World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

Valorization of agricultural waste: Pozzolanic properties of cassava peel ash and effects on the durability of cementitious materials

Cyrille Tchuinte MOYOPO [1], Clautaire Mwebi EKENGOUE [1, 2], Kossi Bollanigni AMEY [2, 4, 5, *], Willy KENOU [3] and Alain Narcisse Sieyapdjie FEUMOE [1]

[1] *Department of Civil and Architectural Engineering, Faculty of Engineering and Technology (FET), University of Buea (UB), Buea, Cameroon.*
[2] *Division of Scientific Research and Innovations, African Scientific Association for Innovative and Entrepreneurship (ASAIE), Yaounde, Cameroon.*
[3] *Department of Civil Engineering, Institut Universitaire de la Cote (IUC), Douala, Cameroun.*
[4] *Laboratory of Structures and Mechanics of Materials (LaS2M), Polytechnic School of Lomé (EPL), University of Lomé-Togo.*
[5] *Research, Innovation and Development Structure (SRID), FORMATEC Institute, Lomé, Togo.*

World Journal of Advanced Research and Reviews, 2026, 29(01), 430-438

Publication history: Received on 28 November 2025; revised on 05 January 2026; accepted on 07 January 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.29.1.4304

Abstract

Ash from cassava peeling, a byproduct of its processing, is rich in pozzolanic properties, making it a promising material for improving concrete durability. This study evaluates the physical (workability), hygrometric (water absorption), and mechanical (compressive and flexural strength) properties of concretes in which cement is replaced by ash (0%, 5%, and 10%) to assess the performance of cementitious elements containing ash. The results indicate that incorporating up to 10% ash reduces the compressive and flexural strength of the concrete by approximately 11.67% and 11.36%, respectively. The concrete also becomes 20.58% more porous, with a 41.18% reduction in its consistency (slump). Strength, water absorption, and slump follow a second-degree polynomial distribution as a function of ash content and concrete age. These results contribute to the development of environmentally friendly building materials suitable for structural elements where strength is less critical. However, these concretes are very useful for constructing drainage systems and for production methods requiring rapid demolding.

Keywords: Cassava peel ash; Pozzolanic properties; Cement replacement; Sustainable concrete; Mechanical properties

1. Introduction

Cement is one of the most widely used construction materials globally due to its durability, versatility, and relatively low cost [1]. However, the production of cement is associated with significant environmental challenges. According to the [2], cement production contributes approximately 8% of global carbon dioxide (CO_2) emissions, primarily due to the energy-intensive process of clinker production. This has caused researchers to explore alternative materials that can partially replace cement in cement-based elements, reducing its environmental effects while maintaining or improving its mechanical properties.

Agricultural waste materials, known as supplementary cementitious materials (SCMs), have emerged as a promising avenue for sustainable construction practices. SCMs such as fly ash, silica fume, and ground granulated blast furnace slag have been widely adopted in concrete production due to their pozzolanic properties, which enhance long-term

* Corresponding author: Kossi Bollanigni AMEY

strength and durability through reactions with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) gel [1]. However, the availability of these conventional SCMs is limited in certain regions, particularly in developing countries where industrial byproducts are scarce [3]. This has spurred interest in agricultural waste ashes, which are abundant, renewable, and locally available as alternative SCMs. Ashes derived from agricultural residues such as rice husk, sugarcane, and corn cob have shown promise in improving concrete properties while addressing waste management challenges (Thomas, 2018).

