ENGLISH VERSION

Resilient-modulus degradation of low-plasticity clays due to coal combustion residuals

Degradación del modulo resiliente, debida a residuos producto de combustión de carbón, en arcillas de baja plasticidad

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Abstract

Coal combustion residuals (CCR) are waste products generated during the operation of coal-fired electric power stations, but the effect of CCR inclusions on the deterioration of road infrastructure at or near power plants remain uncertain. This study measured the resilient modulus (M_r) of low-plasticity clay (FS) mixtures with different proportions of CCR obtained from a coal-fired power station, without any additional cementitious substances or stabilizers. Resilient moduli were determined for both the raw materials (FS and CCR) and for mixtures ranging between 10% and 40% CCR by weight. All materials were characterized physically, chemically, and mineralogically. Resulting physical and mechanical-behavior parameters were compared across the CCR content range, specifically the change in index properties, USCS classification, maximum dry density, and resilient-modulus degradation. Results highlight the strong dependence of the soil's resilient moduli on water content due to the inherent partially-saturated character of the material.

Keywords: *Subgrade, clay, fly ash, coal combustion residuals (ccr), resilient modulus*

Resumen

Los residuos producto de combustión de carbón (RPCC) se generan en plantas termoeléctricas, pero el efecto de la contaminación por RPCC en el deterioro de la infraestructura vial en inmediaciones de dichas plantas es incierto. Este estudio midió el efecto de la presencia de diferentes proporciones de RPCC provenientes de una central termoeléctrica, sobre el módulo resiliente (M_r) de un suelo fino (SF) tipo arcilla de baja plasticidad, sin la adición de cementantes o estabilizantes adicionales. Previa caracterización física, química y mineralógica de los materiales, se obtuvo el módulo resiliente para SF y RPCC y para mezclas en peso entre 10% y 40% de RPCC. Con estos resultados, se comparó el comportamiento físico y mecánico de los materiales, específicamente la variación de propiedades índice, clasificación USCS, densidad máxima seca y degradación del módulo resiliente. Este estudio resalta la fuerte dependencia del módulo resiliente con respecto al contenido de agua del suelo debido al carácter parcialmente saturado inherente a los materiales.

Palabras clave: Subrasante, arcilla, ceniza volante, residuos producto de combustión del carbón (rpcc), módulo resiliente

1. Introduction

In many countries, thermoelectric power plants (specifically coal-fired electric power stations) are a key energy source or, at least, a relevant secondary backup. Among thermal plants, those using coal as a main fuel produce ash waste, generically called coal combustion residuals (CCR). Coal is a rock of organic origin, either sedimentary or metamorphic and, depending on the formation process, it can be classified as peat, lignite, bituminous (sedimentary rock) or anthracite (metamorphic rock) (Ministerio de Minas y Energía and Unidad de Planeación Minero Energética, 2012).

For example, in Colombia, the CCR production is close to 800,000 tons/year (Cárdenas, 2013). Meanwhile, during 2017 in Chile, thermoelectric plants using coal technology were the largest power producers, with a 40% share, equivalent to 29688 GWh (Asociación de generadoras de Chile, 2018), and it is estimated that a plant of 1000 MW can generate 200,000 tons of CCR per year (Revista Electricidad, 2013). Since not all the coal waste has a potential use as additives (ACI Committee 232, 2002) or a lightweight aggregate for concrete (Videla and Martínez, 2001), a great deal is accumulated in the form of embankments or in yards adjacent to the thermal plants themselves. These stockpiles generate a pollution risk for water bodies close by and for underground waters, as well as the contamination produced by particulate material due to its low density and easy wind transport.

Because of its direct proximity, CCR easily come into contact with the own internal road infrastructure and that adjacent to thermoelectric plants, but the effect of CCR contamination on the physical deterioration of this infrastructure, specifically the pavement structures' behavior, is uncertain. The present research studies the resilient modulus (M_r) of two base materials (clay and CCR) and their mixes in variable proportions, with the aim of quantifying, in the laboratory, the degradation of the modulus in the presence of CCR. Therefore, this study allows simulation of the deterioration of a clayey subgrade in the presence of CCR contamination, such as the case of roads in the surroundings of thermoelectric power plants and CCR stockpiles.

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2. Background

The resilient modulus is defined as the ratio of total deviatoric stress to axial strain in a cyclic triaxial test. In fine-grained soils, the resilient modulus is mainly influenced by the soil's water content (NCHRP 2000), the density (Rondón, 2015), and the type of compaction (Seed et al., 1962) and (Lee et al., 1997), quoted in (Rondón, 2015). The use of the resilient modulus as an engineering variable has its origin in the works of (Rondón, 2015).

Previous studies with fine soil (FS) and CCR mixtures, ammended with cementitious materials or stabilizers, have addressed different physical and mechanical properties. (Yarbaşı et al., 2007) analyze three types of additives: silica fume + silt, fly ash + silt and red mud + cement. (Camacho et al., 2006) evaluate the behavior of an expansive clay (bentonite) using individual additions of fly ash, lime and sulfonate oil. Furthermore, in 2016, the Mexican Transport Institute published the technical document "Model for estimating the resilience modulus of compacted fine soils under optimal compaction conditions".

The present research undertakes a physical-chemical characterization of a clayey fine soil (FS) and a CCR, and studies the mechanical behavior of the base materials and their mixtures.

3. Materials and methods

3.1 Base materials

The fine soil (FS) corresponded to a clay for masonry manufacturing, whose source is located in the municipality of Zipaquirá, Cundinamarca (Colombia). The clay is obtained from open-pit mines and, for this study, the samples were obtained from temporary stockpile yards. The fly ash (CCR) derived from the coal combustion was Class C and came from the Thermal Plant of Termopiza Martin del Corral, located in Tocancipá, Cundinamarca (Colombia).

3.2 Fine Soil and CCR Mixtures

The FS and CCR materials were oven-dried at temperatures of 110° and 60°C respectively; the latter with the aim of minimizing the dehydration of the lime, which is a component of fly ash Class C. At 24 and 48 hours respectively, the FS and CCR were quartered according to the indications of the Colombian technical standard INV E104-13 (Method B). The FS was not cured for resilient moduli tests, with the purpose of obtaining a more realistic mixture condition between the FS and the CCR. Three mixtures were prepared with mass percentages of 10%, 20% and 40% CCR, in an approximate quantity of 25 kg per each sample, corresponding to the mass of each test in triplicate. Once the base materials and their mixes were prepared, they were put in a double bag, hermetically sealed, and placed in the curing room, in order to avoid the loss of solids and moisture.

3.3 Physical Properties

Index properties were measured for all five studied materials, that is, FS, CCR and their three mixtures (10%, 20%, 40% CCR). Specifically, the following was measured: particle size with hydrometer (INV E123-13), consistency limits (INV E-125-13; INV E-126-13) and specific gravity (INV E-128-13). Additionally, the optimal moisture content and maximum dry unit weight used in the resilient modulus (M_r) tests were obtained through the standard compaction test (INV E-141-13) for each material. Finally, the methylene blue technique (INV E-182-13) was used to determine the specific surface area (M^2/g) for each material. The specific surface area was calculated with (Equation 1), adapted from (Santamarina et al., 2002):

$$\boldsymbol{S_s = \frac{1}{MM_{mb}} \frac{M_{mb}}{V_{mb}} N\, \Delta V_{mb}\, A_v\, A_{mb} \frac{1}{Ms}} \qquad \textbf{(1)}$$

Where: S_s = specific surface area (m^2/g), MM_{mb} = methylene blue molar mass= 319.87 g/mol, M_{mb} = methylene blue mass dissolved for the test = 10 g, V_{mb} = volume of methylene blue solution for the test = 1000 mL, N = number of additions of methylene blue prior to forming the halo surrounding the spot, ΔV_{mb} = methylene blue volume in each addition = 5 mL, A_v = Avogadro's number = 6.02 x 10^{23}, A_{mb} = area occupied by a methylene blue molecule = 130 $Å^2$/molecule, and M_s = soil mass = 30 g.

