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# Residue from coal combustion for plastic soil improvement

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**Abstract.** The combustion of coal in Hoffman-type furnaces generates ash as one of the process residues. This research seeks to make use of this residue to improve plastic subgrade soils in tertiary roads, considering that in Colombia a large percentage of these are not paved. A soil with high plasticity has been selected to make mixtures with ash dosages that vary from 0% to 15% with respect to the dry weight of the soil. To determine the variation of the physical and mechanical properties of the soil-ash mixtures tests of consistency limits, compaction tests, and California bearing ratio were carried out. The results showed that the mixture in which 12% of the coal combustion residue is added to the soil, as a percentage for the dry weight of the soil, has a better physical behavior and bearing capacity than the soil in its natural state. obtaining an increase of up to 75% in the California bearing ratio.

## 1. Introduction

In Colombia, tertiary roads play a fundamental role in the communication of rural sectors and correspond to those road corridors with less infrastructure and paving development due to the low volumes of traffic that pass through them [1]; this tertiary road network corresponds to 67% of the total road network, where19% corresponds to the secondary network in charge of the departments, 8% is the national network in charge of the nation and 6% is private roads. Currently, the tertiary network has an extension of 142,284 Km, of which 27,577 Km oversee the “Instituto Nacional de Vías (INVIAS)”, Colombia, 100,748 Km in charge of the municipalities, and 13,959 Km in charge of the departments [2].

According to the above, of the 142,000 Km of tertiary roads, only 6% are in good condition [3], so it is important to look for alternatives to improve the subgrade soils of these roads so that they offer minimum possibility conditions to low cost; hence, the use of waste materials in the ceramic industry is proposed to improve this type of road, as an alternative of sustainability. One of these waste materials is the residue that is generated in the manufacture of masonry units, corresponding to the coal ash produced by the combustion of coal in Hoffman furnaces [4].

The use of ash product of the combustion of natural coal in road improvement has been reported in different studies; Wei H, *et al.* [5], and Benassi, *et al.* [6] studied the feasibility of using residual fly ash (FA) and oil shale ash (OSA) to modify a silty clay as subgrade material, obtaining as a result that the soil modified, with the addition of FA and OSA, have a California bearing ratio (CBR) value higher than the soil unmodified. Another study carried out in India evaluated the effect of coal ash on the resistance characteristics of silty clay soils treated with cement, in this study they made mixtures of clayey silt and coal ash with cement, the optimal contents found were 20% and 50%, for which the CBR was 25.19% and 29.14% respectively, compared to the control sample of 4.72% [7].

The reuse of coal ash has also been used in the improvement of pavement layers, in [8] they investigated 345 samples through tests of CBR, Proctor, and resistance to compression of soil mixtures with 3%, by weight of dry soil, cement, and 5%, 10%, 15%, 20% of fly ash obtained from the combustion of coal from thermal power plants in Vietnam, the results showed that both for CBR, Proctor, and compressive strength, coal ash (ash background and fly ash), as waste material in Vietnam, can be reused as good material in the base layer of the pavement.

In Latin American, in the Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas, Perú, performed a study on the stabilization of soils with coal ash for use as an improved subgrade, said ash was obtained from the burning of mineral coal from a brick industry in the city of Chachapoyas, Perú, they used mixtures with the addition of 15% coal ash, 20%, and 25%, by weight of dry soil, showing results that indicate that the addition of these ashes improves the bearing capacity of CH and OH type soils [9,10].

In this research, the behavior of a clayey soil to which a residue from the combustion of coal in the Hoffman furnace of a brick furnace is added is analyzed, with the aim of determining the variation in its limits of plasticity, moisture-dry density relationships and CBR.

## 2. Methodology and materials

The waste used for the project is produced from the incomplete combustion of mineral coal in the Hoffman furnaces of a brickyard in the municipality of Ocaña, Colombia [11], while the soil used to make the mixtures corresponds to a fine soil with characteristics plastic obtained from the town of “Pueblo Nuevo” in the municipality of Ocaña, Colombia. The physical characterization of the materials was carried out by laboratory test as loose unit weight, consistency limits, granulometry, and modified compaction test (Proctor), while the mechanical characterization was carried out by the CBR test [12].

The residue from the combustion of coal in the Hoffman furnace was used as an addition, in the percentage of the dry weight of the soil, to prepare mixtures with dosages of 0%, 3%, 6%, 9%, 12%, and 15%. These soil-residue mixtures were subjected to consistency limits tests, compaction tests (modified Proctor), and CBR tests for samples compacted in the laboratory, all these tests were based on the INVIAS test standards for road materials. Additionally, microscopy tests of the residue were performed, using an image magnification of 100X, for a sample of 1000 µm wide and 700 µm high.

