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RESEARCH ARTICLE

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Development and evaluation of kraft pulp-banana fibre-reinforced cement composites as a sustainable alternative to asbestos cement boards in Africa

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ABSTRACT

Many developing countries, particularly in Africa, still rely on carcinogenic asbestos fibres for producing cement boards used in roofing and cladding. This research focuses on creating a sustainable, affordable, and locally available alternative to asbestos. A specialised laboratory technique, designed to mimic industrial asbestos-cement board production, was used to develop kraft pulp–banana fibre reinforced cement composite boards. Their mechanical, durability, and morphological properties were tested after curing in a humidity chamber. Findings showed that boards made with 10 wt.% kraft pulp and 6 wt.% banana fibres achieved the best performance, with a flexural strength of 14.31 MPa and a deflection of 2.15 mm. Physical and morphological assessments confirmed that lightweight boards with strong fibre-matrix bonding can be achieved using kraft and banana fibres. The results also demonstrate that these hybrid fibre-reinforced cement boards meet relevant standards such as BS EN 12467, indicating that they are a safe and effective potential replacement for asbestos-based products.

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KEYWORDS
Natural fibre; waste cardboard; fibre cement board; cement composite; mechanical properties; affordable housing; African countries

1. Introduction

Over the last half-century, fibre cement boards (FCB) have drawn significant attention as one of the most valuable construction materials, particularly for affordable housing estates in developing nations [1]. Fibre cement board is a building material used in constructing internal and external walls, sometimes for cladding or roofing, partition walls, etc. A fibre cement board material is made from a mix of cement, cellulose fibres (wood has been the most common raw material in its origins), sand, water, and other additives. Cellulose fibres reinforce the material, enhancing its toughness and crack-resistance properties. The strength, durability, and aesthetic design freedom offered by fibre cement boards have all contributed to their widespread use in construction as a viable alternative for traditional building materials such as wood, plasterboard, or asbestos cement board [1]. Asbestos fibres (particularly chrysotile asbestos) have been the major mineral fibre used for the manufacturing of fibre-cement boards by many developing nations of the world due to their combination of excellent properties and relatively low cost [2]. Furthermore, asbestos fibres had a proven record of excellent performance in fibre-cement board production through the use of the Hatschek process, which is the major production method used in the industrial production of fibre-cement boards. Hence, the reason for the extensive use of this mineral fibre in many buildings and construction applications [3].

However, in the early-to-mid 19th century, clinical research by Cook [4], revealed health-related diseases caused by exposure to asbestos fibres. Other research related to occupational exposure [5,6] and non-occupational exposure [7] of asbestos presented facts and data that had a convincing influence on the scientific community. Hence, many developed countries began to establish serious regulatory measures and to some extent ban the use of asbestos fibres. For instance, an asbestos ban came into force in the entire European Union on the 1st of January 2005, in reaction to the continuing chronic asbestos-related diseases

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[2]. Other countries such as Japan, New Zealand, and Brazil followed with a prohibition on the use of asbestos in 2012, 2016 and 2017, respectively [8].

All the aforementioned developed countries were able to establish a ban on asbestos production and use because they possess the equipment, technology, and materials to manufacture non-asbestos fibre cement boards [9,10]. Conversely, most of the developing nations, particularly those on the African continent, do not have access to this new technology, mainly because they are either locked up in patents and/or too expensive to purchase and manage [11,12]. Furthermore, the high cost of advanced technologies (such as extrusion, calendaring, compression moulding, etc.) and specialised materials for producing non-asbestos fibre cement boards have greatly inhibited their adoption, especially in many developing countries, including Africa. These technologies, owned and patented by the Western world (e.g. the European Union) typically include highly advanced equipment and speciality fibres not available to those in many parts of Africa. Thus, many of these developing countries carry on using asbestos fibres not minding the health implications associated with its continuous usage, largely because the safer alternatives presented by the developed world are extremely expensive to purchase and manage. This reality stresses the urgent need for innovative solutions that can be implemented using indigenously sourced materials and technologies that are within the economic reach of these developing countries. The research presented in this paper responded to this issue by developing a kraft pulp-banana fibre-reinforced cement composite as a viable and sustainable alternative. Through the leverage of readily available materials like banana fibres and kraft pulp, this approach not only reduces dependence on highly expensive imports but also promotes the use of sustainable, indigenous resources. The development of this composite suggests a practical and economically viable solution for the production of non-asbestos fibre cement boards, making it accessible to developing countries that have not been able to adopt safer alternatives due to cost constraints. According to recent estimates, there is a strong probability that the occurrence and frequency of mesothelioma and other asbestos-related diseases in the general populace would rise due to current practices and regulatory structures in Nigeria [2,13]. The height of the threat from exposure to asbestos fibre and its related products in many developing countries calls for immediate attention and perhaps a long-lasting solution.

