Original Article

Evaluation of Activated Carbon from Bean Waste in Improving Concrete Performance and Acceptable Properties of Soil and Subgrades

Jesus Fernando Navarro Baquerizo[1], Juan Alvaro Sanchez Gala[1], Ascension Quispe Huaman[1],
Marko Antonio Lengua Fernandez[1,*]

[1]*Department of Civil Engineering, Continental University, Huancayo, Perú.*

*Corresponding Author : mlengua@continental.edu.pe

Abstract - Population growth and urban expansion have intensified the demand for housing and infrastructure, forcing construction on soils with unfavorable geotechnical conditions and accelerating the exploitation of conventional materials such as cement, which accounts for approximately 8% of global CO_2 emissions. At the same time, the accumulation of organic waste in cities such as Huancayo (60 tonnes/day of broad bean husks) generates environmental impacts through methane emissions and pressure on waste management systems. In this context, activated carbon emerges as a sustainable material, characterized by high porosity and adsorption capacity, with promising applications in construction. In this study, broad bean (Vicia faba) residues were valorized through calcination and chemical activation with KOH to obtain activated carbon, which was incorporated into concrete and clay soils at dosages ranging from 0% to 3%. In concrete, workability (slump, temperature) and compressive strength (7, 14, 28 days) were measured. In soils, CBR and bearing capacity were determined under controlled compaction. Results showed that an optimal dosage of 2.5% increased compressive strength from 224.56 kg/cm² to 353.41 kg/cm² (57% improvement at 28 days). CBR values rose from 6.3% to 19.1% in soils, while allowable capacity increased from 0.50 to 2.50 kg/cm², a fivefold improvement. These findings demonstrate that activated carbon from broad bean husks not only mitigates waste disposal but also acts as an innovative, sustainable additive that enhances the performance of concrete and soils, offering replicable solutions for civil engineering.

Keywords - Activated carbon, permissible capacity, subgrade, clay soils, direct cut.

1. Introduction

In Peru, the projected population growth for the year 2030 will reach 36 million inhabitants [1], which will significantly increase the demand for housing and the expansion of urban infrastructure. However, the availability of optimal land for construction is limited, which has led to the occupation of marginal soils with low bearing capacity and high geotechnical vulnerability [2, 3]. This phenomenon, which compromises structural safety, is also directly associated with the environmental footprint of the building industry. As reported by the United Nations Environment Programme (UNEP), this field is responsible for nearly 37% of worldwide CO_2 releases [4]. In particular, cement production is responsible for about 8% of these emissions, due to the calcination of calcium carbonate at high temperatures, which releases between 800 and 900 g of CO_2 per kilogram of clinker produced [5-7]. Likewise, the growing demand for aggregates (sand and gravel) intensifies ecosystem degradation, accelerates erosion, and overexploitation of non-renewable natural resources [8].

In parallel, the city of Huancayo generates approximately 60 tons per day of broad bean (Vicia faba) waste, mainly husks and pods from local markets [9]. Since this organic residue is not properly valorized, it is disposed of in landfills, increasing municipal management costs and contributing to methane (CH_4) emissions, a potent greenhouse gas whose capacity to trap heat in the atmosphere is about 25 times higher than that of CO_2 [10, 11].

Agro-industrial organic residues present technical and environmental advantages that justify their study as raw materials in construction materials: they contain a high amount of carbon and lignocellulosic compounds (cellulose, hemicellulose, and lignin), which favor the generation of activated carbons characterized by elevated porosity and enhanced adsorptive properties [12]. In addition, biomass ashes contain significant amounts of oxides such as SiO_2, Al_2O_3, and CaO, which are key components in pozzolanic reactions and in the improvement of cementitious matrices [13]. Unlike Portland cement, whose production requires

approximately 372 kJ/kg, the conversion of organic residues consumes only about 12 kJ/kg, drastically reducing both energy demand and environmental footprint [14].

For instance, the use of agro-industrial residues such as bagasse ash, rice husk ash, or palm oil waste has demonstrated improvements in the strength and durability of concrete [15], [16]. Likewise, activated carbon derived from biomass has shown successful applications in both civil engineering and environmental remediation: it has been used to reinforce lateritic soils [17], to improve porous pavements against moisture [18], to enhance the compressive strength of lightweight concretes [19], and to adsorb emerging contaminants such as pesticides and persistent organic compounds [20-22].

In this context, it is necessary to examine the research that has explored the valorization of agro-industrial waste in civil engineering. In particular, studies related to biomass-derived activated carbons will be addressed, considering their influence on improving the mechanical behavior of concrete and soils, as well as the contributions and limitations that guide this research.

2. Literature Review

In Malaysia, in the civil engineering department, construction on lateritic soils poses a challenge in geotechnical engineering. To address this challenge, they converted coconut waste into activated carbon for stabilisation. They conducted unconfined compression tests (UCS) and direct shear tests (CDS), using 1%, 2% and 3% activated carbon. They obtained good results; with 2%, the shear strength improved from 49.77 KPa to 121.8 KPa, and with 3%, the compressive strength increased from 200.87 KPa to 545.40 KPa [14]. Similarly, in the same country, to stabilise the subgrade layer of the pavement, they used lime in proportions of 3%, 6%, 9% and 12%, together with Activated Carbon and Coconut Fibre (ACF) at 1%, 2% and 3%. The best results were obtained with 3% ACF and 12% lime, achieving greater compressive strength, reduced voids and better permeability [15].

In the United States, the Department of Civil, Environmental and Architectural Engineering conducted a study to counteract pollution by using granular activated carbon as a substitute for fine sand aggregates in construction mixtures. They evaluated its effect on compressive and tensile strength, using different proportions in the dosage. The results showed that with a 2% addition, significant improvements were achieved in both mechanical properties, suggesting that this material may be a viable alternative for optimising structural performance and contributing to sustainability in the construction industry [16]. In China, the environmental engineering department investigated the use of wood and mineral-activated carbon in concrete in the context of

ecological protection. They evaluated its physicochemical properties and found that a 2% addition improved porosity, permeability, and water retention capacity. In addition, they mention that activated carbon can maintain its effectiveness for approximately half a year [10]. In the same country, but in the civil engineering and architecture department, due to the problems faced by permeable pavement due to runoff, they analysed its behaviour when incorporating activated carbon. The results showed an increase in stability against moisture, which reduces water damage and improves the pavement's service life [17].

In Korea, due to interest in incorporating natural materials into concrete, engineers from the Engineering Society investigated using activated carbon from organic waste to improve its mechanical and physical properties. To do this, they evaluated mixtures with activated carbon dosages ranging from 0% to 10%, with 1% increments. The results showed that the unit weight of the concrete decreased, while water absorption increased. In addition, with a 3% addition, significant improvements were observed in compressive strength, tensile strength, flexural strength, and modulus of elasticity. Based on these findings, they recommended 2% as the optimal dosage to improve concrete performance and 4% as a more viable alternative in practical applications [18].

In Malaysia, at the School of Engineering, due to the increasing use of natural materials in concrete and the promotion of new sustainable additives, they investigated the use of activated carbon as a coarse aggregate. They evaluated the mechanical and thermal properties of concrete using activated carbon obtained from oil palm. The results were favourable, as with an addition of 117 kg/m³, the compressive strength increased from 30 MPa to 50 MPa, while the tensile strength by cracking increased from 2 MPa to 3 MPa [13].

In India, researchers at the Institute of Nanotechnology investigated the development of HDPE nanocomposites reinforced with low-cost, naturally sourced Activated Nanocarbon (ACN). These were manufactured with 2%, 5% and 10% weight loadings and evaluated in terms of mechanical and thermal properties, flammability and weather resistance. The results showed that with 10% ACN, impact resistance increased by 161%, heat deflection temperature by 51%, Vicat softening point by 39% and oxidative induction time by 426%. In addition, flammability resistance increased by 93%, while UV/moisture degradation and gas permeability were reduced by 12% and 60%, respectively. These findings highlight ACN as a promising material for improving the performance of HDPE, offering a sustainable and cost-effective alternative with optimised properties for high-performance applications [19].

In China, the Department of Civil Engineering investigated the use of activated carbon to reduce Volatile Organic Compounds (VOCs) in bituminous materials. As a

result, they found that adding 50% activated carbon achieved a significant reduction in VOCs. In addition, its porous structure allowed it to absorb and reduce these compounds, making the material less polluting [20].

