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Research Article

Ascertaining the physical and mechanical performance of concrete modified with locally sourced coconut fiber ash

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Abstract

This current study evaluated the physical and mechanical performance of concrete modified with locally sourced coconut fiber ash. Concrete specimens were prepared with Portland limestone cement (PLC) partially replaced with locally sourced coconut fiber ash (CFA) in proportions of 0%, 5%, 10%, 15%, and 20%. Tests, including slump, XRF, flexural strength, and compressive strength tests, aided in evaluating the physical and mechanical performance of CFA-modified concrete. XRF analyses revealed the presence of essential elements in cements in CFA: Ca (2.3150 %), Si (3.0900%), and Fe (0.4790%). This affirmed the potential of CFA as a supplementary cementitious material (SCM). Workability of CFA-modified concretes was low: ranged from 20mm to 40 mm for 5% to 20% partial replacement levels. Also, density and water absorption (WA) decreased as CFA concentration in concrete increased. Concrete was classified as normal-weight concrete, with values ranging between 2000 kg/m^3 - 2600 kg/m^3, just like the control. None of the WA values was less than the control for 28 days and 70 days of curing. Compressive and flexural strengths rose to 10% optimum partial replacement levels, beyond which loss of strength set in for days 7, 28 and 70. Empirically, the elemental composition of CFA locally sourced in Ghana was established, affirming its use as an SCM. It also generates an equation model to guide construction practitioners in the use of CFA as an SMC in PLC concrete.

1. Introduction

Cement is the main binding material in concrete for civil infrastructure purposes. Globally, it is estimated that cement production accounts for about 7% contribution of carbon dioxide emissions in the atmosphere [1, 2], significantly contributing to the global climate change being experienced [3, 4]. Whereas sustainable development goal (SDG) 13 calls for actions to combat climate change, and SDG 12 promotes ensuring responsible consumption and production, which, among others, targets reduction in the use of fossil fuel, creating green and decent jobs, promoting quality of life for all, and reducing waste generation through reuse, prevention, recycling, and reduction [5]. The overreliance on some conventional materials, such as Portland cement in the 21st century for concrete and infrastructure construction is a major setback towards the realization of SDGs 12 and

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13, and sustainability in concrete production. It is estimated that the demand for cement increases at a rate of 9% per year across the globe [7, 8]. In view of this, an increasing number of studies within the domain of construction materials have explored the potential of some agricultural by-products, including coconut fiber ash (CFA), whose carbon net worth is lower than cement after recycling, as a supplementary cementitious material (SCM) for concrete production within some national contexts: Nigeria, India, and Malaysia (see [7, 8]). However, none of the studies had evaluated the potential of locally sourced coconut fiber ash from Ghana as a supplementary cementitious material in concrete production. This lack of empirical studies within the context of Ghana is a major setback to Ghana's use of CFA for concretes, thereby reducing the carbon footprint of cement in concrete production. Thus, leaving the effort of the construction industry in Ghana to combat climate change in limbo. Sourcing CFA locally reduces the use of fossil fuel in transporting CFA and Portland cements into Ghana and limits the impact of cement production activities on the environment [1,5,9]. Regarding the use of CFA as an SCM, there is a lack of consensus among researchers regarding the optimal percentage of CFA to replace cement, the elemental composition of CFA, and the performance of CFA-modified concrete. This had been attributed to the varying processes in obtaining CFA, including processing temperature and the origin of the coconut fiber for CFA, among others [1,7, 8]. Furthermore, whereas CFA had been used to replace Ordinary Portland cement (OPC) in some existing studies (see [7, 8]), little is known, if any, of studies that partially replaced Portland limestone cement (PLC) with CFA. PLC is the cement commonly found in Ghana and used in construction. Thus, the relevance of the current study as it seeks to address the weaknesses highlighted in existing studies. It also provides empirical evidence on the potential of CFA locally sourced from Ghana as an SCM in concrete production. This addresses the lack of literature within the context of Ghana on CFA as an SCM, which had derailed the effort of recycling or repurposing CFA for construction purposes in Ghana towards attaining sustainability in concrete production. Finding an alternative use for CFA in concrete promotes agricultural waste valorization. Properties germane to the functional performance of cement-based concrete include the physical and mechanical properties [1,7, 8]. It is against this backdrop that this current study seeks to evaluate the physical and mechanical performance of concrete modified with locally sourced coconut fiber ash. The specific objectives that guided the study were:

- To evaluate the physical performance of CFA-modified concrete, and
- To evaluate the mechanical performance of CFA-modified concrete.