## 3. Results

Characterization tests were carried out for the coal combustion residue and for the soil, as well as tests to determine the physical and mechanical properties of the soil-coal residue mixtures, varying the percentage in which the latter was added to the mixture; the results obtained are detailed below.

### *3.1. Loose unit weight*

The test was carried out according to [13], using the soil samples in a natural state and residue from the combustion of coal in the Hoffman furnace, obtaining, as a result, unit weight of the soil of 0.936 g/cm$^3$, while the residue from the combustion of coal has a loose unit weight of 0.447 g/cm$^3$, which means that the soil has a greater mass per unit volume than the residue, causing a higher volume in mixtures that have a high dosage of carbon residue.

### *3.2. Consistency limits*

The consistency limits tests were carried out according to INVIAS standards [14,15], for soil samples in natural state and mixtures of soil with residue from coal burning in percentages of 3%, 6%, 9%, 12%, and 15% addition. The results showed that the soil in its natural state has a liquid limit of 57.1% and a plastic limit of 43.54%, which is why it is classified as a high plasticity soil. Figure 1 shows the values of liquid limit, plastic limit, and plasticity index for the soil samples in their natural state and the mixtures with the mentioned percentages.

According to Figure 1, both the liquid limit and the plastic limit have a reduction for the sample in the natural state because for the 15% addition of waste to the soil, the liquid limit was reduced to 53.1%, and the plastic limit to 41.22%.

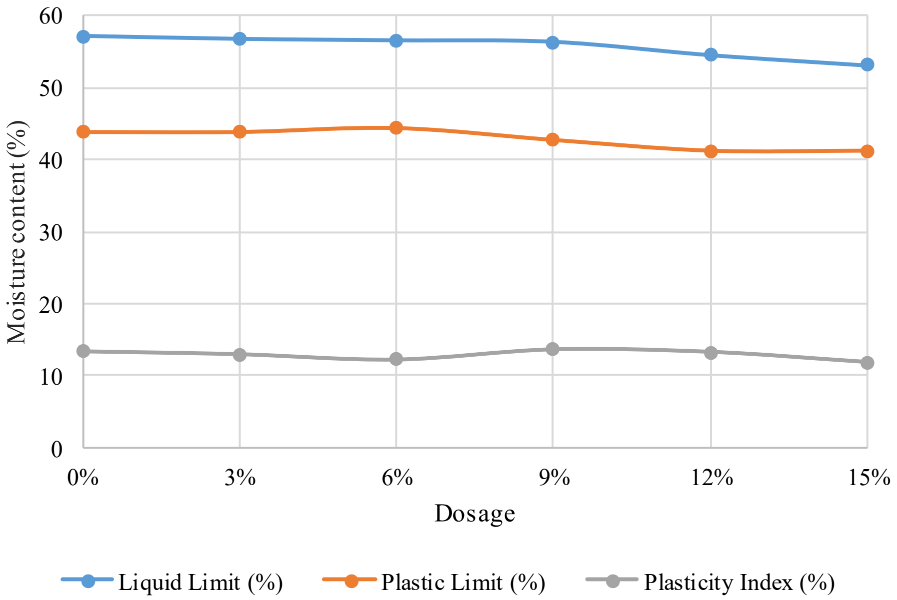


**Figure 1.** Consistency limits of soil-residue mixtures from coal combustion.

*3.3. Granulometry*

The test to determine the particle size of the soil sample was carried out to [16], using a sample of 50 grams of material for the test of decantation of particles utilizing the hydrometer, in Figure 2 the granulometric curve of the soil sample is observed, determining that it is a fine soil, since the 76.3% of the particles have a size less than 0.075 mm.

