHA33-5RL).

All the soils have oddly shaped compaction curves without MDD and OMC well defined. This kind of compaction curve is typically obtained in the Proctor tests of sandy soils because the impact effort used in these is not efficient to compact such soils. The most efficient compaction effort for these soils is the vibration. The compaction curves of all treated materials are similar in shape to the respective natural soils. Due to the compactions were performed immediately or 1 h after the mixing, without enough time to the development of the alkaline reactions. The addition of RHA and lime do not produce textural changes in the sandy soil, which results in a similar trend compaction curve for the stabilized material. The vibration is the most recommended compaction method for sandy soils stabilized with RHA and lime independent of the ash and lime characteristics and proportions.

The dry unit weight (DUW) of all soil-RHA-lime materials are less than its corresponding natural soil for all compaction moistures. The RHA and lime have lower specific gravity and finer grain size distribution than those of the soil, so when added to a soil the specific gravity and the grain size distribution of the mixture are reduced resulting in the DUW decreasing [6, 7]. As a result the MDD of soil-RHA-lime materials are less than those of the soils (**Table 3**).

It is observed from the treatment of VPS and VS (**Figures 3 and 4**) that the MDD decreases as the RHA and lime contents increase, which is in agreement with findings in [6, 7, 14, 16]. However, it can be seen from **Figure 4** that the DUW decreases more with the increasing of lime content than that of the RHA.

The OMC is greater with the adding of RHA and lime for all studied cases (**Table 3**). The results are in agreement with the findings given in [6–8, 14, 16]. One portion of the water added to the mixture is absorbed by the RHA due to its porous characteristic [7, 8]. Another part is consumed by the lime hydration, which is required for alkaline reactions. The soil

Soil	RHA (%)	Lime (%)	MDUW (kN/m ³)	OMC (%)
Perez Bustos	0	0	17.4	5.7
	20	10	13.6	8.6
Sandstone	0	0	18.0	5.7
	20	5	11.8	12.4
Villa Passano	0	0	17.4	4.6
	20	3	16.2	10.4
	20	5	13.5	12.4
Vergara	0	0	18.1	13.3
	15	3	16.8	14.4
	20	3	15.9	14.9
	20	5	13.8	15

Table 3. Maximum dry unit weight and optimum moisture content of soils and soil-RHA-lime materials.

improvement with RHA and lime is water consuming, so it is necessary to add a greater moisture content to reduce the suction effect in the pores and to reach the greatest efficiency of compaction. Following the results of the treatment of VPS and VS, the OMC increases with increase in RHA and lime content.

4.4. Unconfined compression strength

Figure 5 shows the 28-day UCS evolution as function of the RHA and lime contents. A general pattern of UCS gain is observed for all RHA and lime contents. The UCS of VS and SS with 5% lime increases with addition of RHA until an optimum is reached, beyond which the strength begins to decrease. The optimum RHA contents found were about 15% for VS-RHA33-5RL and SS-RHAG-5L and about 20% for VS-RHA33-3RL. The maximum UCS were not reached with the studied RHA contents in the other cases, however they were found fitted in parabolic curves, which demonstrates that they also would have an optimum RHA content greater than 20%.

The 28-day UCS of VS and SS treated with 5% lime are greater than those treated with 3% lime for RHA contents up to the optimum, beyond which the strength of soils with 3% lime tends to be greater than those with 5% lime. A similar trend can be observed in the treated VPS, however the difference of UCS for all given RHA contents are practically negligible. When commercial lime is used, the most economical solution would be to adopt the least possible amount of lime even it means using greater amount of RHA since this is a residue.

The maximum 28-day UCS do not achieve the 345 kPa established to consider as optimum to stabilize a soil [22, 23]. From this and following the criteria suggested by different transport agencies [21, 24], all the studied improved soils can be defined as modified materials rather than stabilized. The shear strength of sandy soils mainly depends on the confining pressure so its UCS (confining pressure zero) is very low. In fact, the UCS of the studied soils is 8.2 kPa (PBS), 5.5 kPa (SS), 0 kPa (VPS) and 15.1 kPa (VS). If modified materials are those that behave as the corresponding untreated soil, the shear strength of studied materials would also depends on the confining pressure and therefore its UCS would be relatively low. The UCS method [22, 23] was developed for soil stabilization with lime and it should be adjusted to be adequately used for soil stabilization purpose using ashes.