Physical and mechanical performance of concrete had been evaluated in previous studies using a combination of parameters such as slump value, temperature, compressive strength, tensile strength, density, and water absorption (see [1, 8]). Regarding the physical performance of concrete, studies including Arimanwa et al. [10] report that the density of CFA concrete specimens increases with an increase in curing age, and for each curing age, density decreases with an increase in CFA concentrations, while none of the concrete specimens with CFA outperformed that of the control specimen [10]. Water absorption was also found to increase as CFA concentration in concrete increases, while the control specimen records the least absorption value [10]. Regarding mechanical performance of CFA concrete, studies including Sanjay and Rajeev [6] report a decreasing compressive strength as CFA concentration increases [6]; whereas according Waqar et al. [8], compressive strength, tensile strength, and flexural strength increase up to the optimum partial replacement level and decrease afterwards as the percentage of CFA replacement for cement increases [8]. In this current study, a combination of slump value, temperature, compressive strength, flexural strength, density, and water absorption aided in evaluating the physical and mechanical performance of CFA-modified concrete. Although this study does not seek to generalize its findings to be the same across the globe, due to the variety in processing the CFA amidst the origin of the coconut species for the CFA, the outcome offers lessons for countries such as, Burkina Faso, Togo, and Côte d'Ivoire, whose coconut species share close resemblances with Ghana. The study helps in practice as it establishes the optimum partial replacement level essential for construction practitioners in the application of CFA as an SCM in concrete production. It also generates an equation model to guide construction practitioners in the use of CFA as an SMC in PLC concrete.

2. Overview of CFA Use in Concrete Within Some National Contexts

In a CFA study in Nigeria by Anifowoshe and Nwaiwu [7], coconut fiber ash was obtained by drying the fresh coconut fibers and then burning the fibers in an oven at a temperature between 600°C - 700°C. The ash was made to cool and sieved using a 150-micron sieve. CFA was used to partially replace ordinary Portland cement in proportions of 0%, 10%, 30%, 50%, 70% and 100% and cured for 7, 14, 28, 42, 63, and 90 days. Flexural strength and compressive strength were determined, as well as the oxide composition of CFA and ordinary Portland cement. The ratio mix of concrete was 1:2:4. The water-cement ratio was 0.55. The results indicated that compressive strength increases with curing time. Also, as the percentage of partial replacement increases, compressive strength decreases. Regarding flexural strength, it was found that flexural strength increases with curing time. Also, flexural strength decreases with increasing level of CFA replacing cement partially. In a related study, CFA was reaffirmed to be an SCM, and that it increases compressive strength and flexural strength of concrete when it partially replaces cement in a concrete mix [11].

In another related study, cement was partially replaced with CFA in proportions of 0%, 5%, 10%, and 15 %. Concrete specimens were tested at ages 7, 14, and 28 days. The study, among others, concluded that compressive strength decreased as the concentration of CFA in concrete increased [12]. In another study by Waqar et al. [8] in Malaysia, CFA partially replaced ordinary Portland cement in proportions of 3%, 6%, 9%, 12%, 15% and 18%. The standard size for coarse aggregate used was 10 mm, whereas the fine aggregate ranged between 0.4- and 2.52-mm. Water-cement ratio was 0.3. A 1% water-reducing superplasticizer, Sika ViscoCrete – 2192, was also added. Workability, tensile strength, flexural strength, and compressive strength properties of concrete were evaluated. Compressive strength increased up to 9% partial replacement and decreased afterwards as the percentage of CFA replacement for cement increased. For each level of CFA replacement, compressive strength increased with age of curing. A similar account was recorded for the flexural and tensile strengths. For flexural strength, 12% CFA recorded the optimum strength beyond which loss of binding integrity sets in. For splitting tensile strength, the optimum strength was at 9% CFA partially replacing cement. The strength performance beyond 28 days was not investigated.

In a study by Sanjay and Rajeev [6] in India, CFA was obtained by drying and burning coconut fiber in the open air with a temperature range of 600 °C to 700 °C. CFA was sieved using a 150-micron sieve. Concrete specimens were prepared with CFA partially replacing ordinary Portland cement in proportions of 0%, 5%, 10%, 15%, 20%, and 25 %. Super plasticizer was added (2.0% by weight of cement). Concrete specimens were tested at ages 7, 28, 60, and 90 days of curing. The slump test results showed that workability of the concrete decreased as the CFA content increased. The compressive strength of CFA concrete increased with curing age but decreased as CFA percentage increased. None of the compressive strength values exceeded that of the control; however, 5% was the optimum among the CFA-modified concrete specimens [6]. The study did not evaluate the flexural strength of the concrete.

Thus, from the literature reviewed, the optimum level of CFA replacement varied from country to country, as well as the temperature for processing the material. None of the studies had Ghana as its focus, or partially replaced Portland limestone cement (PLC) with CFA. The elemental composition of CFA locally sourced from Ghana is not known. Thus, the relevance of the current study as it addresses these weaknesses in addition to demonstrating the physical and mechanical performance of CFA-modified concrete.

2.1 Theoretical Basis of the Study

2.1.1 Loss of Clinker Theory

The loss of clinker theory argues that partially replacing PLC with SCM beyond a certain threshold leads to loss of cementitious binder due to the dilution effect [13]. Hence, establishing the optimum level of partial replacement of CFA in CFA-modified concrete is essential and provides guidance for construction practitioners when preparing CFA-modified concretes.

2.1.2 Synthesis of Literature

Based on the theoretical basis and empirical literature review, this current study conceptualizes that partially replacing PLC with CFA leads to an improvement in the mechanical performance of concrete (compressive and flexural strength) until optimum performance is attained, beyond which the loss of clinker effect sets in. More, CFA concentration in a concrete mix decreases the slump, density, and water absorption of concrete.

