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Development of Eco-Friendly Concrete: Research on the Use of Coffee Husk Ash as a Sustainable Alternative

Bolívar Hernán Maza[1], Danny Vega Hidalgo[2], Dolores Maza Vivanco[3]
[1]Universidad Técnica Particular de Loja
San Cayetano Alto, Loja, Ecuador
bhmaza@utpl.edu.ec ; dgvega3@utpl.edu.ec
[3]Escuela Superior Politécnica Agropecuaria de Manabí
Calceta, Manabí, Ecuador
dvmaza@espam.edu.ec

Abstract **-** The production of Ordinary Portland Cement (OPC) used in construction results in CO_2 emissions. An alternative to produce eco-friendly concrete is to partially incorporate Coffee Husk Ash (CHA) instead of OPC and add Banana Stem Sap (BSS). The effect of CHA and BSS inclusion on the mechanical properties and CO_2 emissions of concrete was analyzed. Three research scenarios were designed with partial substitution/addition percentages: 2%, 4%, 6%, 8%, and 10%. The first scenario involves partially replacing OPC with CHA (ACHA), the second involves adding BSS (ABSS), and the third involves the combination of ACHA and ABSS (SAA). Reduction in settlement was observed in the mixtures with ACHA, while it increased in ABSS and SAA. Compressive strength increased in all three scenarios, with the optimal percentage being 4% for ACHA and ABSS, and 6% for SAA. CO_2 emissions decreased when replacing OPC with CHA. The new concrete is presented as an option to mitigate CO_2 emissions in construction. Use technical civil engineering terminology.

Keywords**:** Eco-friendly concrete, Coffee husk ash, Banana stem sap.

1. Introduction

Today's society faces a problem of high CO_2 emissions into the atmosphere [3]. The Ordinary Portland Cement (OPC) industry emits CO_2, making it one of the largest pollutants in our world [6].The production of one ton of OPC means emitting 0.73 - 0.85 tons of CO2 [27]. In 2019, 90% of countries produced 4.1 Gt of OPC [13]. Ecuador is the country with the highest OPC production in Latin America, producing 6.27 million metric tons in 2019.

The use of OPC concrete increases the demand for this material, resulting in more CO_2 pollution [26]. Partial substitution of OPC with sustainable materials up to 30% demonstrates new concretes that meet national and international requirements [14]. Innovating new sustainable materials in concrete mixtures leads to new eco-friendly concrete [5]. Agricultural solid waste constitutes a significant portion of total waste in our society [24]. Coffee production involves generating over 2000 million tons of coffee husk waste annually [9]. Coffee husk ash (CHA) contains pozzolanic activity in the form of silica that can be used for partial substitution of OPC [7]. Similarly, one hectare of banana cultivation produces 220 tons of waste per year [25]. Banana sap, also known as wique (BSS), can be used as an additive to improve cementitious material compositions [8]. The question arises: How can CO_2 emissions be mitigated in the OPC concrete industry?

We are seeking a concrete mixture that reduces the use of OPC to decrease CO_2 emissions. This research proposes the partial substitution of 2%, 4%, 6%, 8%, and 10% of OPC with CHA and BSS added in the same percentages based on the amount of cementitious material. Mechanical properties, chemical composition of CHA, and CO_2 emissions per m3 of the new concrete are analyzed. The results are subjected to statistical analysis to determine the optimal substitution mixture. The use of CHA and BSS in concrete mixtures is an attractive technique for producing eco-friendly concrete, as these materials exhibit cementitious and adhesive properties. This research aims to innovate a new sustainable concrete in the Anthropocene era with high structural responsiveness.

2. Materials and Methods

2.1. Precursor Materials

The determined values of the material characterization are described in Table 1. Potable water was used for curing and mixing the concrete

Table 1: Physical Properties of Aggregates.

Parameter	Fine	Coarse	Standard Used	
			Fine	Coarse
Bulk Unit Weight, kg/m³	1641.51	1376.04	NTE INEN 858 (INEN, 2010c)	NTE INEN 858 (INEN, 2010c)
Compacted Unit Weight, kg/m³	1823.06	1499.79	NTE INEN 858 (INEN, 2010c)	NTE INEN 858 (INEN, 2010c)
Specific Gravity, kg/m³	2512.50	2664.86	NTE INEN 856 (INEN, 2010a)	NTE INEN 857 (INEN, 2010b),
Fineness Modulu	3.00		NTE INEN 696 (INEN, 2011a)	NTE INEN 696 (INEN, 2011a)
Maximum Nominal Size	-	0.75	NTE INEN 696 (INEN, 2011a)	NTE INEN 696 (INEN, 2011a)
Absorption Percentage	1.64 %	0.76 %	NTE INEN 856 (INEN, 2010a)	NTE INEN 857 (INEN, 2010b),
Moisture Content	3.00 %	0.10 %	NTE INEN 862 (INEN, 2011b)	NTE INEN 862 (INEN, 2011b)