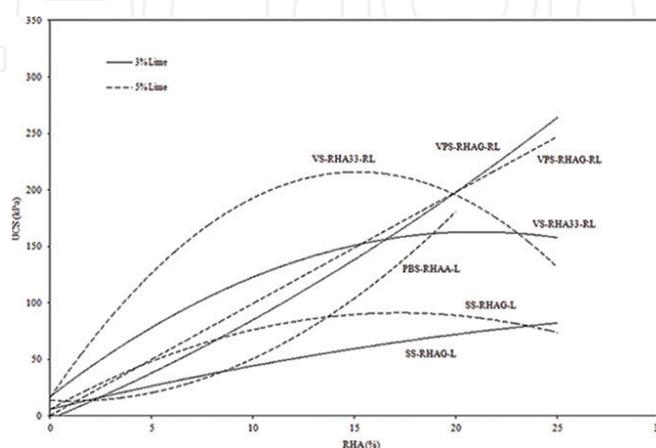


Figure 5. 28-day unconfined compression strength of soils with different RHA and lime contents.

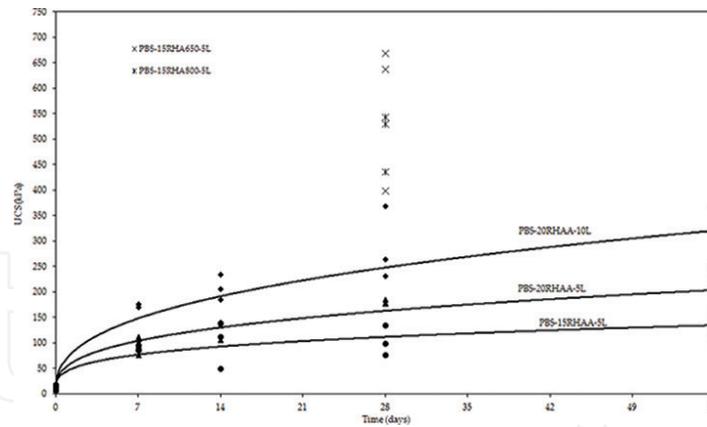


Figure 6. Unconfined compression strength of materials of Perez Bustos soil modified with RHAA and lime as a function of time.

The time dependence of the UCS of sandy soils treated with different residual RHA and lime contents is observed in **Figure 6**. A gain of UCS over time is observed for all studied RHA and lime combinations with a variation rate that reduces with the time. For the same lime content, the initial variation rate is higher when it is added a greater RHA content, 5.6 and 7.6 in the first 7 days for specimens with 15 and 20% RHAA, respectively, and tend to be similar at the later stages, 1.2 and 1.3, respectively, for the same materials from 7 days to 14 days. The initial variation rate is greater when it is increased the lime content maintaining constant the RHA content, 7.6 and 10.8 at 7 days when the lime content varies from 5 to 10%, and tend to be similar (1.3) at the later stages. The dependence of strength development on time provides a considerable factor of safety for designs based on say 7- or 28-day strength [7].

A significant increase of UCS results when RHAC are used, as can be seen in **Figure 6**. The UCS of specimens with 15% of these controlled ashes and 5% lime is greater than that of the specimens with RHAU for all stabilizer contents and times. The UCS of PBS-15RHA650-5L and PBS-15RHA800-5L at 28 days are, respectively, 41 and 36 times greater than that of PBS. They are, respectively, 5.1 and 4.5 times the 28-day UCS of PBS-15RHAA-5L, and 1.8 and 1.6 times 56-day UCS of PBS-20RHAA-10L. The RHA from controlled incineration at temperatures from 650 to 800°C are more reactive than the RHA from incineration in conventional ovens, being needed less amounts of RHA and lime to reach greater UCS.

The UCS of tested materials with RHAC is quite similar, which evidences a similar pozzolanic reactivity for both incineration temperatures. The 28-day UCS of soils modified with RHAC and lime cured for 28 days would be independent of the incineration temperature within the range of 650–800°C.