3. Materials and Methods

Portland Limestone Cement (PLC), CEM II/B-L, rated strength class 42.5 R, was used in this study. X-ray fluorescence (XRF) analysis was performed to determine the elemental composition of cement. Standard elemental composition requirements in PLC include: Ca (Calcium), Si (Silicon), Al (Aluminum), Fe (Iron), Mg (Magnesium), S (Sulphur), Na (Sodium), K (Potassium) [14, 15]. CFA was used as an SCM to replace PLC partially in a CFA-modified concrete. Also, XRF analysis was performed to determine the elemental composition of the locally sourced CFA and to compare it with PLC to ascertain its suitability as an SCM. Potable water, per BS EN 1008:2002, was used for the concrete specimens [16]. It was clean and odorless when smelled. The sieve analysis test was performed in accordance with BS EN 933-1:2012 and BS 1377-3:1990 to determine the particle size distribution of the aggregates for the concrete specimens [17,18].

3.1 Experimental Procedure

Coconut fiber, an agricultural by-product, was cleaned and air-dried under the sun for 7 hours to remove moisture. The sample was burnt in a regulated oven into ashes at a temperature of 500 degrees for 3 hours. It was further sieved to obtain the CFA for the experiment [1, 8]. In this case, the 75µm sieve was used to get a finer CFA particle to replace cement partially. According to Ranatunga et al. [1], the fineness of an SCM is essential as it influences the strength development. Concrete mix design was developed based on the trial mix method to guide the process (see Table 1). Firstly, the control concrete, which had 0% CFA, was prepared to achieve the targeted compressive strength of 20 N/mm^2 at 28 days of curing using cube moulds:150mm x 150 mm x 150mm. In the trial mix design, the water-to-cement ratio was selected as 0.60. Then, PLC was partially replaced with CFA in proportions of 5%, 10%, 15% and 20%. Concrete mixes were named as CFA 0, CFA 5, CFA 10, CFA 15, and CFA 20, when CFA partially replaced PLC in proportions of 0%, 5%,10%,15%, and 20%, respectively. Three concrete specimens each were tested at age 7 days, 28 days, 70 days for compressive strength following BS EN 12390-3:2019 [19], density of concrete was determined in accordance with BS EN 12390 -7:2009 [20], water absorption test of concrete in accordance with BS EN 1881-122: 2011[21], and flexural strength following BS EN 12390-5: 2019 [22]. Concrete was mixed and cured in accordance with BS 1881–125: 1986 and BS EN 12390-2, 2000 [23, 24]. Since CFA is a pozzolanic material that reacts slowly during hydration, compared to cements, compressive and flexural strengths of concrete at age 70 days were essential to understand the strength gained over a longer period. The grading test for coarse aggregates for the concrete mix followed the procedures outlined in BS EN 933-1:2012, which stipulate the sieving method for determining aggregate size [17]. The sieves used were: 22mm, 20mm, 19mm, 14mm, 12.5mm,10mm, 4.75mm, and 2.36 mm. Grading test for fine aggregate (sand) for concrete was done in accordance with BS EN 933-1:2012 [17] and classified following BS 882:1992 and BS EN 12620:2013 [25, 26]. The specific sieves used for the test were: 5mm, 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, 0.15mm, and 0.075mm.

Table 1. Mix design for C20 concrete with cement partially replaced with a CFA

Mix ID	CFA (Kg)	Cement (Kg)	Sand (Kg)	Crushed rock (Kg)	Water-cement ratio (0.60) (Kg)
(CFA 0)	0	1.27	1.91	3.81	0.76
(CFA 5)	0.06	1.21	1.91	3.81	0.76
(CFA 10)	0.13	1.14	1.91	3.81	0.76
(CFA 15)	0.19	1.08	1.91	3.81	0.76
(CFA 20)	0.25	1.02	1.91	3.81	0.76

4. Results and Discussions

From Figure 1, 57.38% of the sample passed through the 0.6mm sieve. Thus, the fine aggregate falls within zone II: medium sand, reference to BS 882:1992 and BS EN 12620: 2013 [25, 26]. This was an indication that the fine aggregate was suitable for the production of general concrete.

From Figure 2, the coarse aggregate for the concrete specimens was well graded with an upper limit diameter (D) not exceeding 20mm and a lower limit diameter (d) not exceeding 4.75mm (see Figure 2). The aggregate met the grading limits for 20mm coarse aggregate for concrete, in reference to BS 882:1992 and BS EN 12620:2013 [25, 26]. This indicates well-graded coarse aggregate for a concrete mix.