- Ethics in the construction industry are a significant resource in the selection and management of aggregate materials, ensuring high standards of quality.
- The quality of aggregates is directly linked to the outcomes of concrete design
- The water-to-cement ratio (w/c) can be easily modified by varying the values in Table 1, affecting the desired quality of concrete.

2.2. Coffee Husk Ash (CHA)

The procedure described by [5] was followed, which initially involves sun-drying the sample to remove surface moisture (Figure 1(a)). The sample was then oven-dried at 600°C for 4 hours to obtain Coffee Husk Ash (CHA) with a dark gray color. It is crucial to maintain the temperature between 500°C to 600°C, as exceeding this limit results in white ash with inactive crystalline silica [12]. The resulting material was ground using a ball mill and sieved using the No. 200 sieve (see Figure 1)

Fig. 1: Cáscara de café seca al sol y ceniza de cascara de café

2.3. Banana Stem Sap (BSS)

Given the lack of relevant research on the incorporation of banana stem sap in concrete, a method was designed to obtain it. The entire banana stem was cut, divided into parts to facilitate handling. Subsequently, the parts were manually squeezed to obtain the necessary amount of sap. The sap undergoes a sieving process to remove impurities.

2.4. Concrete Mix

The concrete mix for $(f_c' = 26\ MPa)$ was directed with ACI using characterized results of the aggregates. It was proposed to substitute 2%, 4%, 6%, 8%, and 10% of OPC with CHA based on the results of [5]. Following the same substitution percentages with CHA, Banana Stem Sap (BSS) was added to increase strength without significantly affecting the water/cement ratio. Three research scenarios were conducted: banana stem sap analysis (ABSS), coffee husk ash analysis (ACHA), and dual analysis with both materials (SAA). Three cylindrical specimens of 10 cm x 20 cm were fabricated for each curing period, totaling nine specimens for each level of the variable [15]. These proportions determined the necessary concrete mixes for the different research scenarios (Table 2).

Table 2: Concrete Mix Proportions for Research Scenarios

Mix	Cement (kg)	Gravel (kg)	Sand (kg)	Water (L)	BSS (L)	CHA (kg)
Pattern	8.71	17.78	15.18	4.05	0	0
ACHA 2%	8.54	17.78	15.18	4.05	0	0.17
ACHA 4%	8.36	17.78	15.18	4.05	0	0.35
ACHA 6%	8.19	17.78	15.18	4.05	0	0.52
ACHA 8%	8.01	17.78	15.18	4.05	0	0.70
ACHA 10%	7.84	17.78	15.18	4.05	0	0.87
ABSS 2%	8.71	17.78	15.18	4.05	0.17	0.00
ABSS 4%	8.71	17.78	15.18	4.05	0.35	0.00
ABSS 6%	8.71	17.78	15.18	4.05	0.52	0.00
ABSS 8%	8.71	17.78	15.18	4.05	0.70	0.00
ABSS 10%	8.71	17.78	15.18	4.05	0.87	0.00
SAA 2%	8.54	17.78	15.18	4.05	0.17	0.17
SAA 4%	8.36	17.78	15.18	4.05	0.35	0.35
SAA 6%	8.19	17.78	15.18	4.05	0.52	0.52
SAA 8%	8.01	17.78	15.18	4.05	0.70	0.70
SAA 10%	7.84	17.78	15.18	4.05	0.87	0.87

2.5. Compressive strength

The simple compression variable of both standard concrete and experimental mixtures was evaluated following standard NTE INEN 1573, using the Shimadzu Concrete 2000x equipment. Testing was conducted at curing ages of 7, 21, and 28 days, and substitution levels (2%, 4%, 6%, 8%, and 10%) of OPC with CHA were based on the findings of [5]. Banana Stem Sap (BSS) was added to increase strength without significantly affecting the water/cement ratio. Axial compression load was applied to cylindrical specimens at a rate of 0.25 ± 0.05 MPa/s [16].