In the United States, the Department of Environmental and Molecular Technology conducted a study on groundwater contamination by perfluoroalkyl and polyfluoroalkyl substances (PFAS), caused by the use of Aqueous Film-Forming Foam (AFFF) in firefighting. These substances, known for their persistence in the environment and their potential adverse health effects, pose a challenge for water remediation. As part of the research, they evaluated the effectiveness of granular activated carbon in adsorbing and removing PFAS, demonstrating its potential as a viable solution for mitigating contamination [21].

In Canada, the Department of Chemical and Biological Engineering conducted a study on the removal of emerging contaminants in water, such as pesticides, pharmaceuticals and Personal Care Products (PPCPs) and Endocrine Disruptors (EDCs). To do this, they used activated carbon as an adsorption method, evaluating its efficiency based on its physicochemical characteristics, adsorbent properties, and environmental factors. The results indicated that activated carbon played a key role in reducing these contaminants, with a high adsorption capacity influenced by the hydrophobicity and nature of the functional groups of the organic compounds [22].

Nevertheless, no studies have examined the valorization of broad bean (Vicia faba) residues to obtain activated carbon intended for applications in concrete and soil improvement, despite the fact that this agro-industrial waste is abundant in the region and presents a high carbon and protein content that makes it suitable for activation processes. Unlike other biomasses already explored, such as rice husk, coconut shell, or palm oil residues, broad bean husks have not been evaluated in this field, which constitutes the main novelty and scientific contribution of the present research.

Therefore, this study evaluates the influence of activated carbon derived from broad bean husks on the physico-mechanical behavior of concrete, including fresh-state parameters (workability and temperature) and hardened performance (compressive resistance), as well as on soil parameters such as CBR and allowable bearing capacity. The investigation seeks to generate scientific evidence supporting the valorization of this agro-industrial by-product in construction, promoting low-cost, sustainable solutions that contribute to reducing cement dependency and mitigating the environmental impacts of the sector.

3. Materials and Methods

This part outlines the materials employed and the tests and processes carried out to obtain activated carbon from bean residues, providing a comprehensive overview of the procedure. The methods applied in each phase of the study will be described, highlighting the preparation techniques, experimental conditions, and tools used.

3.1. Activated Carbon
3.1.1. Haba (Vicia faba)

As a member of the Fabaceae family, *Vicia faba* provides considerable nutritional benefits, as it is rich in protein, fibre, and minerals. It is consumed in various preparations and improves soil fertility by fixing nitrogen, promoting sustainable agriculture [23-27]. However, despite their nutritional and agronomic properties, approximately 60 tonnes of broad bean waste are discarded daily in Huancayo, without any adequate use of this waste. Due to limited research on its possible use in construction materials, this study evaluated its potential as an additive in concrete and soil. To this end, the characteristics of other biomass ashes used in the construction industry were considered. For example, Table 1 shows that bamboo leaf ash contains 78.71% SiO_2, date palm ash contains 13.04% CaO, and corn cob ash contains 7.48% Al_2O_3, all of which are key elements in the reactivity of pozzolanic materials.

Table 1. Elemental composition of ashes derived from biomass [28]

Type	Silica (SiO_2)	Lime or calcium oxide (CaO)	Alumina (Al_2O_3)
Bamboo leaf ash (BLA)	78.71	7.82	1.01
Corn cob ash (CCA)	66.38	11.57	7.48
Date palm ash (DPA)	35.93	13.04	0.65
Olive waste ash (OWA)	11.70	10.20	2.51
Plantain leaf ash (PLA)	48.70	-	2.60

It should be noted that the production of pozzolans requires approximately 68 kJ/kg, and the production of Portland cement reaches 372 kJ/kg, which represents a high energy cost, while the production of biomass ash or organic waste consumes only 12 kJ/kg. This makes biomass ash an environmentally friendly and cost-effective substitute in construction, lowering the ecological impact derived from manufacturing binders such as Portland cement [29].

3.1.2. Obtaining Activated Carbon

Characterized by high porosity and exceptional adsorption capacity, activated carbon can be synthesized from diverse biomass residues such as fruit shells, agricultural waste, and agro-industrial by-products [30, 31], which positions it as an eco-friendly pathway for transforming organic waste into functional adsorbents. The activation process generally involves chemical promoters like zinc chloride, phosphoric acid, or potassium hydroxide, each with a particular impact on the formation and size of the pores [32]. In this study, bean husks, an agro-industrial waste product in Huancayo that is not usually reused, were used, and potassium hydroxide was chosen as the activating agent due to its ability to generate a highly microporous structure [33]. The procedure used to obtain it, according to Muhammad Fazal-ur-Rehman [34], is detailed below. It should be noted that, in this study, a blender was not used, as after combustion, only small particles remained that could be broken down manually, without the need for additional grinding.

Collection and Crushing
The bean residues were collected and crushed into small pieces, thus facilitating subsequent thermal processes.

First Calcination
The crushed material underwent a first calcination by pyrolysis at 500°C in the absence of oxygen, turning it into raw charcoal.

Second Calcination
This raw charcoal underwent a second calcination in order to purify its structure and prepare it for activation.

Grinding
The calcined carbon was ground manually to reduce its size and improve contact with the activating agent.

Potassium Hydroxide (KOH)
KOH was selected as the chemical activator because it effectively promotes the development of a microporous structure in the carbon, enhancing its surface area and adsorption potential.

Dissolution of Potassium Hydroxide
KOH was prepared in distilled water to obtain a uniform activating solution.

Mixing with Carbon and Solution (1:1)
The ground carbon was mixed with the KOH solution in a 1:1 ratio (weight/weight), ensuring uniform distribution of the activator.

Activation
The mixture was subjected to thermal activation at 800°C in an inert atmosphere, which allowed the development of pores and an increase in specific surface area.
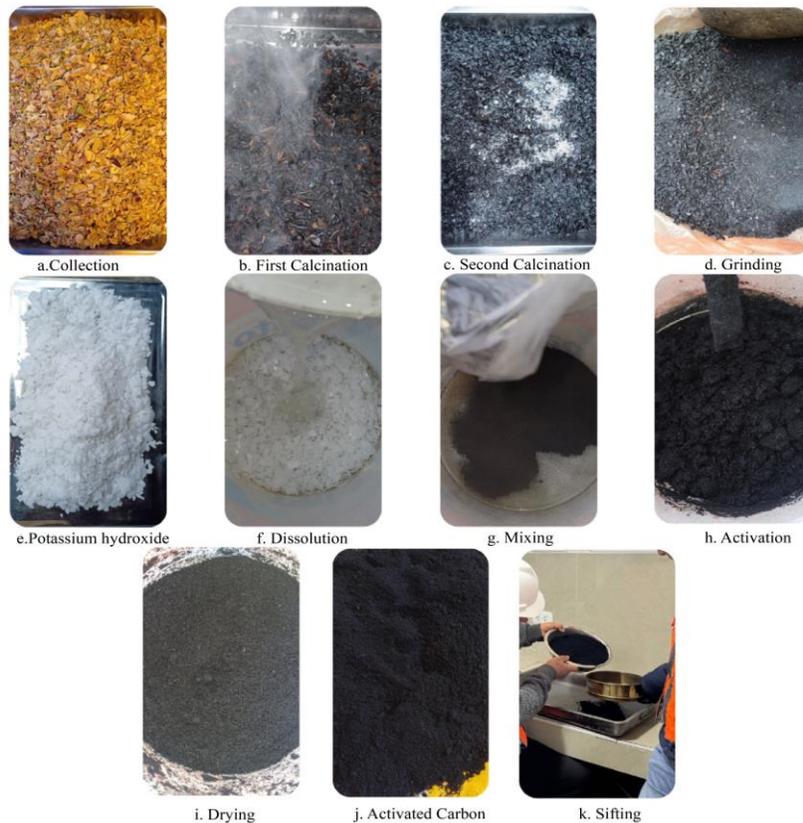

Fig. 1 Process for obtaining activated carbon

Drying

After activation, the product was dried to remove residual moisture.

Obtaining Activated Carbon

Finally, the activated carbon was sieved to obtain particles of 0.5 to 1 mm in size, suitable for use.

The Activated Carbon

It was sieved using a No. 200 mesh (with an opening of 0.075 mm) to obtain fine particles suitable for use.

Once the activated carbon was obtained, dosages of 0%, 0.5%, 1%, 1.5%, 2%, 2.5% and 3% were used [14]. This entire procedure for obtaining activated carbon is shown schematically in Figure 1.