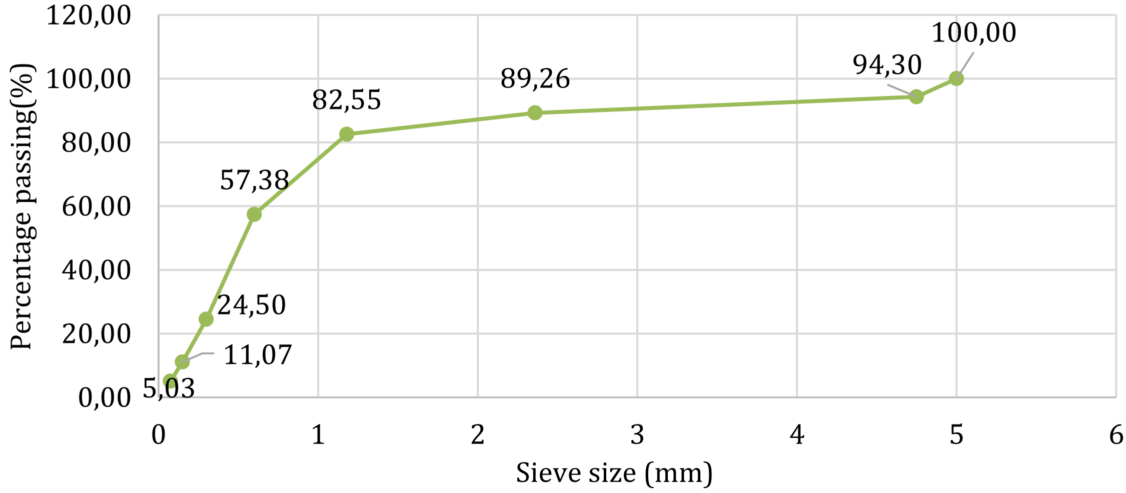

Fig.1. Gradation curve for fine aggregate

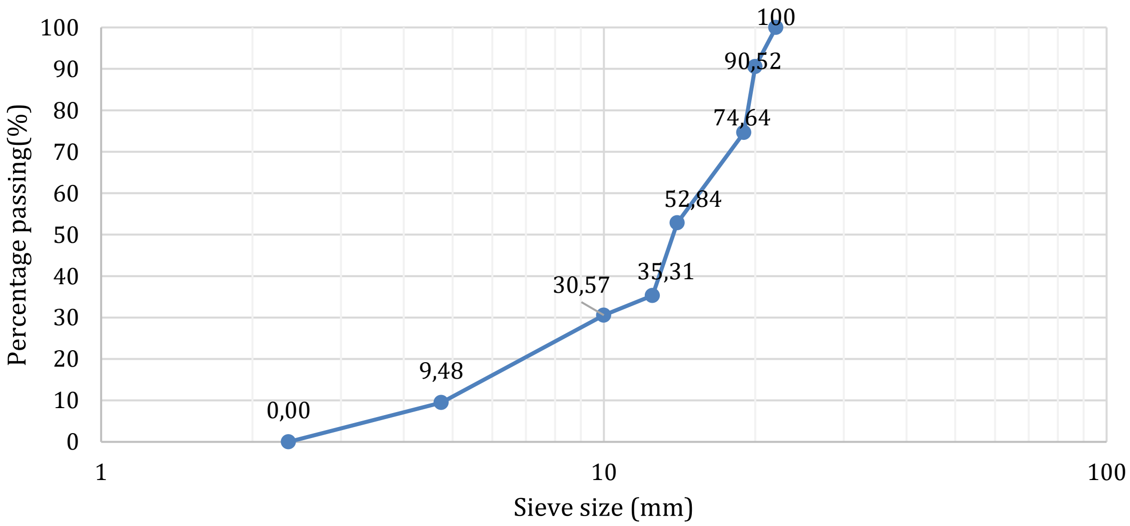

Fig. 2. Gradation curve for coarse aggregates

Table 2. Properties of CFA and PLC

Mater.	Ca	Al	Fe	Si	S	Mg	P	K	Cl	Ti
Cement (%)	44.150	4.1800	3.4650	14.1500	1.8650	2.7750	<0.003075	1.1000	0.0344	0.2680
CFA (%)	2.3150	0.8575	0.4790	3.0900	1.3150	3.6050	2.8850	25.6000	6.0600	0.0465

From Table 2, the elemental composition of CFA was comparable to that of the PLC cement. This affirms the potential of CFA as an SCM. The CFA elements revealed the richness of CFA in Mg (3.6050%), Si (3.0900%), and Ca (2.3150%). Si and Ca are essential elements for the formation of calcium silicate hydroxide and portlandites during hydration, critical for continuous hydraulic and pozzolanic reactivity for continuous strength development and durability of cement-based products [1]. Objective one is to evaluate the physical performance of CFA-modified concrete.