2.6. Estimation of CO_2 emissions

The methodology of [3] was used to calculate CO_2 emissions per cubic meter of concrete. Equations are proposed that consider specific coefficients for traditional concrete, detailed in Table 3, and for the new concrete, taking into account CO_2 emissions during material processing.

Table 3: Factores de emisión de materiales

Material	**Emission factor (kg CO_2/kg)**
Cement	0.83
Coarse aggregates	0.0062
Fine aggregates	0.005
Water	0.000196

Nota. Adapted of "Effect of incorporation of cane bagasse ash on mechanical properties and carbon dioxide emissions of concrete containing waste glass" (p.5), por Arbeláez Pérez et al., 2019, *Boletín de la Sociedad española de cerámica y vidrio*, *62(3).*

The Equation 1 is used for emissions from traditional concrete:

$$CO_{2-e} = \sum_{i-1}^{n} Qi * Fim \tag{1}$$

- CO_{2-e} = CO_2 pollution generated by concrete, $kgCO_2/m^3$.
- Qi =Amount of material used , kg/m^3.
- F_{im} = Material emission factor, $kgCO_2/kg$.

The Equation 2 is used for emissions from the new concrete:

$$CO_{2-e} = \sum_{i-1}^{n} P * t * 0.29kgCO_2/kWh \tag{2}$$

- CO_{2-e} CO_2 pollution generated by concrete, $kgCO_2/m^3$.
- P = Equipment power, kW.
- t = Equipment usage time, h/m

3. Results and Discussion

3.1. Chemical composition

The results of the chemical composition of CHA are shown in Figure 2. Here, the four predominant elements in Coffee Husk Ash (CHA) are CaO, SiO2, Al2O3, and K2O, with CaO being the highest at 12.19% and SiO2 at 10.6%. The values of SiO2 and CaO in CHA are comparable to the results of [12] (17.1% SiO2, 10.07% CaO) and [29] (14.65% SiO2, 13.05% CaO). The sum of SiO2, Al2O3, and Fe2O3 is 18.23%, which is below 50%, excluding the consideration of CHA as type N pozzolan or type F or C fly ash [2] The high alkaline content (K2O = 7.44%) suggests a potential for alkali-silica reaction, which can reduce concrete strength by decreasing connections between paste and inert materials [10]; [12] Therefore, instead of using CHA as a pozzolanic material, it would be more appropriate to consider it as a cementitious material due to the presence of SiO2, Al2O3, and CaO [12].

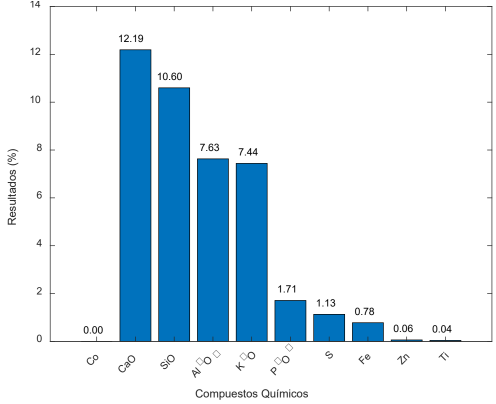

Fig. 2: Chemical composition of CHA

- The appropriate ratio between limestone, aluminum silicate, silicon oxide, and iron oxide is a significant factor in achieving excellent properties of the cementitious material.
- The chemical composition of the cementitious material determines its quality and performance for various applications.
- Adding blast furnace slag, fly ash, or activated silica serves as options to improve certain properties of the cementitious material.
- The appropriate proportion of elements ensures that the cementitious material meets performance and durability standards for construction.

Figure 3 shows changes when the percentage of partial substitution and addition varies. In the case of ACHA, it is noted that the workability of the concrete decreases with a higher percentage of partial substitution, coinciding with previous studies that report a reduction in the slump with more presence of CHA [5], [10];[12]; [29]. Concrete with CHA requires more water due to the absorbent nature and high fineness of CHA's cellular particles [29]. In ABSS, the slump increases significantly when adding BSS, due to the high water content in the composition of BSS [28] Finally, in SAA, there is an increase in slump, although less than in ABSS, since SAA uses both CHA and BSS. The absorption capacity of CHA particles influences the water absorption of the BSS composition, resulting in a moderate increase in slump.

