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5 authors, including:

Ezekiel Babatunde Ogunbode
Federal University of Technology Minna

Bemgba B. Nyakuma
North-Eastern University (Formerly Pen Resource University)

Richard Jimoh
Federal University of Technology Minna

Temitope Lawal
Federal University of Technology Minna

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ORIGINAL ARTICLE

Mechanical and microstructure properties of cassava peel ash–based kenaf bio-fibrous concrete composites

Ezekiel B. Ogunbode[1] · Bemgba B. Nyakuma[2,3] · Richard A. Jimoh[1] · Temitope A. Lawal[1] · Helen G. Nmadu[1]

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Abstract

The study investigated the effects of kenaf bio-fibre (KBF) and cassava peel ash (CPA) on the physical, mechanical and microstructural properties of concrete. The CPA was characterized by microstructural studies such as X-ray diffraction (XRD), scanning electron microscopy (SEM) and X-ray spectroscopy (EDS). The KBF (length, L = 5 cm) and five (5) volume fractions from 0 to 1.0% ($\Delta\%$ = 0.25%) were used with Portland cement (CEM 1). Next, five concrete mixtures were also cast using 10% CPA as a replacement for CEM 1. The results revealed that the inclusion of KBF in concrete and blending CPA with CEM 1 reduced the slump values with no major improvement of the compressive strength. However, blending CPA with CEM 1 and inclusion of KBF in concrete improved the VeBe time of the fresh concrete and the tensile and flexural strengths of the hardened concrete. The SEM results showed that KBF serve as bridges between the cracks and enhanced the load transfer capability of the concrete matrix. Overall, the study demonstrated that the utilization of KBF and CPA in concrete is a technically feasible and environmentally friendly approach to waste valorization and sustainable construction.

Keywords Cassava Peels · Ash · Kenaf fibre · Physicomechanical properties · Concrete composites

1 Introduction

The quest for sustainability has inspired the widespread application of wastes streams as substitute raw materials for cement and aggregates in the building construction industry [1, 2]. The valorization of waste streams in the building construction industry has the potential to address waste management challenges, enhance sustainability and the environmental friendliness of the industry [3, 4]. Furthermore, the application of waste streams as low-cost building materials can lower the prices of building components and raw materials for concrete production [5, 6]. Concrete is considered one of the most important and versatile construction material widely utilized around the world [5]. In addition to its normal applications, higher ductility and energy absorption capacity are typically required for various applications such as industrial floors, highway paving, bridge decks, among others [7, 8].

Numerous scientists and engineers have developed concrete composites to address the basic drawbacks of concrete over the years. The most notable problems with conventional concrete include high brittleness and low tensile strength, which has culminated in the development of fibrous concrete (FC) [3, 9]. FC is a novel material that consists of homogeneously distributed but arbitrarily oriented natural (bio-) or manmade fibres. These include glass, steel and synthetic fibres such as nylon and polypropylene (PP). Others consist of fibres derived from pre- or post-consumer waste streams [10, 11]. The bio-based fibres have lightweight, renewability, high toughness and non-corrosive properties that enhance their preference over synthetic fibres [12–14].

According to Manasa et al. [15], the integration and reinforcement of concrete with natural fibres improve resistance to impact, fatigue, walling and thermal shock. Likewise, natural fibre-based concrete composites promote the concepts of green building and sustainability in the construction industry. The composition of FC includes ordinary Portland cement (OPC), fine or coarse aggregates, along with dispersed and

✉ Ezekiel B. Ogunbode
ezekiel@futminna.edu.ng; bnbevan2@live.utm.my

1 Department of Building, School of Environmental Technology, Federal University of Technology, Minna, Niger State, Nigeria

2 School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia

3 Research Initiative for Sustainable Energy Technologies, North-Bank, Makurdi, Benue State, Nigeria

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discontinuous short fibres randomly mixed with fresh concrete. The addition of bio-fibre mix helps to transfer the load and bridge cracks, and improve the dispersal system of micro-cracks in concrete [16–18]. Besides, bio-fibres enhance concrete properties under compression, tensile and flexure conditions but also under impact blows [3] and plastic shrinkage cracking [19].

The application of bio-fibres in cement-based materials has been widely described in the scientific literature. Wafa [20] revealed that the incorporation of fibres into a concrete matrix alters the compressive strength, toughness and elastic modulus. Other mechanical properties such as flexure, fatigue strength and the impact resistance of the concrete are also enhanced by adding fibres to concrete [20]. Li et al. [21] investigated the physicomechanical properties of hemp bio-fibrous concrete (HBFC). The study examined the effects of fibre content (by weight), fibre length, mixing techniques and aggregate size on the HBFC. Other researchers have examined the material properties and potential application of natural fibres in composites for application as cement paste, mortar, concrete and other construction materials [10, 22]. For example, kenaf fibre improved the mechanical properties (such as compressive, tensile and flexural creep performance) of bio-fibrous concrete (BFC) [23].

The kenaf fibre (KF) has the potential to substitute conventional materials or synthetic fibres as composite reinforcement [24]. The fibres are typically extracted from either the outer (bast) or inner (core) parts of the kenaf plant (*Hibiscus cannabinus* L.). Although native to Africa and Asia, KF has become one of the most extensively farmed natural fibres due to its ability to grow annually in various weather conditions. Hence, it is cultivated commercially in the USA for animal feeds, absorbent for oil spill and food crop. The kenaf plant is a herbaceous crop that grows from 2.4 to 6 m in height within an average 150-day period [25, 26]. The kenaf plants reportedly have an elevated rate of carbon dioxide (CO_2) assimilation, which could enhance the scrubbing of large quantities of the greenhouse gases from the atmosphere. Furthermore, the plant can act as a remediating material by absorbing nitrogen and phosphorous from the soil. Hence, KF is an environmentally friendly material due to its significant ability to control greenhouse emissions [25, 27]. Similar to other natural fibres, KF has low density, high mechanical properties and recyclability [28].