3.4 Chemical and Mineralogical Properties

3.4.1 Mineralogy with X-ray Diffraction (XRD)

The XRD is a test aimed at the qualitative analysis of crystalline mineral phases of any type of geomaterial, using mainly two methods: oriented sample analysis to identify clay minerals and random-mount sample analysis for any mineral (including CCR). The method is based on the interaction of X-rays and the crystalline mineral phase producing the diffraction (Moore and Reynolds, 1997). The samples were grinded to a particle size of <45 µm, and the XRD were carried out in the laboratories of the Instituto Geográfico Agustín Codazzi in Bogota, Colombia.

3.4.2 Scanning Electron Microscope (SEM)

The test allows to visually characterize the microstructure of the sample at high magnifications for organic and inorganic materials, thereby providing information about the texture, size and shape of the grain. Its operation is based on scanning an electron beam over the study microarray, while the submillimeter image detected by a sensor is reproduced on a monitor. The images were obtained with the scanning electron microscope of the Geoscience Department of the National University of Colombia in Bogota, using a 30 kV voltage using the secondary electrons' technique. In total, 29 images were captured, which are all found in (Zambrano et al., 2017).

3.4.3 Total Organic Carbon (TOC)

This study parameter measures water concentration of organic compounds, since it includes all carbon compounds in a single mass. The test was undertaken for three CCR samples, with the support of a Shimadzu TOC-L analyzer (Maryland, USA), available at the Water Quality Laboratory of the Engineering School of the Pontificia Universidad Javeriana in Bogota, Colombia.

3.4.4 Heavy Metal Concentration

Due to operational safety reasons and the CCR chemical characterization, the toxicity characteristic leaching procedure (TCLP) was used for measuring the concentration of heavy metals on a sample, according to the EPA 1311 procedure. The test was carried out in the laboratories of the Chemilab Company in Bogota, Colombia.

3.5 Mechanical Properties: Resilient Modulus (M_r)

3.5.1 Specimen Preparation

According to the Colombian standard INV E-153-13 regarding the triaxial compression test on cohesive soils, three samples were prepared at a 1:2 ratio, with diameter of 7 cm and height of 14 cm. The dry density and moisture content adopted in the samples were the maximum and optimal, respectively, obtained by the standard compaction test (INV E-142-13). Prior to the preparation of the specimens, the material was stored in the curing room for 24 hours. A metal mold of 7-cm diameter and 20-cm high was used for producing the specimens. For the specimens compaction, a monotonic load, rather than dynamic compaction, was applied with a Marshall press (Figure 1). Once the specimens were compacted, they were withdrawn from the cylinder with the help of a hydraulic jack, thus minimizing their alteration (Figure 1).

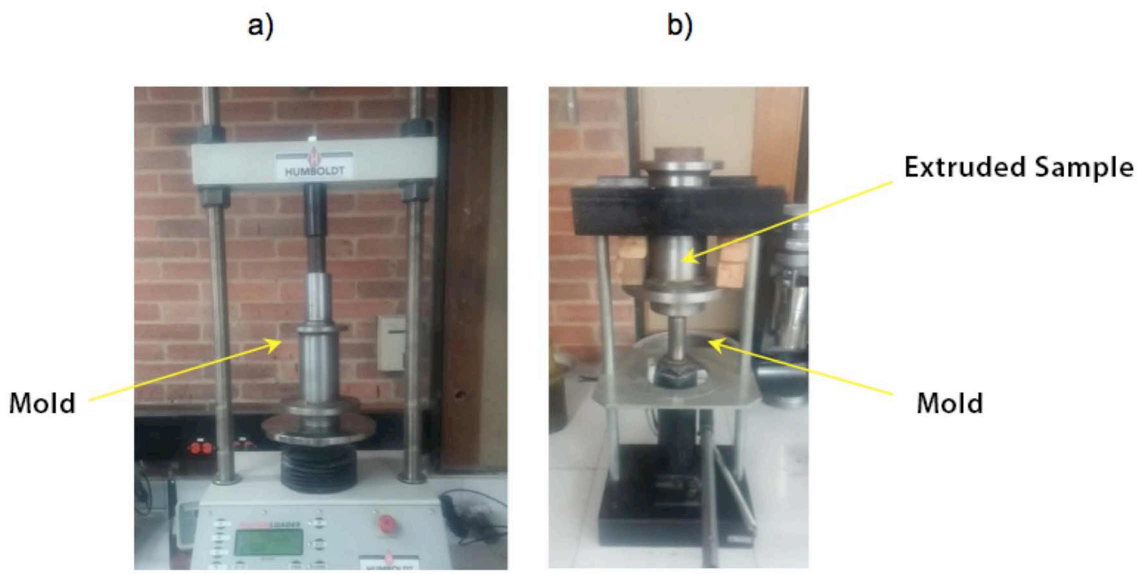

Figure 1. *Compaction (a) and extrusion (b) of the specimens from the mold after the Marshall pressing*

3.5.2 Resilient Modulus Test

Based on the description of the Colombian standard procedure INV E-156-13, the specimens were subjected to axial loading cycles, using the EDS cyclic triaxial compression machine of the Engineering Faculty of the Pontificia Universidad Javeriana of Bogota (Figure 2). The resilient modulus corresponds to the ratio of total stress to axial strain. Each test consisted in 17 cycles, being the first for adjustment, the following 15 cycles corresponded to the execution of the resilient modulus test, and the 17th cycle (final) was for monotonic compressive failure. The axial stress and the chamber pressure were changed in series of five cycles.

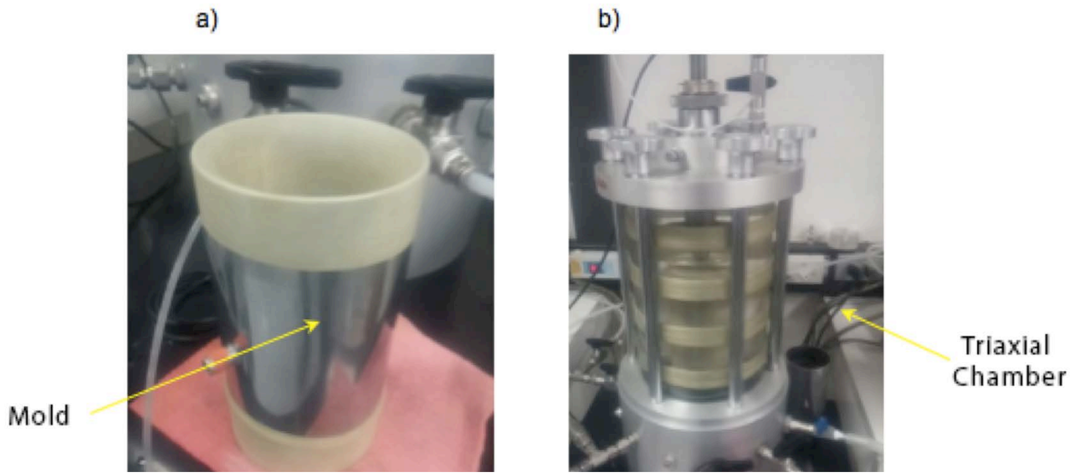

Figure 2. *Assembly for measuring resilient modulus in triaxial compressive chamber*

4. Results and discussion

4.1 Physical Characterization

(Figure 3) shows the results of liquid limit (LL) and plastic limit (PL) for the mixtures based on CCR content (each data in the chart corresponds to the average; the bars represent average plus and minus one standard deviation). The consistent LL decrease is evidenced as CCR increases. The material with 100% CCR turned out to be "non-plastic"; on the other hand, the results show PL increases with CCR additions of 10% and 20% respectively, but a decrease with 40% CCR.