The development of environmentally friendly and affordable green materials for building construction applications has received significant attention in the last few decades [14–18], particularly in developed nations of the world. This is owing to the demand for less energy-intensive materials for use in building construction and the growing concern associated with the enormous CO_2 emissions of the construction industry [14]. However, numerous developing nations, especially those in Africa are yet to catch up on the need to maximise and utilise these sustainable and affordable building materials to tackle the housing demand of their ever-growing populations. According to the latest information from the Centre for Affordable Housing Finance (CAHF) in Africa, the problem of housing demand in many African countries continues to increase proportionately as the population of these countries increases. Many studies [19–28] have looked at the possibility that natural fibre is a resource that is safe for the environment and may be used as an ingredient for reinforcement when producing sustainable bio-composite materials for use in building construction applications. A summary of some related studies is presented below.

According to a study by Khorami [11], which employed kraft pulp and some selected synthetic fibres as an alternative to replacing asbestos fibre in producing fibre cement boards for building applications. The author studied 1–14% of kraft pulp fibre and reported that the optimum kraft fibre-reinforcement content was achieved between 8% and 10% of the cement weight. The author claimed that this optimum kraft fibre content provided a balance between the reinforcing fibres and the cementitious matrix; hence, they displayed the best properties in terms of flexural strength, toughness, and energy absorption.

Mugume et al. [29] described the influence of banana fibre addition at various fibre lengths on the microstructural and mechanical properties of reinforced concrete, they observed in their study that at lesser fibre concentrations of up to 0.25%, the length of the fibre had no discernible effect on compressive strength; however, at higher dosages exceeding 0.25%, shorter fibres were shown to outperform longer ones. Hence, they concluded in their study that banana fibre additions should be kept to a maximum of 1% of the total fibre content for best results, ideally using shorter fibres rather than longer ones.

In a similar study by Solomon and Olorunmeye [30], the influence of fibre volume fraction and length was studied on the mechanical properties of banana fibre-reinforced concrete. In their investigation, the authors reported that the 28-day cured concrete specimen with a combination of 0.5% fibre volume and

30 mm long fibre length achieved the optimum results in splitting tensile strength, flexural strength, and compressive strength with respective 28%, 25% and 22% improvement compared to the plain concrete. They concluded in their study that applying a 0.5% volume fraction and 30 mm length of banana fibre could be suitable for the production of grade 25 concrete for building applications.

Kubra and Leyla [31] researched the production of banana waste fibre-reinforced cement composite boards, incorporating a maximum of 4% fibre content by dry mass of the cement. They compared the results of their study with non-fibre reinforced cement materials and concluded that the banana fibre-reinforced composite board achieved a lower density, improved flexural strength, and the ability to restrict the initiation and growth of cracks within the composite board. Their findings agreed with those reported by another researcher [32] in the literature.

Furthermore, according to preliminary research conducted at the Commonwealth Scientific and Industrial Organization (CSIRO), Australia on the effectiveness of banana fibre as a source of reinforcing ingredient for air-cured plaster, air-cured cement, and autoclaved cement mortar, revealed that these composites, which contained 8% fibre by mass of the matrix, had physical and mechanical properties appropriate for building construction applications [33]. Hence, it is convincing to say that natural fibre is one of the sustainable materials with appropriate thermo-physical qualities, and low ecological effect, coupled with the fact that it is also less expensive and naturally biodegradable.

The pseudo-stem of the banana plant (*Musa sepientum*) yields the lignocellulosic banana fibre, which is a leaf fibre with comparatively strong mechanical qualities. The banana plant is a massive perennial herb that resembles a pseudo-stem due to its leaf sheaths. It can reach a height of 10–40 ft (3–12.2 m) and has 10–14 big leaves encircling it. Up to 9 ft long and 2 ft wide (2.7 m and 0.61 m) are made up of leaves [34]. Banana plants are extensively cultivated and processed as local food in many African countries, including Uganda, Rwanda, Ghana, Nigeria, and Cameroon, to mention a few [35–38]. The cultivation of this peculiar plant and its production in the aforementioned developing countries would provide substantial banana fibres as a by-product to the local industries involved in the manufacturing of fibre cement boards.

In all the aforementioned studies, the production of the composite boards and/or concrete specimens was carried out using the conventional (manual mixing/casting of concrete products) method of concrete production, which is difficult to adapt on an industrial scale. Furthermore, the composite production in most of these studies involved the utilisation of an admixture/aggregate (coarse or fine) to enhance composite strength and improve adherence to the cement matrix. All of which will contribute to increasing the cost of materials as well as the overall cost of production of the composite boards.

Therefore, the current research is aimed at producing cost-effective kraft pulp-banana fibre-reinforced cement composite boards by adopting a uniquely developed method that successfully mimics the industrial production process used for asbestos fibre cement sheets based on Hatschek technology. Thereby making the outcome of this study seemingly and easily adaptable on an industrial scale. Therefore, the current research presented a critical and competitive assessment of the mechanical, durability, and morphological properties of composite boards produced from kraft pulp and banana fibres only without any admixtures/aggregates. Hence, effectively lowers the cost of raw materials and the overall cost of production of the composite boards.

