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Coal ash as a natural additive for subgrade stabilization in the construction of low-volume traffic roads

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ABSTRACT

The road network in Colombia, as reported by the National Roads Institute of Colombia (INVIAS), comprises a total of 206,708 kilometers, with 142,284 kilometers falling under the rural roads with low traffic volume network category. Sadly, an estimated of 96% of these roads are in poor condition. The primary reason behind this issue is the presence of subgrades that exhibit inadequate mechanical performance, largely due to the lack of proper stabilization methods. Moreover, these roads often serve as the sole access and exit routes for rural communities, significantly impacting their connectivity with nearby urban centers. Recognizing this critical issue, this article proposes the use of coal ash for subgrade stabilization during the construction of low-traffic-volume roads. The study conducted demonstrates that coal ash can enhance the mechanical properties of subgrades, leading to an increase in strength and load-bearing capacity. The improved mechanical properties are attributed to the binding and reactive characteristics displayed by the coal ashes, which greatly contribute to soil stabilization. To verify these claims, a series of physical, mechanical, and strength characterization tests were conducted on both natural and treated clayey sand samples obtained from a rural population in Colombia. The detailed analysis of the results shows an improvement in the mechanical properties of the soil due to the use of coal ash as a stabilizing agent.

Keywords: Coal ash; Road Subgrade; Waste Treatment; recycled aggregate

Ceniza de carbón como aditivo natural para la estabilización de subrasantes en la construcción de carreteras de bajo volumen de tráfico

RESUMEN

Colombia cuenta con una extensa red vial que abarca un total de 206,708 kilómetros, según datos del Instituto Nacional de Vías de Colombia (INVIAS), de los cuales 142,284 kilómetros pertenecen a la categoría de carreteras rurales con bajo volumen de tráfico. Lamentablemente, se estima que el 96% de estas vías se encuentran en mal estado. Este problema se debe en gran medida a la presencia de subrasantes con un rendimiento mecánico deficiente, principalmente debido a la falta de métodos adecuados de estabilización. Además, estas carreteras suelen ser las únicas vías de acceso y salida para las comunidades rurales, lo que afecta considerablemente su conectividad con los centros urbanos cercanos. Conscientes de esta problemática crítica, en este artículo se propone el uso de ceniza de carbón para la estabilización de subrasantes durante la construcción de carreteras de bajo volumen de tráfico. El estudio llevado a cabo demuestra que la ceniza de carbón puede mejorar las propiedades mecánicas de las subrasantes, lo que resulta en un aumento de la resistencia y la capacidad de carga. Estas mejoras se atribuyen a las características de unión y reactividad de las cenizas de carbón, que contribuyen significativamente a la estabilización del suelo. Para respaldar estas afirmaciones, se realizaron una serie de pruebas de caracterización física, mecánica y de resistencia tanto en muestras de arena arcillosa natural como tratada, obtenidas de una población rural en Colombia. El análisis detallado de los resultados confirma una mejora en las propiedades mecánicas del suelo gracias al uso de ceniza de carbón como agente estabilizante.

Palabras clave: Ceniza de carbón; Subrasante de carretera; Tratamiento de residuos; agregados reciclados;

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1. Introduction

There is a wide variety of soils that present relatively low load-bearing capacity, high moisture content, and poor consistency, making them unsuitable for constructing a subgrade capable of supporting the structural pavement layers. In such scenarios, the typical solution involves replacing the inadequate soil with selected materials that offer better mechanical properties. However, this option may not always be feasible due to financial constraints, especially when considering the costs associated with material transportation. Furthermore, in the case of tertiary road projects, which operate on tighter budgets, there may not be sufficient economic resources to carry out complete soil replacement. Therefore, a widely used alternative is to employ stabilization methods that upgrades the soil's mechanical properties without the need for complete removal (Labajos & Núñez, 2020). This approach aims to improve the characteristics of the existing soil, to meet the necessary requirements for constructing an adequate subgrade.