Ash activation is key to enhancing its performance in geotechnical and cementitious applications. Although these ashes naturally contain mineral compounds, such as silicon dioxide (SiO_2) and calcium oxide (CaO), as shown in Table 1, which give them some pozzolanic and filling potential, they lack significant active chemical functionality in their original state. Through chemical activation processes, such as in the case of activated carbon derived from bean ash, specific highly reactive surface properties are developed, as shown in Table 2. High total basicity (2290 µmol/g) facilitates the neutralisation of acidic soils and improves compatibility with cementitious matrices, promoting effective interaction with the ions present in the medium. The presence of carboxylic groups (64.7 µmol/g) increases the adsorption capacity of metal cations, while lactones (46.8 µmol/g) and phenols (17.5 µmol/g) provide additional functionalities for the retention of organic and inorganic species, reinforcing its performance in complex media. In addition, a pH value at the zero charge point (pHpzc) of 9.96 ensures a predominantly negatively charged surface in alkaline environments, such as concrete, promoting the fixation of cations such as Ca^{2+}, thus contributing to structural stability.

Table 2. Chemical properties of activated carbon [35]

Components	Value
Total acidity (µmol g^{-1})	94.1
Overall basic character (µmol·g^{-1})	2290
Carboxyl functional groups (µmol·g^{-1})	64.7
Lactone groups (µmol·g^{-1})	46.8
Phenols (µmol g^{-1})	17.5
pHpzc	9.96

The microstructural features of Activated Carbon (AC) were analyzed through Scanning Electron Microscopy (SEM) and presented in Figure 2, confirming the presence of a porous framework composed of micro and mesopores, which generates a large surface area of contact with cement particles and water. This porous texture facilitates the dispersion of cement flocs, improving the workability of the mixture. In addition, activated carbon has the ability to adsorb soluble ions from cement, such as Ca^{2+} and SO_4^{2-}, which modifies the chemical balance of the mixture and prevents early cement agglomeration, generating an effect similar to that of first-rank water-reducing plasticisers. It also acts as an ultra-fine filler material (filler effect), improving the packing of cement particles and creating a denser and more homogeneous matrix. This helps to reduce the internal friction of the mixture, improving its fluidity. Although activated carbon has a water adsorption capacity of 36.43%, not all of the adsorbed water is 'sequestered', as part of it remains available on the surface of the pores, acting as an additional lubricant between the particles.
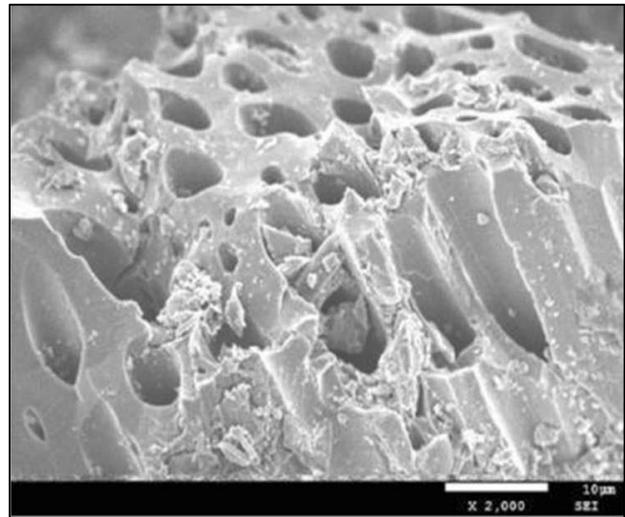

Fig. 2 Activated carbon SEM [10]

3.2. Mix Design

In concrete technology, mix proportioning involves selecting and quantifying the constituents cement, water, fine and coarse aggregates, and chemical or mineral admixtures so that the resulting mixture fulfils predefined criteria related to workability, strength development, and long-term durability.

In this study, the mix design used is detailed in Table 3. Corrected water was used, kept constant at 200 litres per cubic metre (L/m³), in order to maintain a stable water/cement ratio. The amount of cement was set at 358 kilograms per cubic metre (kg/m³), corresponding to Portland I type. Activated carbon was incorporated in varying proportions, from 1.19 to 7.15 kg/m³, according to the corresponding dosage. The aggregates remained constant in all mixtures: 798 kg/m³ of fine aggregate from the Matahuasi quarry and 971 kg/m³ of coarse aggregate, corresponding to ¾" crushed stone obtained from the 3 de Diciembre quarry, located in the province of Huancayo, were used. This configuration ensured the uniformity of the granular skeleton in all mixtures.

Table 3. Materials used for 1 m³ of concrete

Mix design						
Addition	**Water (l)**	**Corrected water (l)**	**Cement (kg)**	**Activated carbon (kg)**	**Fine aggregate (kg)**	**Coarse aggregate (kg)**
0.00%	186.00	200.00	358.00	0.00	971.00	798.00
0.50%	186.00	200.00	358.00	1.19	971.00	798.00
1.00%	186.00	200.00	358.00	2.38	971.00	798.00
1.50%	186.00	200.00	358.00	3.58	971.00	798.00
2.00%	186.00	200.00	358.00	4.77	971.00	798.00
2.50%	186.00	200.00	358.00	5.96	971.00	798.00
3.00%	186.00	200.00	358.00	7.15	971.00	798.00

To produce 1 m3 of concrete, the mix design shown in Table 3 was followed, using hydraulic cement, as it contains compounds that react with water, allowing the mixture to set and harden even in humid environments [36]; Among these components, Silicon Dioxide (SiO₂) stands out, representing approximately 19.9% of the total, as shown in Table 4 [37]. Fine and coarse aggregates were also used, which, being granular materials, contributed volume, strength and stability to the mixture [38]. In addition, water played a key role in the hydration of the cement, facilitating the formation of compounds responsible for setting and strength development [39]. Together, these materials made obtaining a homogeneous and cohesive mixture possible.

Table 4. Portland cement type I [40]

Physical Properties		Chemical Properties	
Property	**Description**	**Chemical Composition**	**Percentage (%)**
Density	3.1 -3.2 g/cm³	**Calcium Oxide (CaO)**	64.7%
Fineness	300 - 500 m²/kg	**Silicon Dioxide (SiO₂)**	19.9%
Colour	Light grey	**Iron Oxide (Fe₂O₃)**	2.1%
Initial setting time	45 minutes	**Aluminium Oxide (Al₂O₃)**	6.5%

Figure 3 shows the materials used, including the previously prepared activated carbon, which was incorporated in different proportions: 0%, 0.5%, 1%, 1.5%, 2%, 2.5% and 3%. Although this material has a high water adsorption capacity (36.43%) [41], it was decided to keep the dosage of all components constant, including the amount of water (200 l/m³), in order to directly evaluate the impact of activated carbon on the properties of concrete. This decision was based on experimental criteria, as modifying the water/cement ratio would have introduced an additional variable that could have made it difficult to accurately interpret the results. This ensures a more controlled and objective evaluation of the specific effect of activated carbon on the mixture.
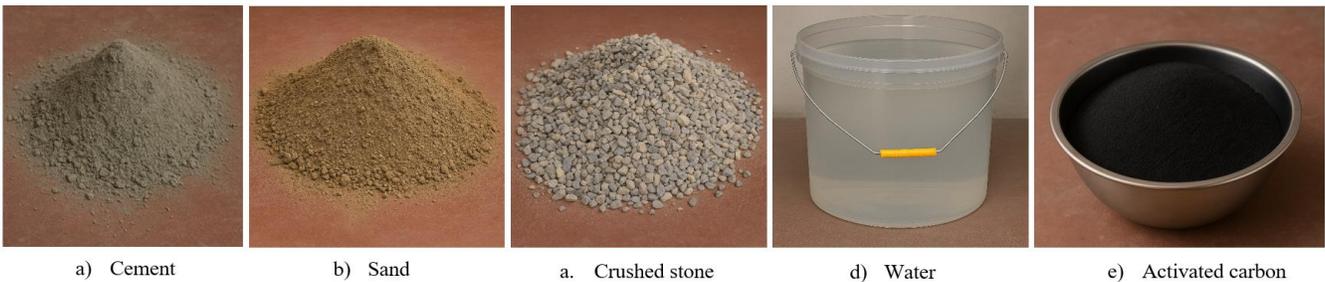

a) Cement   b) Sand   a. Crushed stone   d) Water   e) Activated carbon

Fig. 3 Components of concrete with activated carbon

3.3. Fresh Concrete Tests

In order to assess the behavior of fresh concrete, two evaluations were carried out: settlement (slump) and temperature, applying the methodologies specified in the MTC Materials Testing Manual. These tests made it possible to verify the workability and thermal conditions of the concrete.