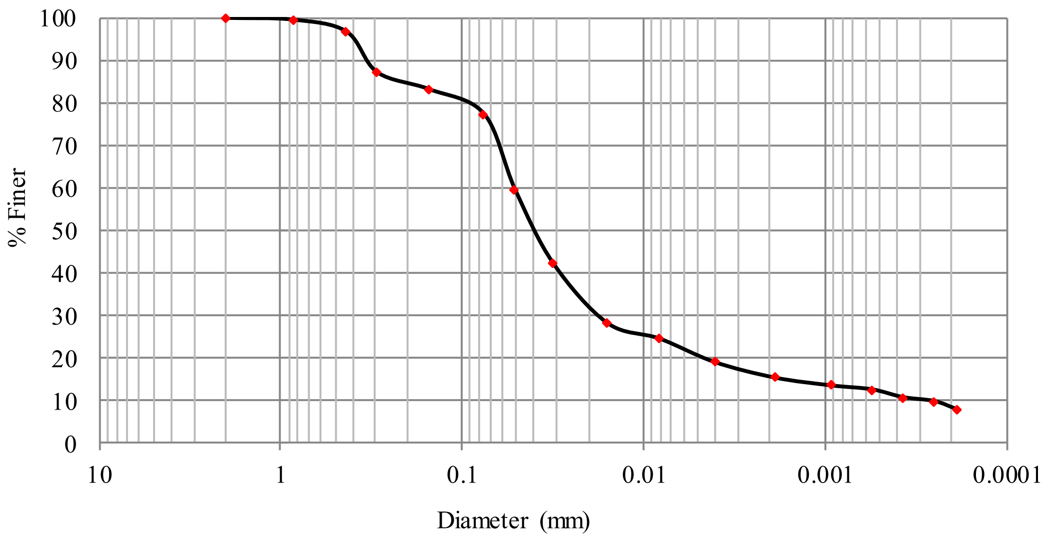


**Figure 2.** Soil grain size curve.

*3.4. Specific gravity*

The specific gravity of the soil used in the study was determined by the INVIAS standards [17], using 50 grams of material for each of the samples, obtaining specific gravity values of 2.80; 2.96, and 2.87, for an average of 2.87, indicating that it is a clay soil since the specific gravity is above 2.70 [18].

### *3.5. Compaction tests (modified proctor)*

The compaction tests were carried out on soil samples in the natural state and mixtures of soil with residue from coal combustion [19], the results showed that the maximum dry density presents a decrease as the percentage of addition of the residue is increased, the same happens with the optimum humidity of compaction, which for the soil sample in the natural state was 23.3% and for the mixture with 15% residue it decreased to 22.6%. Table 1 shows the values for the maximum dry unit weight in g/cm$^3$ and the optimal moisture content.

In Figure 3 the compaction curves for the soil in natural condition and the mixtures are appreciated, observing that the maximum dry density decreases with increasing the percentage of addition of residue to the soil, concerning the optimum humidity, this is reduced by up to 3% for the dosage of 12% of residue concerning obtained for the soil in its natural state.

**Table 1.** Modified proctor compaction test results.

| Dosage | 0% | 3% | 6% | 9% | 12% | 15% |
|---|---|---|---|---|---|---|
| Dry unit weight (g/cm$^3$) | 1.4790 | 1.3462 | 1.4590 | 1.4280 | 1.9100 | 1.3870 |
| Optimal moisture content (%) | 23.3 | 23.1 | 22.9 | 22.7 | 22.6 | 22.6 |

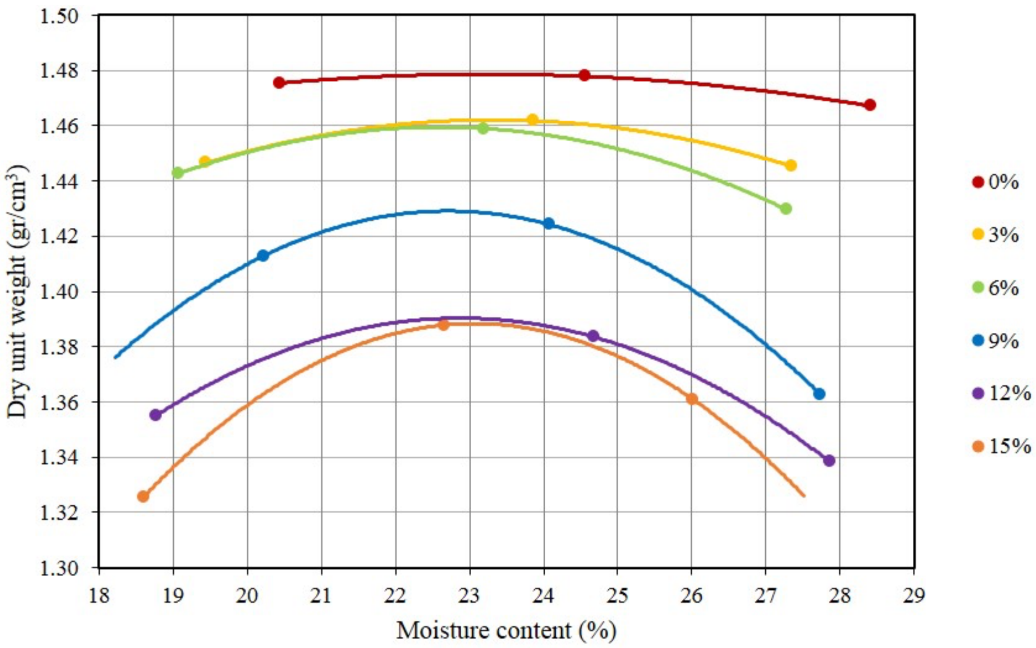

**Figure 3.** Compaction test curves for mixtures with addition of residue from 0% to 15%.

### *3.6. California bearing ratio*

The CBR test was performed on a compacted sample in the laboratory [20], according to the values of maximum dry density and optimal humidity obtained from the modified Proctor test, it was possible to identify that the CBR value for 95% and 90% of the maximum dry density ($\gamma_{d\,max.}$) of the Proctor increases as the percentage of addition of residue to the soil increases (Table 2). As seen in Figure 4, the highest CBR value is obtained for the mixture with the addition of 12% residue from coal combustion.