Recent studies have reported on the growth of novel complementary cementitious materials with outstanding physical, mechanical and durability properties [29, 30]. The novel pozzolanic-based materials are utilized globally due to their economic, ecological and technological benefits. One of the ash-based materials currently gaining the consideration of researchers is cassava peel ash (CPA) [31], which is generated from the combustion of dry cassava peels. In the past, the cassava peels were considered an agricultural by-product disposed of without any commercial return or marginally utilized as animal feed in rural areas. However, cassava peels are currently considered valuable materials for enhancing the strength, durability and performance of concrete [32]. FC comprises pozzolanic materials along with conventional concrete [33–35]. Previous studies have demonstrated that the inclusion of KF can enhance the mechanical properties of concrete [11, 36]. The collective effect of kenaf bio-fibre (KBF) properties and pozzolanic materials such as ash on the properties of concrete is a novel research area that requires major consideration.

Therefore, it is essential to comprehensively examine the performance of various mix proportions of concrete. To the best of the authors' knowledge, studies on the influence of KBF and CPA on the physical and mechanical properties of concrete have not been reported in the scientific literature. Due to the fibrous and pozzolanic nature of KBF and CPA, it is imperative to conduct comprehensive research on their intrinsic properties from the multi-perspectives of materials application, sustainable waste valorization, and circular economy. The main objective of the study was to investigate the combined influence of CPA and KF on the physical, microstructure and mechanical properties of concrete. The characterization of the constituent materials and concrete properties such as workability, compressive, tensile and flexural strength tests was examined. The microstructure of the fabricated concrete was examined by scanning electron microscope (SEM) and the results were compared with fibreless concrete produced from CEM 1 - 42.5 N as the control.

2 Materials and methods

2.1 Materials

In this study, Portland cement (CEM 1 42.5N - Dangote 3X) produced by Dangote Cement Company was used as the binder for the control reference concrete mix. The raw cassava tuber peels used in this research work were collected from a local cassava processing mill in Ogbomosho town, Oyo State, Nigeria. Initially, the cassava peels were dried and screened to eliminate unwanted stems and leaves. The dried cassava peels were subsequently burned in open air using a locally fabricated incinerator described in the literature [37] (Fig. 1a–d). The resulting cassava peel ash (CPA) was sieved to remove extraneous and unburned carbon materials. Next, the resultant CPA particles were ground to sizes below 150 μm using a local milling device. Finally, the ground ash was sieved to 75 μm particles to obtain the CPA used for the subsequent experiments (Fig. 2a).

The bulk chemical and physical properties of the ordinary Portland cement (OPC, CEM 1) and CPA were conducted

Fig. 1 **a** Cassava tuber, **b** dried cassava peel, **c** set up of incinerator, **d** burnt cassava peel ash

using X-ray fluorescence (XRF), as presented in Table 1. The specific gravity of CPA is 2.32 kg/m^3, whereas the specific surface area of CPA determined by the nitrogen absorption method is 4930 cm^2/g compared to 3990 cm^2/g of CEM 1. The EDS analysis (Fig. 2b) showed that the predominant elements in the tested CPA sample were C, O and N in various compounds, although lower amounts of the elements Ca, P, S, K and Na were also observed. Figure 2 c portrays the XRD pattern of the CPA, which indicates the material is mainly in amorphous form. The deconvolution yielded peaks at 30°, 48° and 58° 2 , which correspond to the characteristic (111), (220) and (311) planes of cubic-phase CPA. The scanning electron micrograph (SEM) of CPA is presented in Fig. 2d.

The SEM micrograph of the CPA showed marginal pores at the magnification of × 7000. The pore opening sizes could affect the workability of fresh concrete since it would mean a tendency to absorb water. It could also affect the number of voids and capillaries, thus reducing the density of the packed structure. Figure 2 d showed that the CPA comprises spherical particles with a smooth surface.