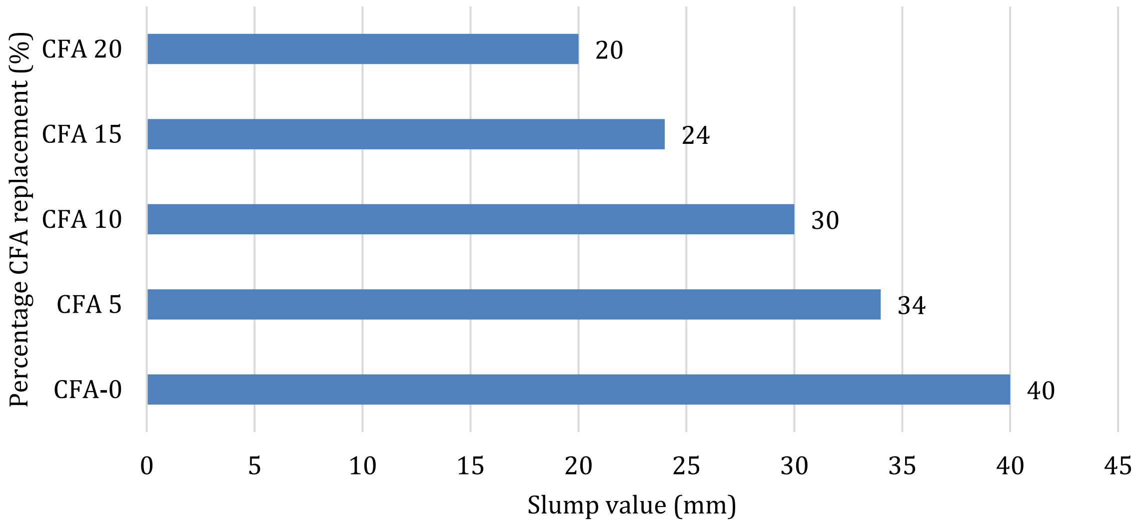

Fig. 3. Workability (slump) of CFA-Modified concretes

From Figure 3, none of the slump values exceeded that of the control specimen. With reference to BS EN 206-1:2000, true slump was ideal for concrete mix, and it ranged from (10mm to 220mm), specifically S1: 10-40 mm slump was suitable for low-workability applications [27]. Thus, with a slump of 20mm to 40mm, recorded by CFA 0, CFA 5, CFA 10, CFA 15, and CFA 20, in this study, the CFA-modified concrete specimens could be classified as S1 slump and ideal for low workability applications. Likewise, from Figure 3, the slump value decreased with a percentage rise in CFA. This indicates a decrease in workability as the CFA concentration increases in the concrete specimens. This affirmed the position of Sanjay and Rajeev [6] that workability decreases when the concentration of CFA as a partial replacement for cement in concrete increases.

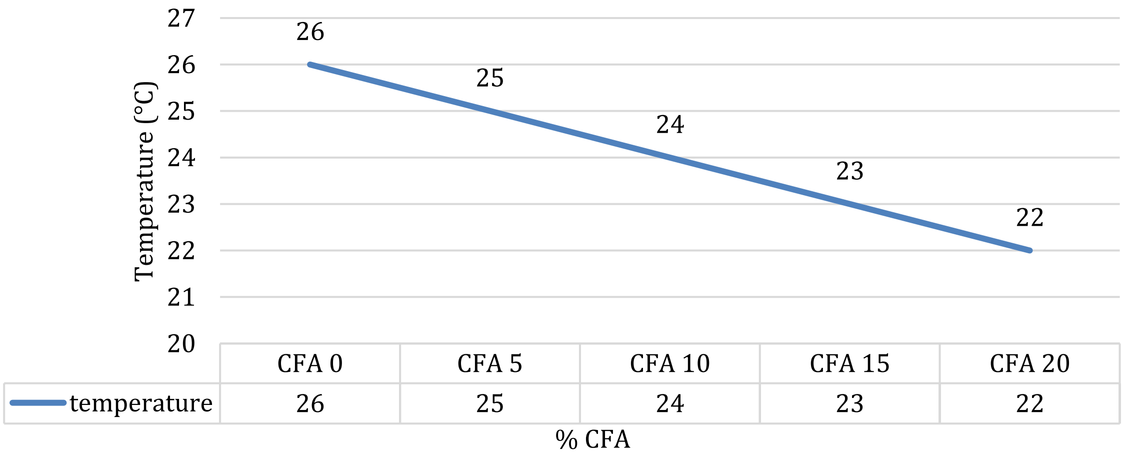

Fig. 4. Influence of CFA on temperature

The temperature for freshly mixed normal concrete should typically range between 10 °C and 32 °C, with 20 °C–27 °C being considered the optimal range for normal concrete [28]. Thus, from Figure 4, the temperature of freshly mixed concrete ranged from 26°C to 22 °C. The trend suggested a decreasing temperature of fresh concrete as the percentage of CFA concentration increased from

0% to 20%. According to Mehta and Monteiro [29], as the level of partial replacement increased, it reduced the heat generated during hydration, thereby lowering the temperature of the fresh mixed concrete [29].