The incorporation of additives in soil stabilization intended for use as subgrade in the structural pavement layers has demonstrated promising results in improving the soil's mechanical properties, as evidenced by researchers from Ecuador, Peru, and Colombia (Huancoillo-Humpiri, 2017; Castillo, 2017; Falen & Cubas &, 2016; Montes, 2010; Flórez Ramirez, 2006). Various materials have been used to achieve subgrade stabilization, including sodium chloride, which has been found to affect the water's surface tension in the soil, resulting in a reduction of the evaporation (Mendez Cerna, 2021; Quispe, 2020; Garnica Anguas et al., 2002). Another material used is pulverized tire rubber, which has been shown to reinforce unstable soils, improving mechanical properties such as shear strength, cohesion, and angle of friction in clayey soils (Hurtado-Dionisio, 2022; Alvarez Castelblanco, 2021; Roman Vásquez, Díaz Suárez, & Torres Frias, 2019). Furthermore, combinations of recycled materials like pozzolan and glass have been explored, resulting in an increased California Bearing Ratio (CBR) from 4.9% to 14.1% (Arango Fernández & Marín Falconi, 2021; Mas, García, Marco & de Marco, 2016). These findings indicate that research is ongoing worldwide to investigate the use of different additives with the aim of finding economically viable and environmentally sustainable alternatives for subgrade stabilization. These two aspects are crucial in the case of low-traffic pavement networks, which are initially unpaved roads whose surface has received a chemical or mechanical stabilization technique while maintaining their geometric conditions, to allow the passage of lighter vehicles than those traveling on the main roads.

Coal ash, a residue produced from coal combustion processes, is widely available due to the substantial production of coal in countries like Colombia (Vallejo, Morales, Morales y Laverde, 2007). Notably, Colombia has witnessed significant growth in coal production over the years. According to the Mining and Energy Planning Unit of the Ministry of Mines and Energy of the Republic of Colombia (2006), coal production increased by around 17 million tons between 1980 and 1990, and further surged by 32 million tons between 1990 and 2004. On the other hand, coal consumption experienced a 39.6% increase between 1980 and 1993 but decreased to 1.9 million tons by 2005. Unfortunately, a significant amount of this coal ash is still disposed of in landfills or dumpsites, leading to severe pollution issues and environmental concerns. Based on these considerations, the use of coal ash as an additive in subgrade stabilization has been investigated (Cañar, 2017; Morales, 2015). Several researchers have explored the application of coal ash in stabilizing different soil types, including highly plastic inorganic clays (CH) and highly plastic organic soils (OH). The addition of coal ash in the range of 20-25% has been shown to significantly enhance the load-bearing capacity of these soils, as indicated by increased CBR values ranging from 6.45% to 17.20% (Cañar, 2017; Morales, 2015). Furthermore, coal ash has proven to be effective in stabilizing poorly graded sands with silt content (SP or SP-SM), resulting in notable improvements in CBR values within the range of 13% to 23% (Ahmad & Zainol, 2020). These results not only demonstrate an improvement in the soil's load-bearing capacity but also indicate a reduction in moisture content and a gradual increase in dry density when coal ash is incorporated. Additionally, it has been reported a decrease in the plasticity index as the percentage of coal ash content increases (Shirin, Islam & Kumruzzaman, 2020). These studies support the feasibility and benefits of using coal ash as additives in subgrade stabilization, as it improves the soil's load-bearing capacity and modifies its physical properties, making it a promising option from both economic and environmental perspectives.

In this research article, physical and strength characterization tests were conducted using a soil sample, of a previously unstudied soil type, obtained from the access road to a rural population in the department of Atlántico, Colombia. These tests included the determination of the soil's physical properties, such as particle size distribution, consistency limits, density, and moisture content. Additionally, strength tests, such as the CBR, were performed to evaluate the soil's load-bearing capacity. Subsequently, additional tests were carried out using different percentages of coal ash, mixed with the natural soil. These tests aimed to assess the effect of coal ash addition on the soil's properties and load-bearing capacity. The obtained results were compared with reference data obtained from reviewed literature, including previous studies on the use of coal ash as additives in subgrade stabilization. Furthermore, an analysis of the results was performed to determine the viability of using coal ash as a naturally occurring additive in subgrade stabilization for low-traffic volumes.