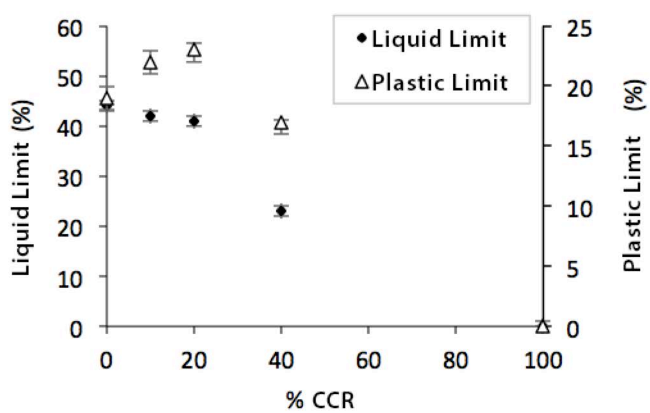

Figure 3. *Variation of liquid limit and plastic limit with the CCR content*

(Figure 4) represents the variation of the plasticity index and the shrinkage limit of the material when the CCR content increases. It is possible to observe that both indexes are inversely proportional to the CCR content. The plasticity index showed a reduction, probably due to the material's grading variation and the absence of plasticity in the CCR. Meanwhile, at 40% and 100% CCR, the mixture shows a c shrinkage limit of zero.

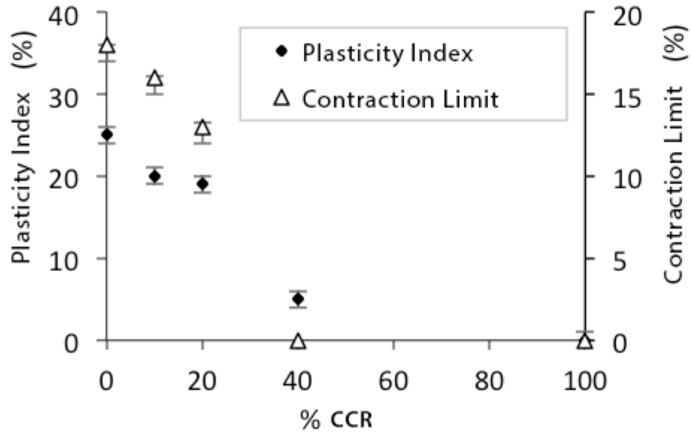

Figure 4. *Variation of the plasticity index and the contraction limit of fine soil with CCR addition*

(Figure 5) shows the variation of the USCS soil classification for different CCR proportions. It can be seen that the original fine soil (FS) corresponds to low-plasticity clay of the CL group. This classification is maintained even with the inclusion of up to 20% CCR, but when it reaches 40%, the material classifies as CL-ML soil.

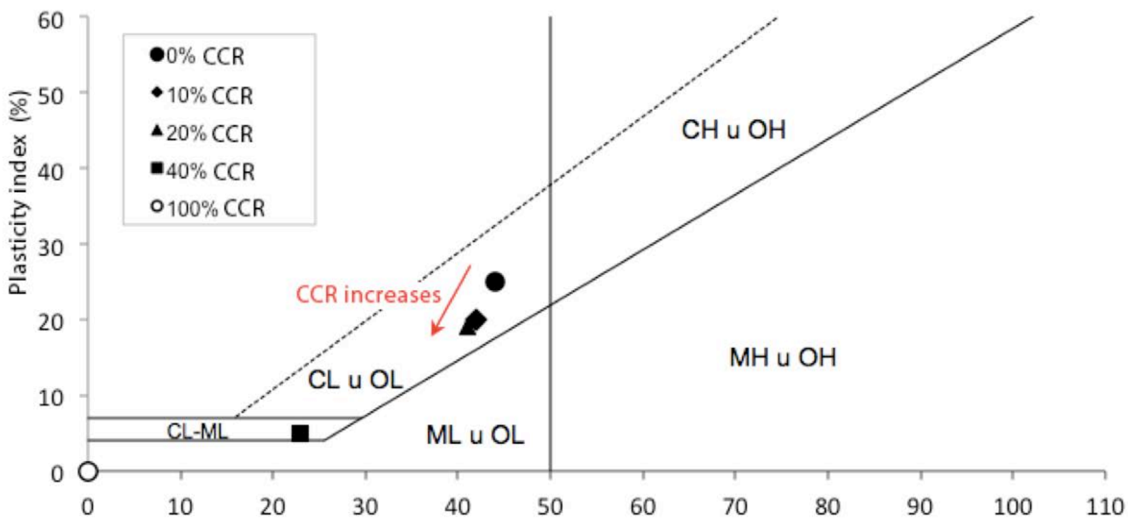

Figure 5. *Casagrande plasticity chart: variation of the USCS classification according to the CCR content*

The methylene spot blue test succeeded to show halos when the clay was chemically saturated with methylene blue (Figure 6). Regarding the specific surface area (Figure 7), 42 m/g were estimated for intact clay (0% CCR), while fly ash (100% CCR) had a value of 11 m^2/g. It was also observed that, the smaller the specific surface area, the lower the shrinkage limit, because the material's capacity to absorb water decreases as the CCR content increases (Santamarina et al., 2000).

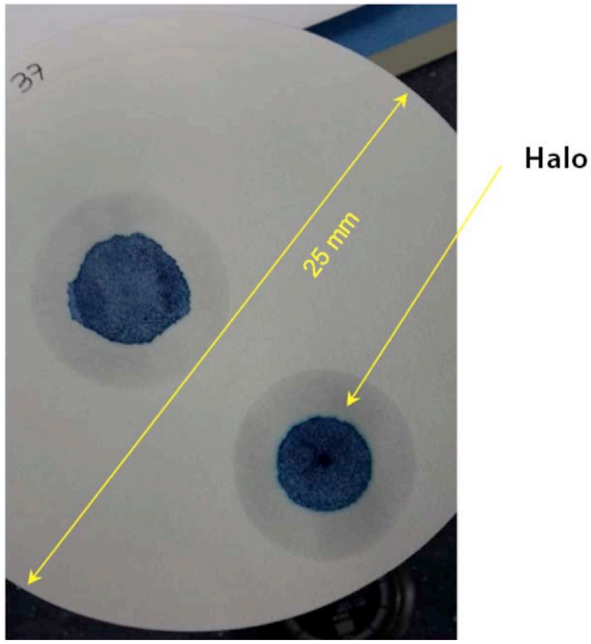

Figure 6. *Halo formed during the methylene blue test*

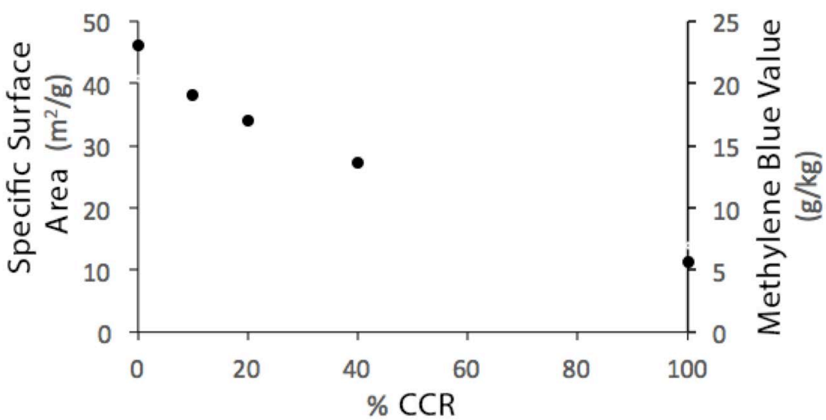

Figure 7. *Results for the methylene blue value and the specific surface area*

(Figure 8) indicates the specific gravity results for solids, and we observe that this property decreases consistently as the CCR proportion increases. This tendency is similar to that reported by (Pérez, 2012), where CH-classified clay was mixed with type-F fly ash in ash proportions of 0%, 20%, 40% and 100%.

For the present paper, the average specific gravity of fly ash (100% CCR) is 2.09. According to the reporting of the ACI, the density of solid fly ash particles ranges from 1.97 to 3.02 Mg/m^3 (ACI comittee 232. American Concrete Institute, 2002). In general, fly ash shows relatively low densities of solid particles if they have high carbon contents.