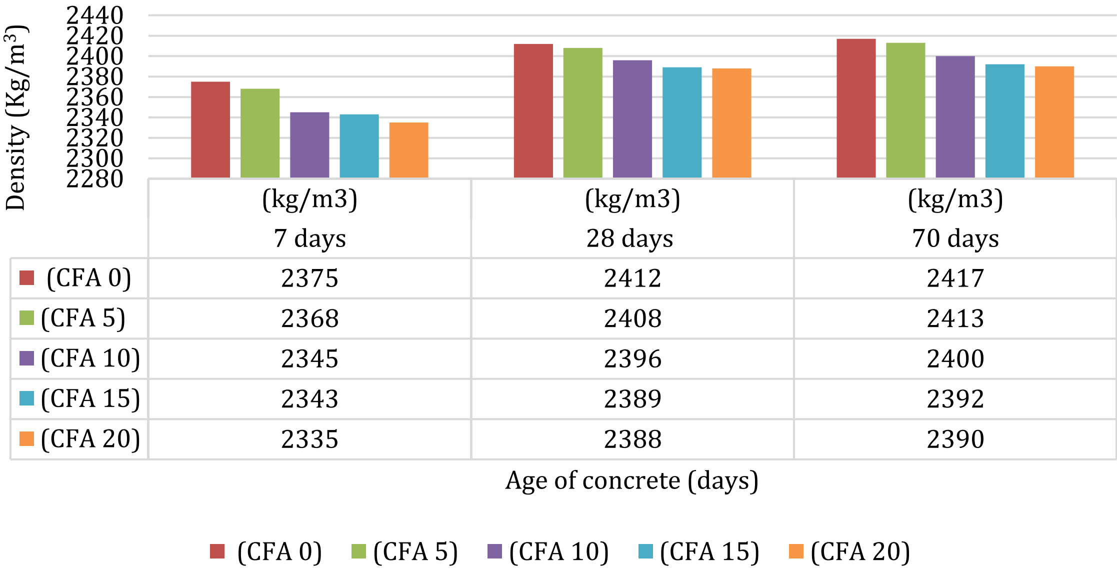

Fig. 5. Density of CFA-modified concretes

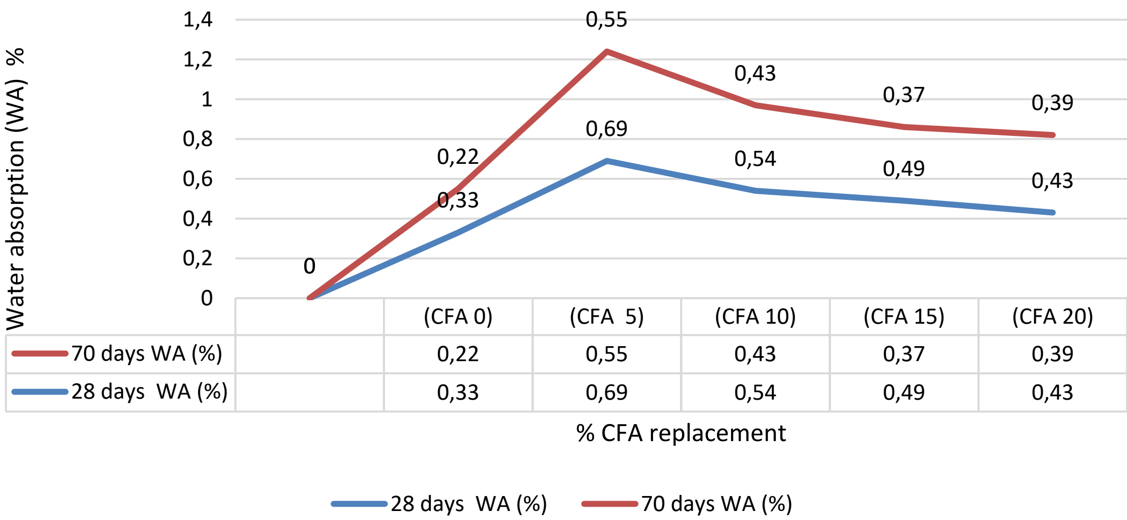

Fig. 6. Water absorption of CFA-modified concretes

According to Arimanwa et al. [10], the density of CFA concrete specimens increases with an increase in curing age, and for each curing age, density decreases with an increase in CFA concentrations, while none of the concrete specimens with CFA concentrations outperformed that of the control specimen [10]. This position was affirmed by the findings of this current study. From Figure 5, the density of concrete increased with age of curing (7 days, 28 days, and 70 days), and within a specific curing age, such as 7 days, 28 days, and 70 days, density was found to decrease as the percentage of CFA replacement increased. Also, none of the densities outperformed that of the control concrete for ages 7 days, 28 days, and 70 days. A phenomenon Ranatunga et al [1] and Arimanwa et al. [10] attributed to the use of comparatively less dense SCM, in this case CFA, to replace a denser PLC in terms of material densities. From Figure 5, in accordance with the BS EN 206-1:2000 [27], the CFA-modified concretes (from 0% to 20% CFA replacement levels) could be classified as normal-weight concretes since the average oven-dry density values were more than 2000 kg/m^3 but did not exceed 2600 kg/m^3.

Water absorption was found to increase as CFA concentration in concrete increases, while the control specimen recorded the least water absorption value [10]. Contrary to this assertion, from Figure 6 of this study, for (CFA 0), (CFA 5), (CFA 10), (CFA 15), and (CFA 20) concrete mixes, water absorption (WA) of concrete decreased with increasing age of curing for both 28 days and 70 days of curing. It also rose up to (CFA 5) and decreased thereafter with an increasing percentage of CFA replacement for each of the days of curing. Again, it was observed that none of the specimens with CFA recorded a WA value that was lower than the control specimen. A phenomenon, Ranatunga et al. [1] attributed to a decrease in total voids in concrete as a result of an increase in C-S-H gel formation during hydration [1].