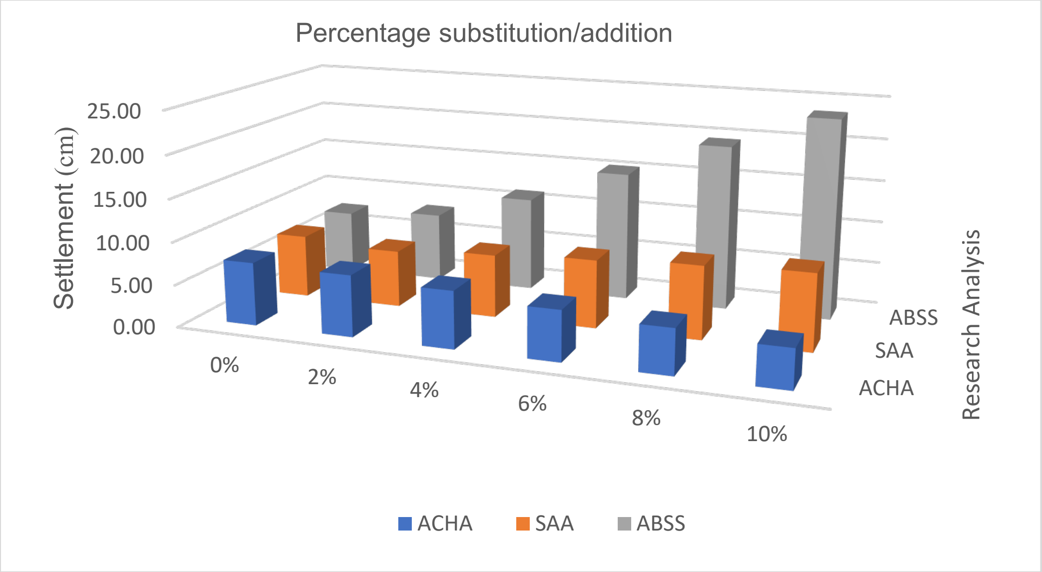

Fig. 3:Slump for research mixtures

- The higher the slump value, the more capacity the concrete has to accommodate under its own weight, directly influencing the quality of the concrete.
- Adequate slump promotes the homogeneity of the concrete mixture, ensuring the correct distribution of materials and high-quality concrete.
- High slump values cause segregation of particles and lower quality concrete.

3.3. Compressive strength

Figure 4 presents the behavior of ABSS concrete mixtures at different ages. It is observed that the increase in curing age is directly related to an increase in the compressive strength of the concrete. There is a significant increase in strength when adding BSS up to 4%, reaching an average compressive strength of 29.38 MPa at 28 days. Comparing with the average strength of the standard at 28 days (26.85 MPa), it is attributed that the addition of 4% BSS results in a 9% increase in strength. However, from 4% addition onwards, the compressive strength begins to decrease due to the high water content in the BSS, which significantly alters the water/cement ratio.

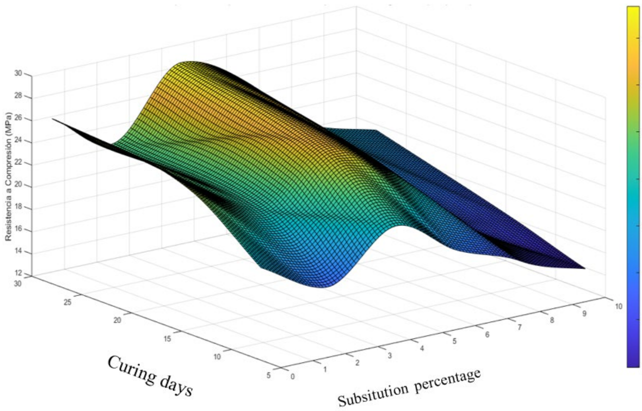

Fig. 4: Compressive strength of ABSS for different curing ages.

- The 2% addition is not sufficient to achieve an increase in strength compared to 4% and 0% addition
- Implementing BSS at 4% improves workability and compressive strength, resulting in higher-quality concrete that eliminates the need for superplasticizer additives.
- The high water content in BSS would achieve better concrete quality by partially substituting water with BSS, and the water/cement ratio would remain stable.