Cassava *(Manihot esculenta)* is one of the most widely cultivated crops in tropical and subtropical regions, particularly in Africa, Asia, and Latin America, with global production exceeding 300 million tons annually (FAO, 2020). Cassava processing generates significant quantities of waste, including cassava peels (CPs), which constitute approximately 10-20% of the tuber's weight [4] and are often discarded as waste [5] or burned openly, contributing to environmental pollution and greenhouse gas emissions [6]. Besides, some studies have shown that cassava peel ash (Ash), obtained by incinerating CPs, contains pozzolanic properties, silica and alumina compounds that can react with calcium hydroxide in cement to form additional binding materials. The pozzolanic potential of ash is attributed to its chemical composition, which typically includes 50-60% silica (SiO_2), 5-10% alumina (Al_2O_3), and minor amounts of iron oxide (Fe_2O_3), as determined by X-ray fluorescence (XRF) analysis [7]. These oxides are critical for pozzolanic reactions, enabling ash to contribute to the formation of secondary C-S-H gel, which improves the microstructure and durability of concrete [8]. The use of ash in concrete aligns with the principles of a circular economy, which emphasizes resource efficiency and waste minimization [9]. By repurposing cassava peels, which are abundant in African countries, the construction industry can reduce its dependence on raw materials and reduce the environmental impacts of waste disposal [10]. Moreover, ash offer economic benefits, as it is a low-cost material compared to usual SCMs, making it an attractive option for low-income regions where cement prices are a significant barrier to infrastructure development [11].

It is from these premises that comes our motivation to consider ash as SCMs in this study. The present study is a real innovation in the field of civil engineering. In fact, in the present study, instead of using ash as partial replacement of cement in concrete production as it has been used before, we used ash as partial replacement of cement in non-structural cement-based elements such as mortars, plaster, or precast panels, focusing on its potential as a supplementary cementitious material. Apart of reducing the total construction cost of buildings, the use of ash to substitute cement also permits to achieve environment efficient, environment friendly, and sustainable constructions, aligning with some specific objectives followed by various organizations involved in this project. At the African Scientific Association for Innovative and Entrepreneurship (ASAIE), the main purpose of the Central Africa Sustainable Cities Initiative (CASCI) program initiated by ASAIE organization with partners including *Laboratoire Energétique Carnot (LEC)*, Promotion Centre of Research for Technological Advancement and Sustainable Development (PCR-TASD) and *PROSOFOR AFRIQUE* is to fight against poverty and rural exodus and stimulate the local economy in Central Africa Region. The integration of ash in construction practices of the population not only from rural areas like Nsanke village and neighboring villages which has been selected as the first sustainable city of CASCI program, but also from urban areas may increase the construction rate and reduce CO_2 atmospheric emissions in Central Africa. By embracing such sustainable construction practices, the civil engineering industry can play a pivotal role in achieving global environmental goals and transitioning toward a circular economy which are one of the Millennium Development Goals (MDGs).

2. Materials and methods

Several batches of samples were prepared for each percentage of cement ash substitution (0%, 5%, and 10% by weight of cement). The preparation of the cement paste cubes consisted of mixing proportions of cement (Figure 1a) and ash (Figure 1b). The ash was obtained from well-dried and ground cassava peels (Figure 1c) with water to obtain a homogeneous paste.

The materials were weighed using a digital balance. The quantities of cement, ash, and water per sample are shown in Table 1. The dry materials (cement and ash) were mixed until a uniform color was obtained. Water was then gradually added to the mixture, with continuous stirring, to achieve the desired consistency. The water/cement ratio (0.4) was kept constant for all samples to ensure comparability.

(a) (b) (c)

Figure 1 Materials used in the preparation of cement paste cubes. (a) Cement; (b) Cassava peeling Ash; (c) Cassava peels

The resulting paste was poured into 40 x 40 x 160 mm molds, vibrated, and then cured for 24 hours. The molds were then removed, and the samples were cured for 7, 14, 21, and 28 days.

The different samples were subjected to compression and flexural strength tests using a compression testing machine (Figure 2a), in accordance with ASTM C39/C39M.

Table 1 Material contents in each sample

Sample	Cement (g)	CPA (g)	Water (g)
0%	475	0	190
5%	451	24	190
10%	427	48	190

Water absorption tests were performed in an oven (Figure 4d) to evaluate the porosity and permeability of the cured specimens, essential parameters for understanding the impact of ash on durability. The specimens were removed from the oven after 28 days and dried for 24 hours. Their dry mass was measured using a balance. They were then immersed in potable water for 48 hours, and their saturated mass was recorded after the surface was dried with a cloth. The percentage of water absorption (*Ta* in %) was calculated for each sample using equation (1)

$$Ta = \left(\frac{W_{sat} - W_{dry}}{W_{dry}}\right) \times 100 \qquad (1)$$

Which W_{sat} the saturated mass of the specimens and W_{dry} their dry mass.