2. Materials and methods

2.1. Research location

The selection of a rural area in Colombia as the research site holds significance due to the fundamental role of agricultural and livestock activities in the country's economy. However, inadequate road infrastructure in these areas poses challenges for transporting agricultural products, particularly during the rainy season, primarily due to the presence of highly plastic clayey soils. Implementing soil stabilization techniques for subgrade construction in low-traffic volume pavements offers a viable solution and substantial improvement for rural communities. By enhancing the load-bearing capacity of the soils and facilitating vehicular movement, improved market accessibility and economic development can be fostered in these remote regions. It is worth noting that this issue extends beyond Colombia, affecting numerous Latin American countries. According to the Organization for Economic Cooperation and Development (OECD), Latin America contributes approximately 13% of global agricultural production. Therefore, the findings of this study may have broader applicability and potential for replication in other countries across the region that face similar transportation, agricultural market access challenges, and soil properties.

The soil samples were collected from a rural access road in the Gallego district, which falls under the jurisdiction of Sabanalarga municipality in the Atlántico department of Colombia (Figure 1). The need for soil stabilization was identified due to the road's impassability and the consequent isolation of local farmers during the region's rainy seasons.

Figure 1. Location of the district of Gallego, Sabanalarga-Atlántico-Colombia.

2.2. Sampling

The sample collection was carried out following ASTM- D420 "Standard Guide for Site Characterization for Engineering Design and Construction Purposes". This standard aims to provide standardized methods for soil and rock sampling and investigation to determine soil distribution characteristics. A total of 50 kg of representative material was collected from the surface and up to a depth of 1.5 meters, following the guidelines established in the standard. The sampling was conducted at two specific points through trench excavation. Subsequently, the samples were appropriately labeled and sent to the laboratory for the corresponding characterization tests. These tests aimed to evaluate the soil properties that would later be used as subgrade in a low-traffic volume pavement.

2.3. Techniques and instruments

Within the framework of this experimental research, the extraction of natural soil from the study area was carried out, which was designated as the control sample and labeled as SN (Natural Soil). Based on the natural soil sample, we prepared four specimens by replacing between 20% and 40% of the soil weight with coal ashes. The specimens are identified as M1, 25% of coal ash, labeled as M2, 30% of coal ash, denoted as M3, and 35% of coal ash, referred to as M4. For all samples, a series of standardized tests were conducted to obtain relevant data. These tests included the determination of particle size distribution (according to the ASTM 422-63 standard), liquid limit, plastic limit, and plasticity index (according to the ASTM D4318 standard), modified compaction test (according to the ASTM D1557-78 standard), and CBR test (according to the ASTM D1883 standard). Based on the results obtained for the natural soil, its classification was carried out using the methodology established by the American Association of State Highway and Transportation Officials (AASHTO) and the Unified Soil Classification System (USCS). Subsequently, the results of the control SN were compared with those obtained for the different variations of coal ash percentages, i.e., M1 (20% of coal ash), M2 (25% of coal ash), M3 (30% of coal ash), and M4 (35% of coal ash). The objective of this comparison was to evaluate if the incorporation of coal ash resulted in significant improvements in the use of natural soil as a subgrade in low-traffic volume roads.

2.4. Procedure

Step 1: Field Sampling of Natural Soil to be properly labeled and preserved for laboratory analysis. (Figure 2).

Figure 2. Rural Road Sample extraction area

Step 2: Acquisition and Mixing of Coal Ash to be applied in different percentages to the specimens of natural soil. (Figure 3).

Step 3: Determination of the characteristics of the control specimen of natural soil, as well as the specimens having different percentages of coal ash, obtaining parameters related to particle size distribution, consistency limits, compaction, and CBR. (Figure 4).

Step 4: Analysis of the data obtained is carried out to determine the impact of coal ash addition to the natural soil and assess whether it improves or not its properties for use as subgrade in low-traffic volume roads.

Figure 3. Mixture of Coal Ash with natural soil.

Figure 4. Execution of tests in the laboratory.