5. Conclusions

The improvement of soils through addition of rice husk ash (RHA) and lime was studied in several researches. Four sandy soils from different locations of Uruguay and four residual RHA (RHAU) produced in conventional ovens were used for this objective. RHA produced

in laboratory with controlled temperature and time (RHAC) were also investigated. Results and analysis of these researches allow to draw the following conclusions:

All the RHAU are black in colour, classifying as high-carbon char, with less or more presence of no burned husk. The RHAU from power-generation oven (RHAG) is the finest and has negligible rice husk content. The X-ray diffractogram (XRD) of the RHA resultant of rice husk incineration in conventional oven of the Arrozur Mill (RHAA) shows peaks of cristobalite, a high-temperature crystalline form of silica and carbon from the crystallization of part of the organic. The organic content of the four RHAU is high to very high, greater than the considered as suitable for soil stabilization. The RHAG has the least loss on ignition, followed by RHAA. The higher loss on ignition is due to the no burned husk presents in these ashes. As the type of ash suitable for pozzolanic activity is amorphous rather than crystallized and with low organic content, the studied RHAU can be defined as low to moderately low ashes.

The RHAC show XRD without clear peaks for incineration temperatures from 500–800°C, indicating that the silica in these ashes is amorphous rather than crystalline. Peak of cristobalite is observed in the RHAC from husk incineration at 900°C. An upper limit of controlled temperature to secure RHA with considerable amorphous silica would be about 800°C, when it is maintained for 4 h. The loss on ignition reduces respect to the RHAU when the incineration is controlled at temperatures between 500 and 900°C, so that is less the greater the temperature. However, the organic content of ashes produced with temperatures until 650°C are still unwanted for soil stabilization purposes, while it is allowable for the ashes incinerated at temperatures equal or greater than 800°C. A lower limit of controlled temperature to secure a RHA with an allowable organic content would be about 650°C, when it is maintained for 4 h. Incineration of rice husk in the temperature range of 650–800°C is found to produce RHA of the highest pozzolanic reactivity.

The DRX of soil treated with RHAU and lime with 28 days show new peaks of antigonite. This is a calcium aluminate silicate hydrate resultant of the reactions between the calcium ions of the lime and the silica of the ash. Despite the RHAU is low reactive, it is still capable to react with the lime to form cementitious products. New peaks of albite, a calcium aluminate silicate hydrate resultants of the reactions between the calcium ions of the lime and the silica of the ash, are observed in the DRX of materials with RHAC and 28 days. When the lime is mixed with RHA, in presence of water, pozzolanic reactions take place to produce cementitious products as calcium silicate hydrate (CSH) and calcium aluminate silicate hydrate (CASH).

The unconfined compression strength (UCS) of soils is improved with adding all RHAU contents. Despite these ashes are low reactive, they can react with the lime to form cementitious products that bond the grains of sandy soils improving their strength. However, the 28-day UCS does not achieve the values established by different transport agencies to consider the soils as stabilized. The materials of soils improved with RHAU and lime can be defined as modified rather than stabilized. Although, modification can produce important strength gain.

The UCS increases with the increase of the RHAU amount until to reach an optimum, beyond which the strength begins to decrease. The optimum RHAU is higher when the lime amount

is less, however it is possible to reach higher UCS when is added the least amount of lime and RHAU contents higher than the optimum corresponding to higher lime contents. When commercial lime is used, it would be a more economical solution since the RHA is a residue.

A gain of UCS over time is observed for all studied RHA and lime combinations. Pozzolanic reactions begin quickly and continue for a very long period of time, even many years, as long as enough free calcium ions and silica are present and the pH remains high. The UCS increase rate is greater at starting and reduces at the later stages.

In countries with high rice production, rice husk and RHA are residues whose final disposition is a big concern, the use of RHA for soil improvement is particularly attractive. It reduces the environmental impact, disposal costs and preserves non-renewable resources such as soils and rocks. It is an economic alternative, particularly in roads, by giving value to a waste material, enabling the use of low-quality materials with reducing transport costs, and improving the pavement performance with reducing maintenance and rehabilitation costs.

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