(a) (b) (c)

(d) (e) (f)

Figure 2 Laboratory analysis of our samples. (a) Compressive strength machine; (b) Compressive strength test; (c) Flexural strength test; (d) Oven; (e) Slump cone; (f) Slump test

To assess the workability of the samples, a slump cone (Figure 2e) was used to perform a slump test (Figure 2f). The mixing process began by weighing the cement and ash using a digital balance. For the 5% and 10% ash mixtures, the cement and ash were mixed dry to ensure homogeneity; water was then added gradually while mixing until a homogeneous paste was obtained. The cone was filled and, after leveling the top of the cone with a trowel, it was lifted vertically, allowing the paste to settle for 30 seconds. The vertical difference between the height of the cone and the highest point of the slumped paste was measured using a ruler.

3. Results

Figure 3, illustrating average compressive strength values for 0%, 5%, and 10% ash over 7–28 curing days, shows a consistent strength increase across all mixes, with the 0% ash control rising from 28 MPa at 7 days to 44 MPa at 28 days, reflecting optimal cement hydration. The 5% ash mix increased from 25.5 MPa to 42.5 MPa, a 3.41% reduction from the control, while the 10% ash mix rose from 22 MPa to 39 MPa, an 11.36% reduction, indicating a pozzolanic contribution that diminishes at higher levels. Figure 4 visually confirms this trend, plotting the percentage reduction (-3.41% at 5% ash, -11.36% at 10% CPA), suggesting unreacted silica or matrix dilution beyond 5%. Depicting average flexural strength values (see Figure 5), shows the 0% ash control increasing from 4.2 MPa to 6 MPa, the 5% ash mix from 3.8 MPa to 5.8 MPa (3.33% below control), and the 10% ash mix from 3.3 MPa to 5.3 MPa (11.67% below), highlighting a slightly steeper relative decline due to bending stress differences. This observation is confirmed by Figure 6, which shows these reductions and demonstrates that the pozzolanic effect of ash is less effective under bending loads for higher substitution rates.

The behavior of compressive strength (R_{ct} in MPa) and flexural strength (R_{ft} in MPa) as a function of the age (j in days) of concrete for different ash contents (t in %) is illustrated by equations (2a) to (2c) and equations (3a) to (3c).

For compression resistance

$$R_{c0} = -0.0153j^2 + 1.2929j + 19.75 \qquad \text{with } R^2 = 0.9996 \qquad (2a)$$

$$R_{c5} = -0.0123j^2 + 1.2536j + 17.375 \qquad \text{with } R^2 = 0.9999 \qquad (2b)$$

$$R_{c0} = -0.0102j^2 + 1.1714j + 14.25 \qquad \text{with } R^2 = 0.9997 \qquad (2c)$$

For flexural resistance

$$R_{f0} = -0.002j^2 + 0.1571j + 3.2 \qquad \text{with } R^2 = 1 \qquad (3a)$$

$$R_{f5} = -0.002j^2 + 0.1657j + 2.75 \qquad \text{with } R^2 = 0.9991 \qquad (3b)$$

$$R_{f0} = -0.0015j^2 + 0.1493j + 2.325 \qquad \text{with } R^2 = 0.9998 \qquad (3c)$$

Figure 7, reveals a clear increase in porosity with ash content, with the 0% ash control at 5.83%, 5% CPA at 6.23% (a 6.86% increase), and 10% ash at 7.03% (a 20.58% increase), based on replicate averages (e.g., 5.8%, 6.0%, 5.7% for 0% ash). This trend suggests that ash's pozzolanic reaction partially densifies the matrix at 5% but becomes less effective at 10%, likely due to unreacted silica. This percentage increase (0%, 6.86%, 20.58%) (see Figure 8) highlights with 10% ash. This increase could result from increased interference between particles or reduced cement bonding capacity, as confirmed by the 11.36% drop in compressive strength, which reaches 39 MPa.