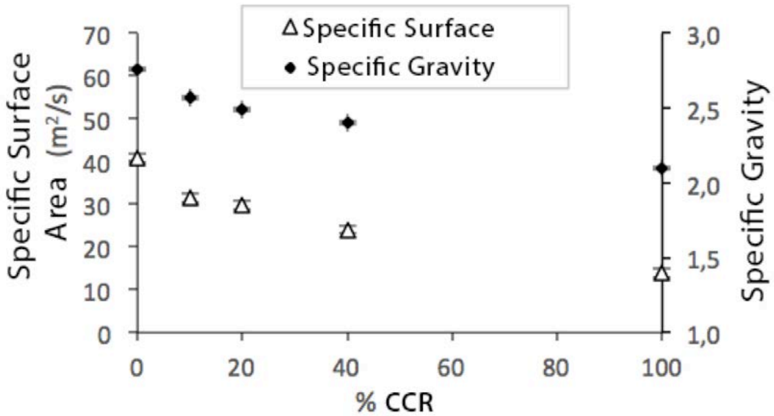

Figure 8. *Variation of specific gravity and specific surface area with CCR addition*

According to the results of particle size distribution, in general the CCR increase causes an increase in the average diameter (D_{50}) of the material's distribution (Figure 9) and (Table 1), except with the 10% addition. The electro-chemical forces derived from the interaction between the dispersant of the hydrometer test and the CCR may have affected the results, although further research is needed to confirm this hypothesis.

Table 1. *Variation of the average size (D_{50}) with the CCR increase*

CCR %	***D_{50} (microns)***
0	*5.2*
10	*3.8*
20	*8.3*
40	*16*
100	*80*

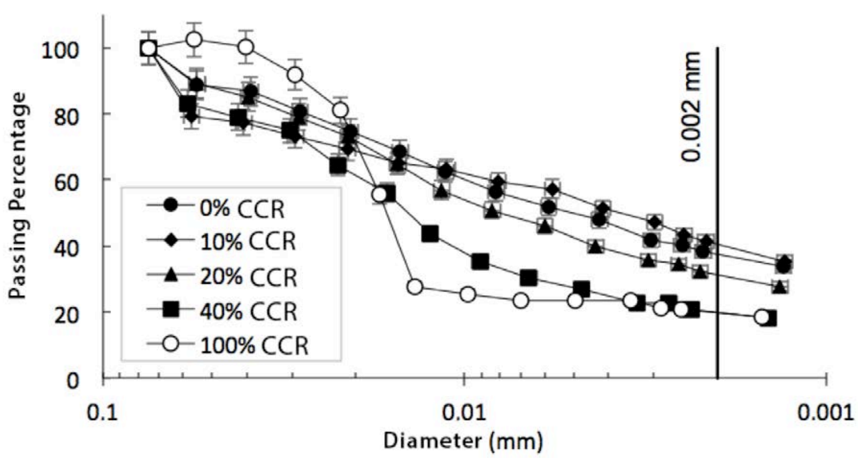

Figure 9. *Grading variation of the material with CCR addition. The vertical line indicates the grading boundaries between silt and clay sizes (0.002 mm)*

Finally, (Figure 10) shows the compaction curve results for all five materials under sudy. It can be observed that the maximum dry unit weight decreased by 30% when the CCR was increased to 40%. Compared with the report by (Pérez, 2012), who mixed fine soil with dry unit weight of 16 kN/m^3 and fly ash of 15 kN/m^3, the dry unit weight of the mixture went from 16 to 16.2 kN/m^3, while a 0.6% increase was observed with the 40% ash content. It should be highlighted that, in that study, the fine soil and fly ash were oven-dried at 60°C and subjected to a modified compaction test. Meanwhile, in the present research, the soil was dried at 110°C and a standard compaction test was carried out.

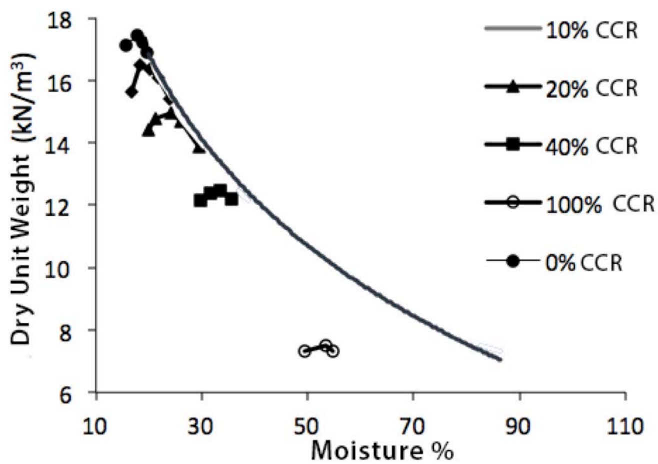

Figure 10. *Compaction curves (the saturation curve is for 0% CCR)*

4.2 Chemical and Mineralogical Characterization of the Materials and Mixtures

(Table 2) shows the values obtained when subjecting the CCR to the TCLP test. All heavy metal concentrations were below the limit of detection.

Table 2. *TCLP results*

Test	*Result (mg/L)*
Total arsenic	<0.010
Total barium	<0.50
Total cadmium	<0.05
Total chromium	<0.1
Total tin	<1
Total lithium	<0.150
Total mercury	<0.002
Total lead	<0.5
Total selenium	<0.005
Total vanadium	<2
Total zinc	<0.05

Concerning the textural and mineralogical characterization, (Figure 11) shows typical CCR microscale images, obtained by scanning electron microscope, which allow observing particle sizes and shapes. The particles' resulting morphology can be divided as follows: cenospheres (solid or hollow spherical particles), perospheres (hollow spherical particles containing other smaller spherical particles) and irregular or elongated particles.

Representative particle diameters were measured using the photographs, obtaining sizes below 75 microns and up to 171 microns. This result is consistent with previous studies (Peña and Ortega, 2014), which maintain that fly ash have particles below 75 and up to 250 microns. The variation of the surface morphology depends on the speed and temperature of coal combustion, the pulverization degree of the ash and the type of coal (ACI Committee 232, 2002). The irregular and angular particles can be associated to minerals that did not undergo a complete combustion, such as coke.

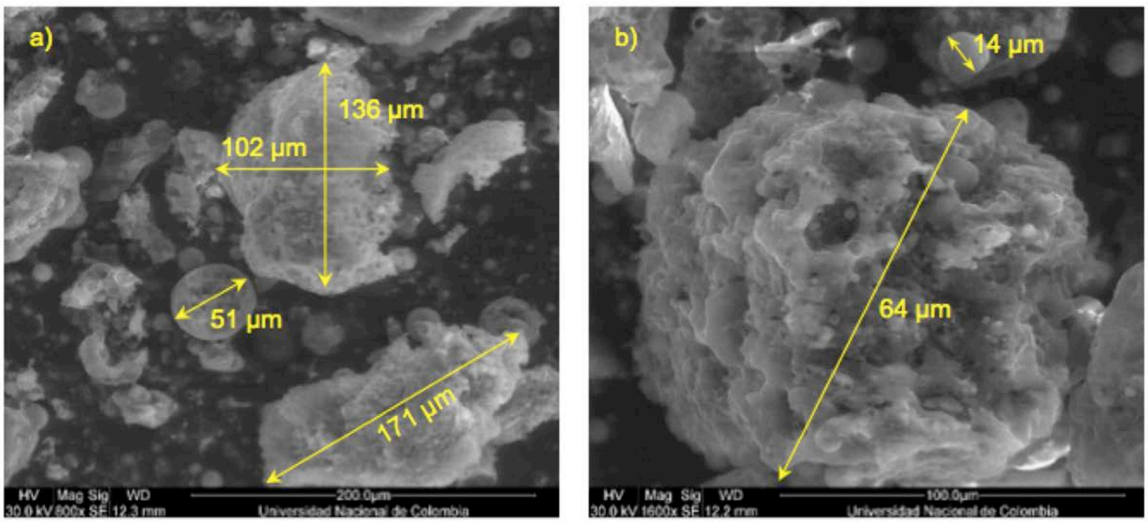

Figure 11. *SEM photographs of CCR: a) 800x, b) 1600x*

(Table 3) shows the results for total organic carbon content of a CCR sample. Since the average carbon content is 12.5%, the results suggest that the combustion efficiency in the thermoelectric plant is close to 87.5%.