Following MTC E 705 [42], the slump test consisted of filling the Abrams cone in three layers, each consolidated with 25 blows of a 16 mm diameter, 600 mm long rod. The cone was removed vertically in a continuous motion of 5–10 s, and the settlement was measured as the height difference, providing the slump value.

The temperature test followed the procedure specified in MTC E 724 [42]. A fully immersed thermometer was inserted into the fresh concrete, ensuring that it did not touch the walls or bottom of the container. The thermometer was left submerged for at least 2 minutes or until the reading stabilised. At this point, the temperature was recorded. This data was essential to ensure that the concrete was within the appropriate temperature range, as temperatures outside the recommended range can affect setting and future mechanical properties.

3.4. Tests on Hardened Concrete
3.4.1. Compressive Strength
The uniaxial compression test (MTC E 704) [42] was applied to 63 cylindrical specimens (Ø150 mm × 300 mm) with activated carbon at 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0%, cured for 7, 14, and 28 days. The monotonic load was applied at a rate of 35 ± 7 psi/s in the testing machine shown in Figure 4, and the maximum load was recorded for the calculation of f'c.
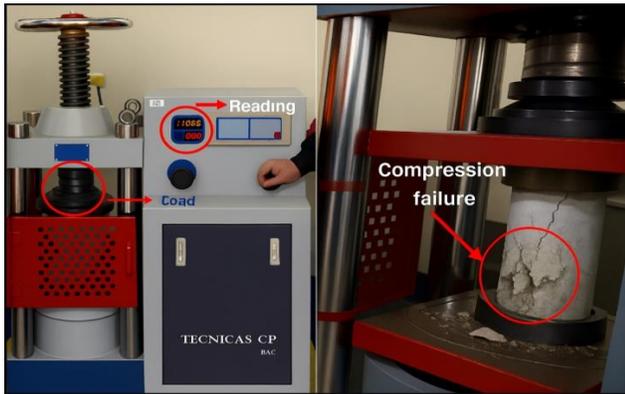

Fig. 4 Compression resistance testing machine

3.5. Soil Sample Testing
3.5.1. Humidity Testing
Humidity testing allows the water content of a soil sample to be determined. To determine the natural humidity of clay soil, standard MTC E 108 [42] was used. The procedure began with obtaining a representative sample of between 100 g and 200 g, which was placed in a clean, dry container.

First, the empty container was weighed (M_0) and then with the wet sample (M_1). The sample was then placed in an oven at a temperature of 105°C - 110°C for at least 24 hours or until it reached a constant weight. After drying, it was left to cool in a desiccator and weighed again together with the container (M_2). The moisture content was calculated using formula 1:

$$Humidity\ (\%) = \left(\frac{M_1 - M_2}{M_2 - M_0}\right) * 100 \tag{1}$$

3.5.2. Granulometry
Granulometry analyses the size distribution of soil particles, determining their proportion of sand, silt and clay [44]. This test was carried out in accordance with standard MTC E 107 [42], using an 8 kg soil sample, which was completely dried and divided into 500 g fractions. Each fraction was sieved using sieves ranging from 3" to No. 200, applying circular movements to keep the material in constant motion on the meshes.

Table 5 shows the particle size distribution, showing 100% passage through the coarse sieves and progressive retention from the 3/8" (9.5 mm) sieve onwards. There is a high content of fines, with 10.60% retained in the No. 200 sieve (0.075 mm) and 89.40% of material passing completely.

Table 5. Granulometric analysis

Sieve	Aperture (mm)	% Retained	% Retained cumulative	% Passing
(1)	(2)	(4)	(5)	(6)
3"	75.000	0.00%	0.00%	100.00%
2"	50.000	0.00%	0.00%	100.00%
1 1/2"	37.500	0.00%	0.00%	100.00%
1"	25.000	0.00%	0.00%	100.00%
3/4"	19.000	0.00%	0.00%	100.00%
3/8"	9.500	0.30%	0.30%	99.70%
N°04	4.750	0.90%	1.20%	98.80%
N°10	2.000	1.70%	2.90%	97.10%
N°20	0.850	1.50%	4.40%	95.60%
N°40	0.425	1.30%	5.70%	94.30%
N°60	0.250	1.00%	6.70%	93.30%
N°140	0.106	1.90%	8.60%	91.40%
N°200	0.075	2.00%	10.60%	89.40%
Fondo		89.40%	100.00%	0.00%

Atterberg Limits

The Atterberg limit tests (MTC E 110 and MTC E 111) [42], based on O'Kelly [45], showed a liquid limit of 42% and a plastic limit of 20%, giving a plasticity index of 22%. These results identify the soil as a fine-grained material of low plasticity (CL group according to USCS), with moderate workability and sensitivity to water content variation. The particle size analysis confirmed 1.2% gravel, 9.3% sand, and 89.4% fines.

3.5.3. Modified Proctor

The Modified Proctor test (MTC E 115 [42]) was performed to determine the compaction characteristics of the soils treated with activated carbon obtained from broad bean residues. In this study, the soil was oven-dried and sieved through a 4.75 mm mesh, then mixed with different percentages of activated carbon (0–3%). Each mixture was compacted in a cylindrical mold (944 cm³), applying the standard compaction energy of 2700 kN·m/m³ specified by the regulation. This process made it possible to evaluate whether the inclusion of activated carbon modified the maximum dry density and the optimum moisture content of the soil, both of which are critical parameters for subgrade performance. After compaction, the wet density was calculated according to Equation (2):

$$\rho m = 100 \; x \frac{(M_t - M_{md})}{V} \tag{2}$$

Where:
pm = wet density (Mg/m³)
Mt = mass of mould + specimen (kg)
Mmd = mass of mould (kg)
V = mould volume (m³)

A sample of the compacted soil was then extracted and dried in an oven at 110°C ± 5°C until it reached a constant weight, thereby determining the moisture content using formula 3:

$$w_{sat} = \frac{(\gamma_d)(G_S) - \gamma_d}{(\gamma_d)(G_S)} x 100 \tag{3}$$

Where:
Wsat = Moisture ratio at full saturation of the soil sample (%).
gw = Specific weight of water, taken as 9.807 kN/m³
Yd = Dry bulk unit weight of the soil mass.
Gs = Relative density of soil solids.
Dry density using Equation 4:

$$\rho d = \frac{p_m}{1 + \frac{w}{100}} \tag{4}$$

Where:
Pd = Dry bulk density of the compacted sample,

expressed in Mg/m³.
w = Gravimetric moisture ratio (%).
Yd = 62.43 ρd in lbf/ft3.

3.5.4. CBR

The CBR test was applied according to MTC E 132 [42] on specimens compacted at 95% and 100% of maximum dry density. Following 96 hours of soaking under a surcharge of 4.5 kg, the penetration load values were obtained to calculate the soil's bearing ratio.

3.5.5. Direct Shear

Soil samples prepared and compacted according to MTC E 123 [42] were evaluated through the direct shear test. Using a shear box apparatus, a horizontal load was progressively applied to induce sliding, and the shear strength parameters (c and φ) were calculated from the recorded displacement data, as shown in Figure 5.

Fig. 5 Direct cutting machine

4. Results

This section will present the results derived from the different dosages of activated carbon in concrete mixtures and their influence on soil characteristics. Variations in mechanical properties, such as compressive strength, will be examined, as well as the impact of activated carbon additions on soil stability and behaviour. The results obtained will allow for a comprehensive evaluation of the effects of these additions on both concrete and soil.

4.1. Slump

Figure 6 illustrates the performance of concrete mixtures incorporating broad bean husk–derived activated carbon, analyzing slump and compressive strength at curing ages of 7, 14, and 28 days.

At 7 days (panel a), the data revealed that compressive strength increased progressively with the addition of activated carbon, reaching its highest values between 2% and 2.5%. This trend indicates that the porous microstructure of the

additive favored better particle packing and hydration kinetics, accelerating strength gain at early ages. The polynomial regression ($R^2 = 0.90$) confirmed the reliability of this correlation, reaching a maximum compressive strength value of 199.99 kg/cm² when using 2.5% activated carbon. The slump also increases progressively from 3.5' (without addition) to 6' for the addition of 2.5% activated carbon, indicating a simultaneous improvement in workability and initial strength. However, a higher addition (3%) causes a decrease in strength to approximately 179.21 kg/cm², suggesting an overdose of the addition that negatively affects the initial mechanical properties.