The influence of ash on the water absorption (T_a in %) of concrete as a function of the ash content (t in %) can be illustrated by equation (4).

$$T_a = 3.4305t^2 - 1.4305t \qquad \text{with } R^2 = 1 \qquad (4)$$

Figure 9 illustrates a decrease in maneuverability to 85 mm (average of measurements at 85 mm, 90 mm and 80 mm) for the control without Ash, to 70 mm (average of measurements at 70 mm, 75 mm and 65 mm, i.e. a reduction of 17.65%) for the control with 5% Ash and to 50 mm (average of measurements at 50 mm, 55 mm and 45 mm, i.e. a reduction of 41.18%) for the control with 10% Ash. This decrease, despite a constant water/cement ratio of 0.4, is probably due to increased water absorption or viscosity caused by the 0.075 mm fine particles of the ash. This reduction (0%, -17.65%, -41.18%) (see figure 10) highlights a non-linear loss of maneuverability, with 5% of ash remaining practical (70 mm) while 10% of ash (50 mm) suggest handling difficulties, in correlation with the 11.36% reduction in resistance at 39 MPa.

The smoothing curve of the evolution of slump (A in mm) on the Abrams cone as a function of the ash content (t in %) is given by equation (5).

$$A_r = -0.1t^2 - 2.5t + 85 \qquad \text{with } R^2 = 1 \qquad (5)$$

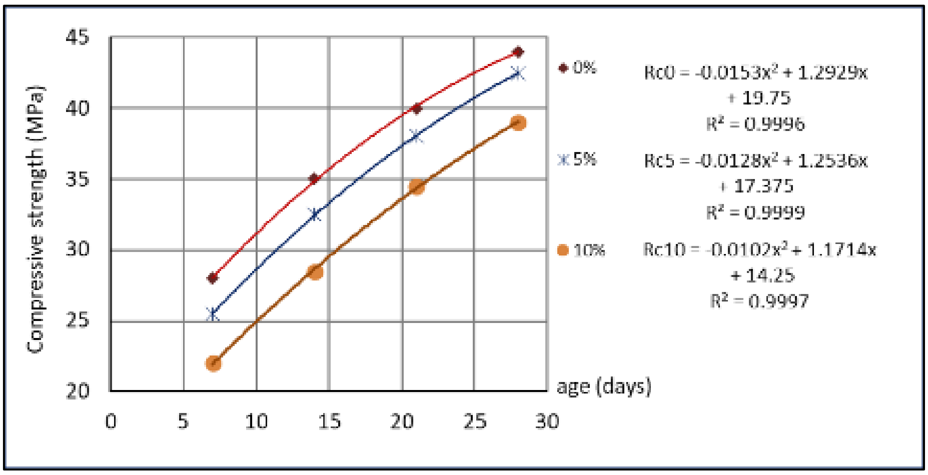

Figure 3 Evolution of compressive strength as a function of concrete age for different ash values.

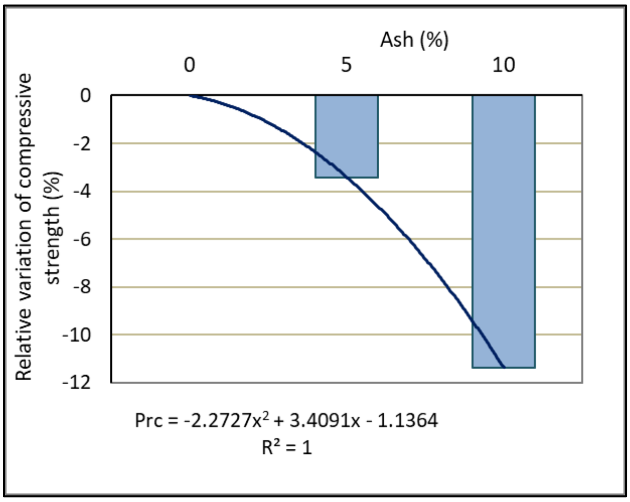

Figure 4 Relative variation of concrete compressive strength as a function of ash content.