2. Materials and methods

2.1. Materials

The raw banana fibre utilised in the current study was industrially treated (bleaching of fresh plant stems through alkalisation/hydrolysis) and was supplied by the Company, World of Wool, whose original trading name was Europa Wools Limited, England. Recycled cardboard, or carton paper, served as the main source of kraft pulp fibre. Hanson Heidelberg Cement Group, UK, supplied standard Ordinary Portland Cement (OPC) type I, with high sulphate (HS52) BSEN 197–1 BSEN I, 52.5N. The Composites and Advanced Materials Centre provided the conical flask, vacuum pump, rectangular steel mould, rubber bung, hose, and other items required to successfully mimic the Hatschek method in the laboratory. Figure 1 displays the camera photo images of all the materials used in this research.

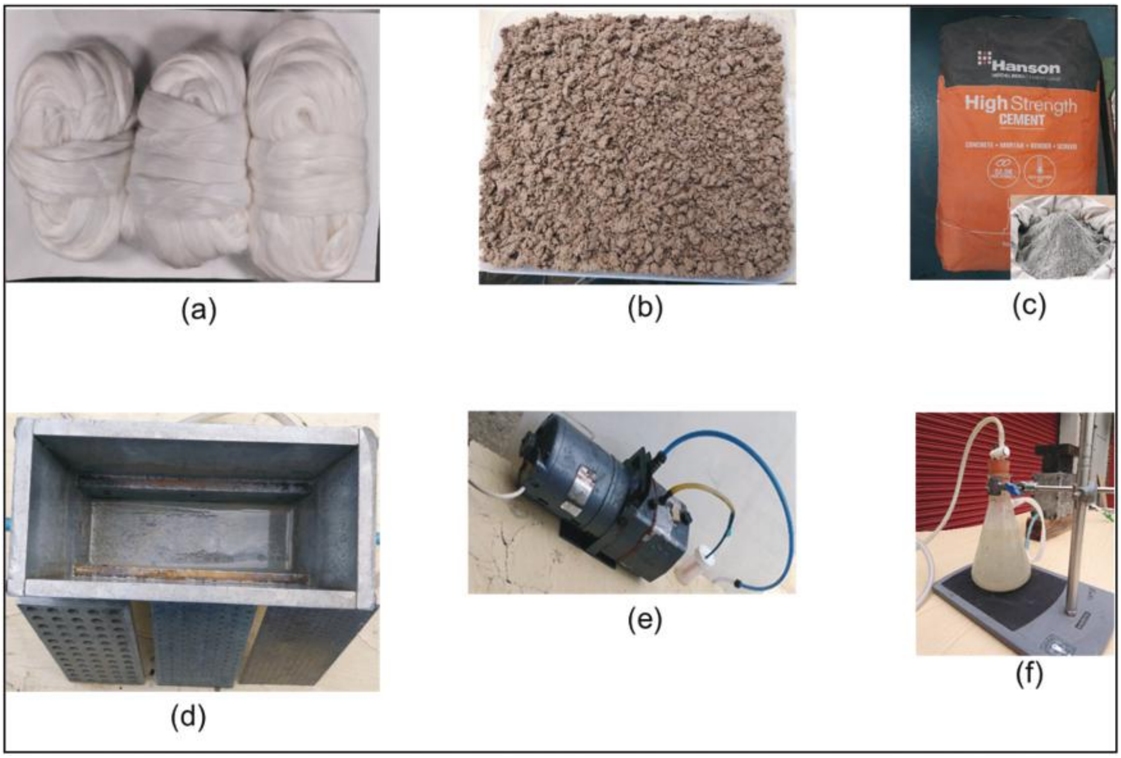

Figure 1. Photo images of the materials used in this research (a) banana fibre, (b) waste kraft fibre, (c) OPC, (d) mould and perforated metal plates, (e) vacuum pump, (f) conical flask and hose.

2.2. Methods

2.2.1. Preparation of banana fibre

The fresh banana fibres that Europa Wools Ltd. supplies are continuous, long strands that weigh about 4 m per 100 g of fibre. Since the fibres were acquired in an unusable state, they were manually chopped into short, distinct fibres that ranged in length from 4 to 6 mm before being incorporated into the composite boards. A photographic image of the banana fibres utilised in the current research and its preparation process is shown in Figure 2.

2.2.2. Mechanical and physical properties of banana fibres

According to ASTM D3822-07 [39] guidelines, the mechanical properties of the fibre (tensile strength and Young's modulus) were measured with the help of a single leadscrew Tensile Tester identifiable as DEBEN micro tester with model number MT200, which is fitted with a Leica 0.5X microscope. A gauge length of 10.2 mm was utilised for the soft cardboard mounting card while employing a 5 N load cell over a motor speed of 0.1 mm/min. Table 1 presents the physical and mechanical attributes of the fibres utilised in the current research. Ten (10) samples of the single fibres were analysed in each case, and Table 1 shows the average findings.

2.2.3. Thermogravimetric analysis (TGA)

To check the banana fibre's stability and heat resistance in the cement matrix's alkaline environment, as well as during the cement hydration process. The thermal characteristics of banana fibre were measured at a heating rate of 10°C/min over a temperature range of 30–600°C utilising a TGA Q500 equipment manufactured by the TA instrument. The ramp method for the TGA test was employed while conducting the test in a nitrogen atmosphere.