At 14 days (panel b), the trend described above is maintained, but with greater clarity and statistical consistency ($R^2 = 0.92$). The optimum value identified between 2% and 2.5% incorporation reached a maximum compressive strength of 259.57 kg/cm², evidencing that this dosage notably

enhanced the structural performance of the concrete. The slump at this proportion was 6", which facilitated placement while maintaining mixture stability.

At 28 days (panel c), the correlation between activated carbon content and compressive resistance was further strengthened, with a determination coefficient ($R^2 = 0.94$) that indicates a nearly linear and highly reliable predictive relationship.. The maximum strength peak observed is 353.41 kg/cm², again within the optimal range between 2% and 2.5% activated carbon. The increased settlement (from 6" with a 2.5% addition) is advantageous for construction operations, ensuring adequate concrete consolidation. When this optimal range is exceeded and reaches 3%, the strength drops to approximately 321.98 kg/cm², reinforcing the importance of not exceeding the optimal dosage threshold.
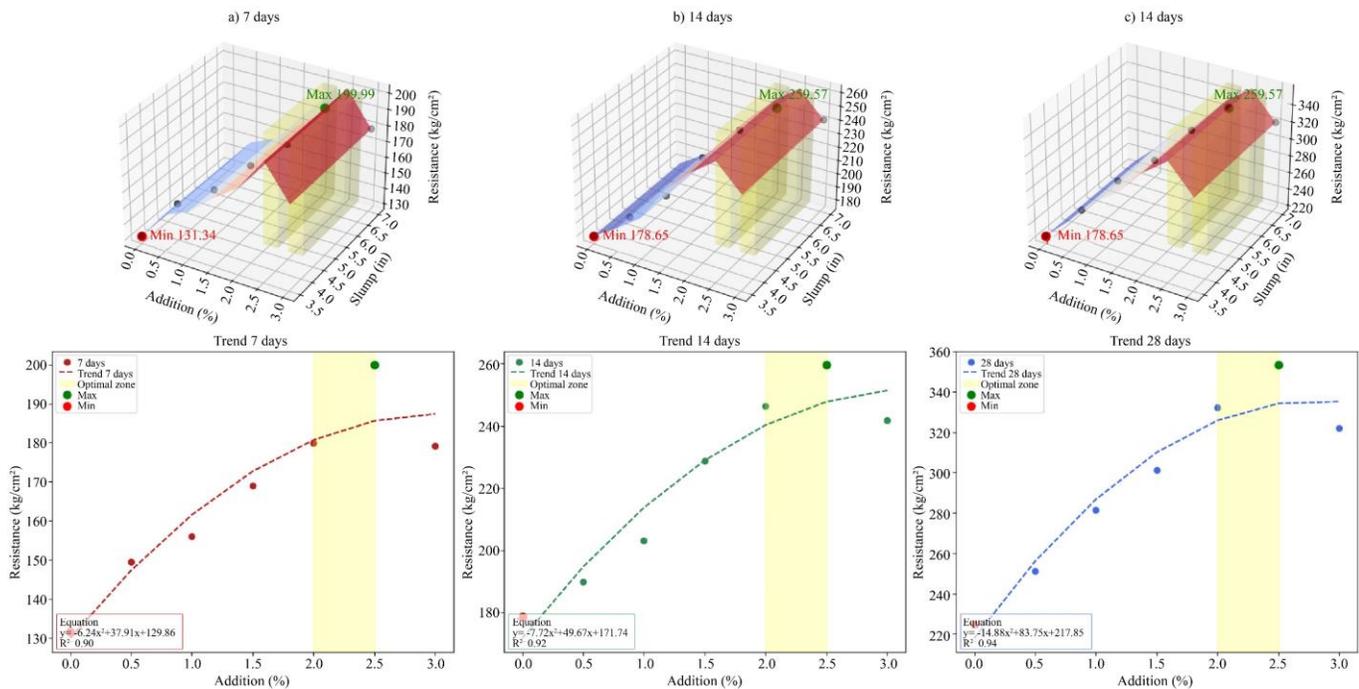

Fig. 6 3D surface graph of slump vs Compressive strength of concrete

4.2. Temperature

Figure 7 illustrates the influence of AC addition and temperature on the compressive strength of concrete at 7, 14, and 28 days, with results shown in panels a), b), and c).

For panel a) (7 days), the data reveal a progressive enhancement in compressive resistance as the percentage of activated carbon increases, reaching an optimal range between 2% and 2.5%, with maximum values between 179.99 and 199.99 kg/cm². The quadratic regression showed a strong fit ($R^2 = 0.90$). A moderate rise in mixture temperature was observed, from 11.5 °C in the control to 15.8 °C at 2.5% incorporation. This behaviour is associated with the porous

nature of activated carbon, which influences the hydration kinetics by retaining and gradually releasing water, thereby promoting a denser matrix, slightly increasing the temperature through partial adsorption of the mixture water, generating greater friction and localised heat release. However, this thermal increase does not negatively affect early strength, but rather favourably accompanies the development of strength, always within a thermally suitable range for cement hydration. In panel b) for 14 days, the previously observed trend is reinforced with greater clarity ($R^2=0.92$). The optimal addition range (2%-2.5%) provides a significant maximum strength of approximately 246.32 and 259.574 kg/cm², demonstrating the ability of activated carbon to substantially improve

intermediate strength. In this optimal range, the temperature reaches values of 15.8°C (2.5% addition), which is thermally favourable and allows for effective cement hydration. It is important to mention that, when exceeding the optimum limit (3% addition), a slight decrease in strength is observed, suggesting a critical point of saturation of the activated carbon, generating possible limitations in the complete hydration of the cement due to excessive water retention.

Finally, in panel c), which represents strength at 28 days, the greatest statistical robustness is observed (R²=0.94). The maximum strength value (332.05 and 353.41 kg/cm²) occurs again in the optimal range of 2%-2.5% addition, corroborating the long-term effectiveness of activated carbon. The recorded temperature reaches up to 15.8°C (2.5% addition) at these addition levels, which is acceptable and does not pose a

significant thermal risk in terms of setting or damage to the final properties of the concrete. This finding highlights that, although the temperature increase is constant and correlated with the addition, it does not represent a structural threat; on the contrary, it favourably accompanies resistance at advanced ages. This relationship confirms a clearly defined and statistically validated range (2%–2.5% activated carbon) that provides significantly improved mechanical strength without significant adverse effects from the slight increase in temperature in the mixture. These results suggest that the positive interaction between controlled temperature and moderate addition of activated carbon is a recommended practice from a technical point of view, ensuring the proper development of strength and optimisation of the mechanical properties of concrete.
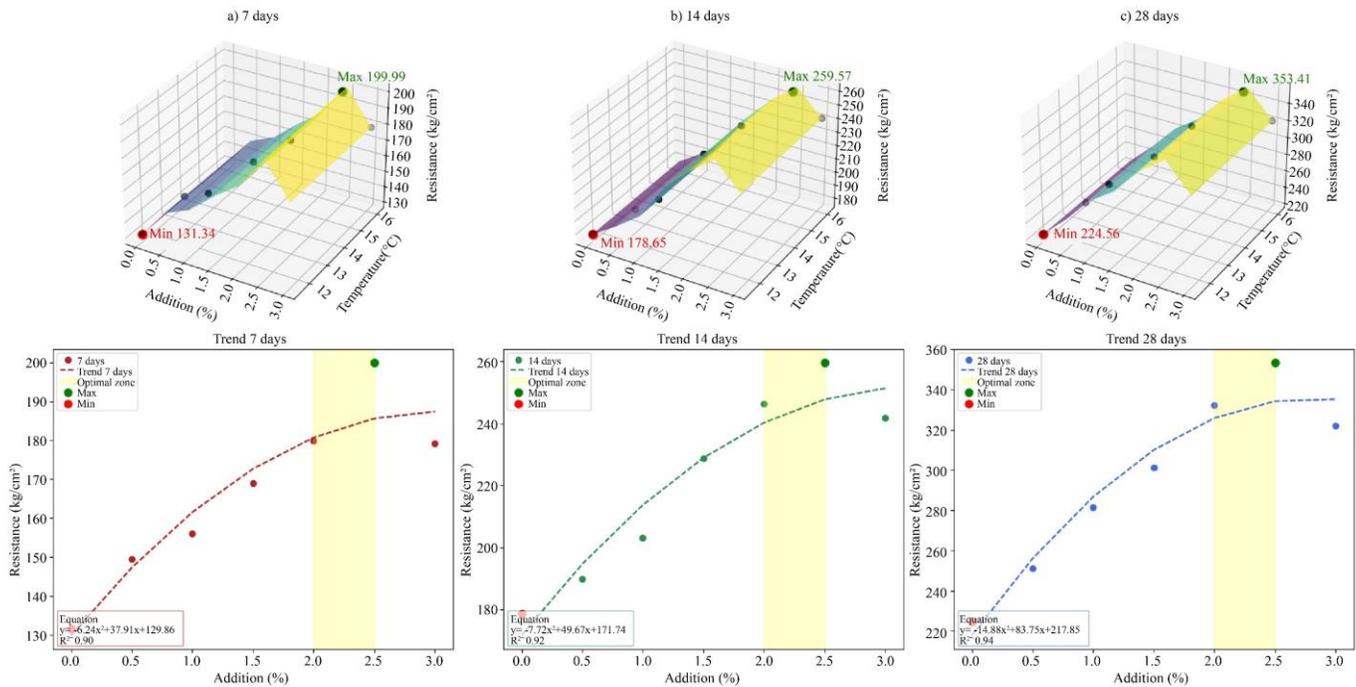