3. Results and discussion

3.1. Granulometry

The results of the particle size distribution test are presented in Figure 5 and Table 1. The results indicate that these samples of natural soil cannot be used in a pavement structure without prior treatment due to their high fines content, with a percentage exceeding 40%. The inclusion of coal ash in the analyzed soil renders the sample more uniform and mitigates the fines percentage.

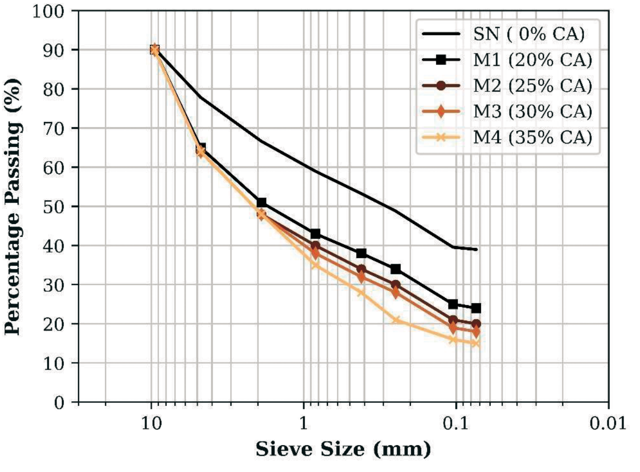

Figure 5. Results of the granulometric analysis.

Table 1. Results of particle size distribution.

Sieve(mm)	Percentage passing				
	SN	M1	M2	M3	M4
9.52	0.90	0.90	0.9	0.9	0.9
4.75	0.78	0.65	0.64	0.64	0.64
1.9	0.67	0.51	0.48	0.48	0.48
0.84	0.59	0.43	0.4	0.38	0.35
0.42	0.53	0.38	0.34	0.32	0.28
0.25	0.49	0.34	0.3	0.28	0.21
0.105	0.40	0.25	0.21	0.19	0.16
0.074	0.39	0.24	0.2	0.18	0.15

3.2. Liquid limit (LL).

Based on the results obtained from the Casagrande cup laboratory test, in accordance with Methodology A of ASTM D 4318 standard, a linear regression was performed to determine the liquid limit of each sample. For the natural soil (SN), a liquid limit value of 25.81% was obtained. For M1 sample (with 20% coal ash), a value of 31.62% was estimated, while M2 sample (with 25% coal ash) had a liquid limit of 36.68%. M3 sample (with 30% coal ash) yielded a value of 37.78% for the liquid limit, and M4 (with 35% coal ash) had a liquid limit of 38.74%. These results are presented in Table 2 and depicted in Figure 6.

3.3 Plastic limit (PL).

The plastic limit was determined for each of the analyzed samples, and the results obtained are presented in Table 2. The plastic limit represents the moisture content at which the soil transitions from a plastic state to a semi-solid state. The results indicate that the natural soil (SN) has a plastic limit of 4.84%. With the addition of coal ash in samples M1, M2, M3, and M4, the plastic limit gradually increases. This suggests that the inclusion of coal ash enhances the soil's plasticity and its ability to retain water. These findings highlight the impact of coal ash on the soil's plasticity, which is essential in determining soil workability and susceptibility to deformation. The gradual increase in the plastic limit with higher percentages of coal ash (see Figure 6) demonstrates the potential of coal ash as a beneficial additive to improve the soil's engineering properties.

3.4 Plasticity index (PI).

The plasticity index was calculated, and the results are summarized in Table 2 and Figure 6. According to these results, the natural soil can be classified as highly plastic, as its plasticity index is greater than 20. On the other hand, samples M1 and M2 exhibit moderate plasticity, as their plasticity indexes fall between 10 and 20. For samples M3 and M4, a plasticity index lower than 10 indicates a soil with low plasticity. The inverse relation between plasticity index and percentage of coal ashes allows us to conclude that the coal ashes addition mitigates the occurrence of swelling in the natural soil, which benefits the performance of the subgrade.

Table 2. Results of the consistency limits.