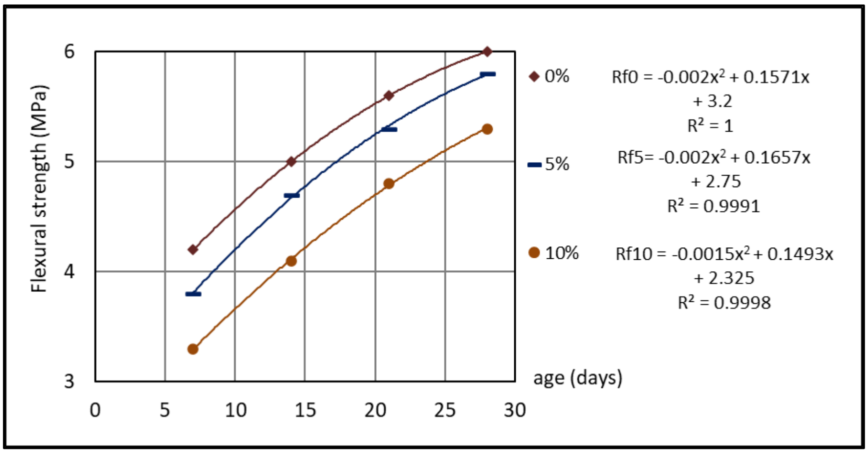

Figure 5 Evolution of flexural strength as a function of concrete age for different ash values.

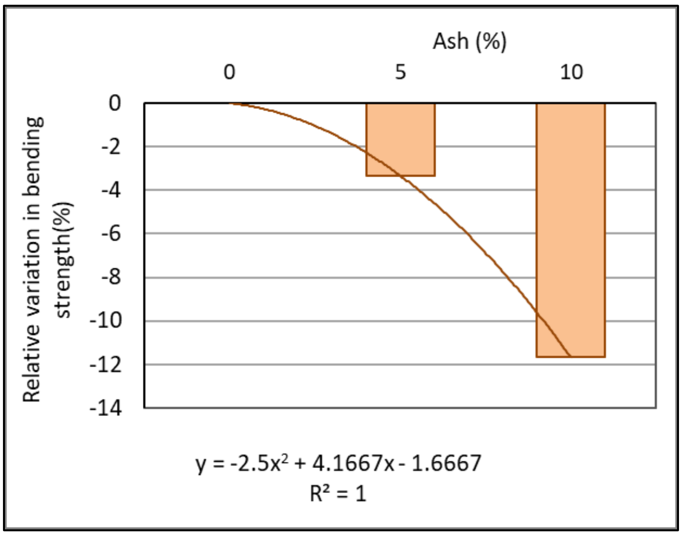

Figure 6 Relative variation of concrete flexural strength as a function of ash content.

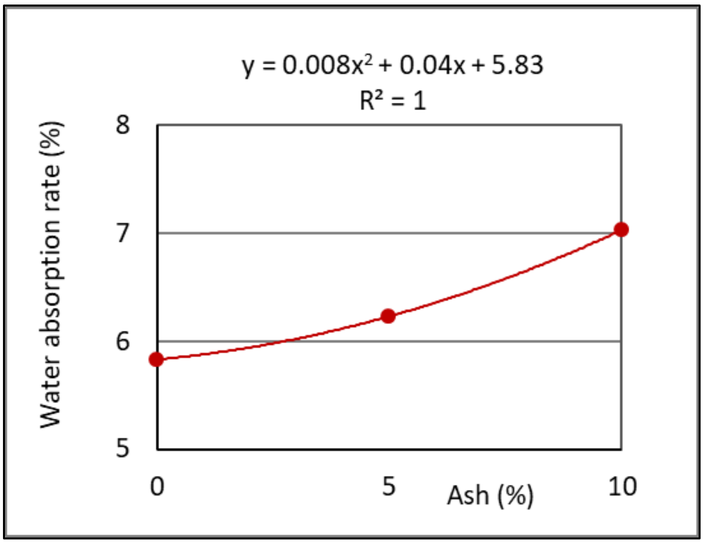

Figure 7 Evolution of water absorption as a function of ash content at 28 days of concrete age