Table 3. *Results for total organic carbon (TOC)*

Sample	***Sample Weight (mg)***	***mg C***	***Carbon %***
1	*38.0*	*4.571*	*12.0*
2	*38.5*	*4.862*	*12.6*
3	*35.0*	*4.493*	*12.8*

Finally, (Figure 12), (Figure 13), (Figure 14), (Figure 15) and (Figure 16) show the results of the X-ray diffraction (XRD) performed on clay specimens (0% CCR) and fly ash (100% CCR). From these figures, (Figure 12), (Figure 13), , (Figure 14) and (Figure 15) refer to clay (FS) and show diffraction patterns resulting from the oriented sampling technique aimed at identifying the clay mineral. On the other hand, (Figure 6) applies to the CCR and corresponds to random-mount diffraction patterns.

The clay minerals predominating in the fine soil of this study are kaolinite and illite, which are minerals type 1:1 and 2:1, respectively. The basal spacing measures approximately 7 Å in kaolinite and 10 Å in illite. In the first, layers are bonded by hydrogen bonds, while in the second, the structure is stabilized with potassium cations (Bartolome, 1997). Both the hydrogen bonds and the potassium stabilization favor low water absorption and low susceptibility to shrinkage, which indicates that both clay minerals suffer very small changes in their volume in the presence of hydration. Furthermore, clay results indicate that the main non-clayey mineral is quartz (spacing d ≈ 3.34 Å).

Regarding the CCR, the XRD results reveal that the main mineral is quartz (higher than 50%), with traces of hematite iron oxide. In general, quartz is present in all types of fly ash, as a result of coal pollutants (ACI Committee 232, 2002).