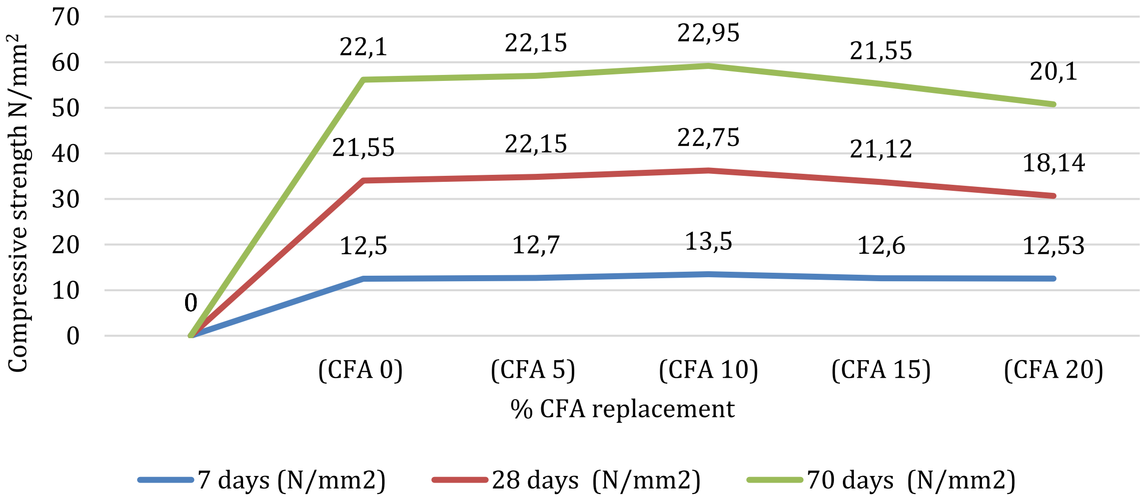

Fig. 7. Compressive strength of CFA-modified concretes and ages of curing

The targeted compressive strength at 28 days of curing for this study was 20 N/mm².According to Waqar et al. [8] compressive strength of CFA concrete increased up to 9 % partial replacement and decreased afterwards as the percentage of CFA replacement for cement increased. For each level of CFA replacement, compressive strength increases with age of curing [8]. From Figure 7, the compressive strength of the concrete specimens increased from ages 7 days, through 28 days, to 70 days. An indication of continuous hydration and pozzolanic reaction within the concrete specimens [1]. Also, for all the days (7 days, 28 days, and 70 days), compressive strength rose progressively to 10% partial replacement level, beyond which any additional increase in CFA resulted in a loss of clinker effect. This 10% optimum replacement level was higher than 9% recorded by Waqar [8] in Malaysia, and 5 % by Sanjay and Rajeev [6] in India. Thus, the case in Ghana suggested an improvement in the optimum level of partially replacing cement with CFA. This affirmed that the behaviour of CFA concrete is country-specific owing to the origin of the material and the temperature at which the material was processed, among others [1]. At age 7 days, (CFA 5), (CFA 10), and (CFA 15) improved early compressive strength of concrete better than the control, while at (CFA 5) and (CFA 10), CFA improved compressive strength at 28 days and 70 days better than the control. Furthermore, in this study, a regression model was developed to practically guide construction practitioners for the ease of applying the CFA concrete mix for optimum results, as presented in Table 3.

From Table 3, R^2 values ranged between 0 and 1. According to Kutner et al. [30] and Montgomery et al. [31], an R^2 value below 0.2 means a very weak relationship, 0.2-0.4 shows a weak relationship, 0.4-0.6 means a moderate relationship, 0.6-0.8 shows a strong relationship, and values above 0.8 implies a very strong relationship between the variables [30, 31]. The R^2 values for the 7-day compressive strength model, 28-day compressive strength model, and 70-day compressive strength model were 0.514, 0.975, and 0.903, respectively (see Table 3). Indicating a moderate to very strong relationship. From Table 3, (Y) is the compressive strength, and the compressive strength models confirmed that the optimum level of partial replacement was 10%.

Table 3. Equation to guide optimization of compressive strength of CFA concretes

Model	Equation	R^2 (goodness of fit)	Remarks
For 7-Day Strength (Y_7)	$Y_7 = [-0.0064x^2 + 0.1272x + 12.454]$	0.514	An indication that 51.4 % of the change in compressive strength of concrete at age 7 days can be predicted from the proportions of CFA, a moderate model fit.
For 28-Day Strength (Y_{28})	$Y_{28} = [-0.026829x^2 + 0.379571x + 21.371]$	0.975	An indication that 97.5 % of the change in compressive strength of concrete at age 28 days can be predicted from the proportions of CFA, a very strong model fit.
For 70-Day Strength (Y_{70})	$Y_{70} = [-0.014857x^2 + 0.2051x + 21.947]$	0.903	An indication that 90.3 % of the change in compressive strength of concrete at age 70 days can be predicted from the proportions of CFA, a very strong model fit.