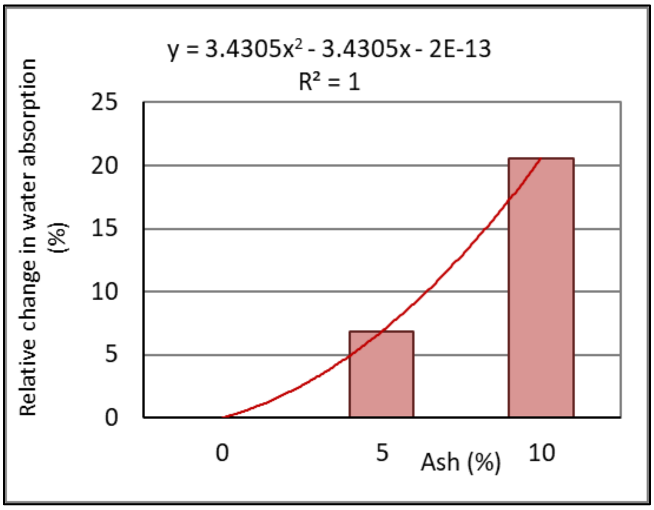

Figure 8 Relative variation of concrete water absorption as a function of ash content.

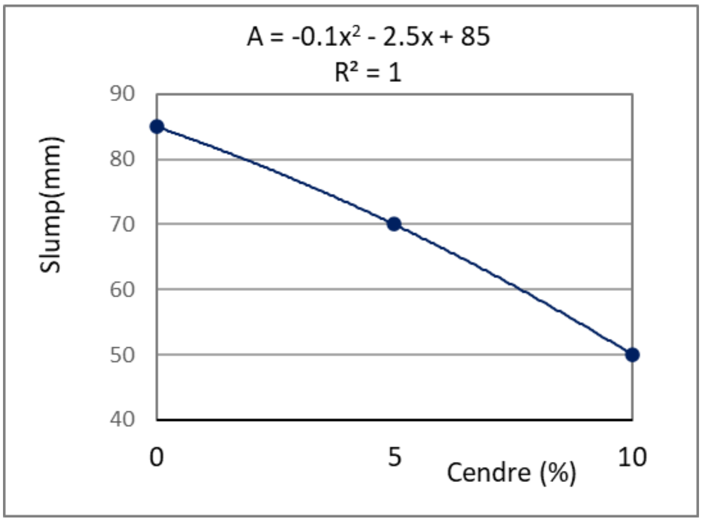

Figure 9 Evolution of slump of fresh concrete as a function of ash content

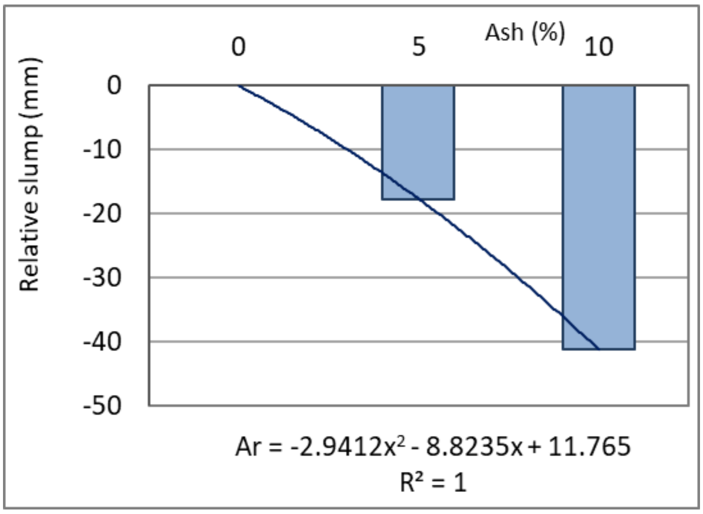

Figure 10 Relative slump of fresh concrete as a function of ash content

4. Discussions

The results from compressive and flexural strength tests, as shown in Figures 5–8, confirm ash's promise as a partial cement replacement, particularly at 5%, where 28-day compressive strength (42.5 MPa) is 3.41% below the 44 MPa control (Figure 3), and flexural strength (5.8 MPa) is 3.33% below 6 MPa (Figure 5). This aligns with Obilade (2014) [12], who reported 90–95% control strength with 5% ash due to pozzolanic densification. Figure 4 and Figure 6 illustrate the 11.36% and 11.67% reductions to 39 MPa and 5.3 MPa at 10% ash, respectively, consistent with Ettu et al. (2013)'s [13] (finding of clinker dilution at higher ash levels. This suggests 5% ash is viable for mortars or plaster, reducing cement use sustainably.

Figures 9–10 highlight durability concerns, with water absorption rising from 5.83% to 6.23% (6.86% increase) at 5% ash and 7.03% (20.58% increase) at 10% ash (Figure 59). This porosity increase (see figure 8), matching Obilade (2014)'s [12] observations on ash porosity and Raheem and Adesanya (2011)'s [14] note on slower kinetics, suggesting 5% ash's denser matrix supports non-critical use, while 10% ash's higher absorption risks moisture damage.

The subsidence decreases from 85 mm to 70 mm (i.e. a reduction of 17.65%) at 5% Ash and to 50 mm (i.e. a reduction of 41.18%) at 10% Ash (figure 9). Figure 12 reflects Obilade (2014)'s [12] finding of increased water demand, with 5% ash's 70 mm slump suitable for mortars, while 10% ash's 50 mm poses challenges, as noted by Raheem and Adesanya (2011) [14]. No shear slump [15] is promising. Future work could explore 56-day curing or superplasticizers to optimize these properties.

5. Conclusion