Figure 5 exhibits the compressive strength in response surface for different ages for ACHA, showing an increase by partially substituting OPC with CHA up to 4%, with an average compressive strength of 28.99 MPa at 28 days. This result is consistent with the study by [5], which reports an increase in compressive strength when partially substituting 5% of OPC. Comparing with the average strength of the standard at 28 days of curing (26.85 MPa), there is an 8% increase by partially substituting OPC with CHA at 4%. The increase in CHA reduces the amount of cement in the mixture, resulting in a decrease in cement hydration reactions. However, the use of high percentages of CHA requires more water, which limits the availability of water for cement hydration [10]

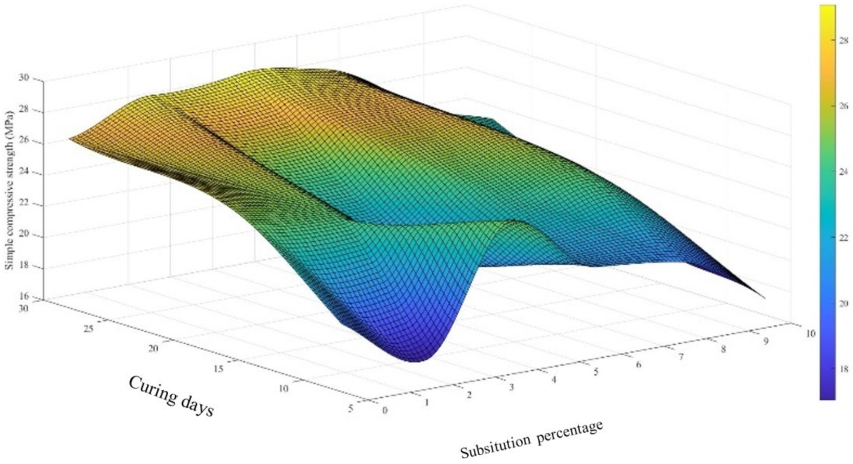

Fig. 5: Compressive strength of ACHA for different curing ages

- The inclusion of CHA results in variations in strengths at 7 and 14 days of curing, but the quality of the concrete improves upon reaching 28 days of curing.
- The range of 4% - 6% partial substitution shows the optimum point for sustainable construction.
- Partial substitution of OPC with CHA at 4% improves compressive strength, resulting in high-quality concrete that contributes to sustainable construction
- The use of CHA in construction opens doors for recycling agricultural waste, avoiding dumping.

The results of the simple compression tests for SAA indicate a trend of increasing strength with curing time (Figure 6). There is a notable increase in strength with 6% substitution/addition, reaching an average compressive strength of 26.98 MPa. Comparing with the average strength of the standard (26.85 MPa), there is a 0.5% increase when applying 6% substitution/addition. However, there is a significant decrease from 6%, as the partial substitution of OPC with CHA reduces the amount of cement in the mixture, and the addition of BSS affects the water/cement ratio.

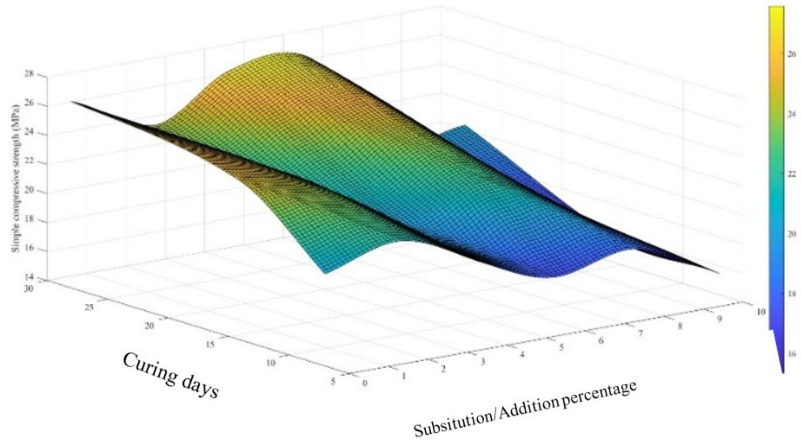

Fig. 6: Compressive strength of SAA for different curing ages

- The increase in curing time shows a linear relationship with an increase in compressive strength.
- SAA improves compressive strength, slump, and reduces the need for OPC, resulting in sustainable and efficient concrete.

3.4. Estimation of CO_2 emissions

The CO_2 emissions are shown in the table 4 for using a kiln of 1.92 kW and a mill of 0.75 kW for 4 hours.