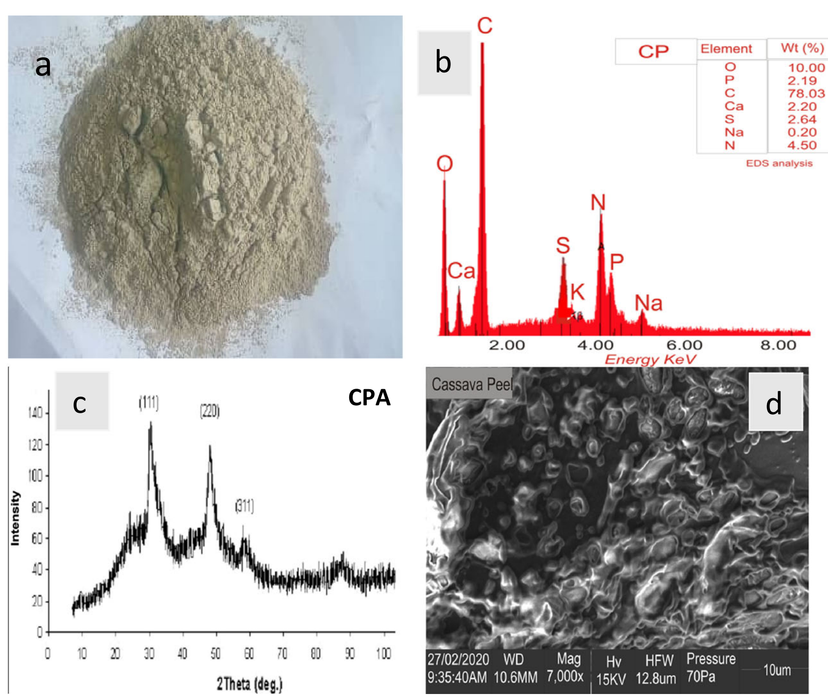

Fig. 2 **a** Calcined CPA photo, **b** EDS image, **c** XRD pattern, **d** SEM image of the CPA sample used in the study

Table 1 Physical properties and chemical composition of PC (CEM 1) and CPA

	Materials	CEM 1	CPA
Physical properties	Specific gravity (kg/m^3)	3.15	2.32
	Blaine fineness (cm^2/g)	3990	4930
	Soundness	1.0	2.0
Chemical properties	SiO_2 (%)	21.5	83.0
	Al_2O_3 (%)	1.6	2.9
	Fe_2O_3 (%)	1.2	2.7
	CaO (%)	64.0	1.3
	MgO (%)	2.9	0.8
	K_2O (%)	0.0	2.8
	SO_2 (%)	4.5	0.0
	LOI* (%)	0.0	5.6

**LOI*, loss on ignition; *CEM 1*, CEM 1 42.5N - Dangote 3X

The fine aggregate used for this study was obtained from river sand with maximum aggregate size passing through a 4.75-mm sieve at the saturated surface dry condition. The fineness modulus and specific gravity of the fine aggregate are 2.3 and 2.58, respectively with water absorption of 0.70%. The coarse aggregate consists of crushed granite of maximum size (10 mm), specific gravity (2.7) and water absorption (0.5%). The mixing and curing processes were performed using tap water throughout the study, whereas the concrete workability was enhanced using Conplast SP 430 (polymer-based superplasticizer) based on 1.0%/wt of the cement-based materials. The ratio of the water-to-binder (w/b) was fixed at a constant value of 0.40 for the entire batches examined in the study.

The kenaf bio-fibre (KBF) was collected from Manchok, Kaura Local Government Area of Kaduna State, Nigeria. The KBF was subjected to alkaline treatment (or mercerization method) to reduce its water sorptivity characteristics (i.e. hydrophilic property) and degradation rate. For each test, the KBF was chopped to a length of 50 mm (Fig. 3a and b). Table 2 presents the physical and lignocellulosic properties of the KBF, whereas Fig. 4 shows the SEM micrograph.

2.2 Mix proportioning

The mixing process for natural fibrous concrete was performed according to the procedure described in the literature [3]. On the other hand, the plain concrete was designed simultaneously in accordance with the British DOE concrete mix design proportioning method (DOE method). In the first phase of mixing the fibrous, the coarse and fine aggregates were charged into the concrete mixer and blended with one-quarter of the water required for mixing for 4 min. The mixer was stopped for 2 min to allow the air-dried aggregate to absorb the water required for saturation. The pause prevents the absorption of the superplasticizer by the aggregates. Subsequently, the Portland cement (CEM 1) and CPA cementing material were poured into the mixer. The mixing was restarted, and the stirring continued 6 min with the addition of the second- and third-quarter of the mixing water.

All the water and fibre soaked were slowly drizzled into the matrix to ensure an even distribution of the fibres. A large drop in the fresh concrete workability was observed due to the hydrophilic characteristic of KBF in the mix, which resulted in major absorption of water intended for the concrete mixture and hydrolysis. The superplasticizer was then discharged in the fourth-quarter of the mixing water before adding to the concrete mix and stirring for 5 min. Mixing was stopped for 2 min. Next, the mixture was stirred again for another 4 min before being poured and cast into the required oiled steel, plastic and wooden moulds. The concrete mixtures were homogenized using the oscillatory type pan mixer with a normal capacity of 0.02 m^3. All the specimens were cast and water cured based on the ASTM C192 standard [38]. Table 3 shows the mix proportions of the FC examined in this study. In total, 10 concrete mixes were prepared with the first batch (S1) designated as the control mix (i.e. plain or without any fibre or CPA). From the 10 mixes, five sets comprise 100% Portland cement (CEM 1) cementing material with the fibre volume portions: 0%, 0.25%, 0.5%, 0.75% and 1.0% (S1–S5). The other five sets were produced with 10% CPA to substitute Portland cement (CEM 1) for identical fibre volume portions (S6–S10).

Fig 3 **a** Curl kenaf bio-fibre; **b** alkaline treated 50-mm length chopped kenaf bio-fibre

Table 2 Properties of KBF

Physical properties		Chemical properties		Mechanical properties	
Length (mm)	50	Cellulose (%)	54	Tensile strength (N/mm^2)	704
Diameter (μm)	65.4	Hemicellulose (%)	22	Elastic modulus (GPa)	39.77
Density (g/cm^3)	1.2	Pectin (%)	2.0	Elongation at yield (%)	1.77
Reaction with water	Hydrophilic	Lignin (%)	4.79		

2.3 Test program and test method

The slump and VeBe test methods described in the British Standards [39] and [40], respectively, were employed to investigate the fresh state properties of the FC and concrete samples. The test for compressive strength was conducted using 100 mm × 100 mm × 100 mm cube-sized samples [41, 42]. The cylindrical specimens (100 mm × 200 mm) were used for the splitting tests for tensile strength [43] and elastic modulus [44]. Next, prism samples with dimensions 100 mm × 100 mm × 500 mm were produced based on the British standard [42] to examine the flexural strength of the samples. All the strength experiments were performed at the age of 7, 28 and 91 days. Lastly, scanning electron microscopy (SEM) was employed to examine the microstructural and morphological properties of the samples.