Fig. 7 3D surface graph of temperature vs. Compressive strength of concrete

4.3. Compressive Strength

Figure 8 shows the compressive behavior of concrete at 7, 14, and 28 days of curing, analyzed as a function of the proportion of activated carbon incorporated.

At 7 days (blue curve), strength increased progressively from a baseline of 131.34 kg/cm² (control mix) to a peak of 199.99 kg/cm² with 2.5% addition, equivalent to a 52% improvement over the reference specimen. This initial enhancement indicates that the incorporation of activated carbon favours early densification of the matrix, improving compaction and promoting the development of a stronger structure, probably due to the effect of filling fine pores or reducing permeability, thus improving early strength, a key

aspect in rapid commissioning applications. For the 14-day curve (orange curve), the concrete continues to show considerable improvements in strength, starting at 178.65 kg/cm² without addition and reaching a maximum value of 259.57 kg/cm² at an addition of 2.5%. The relative increase observed at this age is 45%, which reinforces the hypothesis that the optimal addition of activated carbon improves initial strength and promotes consolidation and the development of intermediate strengths due to a potential pozzolanic or nucleation effect generated by the particles in the addition. Finally, at 28 days (green curve), the absolute maximum compressive strength value (353.41 kg/cm²) is obtained, also with a 2.5% addition, contrasting significantly with the initial value without addition (224.56 kg/cm²), which represents a net

increase of 57%. This result is critical from a structural design perspective, clearly indicating the benefit of using activated carbon in proportions close to 2.5%. Furthermore, it is observed that higher percentages (such as 3.0%) generate a slight decrease in strength (321.98 kg/cm²), suggesting the

existence of a critical threshold in the dosage of the addition, beyond which the mixture could present saturation or localised segregation of the material, causing adverse effects on the cement matrix.
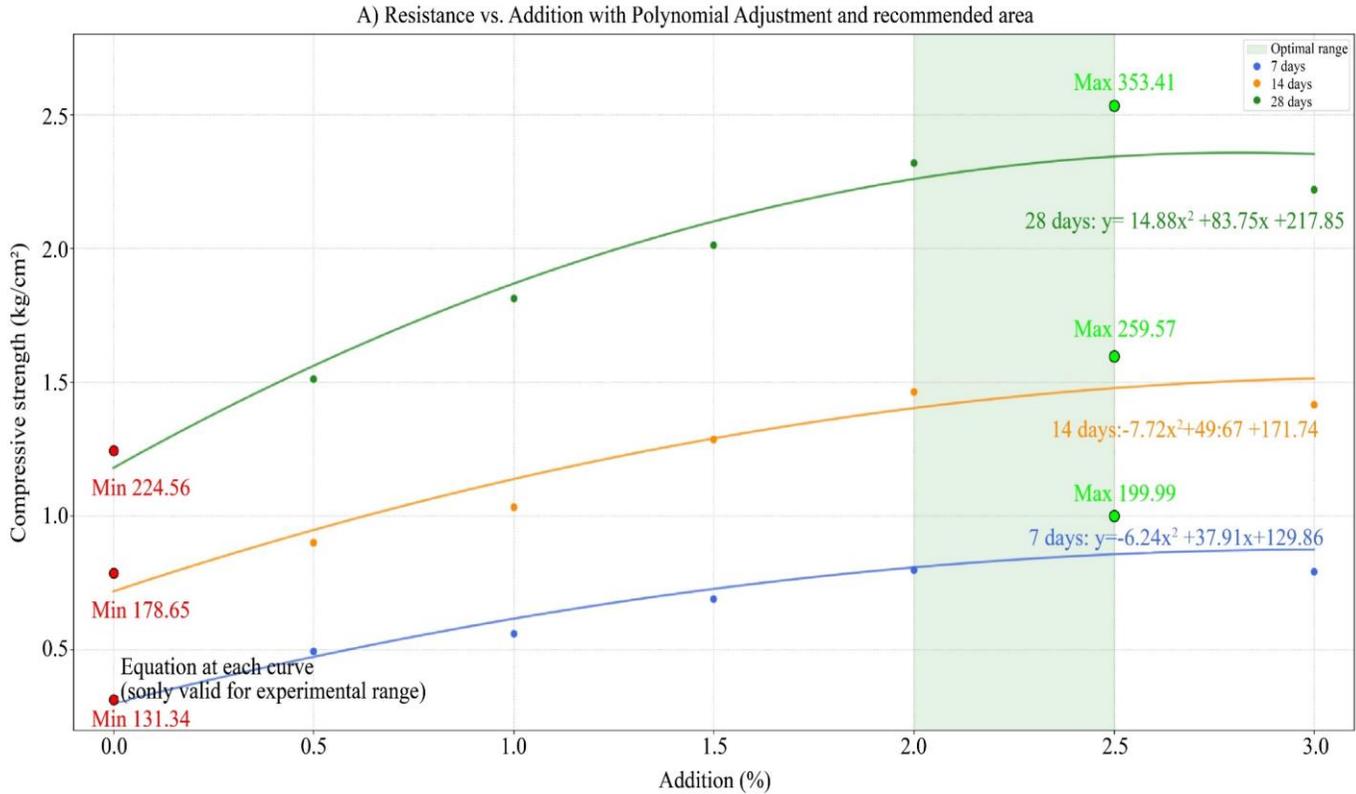

Fig. 8 Effect of adding activated carbon on compressive strength

4.4. CBR

Figure 9 shows the effect of Activated Carbon (AC) incorporation on the geomechanical and compaction properties of the soil. Panel A depicts the relationship between moisture content and maximum dry density obtained through the Modified Proctor test, distinguishing each result according to the proportion of activated carbon added. The analysis shows that as the additive content increases up to approximately 2%, the maximum dry density also rises, reaching a peak of 1.86 g/cm³ at a moisture content of 16.6%, considered the optimal condition. However, when the addition exceeds 2%, the results show a downward trend, indicating that excessive dosing of the addition limits the soil's compactability, an effect that is highlighted by the use of a different colour in the graph.

Panel B presents a surface graph analysing the behaviour of the CBR as a function of the addition of activated carbon and the degree of compaction (95% and 100%). It is evident that CBR resistance improves progressively with increasing addition percentage, reaching maximums of 12.7% (95% compaction) and 19.1% (100% compaction) at around 2.5%

addition. However, when this optimal range is exceeded, the strength decreases, which coincides with what is observed in the maximum dry density. It is also noteworthy that 100% compaction generates higher CBR values across the entire addition range, underscoring the importance of achieving adequate densification of the treated soil.