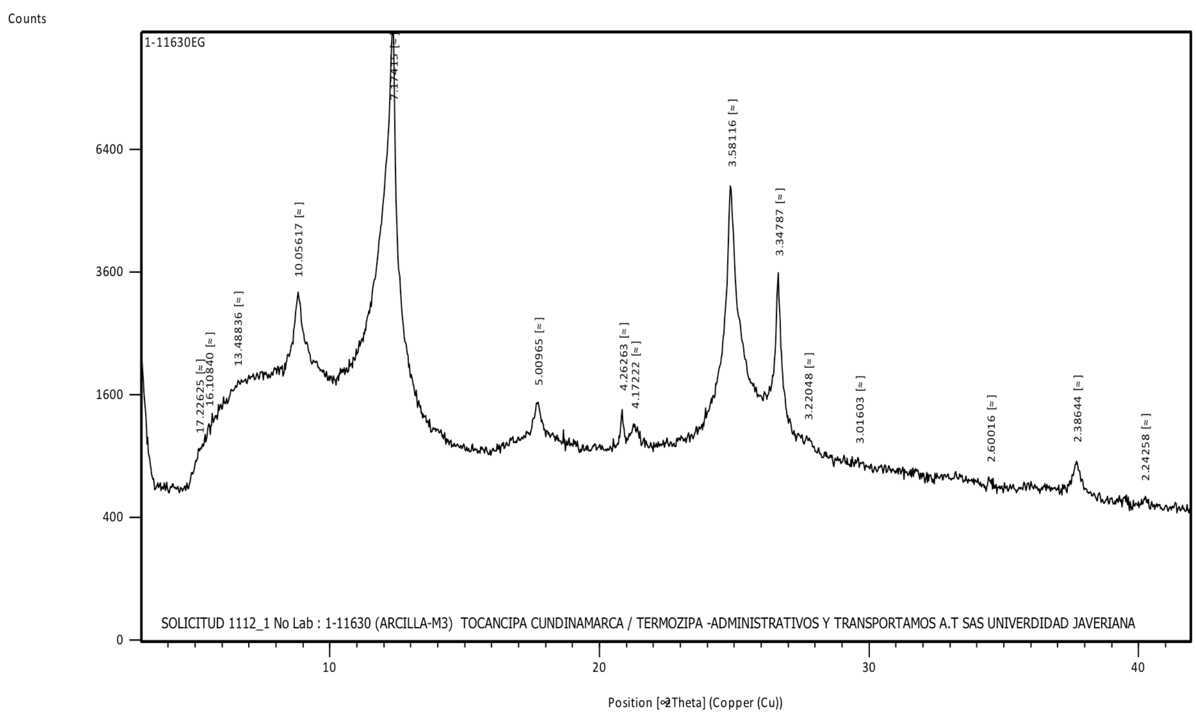

Figure 12. *Diffractogram of FS with ethylene glycol*

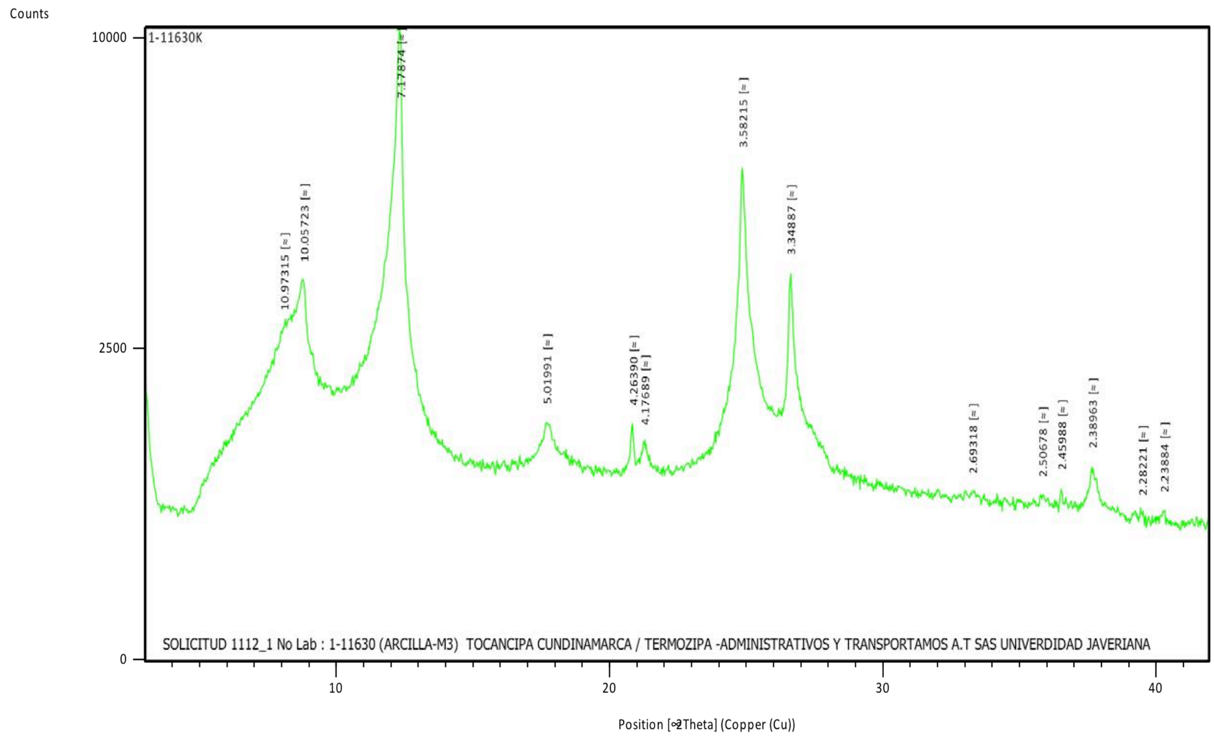

Figure 13. *Diffractogram of FS with potassium (K)*

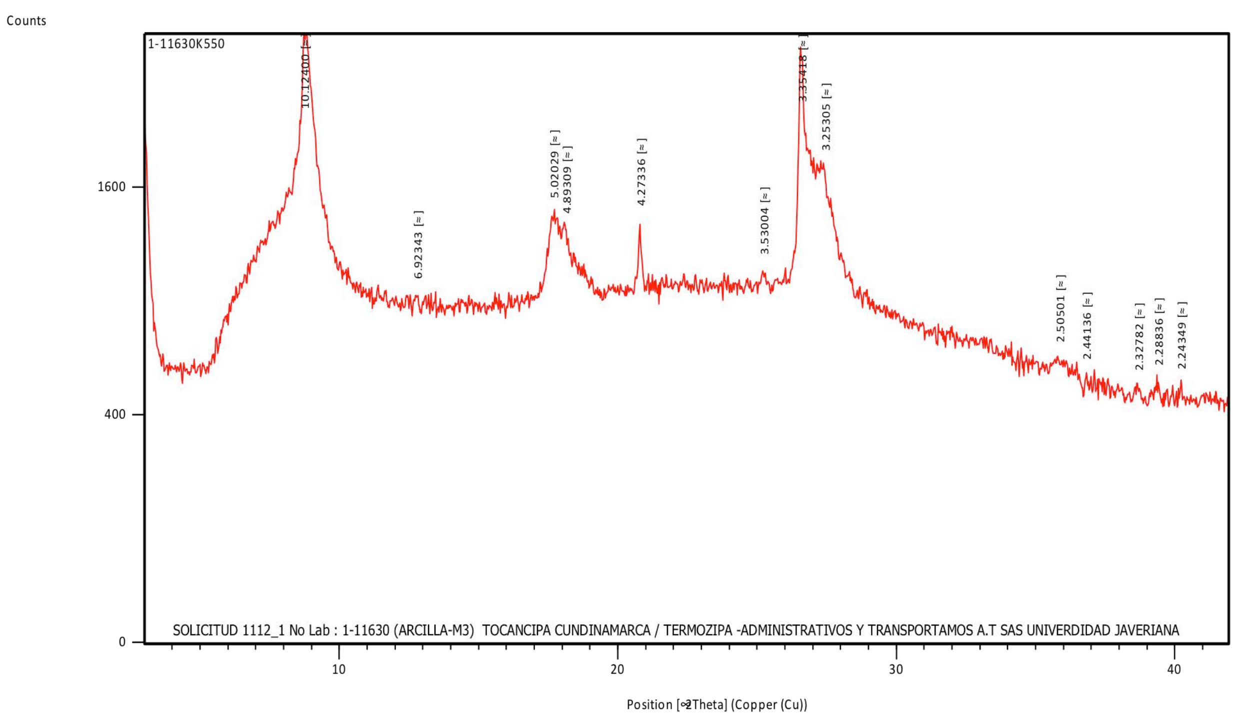

Figure 14. *Diffractogram of FS at 550°C*

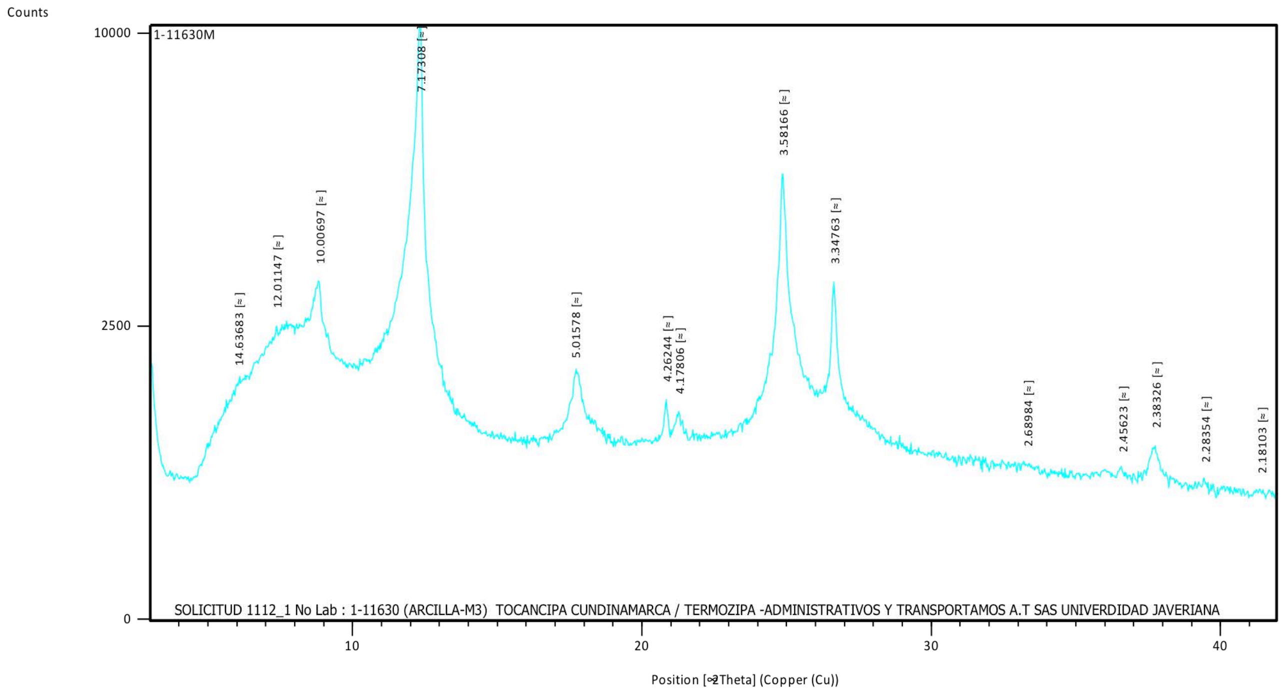

Figure 15. *Diffractogram of FS with magnesium (Mg)*

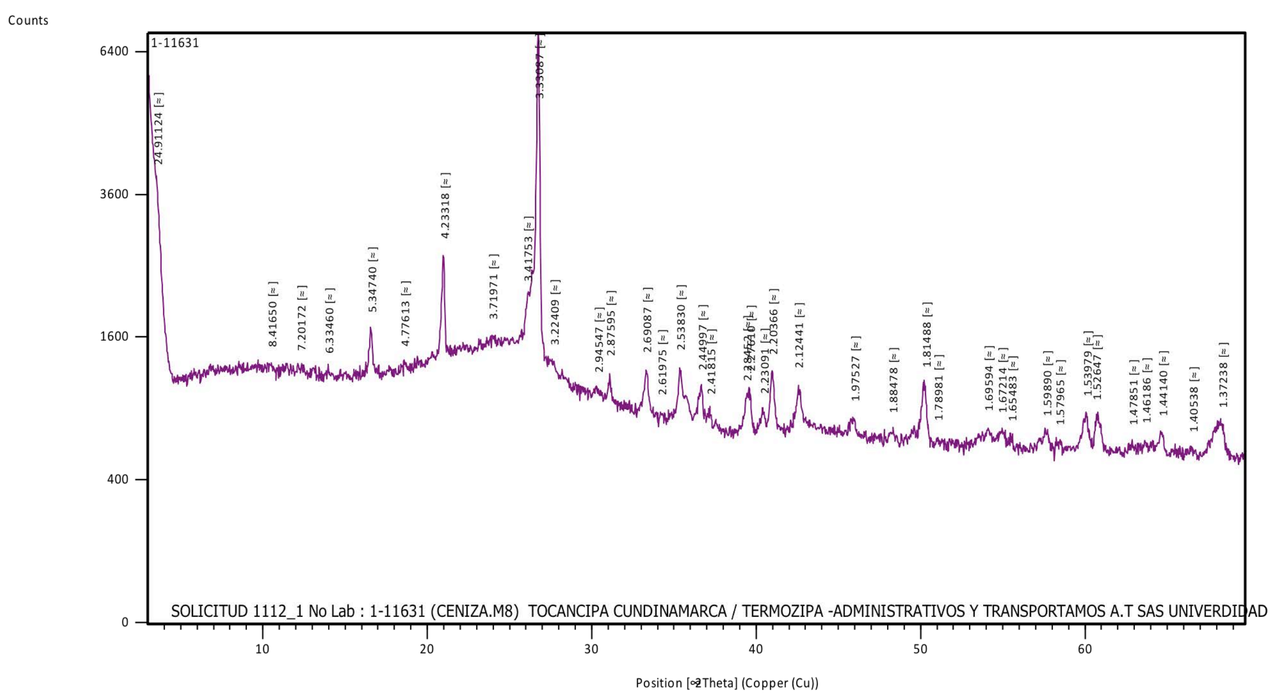

Figure 16. *CCR Diffractogram*

4.4 Mechanical Characterization: Resilient Modulus (M_r) of Base Materials and Their Mixtures

(Figure 17), (Figure 18) and (Figure 19) show the resilient modulus results based on deviatoric stress, for three different confinement stresses, and each of the five types of materials according to the CCR content. The graph results are represented in percentages plus/minus standard deviation. As indicated above, each M_r result corresponds to 15 load cycles at total deviatoric stress.