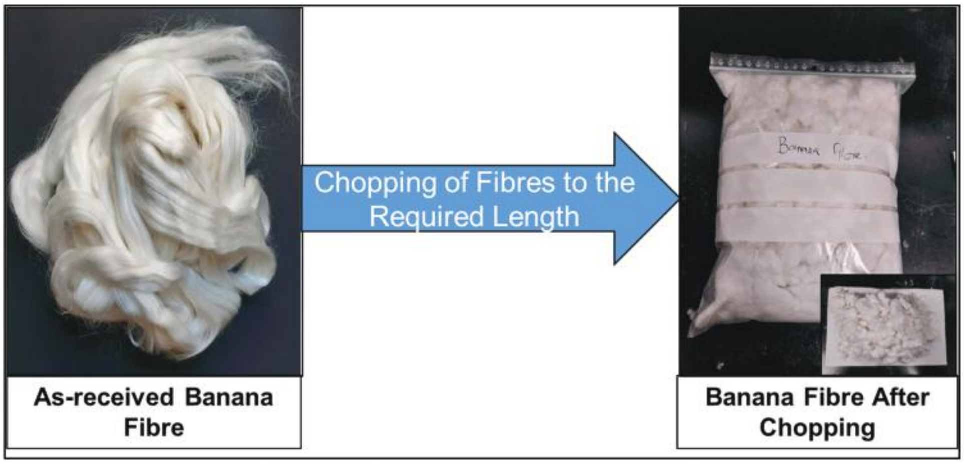

Figure 2. Image of the as-received fresh banana fibres and the prepared chopped fibres.

Table 1. Physical and mechanical attributes of the banana fibre.

Fibre Type	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Average length (mm)[a*]	Average diameter (mm)[b*]	Aspect ratio (length/ diameter)
Banana	632	25 ± 6.65	0.02 ± 0.01	5.8	0.03	193.33

a*, b*- Average of 10 measurements obtained from high-resolution Nikon Eclipse ME600 Microscope.

2.2.4. Production of kraft pulp fibre

Paper stores on the Cranfield campus provided recycled cardboard (cartons), which served as the main source of Kraft pulp fibre. Firstly, the carton papers were manually shredded into smaller units and all the foreign adjoining materials such as pins and glues were removed. After that, the carton papers were submerged in clean water for 48 h in the laboratory, using a 5:1 water-to-cardboard weight ratio. After 2 h of pulping the soaked carton papers with a leisure direct small washing machine with model number GWL-82718, the pulped carton paper was ground using a Kitchen type Table-top Blender with model TBBL20 at a low speed for a further 8–10 min. The product that came out of the blender was manually drained of the water used for the pulping process. The end product was stored at 3 ± 1°C in zip bags. The weight of the fibre plus water divided by the weight of the oven-dried kraft pulp fibre produces a kraft pulp fibre with a 70% average moisture content. Figure 3 demonstrates a pictorial representation of the production technique employed for producing the kraft pulp fibre.

2.2.5. Development of cement composite boards reinforced with kraft and banana fibres

The first production technique utilised in the industrial production of fibre cement board was developed by Ludwig Hatschek in the 1890s, and it was named after him as the Hatschek method. To create the fibre cement flat sheet, Ludwig combined Portland cement, reinforcing fibres, and cellulose with water to create a slurry. This slurry is then put inside a standard paper-making machine, where a cylindrical-shaped sieve or sieves rotate the slurry and then through a conveyor belt [11]. The production technique for the fibre cement board used in the current study was an inventive laboratory simulation of the Hatschek method. Banana fibre was used as individual reinforcing fibres to produce fibre-cement composite boards reinforced with various percentages (2, 4, and 6 wt.%) of banana fibre in the lab using the Hatschek procedure developed in the lab. The fibre was manually cut into short, distinct fibres that ranged in length from 4 to 6 mm, in accordance with the mix design displayed in Table 2. Next, a digital weighing scale (Scout Pro) having a 6-digit display and a precision of ±0.1 g was used for weighing each of the component materials (Kraft pulp, fibres, and cement matrix).

The composite production method described in the work of Taiwo et al. [40] was followed. To produce a fibre cement board using this method, 750 ml of water and a known weight of kraft pulp fibre were initially mixed using a portable handheld mixer running at 600–1900 rpm for approximately

Figure 3. Series of images showing the process of obtaining the kraft pulp fibre.

Table 2. Mix design for the production of cement composite boards.