Sample	Percentage of Coal Ash	LL (%)	PL(%)	PI(%)
SN	0	25.81	4.84	20.97
M1	20	31.68	16.83	14.85
M2	25	36.68	24.53	12.15
M3	30	37.78	28.79	8.99
M4	35	38.74	30.43	8.31

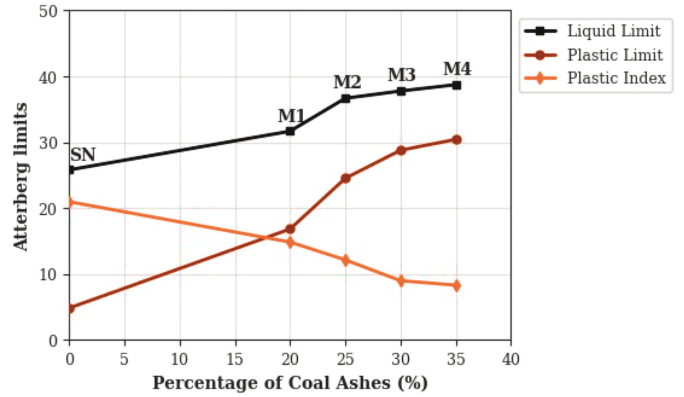

Figure 6. Atterberg limit results.

3.5 AASHTO and USCS classifcations

Based on the laboratory test results, the natural soil is classified as SC (clayey sand) according to the Unified Soil Classification System (USCS). Furthermore, based on its grain size distribution (Table 1) and consistency limits(Table 2), the natural soil is classified as A-6 (2) according to AASHTO soil classification system. According to this classification, this type of soil is not suitable for use as pavement subgrade, as it is considered fair to poor according to AASHTO criteria. In contrast, all specimens with the addition of coal ashes are classified as A-2-6, which are described as competent soils with applications in pavement structural layers. Hence, the addition of coal ashes leads to an improvement in the properties of the natural soil.

3.6 Proctor Compaction Test

Figure 7 presents the results of the Proctor compaction test for each sample, according to the procedure described in ASTM D1557 standard, compaction is carried out using the modified hammer. The SN specimens showed an optimum moisture content of 30% and a maximum dry density of 2.17 g/cm³. For the M1 specimens, the values were 32% for optimum moisture content and 2.29 g/cm³ for maximum dry density, respectively. The M2 specimens had an optimum moisture content of 37% and a maximum dry density of 2.57 g/cm³. However, there was a decrease in maximum dry density for the M3 and M4 specimens, with values of 2.52 g/cm³ for the M3 sample and 2.44 g/cm³ for the M4 specimens. The optimum moisture content percentages for the M3 and M4 specimens were 43% and 47%, respectively. These results indicate variations in both maximum dry density and optimum water content of the soil specimens with the addition of coal ashes. The findings suggest that an addition of around 25% of coal ashes appears to be the optimum value for improving the soils mechanical properties.

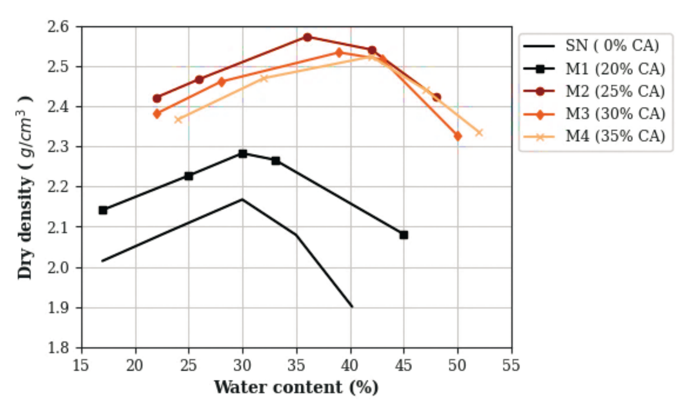

Figure 7. Proctor Compaction Test results.