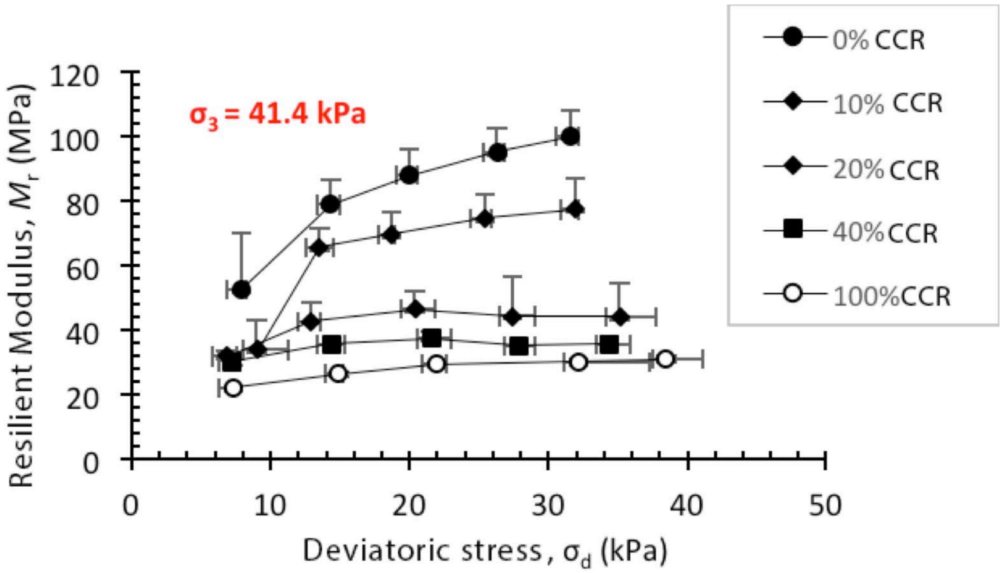

Figure 17. Variation of M_r at confinement stress of 41.4 kPa

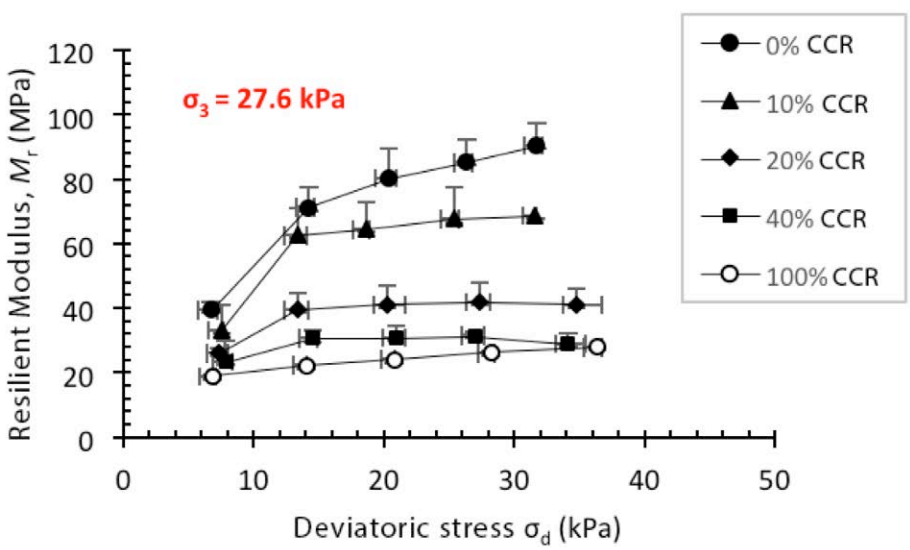

Figure 18. Variation of M_r at confinement stress of 27.6 kPa

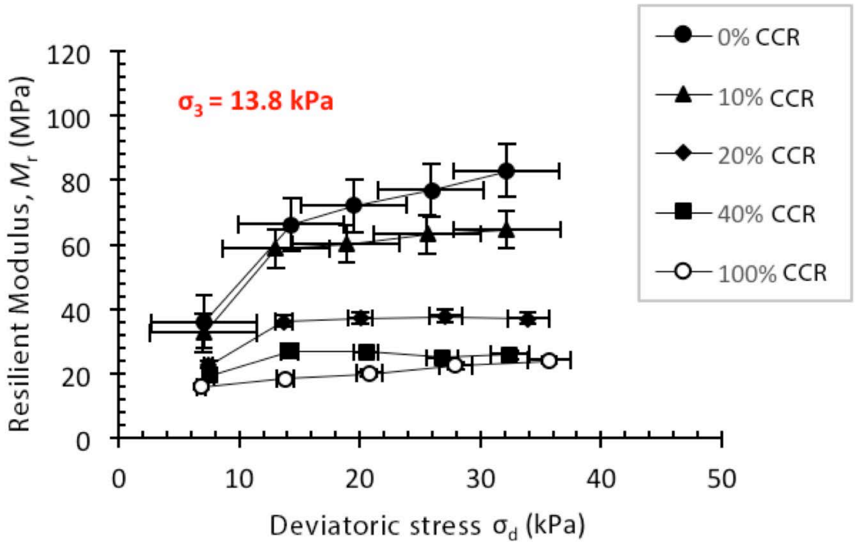

Figure 19. *Variation of M_r at confinement stress of 13.8 kPa*

4.4.1 Resilient Modulus of Fine Soil (FS)

In general, a soil's M_r is not a constant property, because it depends on the density, the water content and the compaction method (NCHRO, 2000) (Instituto Mexicano de Transporte, 2016); (Rondón and Reyes, 2015). The results obtained in this research (Figure 17), (Figure 18) and (Figure 19) evidence an increase of M_r as the deviatoric stress (σ_d) and the confinement stress (σ_3) increase. (Table 4) summarizes the results.

Table 4. *Summary of resilient modulus results*

Material	*Maximum Dry Unit Weight (kN/m^3)*	*Water Content (%)*	*M_r (MPa)*	
			Minimum	*Maximum*
FS 100% + 0% CCR	17.4	17.9	40	91
FS 90% + 10% CCR	16.4	18.4	33	69
FS 80% + 20% CCR	14.9	24.2	26	35
FS 60% + 40% CCR	12.4	33.4	24	34
FS 0% + 100% CCR	7.5	53.3	19	36

According to the reports of Pérez and Garnica (Instituto Mexicano de Transporte, 2016) based on 14 soil samples classified as silt and clay, the M_r decreases as the deviatoric stress increases, and increases as the confinement stress increases. Likewise, many researchers quoted by (Rondón and Reyes, 2015) report that the M_r of fine soils generally decreases as the deviatoric stress increases.