Mix	Sample designation	Matrix Material (Cement) (g)	Kraft Pulp Fibre (K) (g)	Banana Fibre (BN) (g)
1	Control	200	0	0
2	K5	190	10	0
3	K10	180	20	0
4	K15	170	30	0
5	K20	160	40	0
6	K10-BN2	176	20	4
7	K10-BN4	172	20	8
8	K10-BN6	168	20	12

5 min. This ensures that the kraft pulp fibres are distributed uniformly throughout the water. Then, the kraft pulp mixture was mixed with the appropriate amount of banana fibre and the cement matrix, and everything was thoroughly mixed for 5 more minutes to achieve homogeneity. After mixing, the resulting slurry was successively poured into the rectangular steel mould measuring 180 mm by 80 mm that was already assembled, as shown in Figure 4(a). To remove the extra water from the combined slurry, the vacuum pump that was attached to the mould was turned on. The conical flask, which was intended for collecting the extra water, was fastened to one end of the mould. Applying a uniform weight of 12 kg on the mould while maintaining the vacuum pump running allowed the specimen to be compressed and any remaining water that could have become trapped in the now-thickened slurry was forced out. The vacuum pump was allowed to run for an additional 2–3 min before the sample was demoulded manually onto a levelled rectangular surface. Afterwards, the specimen was left for 15–20 min in the laboratory's air, the demoulded specimens were put in a high-humidity chamber for the completion of the curing and/or cement hydration process. The fibre cement board samples produced using this method were allowed to undergo cement hydration and/or curing by being put in a high-humidity chamber maintaining a temperature of 25 ± 2°C and 95% relative humidity. After curing the specimen for the appropriate number of days, they were evaluated for flexural properties following BS EN 12,467 [41] requirements after 7, and 14 days of hydration. For every mix design, ten samples were produced, of which 5 were tested after 7 days and the other 5, after 14 days of hydration. Every specimen has a dimension of 180 × 80 mm and, a thickness of 8–10 mm. Figure 4 shows the schematic of the basic elements of the industrial Hatschek process for fibre cement board production and the setup for the laboratory-replicated Hatschek process.

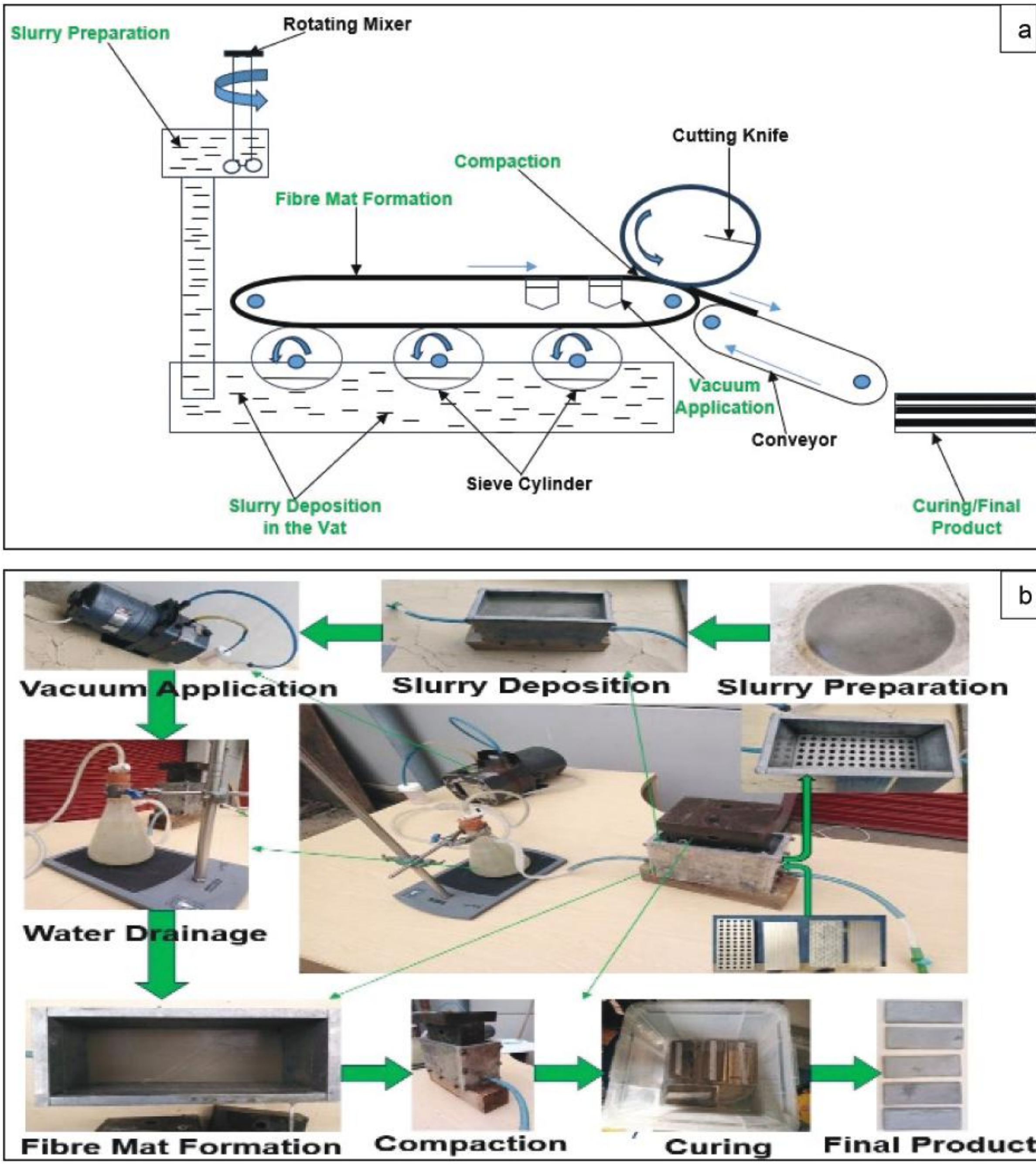

Figure 4. (a) Basic elements of the industrial Hatschek process for FCB production (b) setup for the laboratory simulated model.