3.7 California Bearing Ratio (CBR)

Figure 8 presents the stress-strain results obtained during the CBR tests. It is evident that the natural soil specimens exhibit the lowest strength among all the samples tested. Conversely, consistent with the results observed in the Proctor compaction test (Figure 7), the specimens having a 25% percentage of coal ash addition exhibits the highest strength, while the remaining treated specimens present similar strength results. Furthermore, the inclusion of Coal Ash led to an increase in the stiffness of the samples respect to the untreated soil samples, that could be beneficial for other applications such as footings.

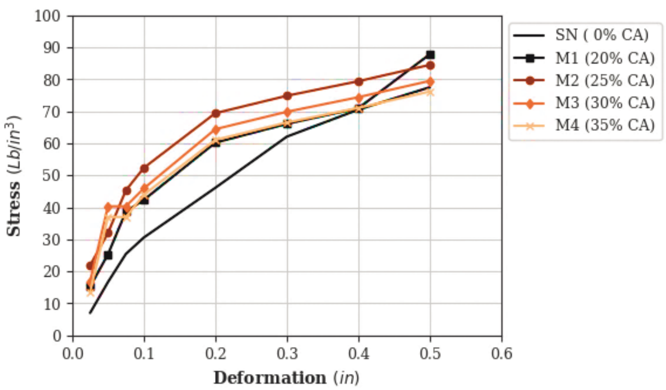

Figure 8. Stress vs strain results

Table 3. CBR test results.

Type	Percentage of Coal Ashes	Maximum dry density gr/cm³			CBR	
		Specimen 1	Specimen 2	Specimen 3	100%	95%
SN	0%	1,88	2,17	2,19	5,3	4,3
M1	20%	2,10	2,34	2,33	5,9	5,1
M2	25%	2,56	2,58	2,57	6,2	5,6
M3	30%	2,18	2,35	2,50	5,7	4,9
M4	35%	2,20	2,35	2,40	5,5	4,3

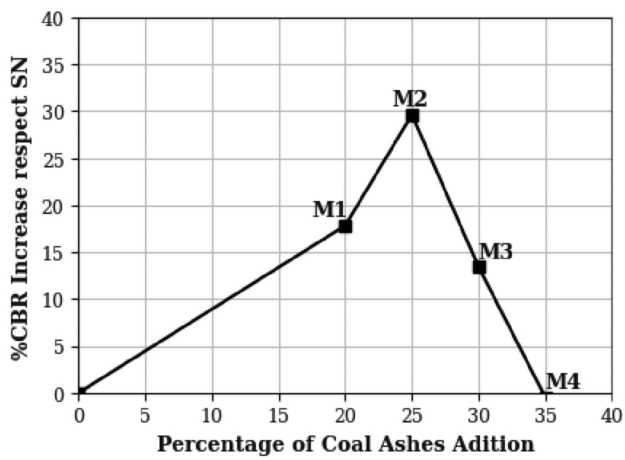

Figure 9. Variation of CBR increase with respect to the percentage of coal ashes.

4. Conclusions

According to the results obtained in the laboratory tests, adding carbon ashes improves the mechanical properties of SC-type soils. An increase in the liquid and plastic limits is observed as the percentage of carbon ashes in the sample rises, leading to a decrease in the plasticity index. This effect is particularly advantageous for treating highly plastic soils.

Regarding density, it can be concluded that the addition of 25% carbon ashes in weight to the sample increases the maximum dry density by around 18%. However, exceeding 25% of carbon ashes addition led to lower increases in dry density.

Regarding the CBR, it was found, according to the reviewed literature, that the optimal content of carbon ashes addition in the sample to improve the properties of the natural soil depends on the soil type analyzed. Other authors suggest different optimal values for the inclusion of carbon ashes compared to those found in the current research. For the case under study, the optimal value is 25%, as this increment raises the CBR value to 30% of the sample, representing a significant improvement in load-bearing capacity.

Lastly, future research endeavors could test the suitability of carbon ashes for improving the performance of soils having better mechanical properties that the one used in this paper. Since carbon ashes pose as a suitable alternative for enhancing the mechanical properties of soils. In addition, the inclusion of carbon ashes led to an increase in the stiffness, that could be beneficial for other applications such as footings.

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