3 Results and discussion

3.1 Workability

The workability of the fresh concrete mixes was examined through the slump and VeBe tests. The results for the concrete mixes are shown in Table 3. The control mixture without fibre or CPA exhibited a slump value of 190 mm. As observed, the slump values of the concrete mixtures decreased with increasing fibre contents. The addition of fibres based on the volume portions of 0.25%, 0.5%, 0.75% and 1% decreased the slump to 120 mm, 75 mm, 50 mm and 40 mm, respectively. It can be deduced that the substitution of 10% CPA reduced the slump to values above Portland cement (CEM 1). Similarly, an increase in fibre content influenced the slump of CPA-based fibrous concrete, where 90 mm, 60 mm, 40 mm and 20 mm were obtained for equivalent volume fractions. This agrees with the findings of other researchers that used jute fibre and wheat straw ash [45] and sisal and periwinkle shell ash [46]. It can be inferred that the higher the fibre and CPA content in the concrete mix, the higher the value of VeBe time.

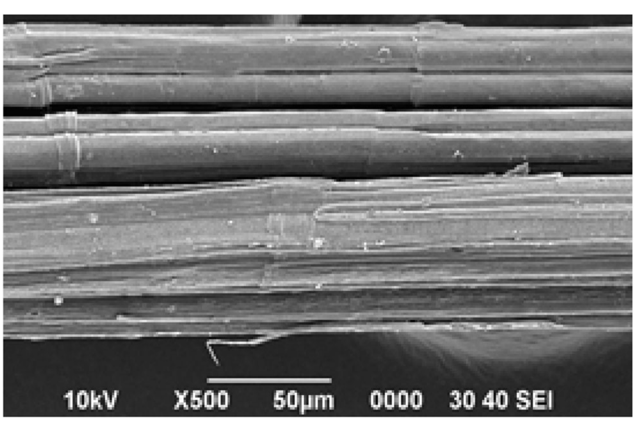

Fig. 4 SEM image of kenaf bio-fibre

3.2 Compressive strength

Figure 5 presents the results of the compressive strength test for the concrete mixtures examined in this study. The results show that the addition of KBF and CPA reduced the compressive strength of the cube. Comparison of the control mix (without KBF and CPA) showed that the concrete containing fibres at 0.25%, 0.5%, 0.75% and 1% had a corresponding decreased compressive strength by 5%, 8%, 15% and 20%, respectively after 28 days of ageing. The decrease in compressive strengths of 15%, 14% and 4% was observed in the concrete containing 10% CPA for the curing period of 7, 28 and 91 days respectively when matched with the Portland cement (CEM 1) concrete. For the fibrous mixtures containing 10% CPA and 0.5% fibre, the compressive strength decreased by 31%, 22% and 11% for similar curing times when compared to the Portland cement (CEM 1) concrete with similar fibre content.

The strength behaviour of concrete is principally affected by the tensile strength of fibres. Hence, fibres with greater tensile strength transmit higher tensile stress from a cracked region in concrete to other fibres [47]. In this study, the tensile strength of KBF is about 704 N/mm^2 or approximately equal to other virgin bio-fibres. The lower compressive strength of the fibrous mixtures could be due to the structural reorganization of voids on the addition of the KBF. However, the observation may also be due to the occurrence of a weak interfacial bonds between the particles of KBF and the cement-based CPA [48]. The results revealed that the compressive strength of the reinforced concrete is influenced by the presence of the KBF. However, the failure mode changed from brittle to ductile state.

Table 3 Concrete mixtures containing different amount of kenaf bio-fibre and CPA

Mix	Vf (%)	Vf (kg/m^3)	CPA (%)	CPA (kg/m^3)	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Water (kg/m^3)	Slump (mm)	VeBe time (sec)
S1	-	-	-	-	539.00	850.00	814.00	205.00	190.00	2.80
S2	0.25	3.00	-	-	539.00	850.00	814.00	205.00	120.00	5.10
S3	0.50	6.00	-	-	539.00	850.00	814.00	205.00	75.00	7.90
S4	0.75	98.00	-	-	539.00	850.00	814.00	205.00	55.00	9.00
S5	1.00	12.00	-	-	539.00	850.00	814.00	205.00	40.00	13.60
S6	-	-	10.00	53.10	485.10	850.00	814.00	205.00	155.00	3.90
S7	0.25	3.00	10.00	53.10	485.10	850.00	814.00	205.00	90.00	7.20
S8	0.50	6.00	10.00	53.10	485.10	850.00	814.00	205.00	60.00	10.00
S9	0.75	9.00	10.00	53.10	485.10	850.00	814.00	205.00	40.00	14.40
S10	1.00	12.00	10.00	53.10	485.10	850.00	814.00	205.00	20.00	16.80

3.3 Splitting tensile strength

Figure 6 displays the influence of KBF on the splitting tensile strength of concrete. As observed, the splitting tensile strengths of the concrete samples containing KBF are markedly greater than the control. Once the splitting occurred and was sustained, the KBF helped to bridge the fragmented portions of the samples. Likewise, the KBF transmitted the stress from the matrix to the fibres, thereby supporting the whole tensile stress. The transmitted stress eventually enlarged the capacity of the tensile strain of the concrete matrix. Hence, the tensile strength of the fibrous mixtures improved more than the equivalent non-fibrous concrete. Further analysis revealed that the combination of CPA and KBF enhanced the tensile strength of concrete as illustrated in Fig. 6. For example, the tensile strength of concrete with Portland Cement (PC-CEM 1) after the 28-day period increased by 16.56%, 25.15%, 27.30% and 20.25% for the KBF with the content of 0.25%, 0.5%, 0.75% and 1.0%, respectively, when associated with the plain concrete without fibre.