It should be noted that the increase in CBR observed at 2.5% activated carbon addition, despite the slight decrease in dry density and optimum moisture content, suggests that the improvement mechanism induced by the addition does not depend exclusively on maximum compaction. In this range, the action of activated carbon on the soil matrix enhances resistance to penetration through friction and internal cohesion mechanisms, compensating for the lower density. Thus, the CBR response results from the balance between compaction and the characteristics of the addition, highlighting the importance of considering both factors in the design. This behaviour is not unusual in treated soils, where the mechanical response may be more influenced by the soil-addition interaction than by the absolute density achieved.
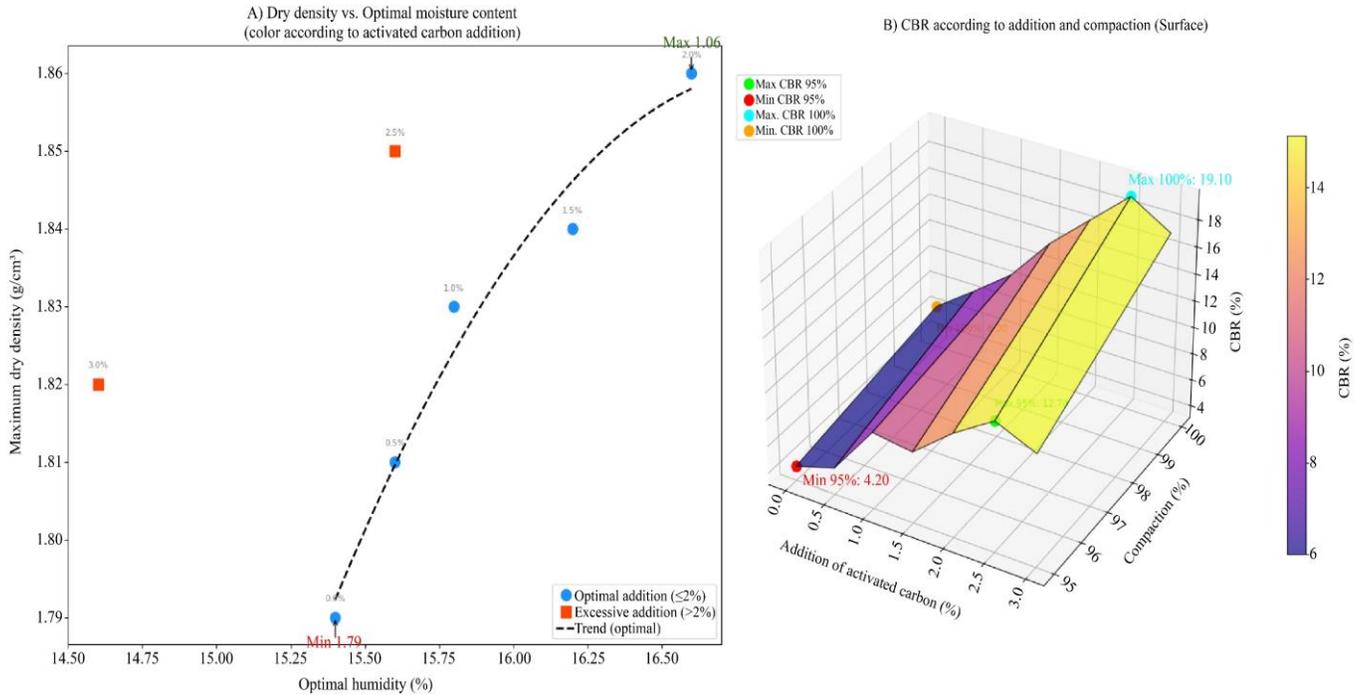
Fig. 9 Effect of adding activated carbon on the dry density, optimum moisture content, and CBR of compacted soils

4.5. Admissible Capacity

Figure 10 shows the evolution of the admissible capacity of clay soil as a function of the percentage of activated carbon added, representing the trend observed in the experimental data using a quadratic polynomial fit (R^2 = 0.892). Initially, untreated soil has a limited allowable capacity, quantified at 0.50 kg/cm², reflecting the low inherent strength of clay soils in their natural state. When small amounts of activated carbon are added (e.g., 0.50% and 1.00%), a gradual improvement in allowable capacity is observed to 0.70 kg/cm² and 1.10 kg/cm², respectively. This initial behaviour could be explained by the physical and chemical interaction between the fine soil particles and the porous structure of the activated carbon, which promotes a reduction in the free interstitial water content, favouring an increase in cohesion and mechanical stability.

The progressive incorporation of the addition generates more marked increases, reaching values above 2.00 kg/cm² for additions between 2.00% and 2.50%, with the latter percentage (2.50%) being the optimum point clearly identified in the graph, with a maximum allowable capacity of 2.50 kg/cm². This maximum value reflects a 400% improvement over the soil in its natural state, which represents a notable advance from a practical and technical perspective, enabling applications of the treated soil in more demanding structural and geotechnical situations.

However, the behaviour observed when this optimum threshold is exceeded is noteworthy, as an addition of 3.00% causes an abrupt reduction in the allowable capacity to 1.90

kg/cm². This decrease could be associated with a phenomenon of saturation or dispersion of the activated carbon, generating less dense internal structures or causing segregation or internal structural alteration processes that negatively affect the mechanical behaviour of the soil.

Consequently, from a technical and engineering design perspective, it is essential to control the percentage of activated carbon added strictly, with a dosage not exceeding the recommended optimal range (between 2.00% and 2.50%). This range provides maximum mechanical efficiency and ensures that the treatment provides significant benefits in terms of bearing capacity, structural stability, and reduced risk of differential settlement.

According to the research of Salehi et al. on soil stabilization with lime and cement, it was determined that by adding up to 5% lime, the CBR index and free compressive strength increased by 1.37 and 1.24 times, respectively, although cement generated greater improvements in CBR. These results agree with the findings of the present study, where a significant increase in CBR was observed when reaching 100%, with an increase of 154% when adding 9% lime, 334% when incorporating 15% cement, and 551% with a dosage of 6% calcium chloride. These data highlight the effectiveness of these stabilizers, especially cement, in improving the mechanical resistance of the soil and, therefore, its bearing capacity, which makes them a viable and efficient alternative for the construction of safer and more durable foundations.
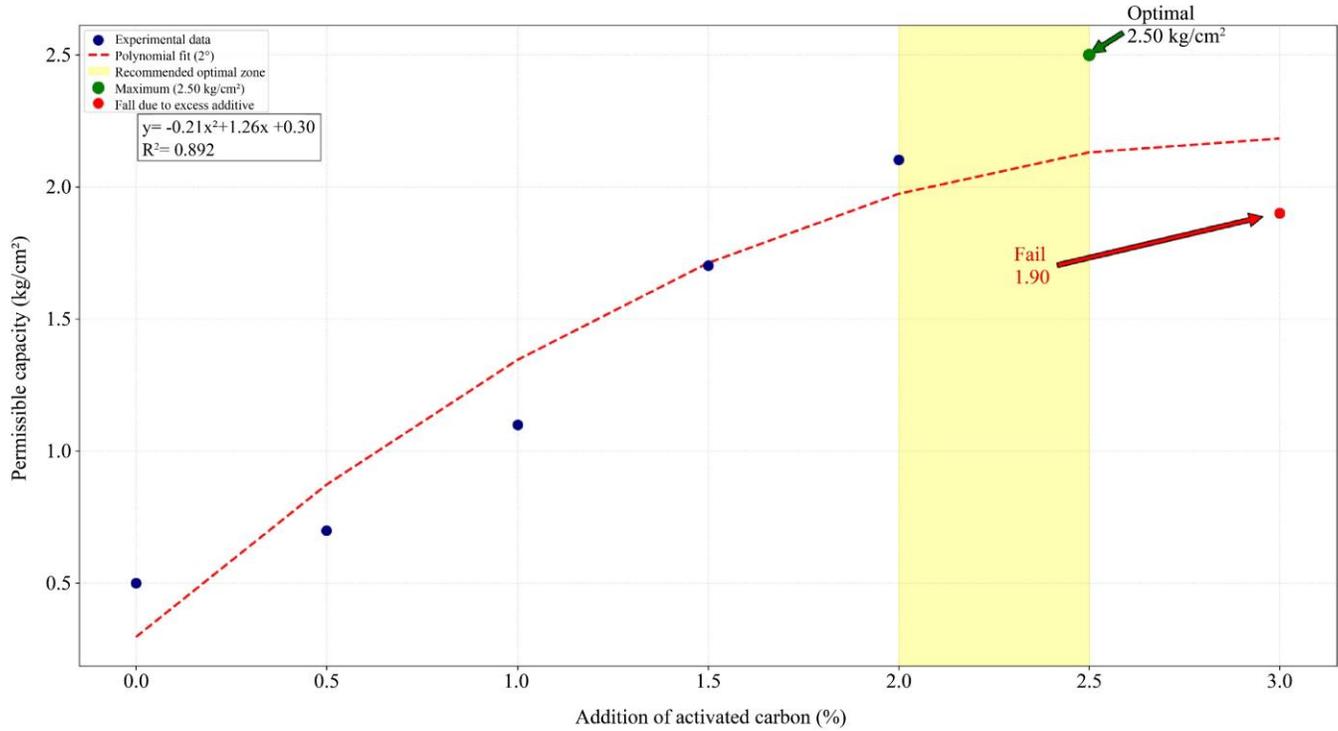
Fig. 10 Effect of adding activated carbon on the permissible capacity of the soil