According to [8] flexural strength of CFA concrete increased progressively up to 12 % optimum partial replacement and decreased afterwards as the percentage of CFA replacement for cement increased. This position was supported by the findings of this current study. From Figure 8, flexural strength increased from day 7 days to 70 days for each of the specimens, an indication of continuous hydration and pozzolanic reactivity within the concrete specimens. However, the optimum level of partial replacement was 10%, and when compared to the study in Malaysia by [8], it was lower. Thus, affirming that the behavior of CFA is context-specific.

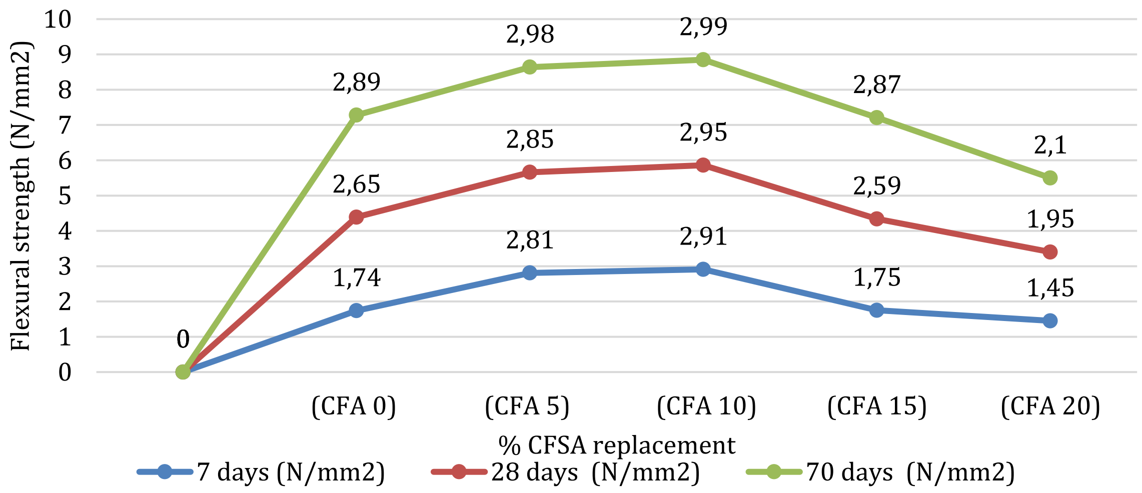

Fig. 8. Flexural strength of CFA-modified concretes and ages of curing

5. Conclusions

This current study sought to evaluate the physical and mechanical performance of concrete-modified with locally sourced coconut fiber ash. Base on the findings of the study, it could be concluded that:

- CFA in Ghana is a potential supplementary cementitious material for PLC. Elements of cement were also found to be present in CFA. The elements include Ca (2.3150 %), Si (3.0900%), and Fe (0.4790%). This affirmed the potential of CFA as a supplementary cementitious material (SCM).

- In relation to the physical performance of the CFA-modified concrete specimens, it was observed that the workability of CFA concrete decreased as the concentration of CFA in concrete increased. Workability of CFA-modified concretes was low: ranging from 20mm to 34 mm for 5% to 20% partial replacement levels. Temperature continually decreased as CFA concentration increased from 0% to 20%. The density of CFA concrete decreased with an increase in the concentration of CFA in a concrete mix. Water absorption of CFA concrete decreased with increasing concentration of CFA in a concrete mix. None of the WA values was less than the control for 28 days and 70 days of curing.
- Regarding the mechanical performance of CFA-modified concrete, compressive strength and flexural strength rose progressively to 10% as the concentration of CFA in concrete increased, then declined beyond the 10% optimum partial replacement level, as a result of the dilution effect of concrete. At age 28 days of curing, CFA 10 concretes recorded the maximum compressive strength of 22.75 N/mm^2 and flexural strength of 2.95 N/mm^2, exceeding compressive strength values of 21.55N/mm^2 and flexural strength of 2.65N/mm^2 recorded by the control specimens.
- . In accordance with the BS EN 206-1:2000 [27], CFA concrete specimens and the control specimen were classified as normal-weight concrete.
- The study found an alternative use for coconut fiber, otherwise a waste material polluting the environment, in CFA-modified concrete. This promotes agricultural waste valorization and material circularity.
- Empirically, the elemental composition of CFA, sourced locally from Sekondi-Takoradi in Ghana, has been established, which hitherto was largely absent in existing literature. This has broadened the frontiers of existing literature on CFA as an SCM.
- Practically, it has developed a regression equation that will aid construction practitioners in Ghana in determining the optimal level of partially replacing PLC with CFA in concrete mix in order to maximize compressive strength.
- Moreover, this study provides the basis for future studies on sourcing SCMs locally for the intended purpose.
- By finding alternative uses for CFA in concrete production will lessen the overreliance on cement for concrete, which will translate into reducing the carbon footprint of concrete, thereby contributing to addressing SDG 13: climate action, and SDG 12: responsible consumption and production. It also promotes waste valorization.
- Policy-wise, knowledge of the optimal replacement level and physical and mechanical performance of CFA-modified concretes will inform the development of standards by the government and policy makers in developing relevant standards and codes to regulate the use of CFA as SCM.

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