Furthermore, the blending of the CPA with the fibrous mixtures improved the splitting tensile strength with similar trends such as the PC (CEM 1) samples encompassing CPA. In other words, the mixture of KBF and CPA considerably improved the splitting tensile capacity of the mixtures. This observation occurred at lower rates when compared to the PC (CEM 1) mixtures at a primary age, which is ascribed to the pozzolanic nature of the CPA. At the age of 91 days, the KBF and CPA enhanced the tensile strength by 12.00%, 14.67%, 19.20% and 6.93% for similar fibre volume portions when associated with the mixtures without any CPA or KBF content. This improvement could be credited to the greater contact area among KBF, aggregates and cement paste, which resulted in an enhanced concrete performance at an advanced age. Similar observations have been made by Prakash et al. [49], who found that the addition of Roselle fibre to concrete mixtures containing fly ash and metakaolin ash have a positive effect on the concrete tensile strength.

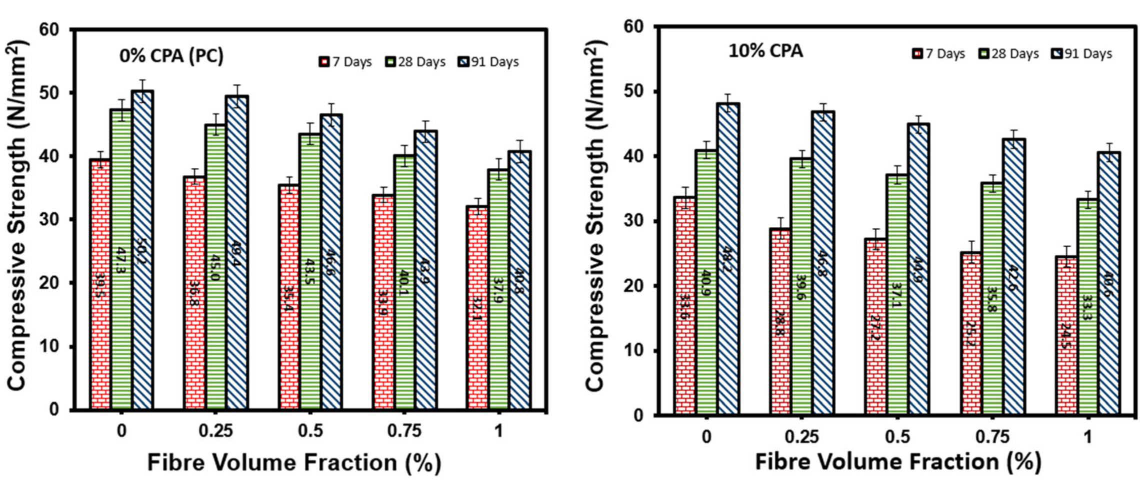

Fig. 5 Compressive strength of PC (CEM 1) and CPA kenaf bio-fibrous concrete mixtures

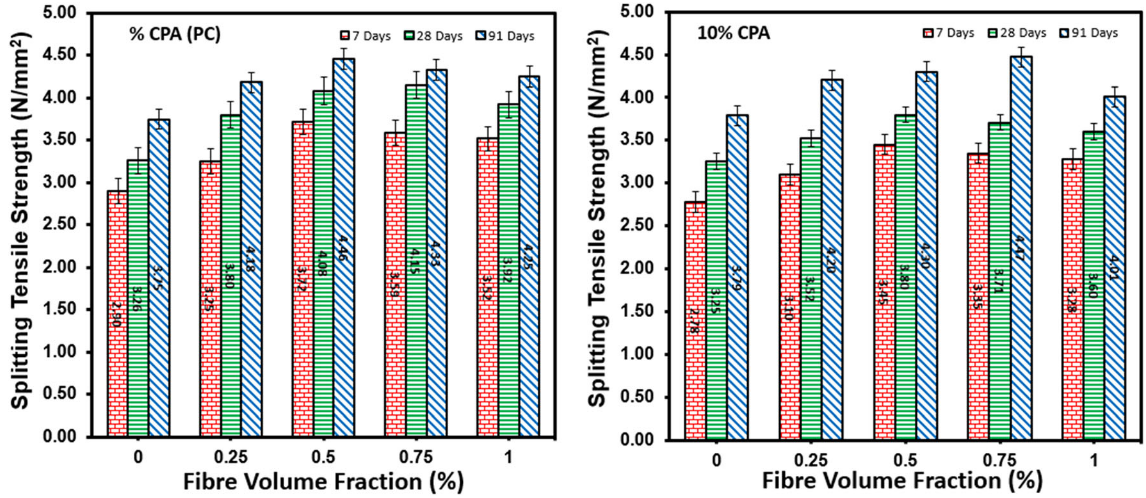

Fig. 6 Splitting tensile of PC (CEM 1) and CPA kenaf bio-fibrous concrete mixtures