**Table 2.** Results of the CBR test.

| Dosage | 0% | 3% | 6% | 9% | 12% | 15% |
|---|---|---|---|---|---|---|
| CBR (95% $\gamma_{dmax.}$) | 10.10% | 15.80% | 9.10% | 12.00% | 21.30% | 17.70% |
| CBR (90% $\gamma_{dmax.}$) | 7.80% | 14.80% | 8.30% | 10.00% | 14.10% | 14.50% |
| Expansion 56 strokes | 1.120% | 0.628% | 1.152% | 1.040% | 0.361% | 0.559% |

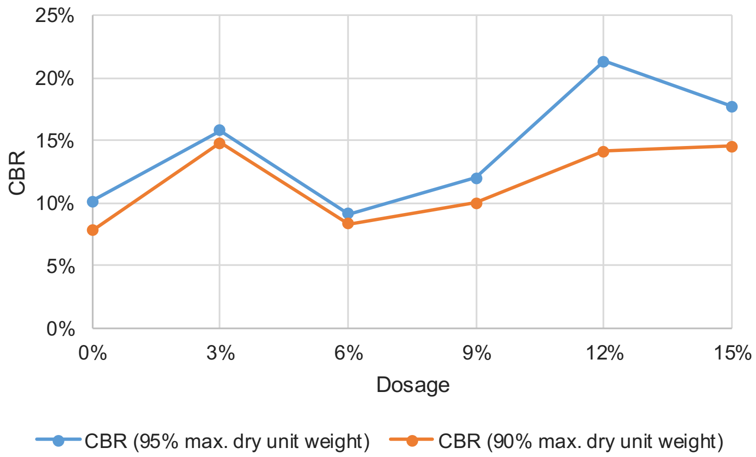


**Figure 4.** Variation of the CBR value for soil-residue mixtures.

*3.7. Determination of particle size by means of an optical microscope*

An optical microscope was used to characterize the particles of the coal combustion residue, through a 100X magnified image of the sample 1.00 mm long by 0.70 mm high, identifying irregularity in the size of the particles. particles of the residue, since particles with a diameter of 90 µm, 73 µm were found, even particles with sizes smaller than 11 µm, as shown in Figure 5.

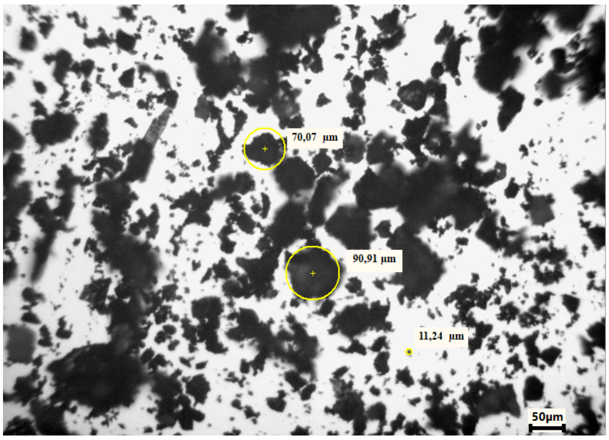


**Figure 5.** 100X magnified image of the residue from the combustion of coal in a Hoffman furnace.

## 4. Conclusions

The addition of residue from the combustion of coal in Hoffman furnaces, in the process of manufacturing masonry blocks, to a high plasticity floor, has a low, but appreciable influence on its plasticity characteristics, allowing its plasticity index to be reduced to as low as a maximum of 10%, for the maximum dosage analyzed, with respect to that of the soil in its natural condition. The mixture of soil with residue from the combustion of coal in Hoffman furnaces, in the brick manufacturing process, presents an appreciable improvement in its California Bearing Ratio bearing capacity. Soil California Bearing Ratio can be improved up to 75% for the 12% residue mix.

The use of the residue generated by the combustion of mineral coal in Hoffman furnaces makes it possible to obtain an improvement in the physical properties of the soil in terms of reducing its plasticity and a notable improvement in its mechanical properties in terms of its bearing capacity; This indicates that the waste analyzed is a good option to perform the improvement of the soils of subgrade of roads, especially tertiary roads, allowing the use of waste material in the industry of the manufacture of ceramic products, as a sustainable construction solution.

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