2.2.6. Characterisation of the developed fibre-cement composite boards

Mechanical Property Test

In accordance with BS EN 12,467 [41] standards, the cured samples are subjected to a three-point bending/flexural test using an Instron 4467 Electromechanical testing machine. The sample has only to be simply supported, with one support permanently fixed, and the other should be free to move following the standard in order to align the sample. The radius of the upper face of every support further needs to be within the range of 3–25 mm to meet the specification given in BS EN 12,467 [41]. The equipment used for testing is seen applying a load to the sample in Figure 5(a), while Figure 5(b) shows a cross-section of a fractured sample after the bending test. All the samples were examined at a constant rate of loading using a crosshead speed of 5 mm/min to ensure that breaking occurs between 10 and 30 seconds of loading. This

Figure 5. (a) Bending test machine applying load on specimen (b) a cross section of fractured specimen after bend test.

guarantees that the sample meets the requirements listed in the standard. The span of the supports was set and held constant at 125 mm during the test. The flexural strength of the fibre cement board is known as the modulus of rupture (MOR), and it is calculated by applying the formulation of Equation 1.

$$MOR = \frac{3FL_s}{2be^2} \tag{1}$$

Where:

F = breaking load (N)
L_s = span between the axes of the supports (mm)
b = width of the specimen (mm)
e = thickness of the specimen (mm)

2.2.7. Determination of moisture movement of banana fibre reinforced composite boards

Following ASTM C1185-08 [42], the specimens were examined for moisture movement using a Gallenkamp TH340L environmental conditioning chamber, which can condition specimens at temperatures ranging from −40°C to 180°C and relative humidity levels from 10% to 98%. This was done to gain an understanding of the distinctive behaviour of the fibre-cement board when they are exposed to various climate conditions. For testing, three (3) samples were prepared. The samples have dimensions of 80 mm in width and 100 mm in length. The samples underwent practical equilibrium conditioning at 23 ± 2°C and 30 ± 2% relative humidity for 24 h. Following conditioning, the length of each sample was measured to the nearest 0.02 mm. The samples underwent additional conditioning to reach practical equilibrium at 23 ± 2°C and 90 ± 5% relative humidity for another 24 h. The length of each sample was measured and recorded one more time. Equation 2 was applied to determine the moisture movement (% change in length) based on these measurements.

$$L_m = \frac{L_{90RH} - L_{30RH}}{L_{30RH}} \times 100 \tag{2}$$

Where:

L_m = The change in length or linear moisture movement (%)
L_{90RH} = Length of the specimen at relative humidity of 90%, (mm)
L_{30RH} = Length of the specimen at relative humidity of 30%, (mm)

2.2.8. Water absorption characteristics of banana fibre reinforced composite boards

Water absorption was carried out per ASTM C1185-08 [42]. A temperature of 90 ± 2°C was used to dry three (3) 180 mm by 80 mm specimens of each board composition to a constant weight. Following the process of drying, the samples were allowed to cool inside the desiccator before being weighed to the closest

0.01 g. After that, the samples were soaked for 48 ± 8 h in clean water at 23 ± 2°C. After the allotted time, every sample was meticulously dried with blotting paper and weighed once more. Equation 3 was employed to get the percentage of water absorption.

$$W_A = \frac{W_S - W_D}{W_D} \times 100 \tag{3}$$

Where:

W_A = Water absorption, (%)
W_D = Dry weight of the specimen (g)
W_S = Saturated weight of the specimen (g)

2.2.9. Determination of the density of manufactured specimens

The density of the produced fibre-cement composite boards was determined in accordance with ASTM C1185-08 [42] by applying the water displacement method and adhering to Archimedes' principles. Initially, three (3) 180 mm by 80 mm specimens of each board composition were dried to constant weight in an oven set to 90 ± 2°C. Following the process of drying, the samples were allowed to cool inside the desiccator before being weighed to the closest 0.01 g. Following that, the samples were soaked in clean water at a temperature of 23 ± 2°C for 48 ± 8 h. After this time, each specimen was weighed underwater using Archimedes' principle to determine the suspended weight. Following a meticulous process of blotting the specimens dry, the saturated weight was determined and documented. The density of the samples was computed using Equation 4 as defined below.

$$D = \frac{W_D}{W_S - W_w} \times \rho \mathrm{w} \tag{4}$$

Where:

D = Density, in. (g/cm^3)
W_D = Dry weight of specimen, (g)
W_S = Saturated weight of specimen, (g)
W_w = Weight underwater (Suspended weight), (g)
ρ_w = Density of water, (g/cm^3)

2.2.10. Morphological examination of the fractured specimen using SEM

The fibre failure/fracture mechanism and fibre dispersion inside the composites were investigated on the broken surfaces of the fibre cement board specimens by utilising a scanning electron microscope (SEM), Tescan VEGA 3 equipped with an Oxford instrument detector. All fractured samples were inspected using the low vacuum mode in order to reduce specimen charging and improve conductivity for better imaging.