Table 4: CO_2 Emissions for 1m3 of Concrete

Mixture	Cement (kg)	Gravel	Sand	Water	BSS	CHA	CO_2 (kg CO_2/m^3)
Standard	439.91	900.80	768.60	200.46	0	0	374.59
ACHA 2%	431.11	900.80	768.60	200.46	0	8.80	370.39
ACHA 4%	422.31	900.80	768.60	200.46	0	17.60	363.08
ACHA 6%	413.52	900.80	768.60	200.46	0	26.39	355.79
ACHA 8%	404.72	900.80	768.60	200.46	0	35.19	348.48
ACHA 10%	395.92	900.80	768.60	200.46	0	43.99	341.18
ABSS 2%	439.91	900.80	768.60	200.46	8.80	0.00	374.59
ABSS 4%	439.91	900.80	768.60	200.46	17.60	0.00	374.59
ABSS 6%	439.91	900.80	768.60	200.46	26.39	0.00	374.59
ABSS 8%	439.91	900.80	768.60	200.46	35.19	0.00	374.59

ABSS 10%	439.91	900.80	768.60	200.46	43.99	0.00	374.59
SAA 2%	431.11	900.80	768.60	200.46	8.80	8.80	370.39
SAA 4%	422.31	900.80	768.60	200.46	17.60	17.60	363.08
SAA 6%	413.52	900.80	768.60	200.46	26.39	26.39	355.79
SAA 8%	404.72	900.80	768.60	200.46	35.19	35.19	348.48
SAA 10%	395.92	900.80	768.60	200.46	43.99	43.99	341.18

It is reported that the standard mixture emits 374.59 kg of CO2 per cubic meter, with previous studies reporting similar results. CO_2 emissions are significantly reduced using materials (ACHA and SAA). Figure 7 shows reductions in CO2 emissions as substitution percentages are manipulated. This reduction is attributed to the substitution of cement with CHA.

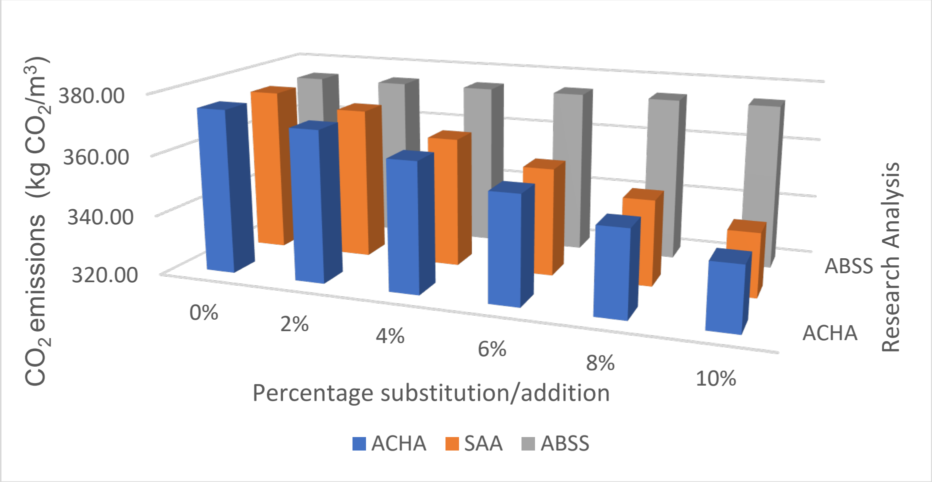

Fig. 7: Em CO_2 emissions

- The processing of cementitious materials increases CO2 emissions due to electrical usage
- Partial substitution of OPC in concrete mixes directly influences the mitigation of CO2 emissions.

4. Conclusion

In this research, the partial replacement of OPC by CHA (ACHA), the addition of BSS (ABSS), and the combined evaluation of these materials (SAA) were analyzed to reduce CO_2 emissions without sacrificing the quality of concrete. The chemical composition of CHA, the settlement, the compressive strength of the new concrete, and the emissions of CO_2 per m3 C were analyzed. The chemical composition of CHA revealed high contents of CaO, SiO2, Al2O3, and K2O, suggesting its classification as a cementitious material rather than a pozzolan. Loss of slump was observed when increasing the partial substitution in ACHA mixes, while ABSS experienced a significant increase when adding BSS. As for the compressive strength, ABSS showed an increase with an optimal 4% addition of BSS. ACHA mixes increased their strength by partially substituting OPC with CHA up to 4%. SAA showed an increase in strength up to 6% substitution/addition but decreased thereafter due to the reduction of cement and alteration of the water/cement ratio. The implementation of alternative materials reduced CO_2 emissions, with the partial substitution of OPC by CHA being the main contribution to the decrease. The use of coffee husk ash and banana sap in concrete is presented as a sustainable solution, reducing the environmental burden associated with construction. The finding of a new concrete implemented with alternative cementitious materials NC (CHA and BSS) reduces CO_2 emissions by 5% and increases compressive strength by 9%.

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