3.4 Flexural strength

The study has shown that the KBF concrete exhibited considerably enhanced flexural strength when compared to the plain fibre less concrete. The flexural strength development displayed in Fig. 7 had a similar style of development with the tensile strength. The concrete mixture with 0.5% KBF inclusion produced the highest flexural strength with a strength value of 6.2 N/mm^2 at the curing period of 91 days. This strength value is 19% greater than the control mixture that is not CPA based or fibreless. The introduction of CPA in the concrete mix enhanced the flexural strength of the concrete predominantly at later ages similar to the tensile strength. The attained improvement in flexural strength ensued due to the crack bridging characteristic of fibres in the tension region of the prism samples. The KBF can grip the face of the crack parting through stretching, thereby resulting in a greater capacity for energy absorption, along with relaxing the stress in the micro-cracked region that connects the edge of the fissure [5]. Nonetheless, an additional increase in fibre volume fraction is occasioned in lesser flexural strength. The occurrence may be ascribed to the reduction in the concrete workability at high mixture contents. Factors such as insufficient concrete compaction, unbounded fibres or cracks, poor fire-matrix bonding and possible additional micro-cracks in concrete are linked to the higher amount of porosity in concrete [5].

3.5 Relationship of compressive, tensile and flexural strengths

Regression analysis was conducted using Microsoft Excel 2013 to determine the relationship between the three selected mechanical properties tested on the concrete. The power-law method was adopted in the regression analysis to examine the compressive, tensile and flexural strengths of the concrete. The importance of KBF on the concrete splitting tensile strength with or without the CPA was highlighted after the analysis. The splitting flexural and tensile strengths of the CPA-based KBFC are presumably related to the square root

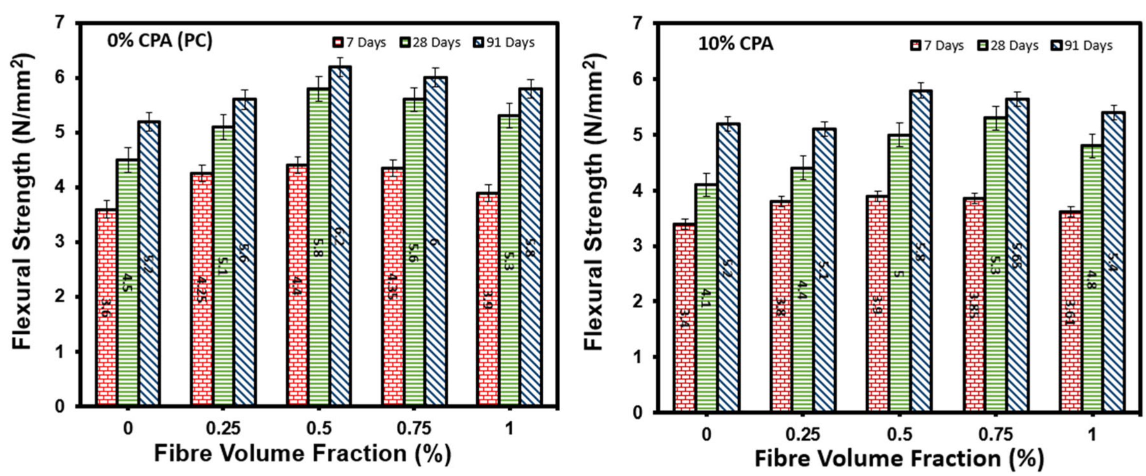

Fig. 7 Flexural strength of PC (CEM 1) and CPA kenaf bio-fibrous concrete mixtures

of their cube compressive strength as presented in Eqs. (1) and (2). Likewise, the splitting tensile of the CPA-based KBFC is predictably proportional to the square root of their flexural strength as shown in Eq. (3).

$$f_t = K\,(f_{cu})^{x} \quad (1)$$

$$f_f = K\,(f_{cu})^{x} \quad (2)$$

$$f_t = K\,(f_f)^{x} \quad (3)$$

where f_{cu} denotes cube compressive strength, f_f is flexural strengths and f_t is tensile strengths of concrete at different curing periods. K implies the constant value at different ages obtained from the regression analysis. Therefore, Eqs. (4)–(6) were resultants for defining the relations between the tensile-compressive strengths, flexural-compressive strengths and tensile-flexural strengths of all mixtures at the age of 7, 28 and 91 days.

$$f_t = 0.9734 f_{cu}^{\,0.3748} \quad (4)$$

$$f_f = 1.7161 f_{cu}^{\,0.5028} \quad (5)$$

$$f_t = 0.4040 f_{cu}^{\,0.6848} \quad (6)$$

The relationships between compressive, tensile and flexural strengths with the experimental data are presented in Fig. 8a–c. As observed, there is a good relationship between the tensile and compressive strengths, tensile and flexural strength as well as the flexural and compressive strengths at all ages. The determinant coefficient (R^2) that describes how the general change in the dependent variables is typically accounted for by the regression equation was established as 0.73, 0.84 and 0.72 for Eqs. (3)–(5), respectively. Furthermore, the results showed that for the CPA-based KBFC, the tensile and flexural strength values are closely related to each other, while the strength development ratio adheres to a similar pattern observed for the fibrous concrete mixtures with Portland cement. It was also observed that an increase in the tensile strength increased the flexural strength following Eq. (6). The findings of the current study suggest that the entire strength parameters for the fibrous mixtures containing CPA are in good agreement with the characteristic values of the KBFC from Portland cement (CEM 1).