In the present research, the M_r increase by deviatoric stress, although contrary to the trend reported by other researchers, is consistent with multiple tests, and can be explained as follows:

- *In this research, the maximum dry density is high compared with previous studies (Rondón and Reyes, 2015). Likewise, the reference value for clays such as those studied by Pérez and Garnica (Instituto Mexicano de Transporte, 2016) ranges between 10 and 15 kN/m^3, while in this study it is 17.4 kN/m^3. In fact, these and other researchers report that the M_r of cohesive soils increases with the unit weight (NCGRP, 2000).*
- *The water content affects the result, since in this case it is 17.9% for clay, while Pérez and Garnica (Instituto Mexicano de Transporte, 2016) report values between 24 and 36%. Other researchers (Rondón and Reyes, 2015) show that M_r increases when the water content is lower than the optimal and vice versa. When studying the effect of water content variations on the M_r in relation to the optimal for three soils class CL and CH, these researchers found that the M_r increases up to 200% when compacted below the optimal.*
- *The water content effect can be qualitatively understood when considering that the materials studied herein are partially saturated; therefore, their pore pressures are negative, which means suction between clay particles. This effect increases the effective stress and improves the overall stiffness of the specimens.*
- *The compaction method in the present research is static, which produces a more uniform accommodation of soil particles, thereby obtaining normal and shear stresses different from those obtained by dynamic compaction (Secretaria de Comunicaciones y Transportes & Instituto Mexicano del Transporte, 2001).*
- *Finally, the specimens' preparation method is a factor that may have influenced the results, since the grading of the material, when received from the source, evidenced coarse aggregates up to a diameter of 5 mm. The samples for determining the index properties were macerated, but not so for the preparation of SF and CCR mixtures. Therefore, it is likely that, during the preparation of the specimens for compaction and resilient modulus, not all of the materials' particles were completely hydrated. This may have caused a lower water content than that reported by other researches (Instituto Mexicano de Transporte, 2016), thus entailing greater suctions.*

In order to evaluate the reasonableness of results, (Figure 20) shows a graph of M_r vs. σ_d/σ_3 for clayey soil (0% CCR). The potential regression proposed by Pérez and Garnica (Instituto Mexicano de Transporte, 2016) can be applied to this ratio, expressed as follows:

$$\boldsymbol{M_r = k_1\left(\frac{\sigma_d}{\sigma_3}\right)^{k_2}} \qquad \textbf{(2)}$$

Where M_r = resilient modulus (MPa), σ_d = deviatoric stress (kPa), σ_3 = confinement stress (kPa), k_1 and k_2 = fitting parameters. The regression results show that k_1 = 63.0 MPa and k_2 = 0.516.

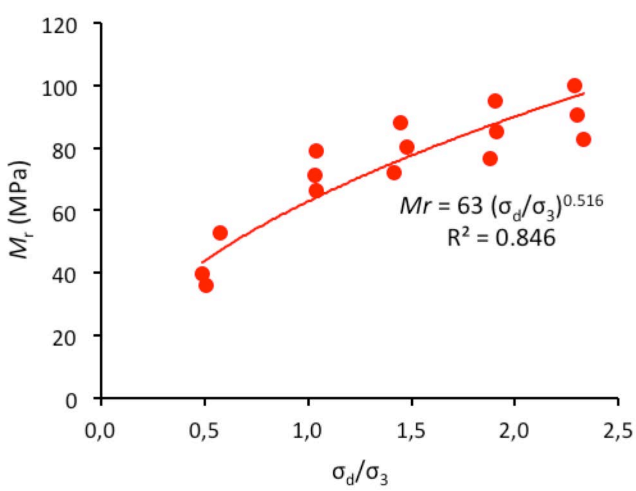

***Figure 20.** Fitting of resilient modulus results for fine soil (0% CCR) using the model of (Instituto Mexicano de Transporte, 2016)*

The clay parameter ranges reported by (Instituto Mexicano de Transporte, 2016) are: k_1 = 88 at 108 MPa, k_2 = -0.139 at -0.108. It is possible to observe that, although the value calculated for k_1 is close to those reported in the literature, and the goodness of fit is reasonable (Figure 20), the value of k_2 shows the opposed tendency of M_r vs. σ_d highlighted above.

Considering that the water content has a great relevance on the resilient modulus results, and that the tendency in the present research is opposed to that of previous studies, an additional exercise was carried out using the original data of the study of Pérez and Garnica (Instituto Mexicano de Transporte, 2016). The latter uses 35 soil samples (14 clays, 12 silts and nine sand-clayey to sand-silty soils) and reports, for all soils, consistency limits, fraction passing No. 200 sieve, optimal moisture and saturation degree. The present work used these data to run a multiple linear regression for parameters k_1 and k_2 of (Equation 2), thereby finding the following:

$$\boldsymbol{k_1 = -32.68 + 2.78\,LL + 0.0013\,CF - 1.08\,w_{\acute{o}pt}} \qquad (3)$$

$$\boldsymbol{k_2 = 0.460 + 0{,}00554\,IP - 0.0212\,S} \qquad (4)$$

Where: LL = liquid limit (%), CF = fraction passing No. 200 sieve, w_{opt} = optimal content of compaction water (%), IP = plasticity index (%), S = saturation degree (%).

By substituting (Equation 3) and (Equation 4) in (Equation 2), and applying the results of index properties obtained for the clay (= 0% CCR) in the present study, (Figure 21) shows that this new regression is reasonably close to the average laboratory results.

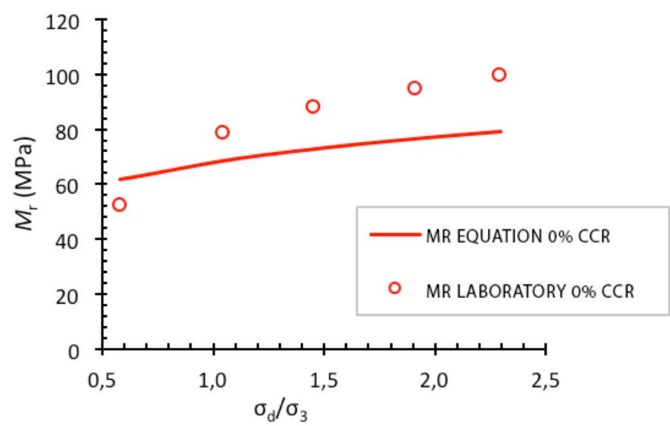

Figure 21. *Comparison of average laboratory results with multiple linear regression model (FS with 0% CCR)*

4.4.2 Resilient Modulus of the CCR (Fly Ash)

The average M_r obtained for CCR ranged between 19 and 36 MPa. The corresponding properties of the material were maximum dry unit weight of 7.7 kN/m^3, 52% optimal moisture, variable grading in shape and size (1 to 300 microns), mineralogy dominated by quartz and traces of hematite, and mainly vitreous texture (60-90% of the mass) with solid or hollow grains (Velandia et al., 2015). Consequently, the tested material is more similar to a loose granular soil than to a cohesive one, so the particles are relatively free to move in relation to each other. In the technical literature it was not possible to find resilient modulus data that allow comparing the obtained results.

4.4.3 Resilient Modulus of Fine Soil and CCR Mixtures

The behavior of M_r among the materials with 0% CCR and 10% CCR is proportional and the curves are relatively parallel to each other (Figures 17)(Figure 18) and (Figure 19). However, above 20% CCR, the curves tend to be more parallel than those of fly ash. This behavior is associated to the reduction of the maximum dry density (Instituto Mexicano de Transporte, 2016) and also to the water content increase. The mixtures' water demand increase may be due to the increase of the CCR quantity (ACI Committee, 2002).

5. Conclusions

The present paper simulates the mechanical deterioration degree of a clayey subgrade when contaminated with coal combustion residuals (CCR), as is the case in internal roads or adjacent to coal-based thermoelectric plants or CCR stockpiles. The following conclusions arise from the study:

The consistency limits, plasticity index, specific surface area and specific gravity decrease as the CCR proportion increases. In turn, this explains that the USCS classification of the mixture changes from class CL to CL-ML when the CCR content reaches 40%. At the same time, the particle size parameter D50 increases with the CCR proportion.

The resulting tendency in the behavior of the resilient modulus (M_r) in relation to the total deviatoric stress (σ_d), opposed to that reported to previous studies by other researchers, can be explained by the low water contents in all five tested materials (all partially saturated), which entail great suctions, high effective stresses and high stiffness. Further reasons for explaining the resulting tendency include: high maximum dry densities in the present study and the preparation method of the specimens.

The degradation of the M_r of the material, caused by the increase in the CCR fraction, is associated to the dry density reduction and the relative increase of the water content in the mixtures.

The available scientific information regarding the M_r in CCR is almost inexistent; therefore, the comparison of data obtained in the present study with previous researches is not a trivial matter.

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