5. Discussion

Hyun and Chan [18] observed that the incorporation of residual activated carbon enhanced the structural behavior of concrete, identifying 2% as the most efficient incorporation level. Similarly, Chu et al. [41] documented that activated carbon obtained from oil palm residues increased compressive strength from approximately 30 MPa to 50 MPa and improved splitting tensile resistance from 2 MPa to 3 MPa. In the present study, activated carbon from bean husks achieved comparable or even superior outcomes, showing a 48% improvement in compressive strength after 28 days when the addition ranged between 2% and 2.5%. This improvement can be explained by a synergy of mechanisms: (i) the porous and microporous structure of the additive refined the cement matrix, reducing microvoids [30, 31]; (ii) its chemical surface functionalities, such as carboxyl and phenolic groups, enhanced the nucleation of hydration products (C–S–H gels), improving compaction and bond strength [35]; and (iii) its adsorption capacity dispersed cement particles more effectively, promoting homogeneous hydration and early densification [33]. These combined effects explain why the increase observed exceeded those reported for conventional pozzolanic ashes such as rice husk or sugarcane bagasse [5, 12], and why it represents a state-of-the-art improvement.

The progressive addition of activated carbon also enhanced workability, as reflected in increased slump, a behaviour previously observed in concretes with coconut- and palm-based activated carbon [13, 41]. In the present case, the improvement is attributed to the filler effect and the water adsorption properties of bean-husk-derived activated carbon, which temporarily retained water in its pores and released it gradually during hydration. This "internal curing effect" favoured strength development, particularly at 14 and 28 days, while still maintaining adequate workability. However, when the dosage exceeded 2.5%, excessive porosity was introduced, generating a decrease in strength, which agrees with the threshold behaviour reported in other biomasses [16, 19].

In soils, Sakina et al. [14] demonstrated that coconut-activated carbon improved shear strength in weak lateritic soils, increasing values from 49.77 kPa to 121.8 kPa. The present research confirmed and extended this finding, since a 320% increase in allowable bearing capacity was recorded with a 2% addition of bean-husk-derived activated carbon. The improvement was attributed to two complementary mechanisms: a packing effect that reduced voids and improved density, and enhanced particle-to-particle bonding resulting from the chemical interaction of the additive with clay minerals, similar to the effect observed when lime or cement is used as a stabiliser. However, unlike cement, which requires high energy input (372 kJ/kg) and contributes to 8% of global CO_2 emissions [5, 6], the production of activated carbon from organic residues consumes only about 12 kJ/kg [14], highlighting its superior sustainability.

When compared with other biomass ashes, such as bamboo leaf, corn cob, or date palm, which contribute primarily SiO_2, CaO, or Al_2O_3 to improve pozzolanic reactivity [28], bean husks offer a distinctive advantage. In

addition to their carbon-rich matrix, they contain proteins and nitrogenous compounds [23, 24] that favour surface basicity and cation exchange, enhancing chemical affinity with Ca^{2+} ions. This particularity explains why the compressive strength in concrete and CBR values in soils improved more significantly than in other studies based on rice husk [5], palm [13], or coconut [14]. Taken together, the results demonstrate that bean-husk-derived activated carbon not only equals but in many cases surpasses the performance of other agro-industrial residues and traditional stabilisers. Its novelty lies in being an abundant and underutilised waste in Peru (60 tons/day [9]) with a dual benefit: improving the performance of cementitious and geotechnical materials while reducing environmental impacts associated with waste disposal and cement consumption. Unlike existing state-of-the-art approaches, this research introduces a waste stream that has never been valorised in civil engineering applications and scientifically explains the physicochemical mechanisms underlying its superior behaviour.

6. Conclusion

In conclusion, the progressive addition of activated carbon significantly increased the slump of the concrete, improving its workability. The increase in slump, from 3 ½" in the mixture without addition to 7" with 3%, indicates a reduction in the internal cohesion of the mixture, facilitating its placement on site. This behaviour is advantageous for elements where high fluidity is required, such as complex formwork or difficult-to-access pours. However, caution is recommended in vertical or thin elements, where an overly fluid mixture could cause segregation. The range of slumps obtained is within acceptable limits, so the addition of up to 2.5% activated carbon can be considered favourable from an operational and quality standpoint.

In relation to temperature, the increase observed with higher doses of activated carbon from 11.5 °C to 16.1 °C reflects greater internal friction during mixing, resulting from water adsorption by the porous structure of the additive. This slight temperature increase did not negatively affect cement hydration, as it remained within a safe temperature range. In cold-weather applications, this property could favour setting and reducing waiting time; however, monitoring the temperature to avoid possible accelerated setting effects is recommended in warm areas. The thermal behaviour of concrete with activated carbon can be an advantage in certain environmental conditions, provided it is properly controlled on site. On the other hand, compressive strength showed a notable increase with the addition of up to 2.50% activated carbon, achieving a 48% improvement at 28 days compared to concrete without addition. This suggests that activated carbon promotes compaction and optimises the microstructure of concrete, possibly due to its adsorption capacity and filling effect. However, higher percentages reduced this strength, indicating a saturation point that affects the integrity of the material. Thus, the optimal dosage (2.50%) appears to be the most suitable for structural elements requiring high mechanical strength, such as slabs or columns, avoiding excesses compromising quality. These results highlight the potential of activated carbon as an efficient additive, without the need to increase the proportion of cement.

As for the CBR, it increased proportionally with the incorporation of activated carbon up to 2.50%, reaching maximum values of 17.10 and 19.10, reflecting an improvement in the shear strength of the treated soil. This reinforcement can be attributed to pore filling and improved compaction induced by the addition. Above this dosage, the CBR showed a slight decrease, indicating a limit to the mechanical benefit. Thus, the use of 2.50% activated carbon is ideal for improving soils with low bearing capacity, such as bases or sub-bases, increasing their strength and structural stability. Excessive amounts could cause adverse effects, such as loss of cohesion or excessive stiffness, which are not conducive to soil-structure interaction.

The allowable capacity of the clay soil increased fivefold with the addition of 2.00% activated carbon, rising from 0.5 kg/cm² to 2.5 kg/cm², demonstrating a significant improvement in its ability to withstand vertical loads. This behaviour is explained by the stabilising effect of the addition, which reduces plasticity and improves compaction. However, higher percentages caused a decrease, suggesting that excessive addition can lead to excessive rigidity or destabilisation of the soil structure. In this context, the 2.50% dosage is the most efficient for soils with low bearing capacity, allowing them to support higher loads without excessive settlement. Its application is recommended in shallow foundations or embankments, where soil improvement is required without resorting to more expensive techniques.

One of the limitations of the study is that the dosage was kept constant, with a water/cement ratio of 200 l/m³, for experimental purposes. Although this ratio could be optimised in practice, doing so would involve introducing additional variables that were not part of the scope of this research. Furthermore, the study was conducted exclusively at the laboratory level, using test tubes and controlled samples, without considering the actual behaviour of the concrete or the treated soil under construction conditions or in response to environmental cycles such as humidity, temperature variations or freezing and thawing processes. On the other hand, only bean husks were used as raw material and potassium hydroxide (KOH) was applied as the sole activating agent, without comparing the effect of other biomasses or alternative activators that could modify the microstructure and properties of the activated carbon. Furthermore, thermal activation was carried out at a fixed temperature of 800 °C, without evaluating other temperatures that could influence the development of porosity and the chemical functionality of the material obtained. Future research should focus on the long-

term durability of concrete with activated carbon, particularly under aggressive environments such as sulphates and chlorides. It is also recommended that other biomass precursors and activating agents be evaluated to analyse their influence on microstructure, reactivity, and mechanical performance. Likewise, the effect of activation parameters such as temperature and time on pore formation should be

investigated, as these factors govern the modulus of elasticity, shear strength, and durability of concrete and soils. Large-scale validation and the incorporation of complementary additives or fibres are also required to confirm the technical feasibility and multifunctional potential of activated carbon in civil engineering applications.

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