3. Results and discussion

3.1. TGA thermograms of banana fibre

In a bid to understand the interaction between the banana fibre and the cementitious matrix environment, the thermogravimetric properties of the fibre were examined in a Nitrogen atmosphere, and the result is presented in Figure 6. A three-stage degradation curve was noted in the thermal characteristics of the fibre. The initial phase of the decomposition profile, which spans a temperature range of 25–300 °C, is the elimination of the fibre's moisture content. Due to their lower heat stability, the non-cellulosic fibre components, such as hemicellulose, waxes, and other non-crystalline components, decompose in the second stage of the degradation profile. Additionally, it was noted that the banana fibre had only lost roughly 47% of its weight at a temperature of about 350°C. This is because banana fibre has a lower percentage of non-cellulosic components than the majority of other vegetable fibres, for example, compared to bamboo fibre. This was verified by Komal et al.'s [43] research, which examined the impact of chemical treatment on the degradation and thermal behaviour of polymer composites reinforced with banana fibres. They found that, on average, banana fibres have a lower non-cellulosic content than other vegetable fibres.

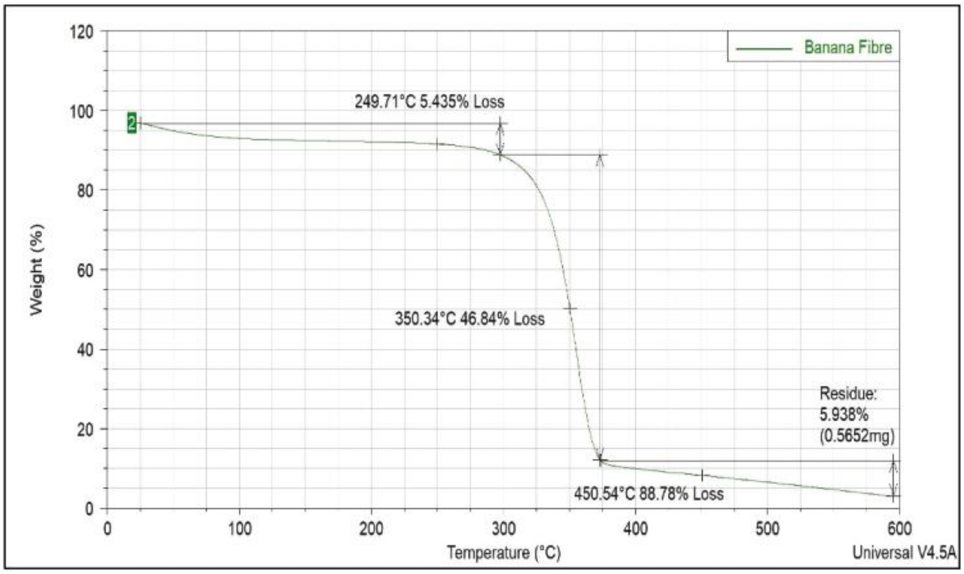

Figure 6. The TGA curves of banana fibre in a nitrogen atmosphere.

Furthermore, at 375°C, the temperature that marks the onset of the third stage of the decomposition profile, the cellulosic component of the fibre has not decomposed. As a result, the likelihood of the fibre degrading during the cement hydration process is reduced. This indicates that the fibre will not decay during the cement hydration process, since the temperature of the hydration process is only roughly 100°C. Additionally, at 600°C, the weight of the residual banana fibre was just 5.93%, according to the TGA curve. The fibre's heat stability was further demonstrated by the minimum percentage in the fraction of char content, which indicates that less banana fibre had been burnt off during the experiment. This was in agreement with the findings of Asim et al. [22], who found that a material's thermal characteristics improved with decreasing char content at test completion. As a result, the banana fibre displayed a stronger resilience against thermal decomposition.

3.2. Failure profiles of cement board samples under flexural load

The image in Figure 7 presents the failure profiles of different composite samples, including the control, kraft fibre-reinforced composites (K5, K10, K15, K20), and kraft-hybrid-banana fibre-reinforced composites (K10-BN2, K10-BN4, K10-BN6). These profiles provide insight into the failure mechanisms of the boards under flexural load. Firstly, the failure of the control sample shows clean, straight cracks, indicating brittle fracture behaviour. The fracture lines seem to propagate directly through the matrix without much deviation, thus, indicating the absence of any fibre reinforcement or its interference. The brittle nature of the fracture is typical of cement-based materials without fibres, where the load-bearing capacity beyond the peak load is minimal. This also explains the absence of significant energy absorption after the peak flexural strength is reached. On the other hand, the fracture lines in the K5 sample are slightly more irregular than in the control, with some resistance evident in the form of jagged crack paths. The cracks in the K10 sample showed more branching and deviation from a straight path, indicating better resistance to crack propagation compared to K5. The fibres possibly contributed to bridging cracks and delaying composite failure. In the same vein, the K15 sample shows a further improvement in crack profile, with significant fibre pull-out and crack bridging. The cracks are more twisted, showing that the fibres are arresting crack propagation effectively. While the K20 sample shows the most irregular crack pattern of the kraft fibre-reinforced composites. This indicates a high degree of fibre-matrix interaction, where the fibres help absorb energy and prevent brittle failure. However, it was observed that increasing the kraft fibre content (from K5 to K20 sample) results in a noticeable improvement in the toughness of the composites. Higher fibre content leads to increased crack bridging, pull-out mechanisms, and energy absorption during failure. This is consistent with the flexural strength and toughness enhancements typically associated with fibre reinforcement. For