This study explored experimentally the partial replacement of cement with ash in cement paste, confirming its sustainable potential through detailed analyses. In the laboratory, experimental tests, including compressive and flexural strengths, workability and durability were conducted to assess the performance of ash-blended cement elements. The results indicate that 5% ash mix proves viable for non-structural applications like mortars or plaster, with compressive strength at 42.5 MPa and flexural strength at 5.8 MPa, both within 3–4% of the 44 MPa and 6 MPa control, respectively. The "Water Absorption Rise Trend" indicates a manageable 6.86% increase to 6.23% at 5% ash, while the 20.58% rise to 7.03% at 10% ash suggests porosity limits. Workability shows a 17.65% slump reduction to 70 mm at 5% ash, suitable for use, but a 41.18% drop to 50 mm at 10% ash highlights challenges, as reinforced by "compression - workability" and "compression - absorb" trends. These findings validate ash's pozzolanic potential, reducing cement's 8% global CO^2 footprint by up to 5% per mix. While the present study contributes to the development of eco-friendly construction materials and provide an approach for using agricultural waste in cement-based applications, promoting sustainability in the construction industry, it also stands as a road towards many other research works in construction Engineering. Therefore, future research should test 7% ash with 90-day curing, incorporate aggregates, and use superplasticizers to address 10% ash's 39 MPa strength and 7.03% absorption.

Compliance with ethical standards

Acknowledgments

We are grateful to all IUC lab technicians for their intense assistance and collaboration during laboratory tests section at IUC of Douala.

Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contributions

All authors made significant contributions to the conceptualization, design, data collection, data analysis, manuscript writing and editing, and manuscript proofread. C.T. Moyopo and C.M. Ekengoue conceptualized and designed the study. W. Kenou made available the laboratory for laboratory tests. C.T. Moyopo designed the data collection tools, performed laboratory and data analysis, results interpretations and conducted the study. C.M. Ekengoue and A.N.S. Feumoe conducted manuscript writing and editing, and manuscript proofread. K. B. Amey conducted data analysis, manuscript writing and editing. C.M. Ekengoue and W. Kenou gave overall guidance for the study. All the authors gave final approval to the manuscript for journal submission and are responsible for the content of the manuscript.

Funding

This work is funded entirely by the authors themselves.

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