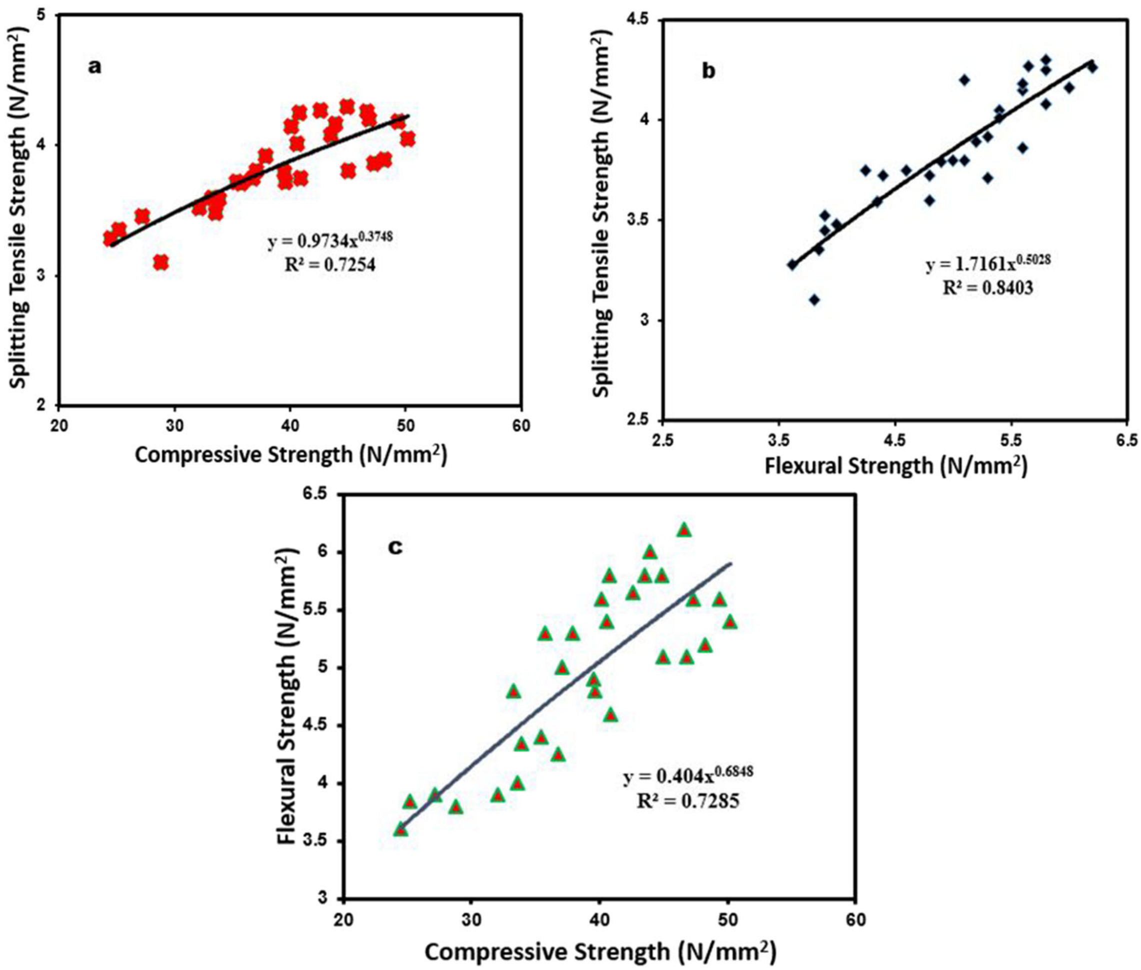

Fig. 8 Relationship of the **a** splitting tensile-compressive, **b** flexural-compressive and **c** splitting tensile-flexural strengths of concrete

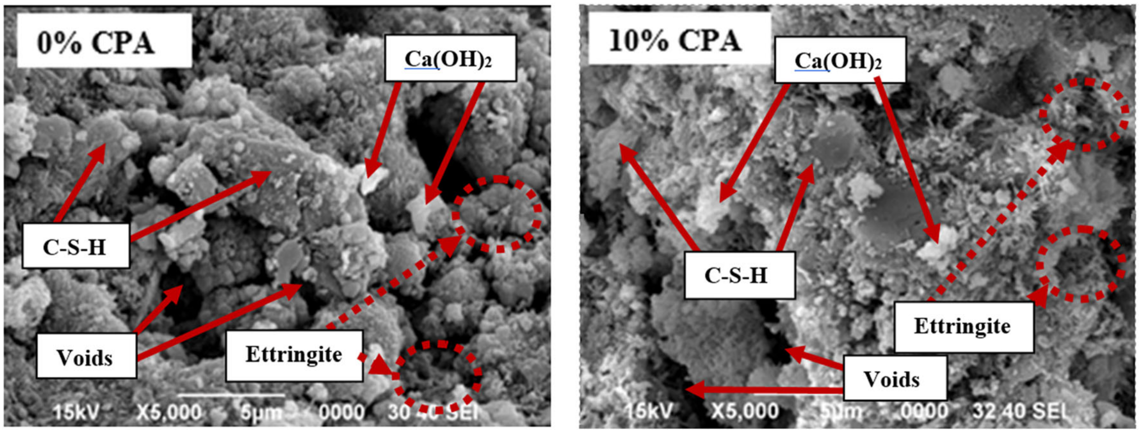

Fig. 9 SEM of PC (CEM 1) and CPA concrete mix at 91 days of hydration period

Largely, it is recognized that the splitting tensile and flexural strengths of concrete CPA-based KBFC are affected by similar reasons as the cube compressive strength. Such reasons are ascribed to the aggregate type, curing period, sample size, test method and w/c ratio employed in the research work [50]. Other factors such as the forms, shape, length, aspect ratio and content of the fibre could affect the splitting flexural and tensile strengths of KBF concrete. Lastly, the amount of test samples is a key issue since a greater test data range could deliver a greater accuracy on numerical authentication for numerous subjects [5].

3.6 Microstructural properties

The microstructure analysis of the CPA-based KBF concrete and the concrete samples with PC (CEM 1) and CPA content after 91 days of ageing were tested. The PC (CEM 1) and CPA samples examined using SEM showed the formation of C-S-H gel. As observed in Fig. 9, the C-S-H gel is more evenly secure in CPA concrete over the CEM 1 concrete specimen after the 91-day hydration period. The finely secure C-S-H gel and the formation of extra C-S-H gel can be ascribed to depletion of portlandite by the pozzolanic action of CPA. Consequently, the concrete mixtures exhibited better performance based on the strength properties. The observed enhancement in the performance is due to modification of the concrete matrix by the addition of CPA that lowered the content of $Ca(OH)_2$ and influenced the pozzolanic reaction in the concrete.

Figure 10 shows the SEM of the fibre-matrix interface of the CPA-based KBF concrete composite and the bridging action of fibres after fracturing in concrete. As observed, there is a good interface and bond of the fibre-matrix depicted in the results of the flexural and tensile tests of concrete containing the KBF. Furthermore, the SEM micrograph showed that the KBF along with the cement provided strong interfacial bonding (Fig. 10c) in the concrete. The strong interfacial bonding observed reduced the interface size of the crack. Hence, the strength of the fibrous concrete increases due to a decrease in the cracks.

4 Conclusions

The outcome of the experiments conducted in this study presented the following conclusions:

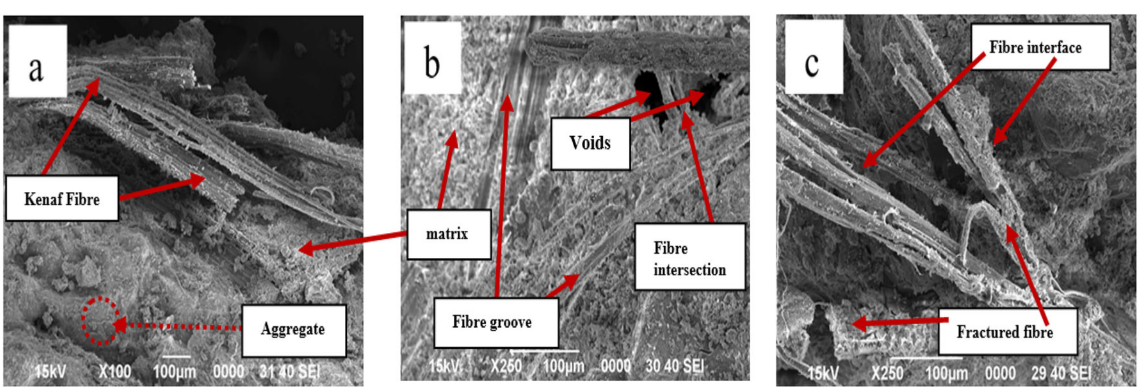

Fig. 10 SEM of **a** the fracture surface, **b** bridging action and **c** fibre-matrix interface of concrete containing 0.5% kenaf bio-fibre at 91 days of curing period

1. The inclusion and increase of the KBF volume fractions in the concrete mix generally decreased the workability of the concrete. The slump data of fibrous samples at 1.0% fibre decreased to 40 mm in comparison with 190 mm of CEM 1 plain concrete. Likewise, the addition of CPA lowered the workability of the fibrous and non-fibrous concrete mixtures. Lastly, the increase in fibre content in the fresh concrete mixture increased the VeBe time.
2. The incorporation of KBF in the concrete mix generally lowered the compressive strength of the concrete mixtures regardless of the content of CPA. The largest decrease in the early age (7 days) strength development happened at 19% and 38% for CEM 1 and CPA mixtures, respectively for 1.0% fibre content. After an additional rise in the hydration days up to 91 days, the decrease in strength improvement plunged to 19% and 19% for the CEM 1 and CPA mixtures, respectively. The strength development observed after further curing days of the concrete specimen was due to the pozzolanic behaviour of CPA in the concrete.
3. Kenaf bio-fibres positively and significantly influenced the tensile strength and flexural strength of the PC (CEM 1) and CPA-based concrete. The largest strength gain in the flexural and tensile strengths was witnessed in concrete samples with the fibre content of 0.5% after 91 days of ageing.
4. The microstructure analysis showed that the interfacial interactions of KBF, $Ca(OH)_2$ and C-S-H gel of the cement-based materials produced a robust bonding that enhanced the capacity of the load transfer in the matrix.
5. The exploitation of natural plants and agricultural waste streams such as kenaf bio-fibre and cassava peel ash, respectively, for concrete production, could yield economic and technical value for the construction business. Likewise, it has significant environmental benefits for the sustainability of the earth's resources.

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Data availability All related data is presented in the manuscript.

Declarations

Competing interests The authors declare no competing interests.

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