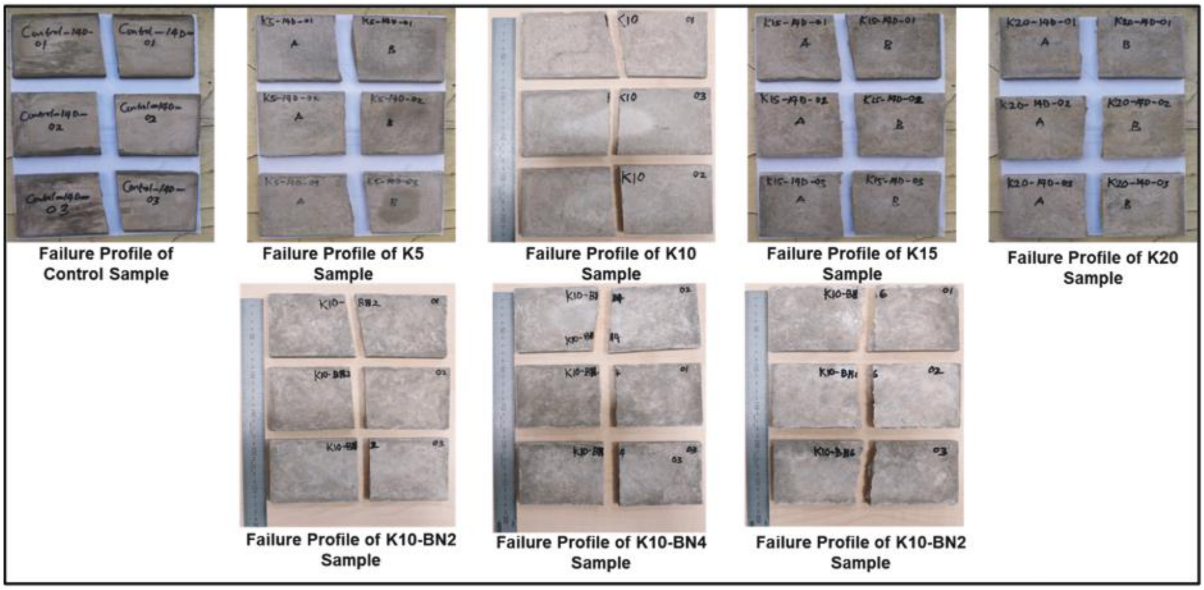

Figure 7. Camera photo of the failure profiles of the composite boards and the control sample.

the composite boards reinforced with kraft and banana fibres, the failure profile shows a more complex fracture mechanism compared to the K10 kraft-only sample. The presence of the banana fibres introduces a rougher, more irregular failure surface, suggesting better energy dissipation through fibre pull-out. Furthermore, the hybridisation of kraft and banana fibres appears to enhance the toughness and ductility of the composites. The failure mechanisms involve a combination of fibre pull-out, crack deflection, and fibre bridging. As the banana fibre content increases from K10-BN2 to the K10-BN6 sample, these mechanisms become more pronounced, indicating a synergistic effect between the kraft and banana fibres. The presence of banana fibres improves the composite's capacity to withstand higher deformation before failure, which is reflected in the results of the flexural performance of the hybridised composite boards as discussed later in this research.

In the industrial manufacturing of fibre cement boards, the Kraft pulp fibre is utilised to form a system that retains the cement particles in place during the water vacuuming phase of the Hatschek process [44–46]. In the laboratory-simulated Hatschek method, using Kraft pulp as a processing and reinforcing fibre has several benefits. For example, the fibre's enhanced surface roughness improves its adhesion to the matrix. The small length of these fibres also contributes to the uniformity and distribution of other natural fibres that reinforce the matrix, improving the fibre-matrix interaction and increasing the efficiency of reinforcement.

Figure 8 illustrates the flexural strength of FCB produced using different amounts of Kraft pulp at 7 and 14 days of hydration. It was noted that the continuous hydration process, which yields cement hydration products such as calcium silicate hydrate (C-S-H) and portlandite ($Ca(OH)_2$), caused the composite board's flexural strength to rise consistently as the hydration period extended from 7 to 14 days. Furthermore, up to a maximum of 10 wt.%, the flexural strength of the composite board increases consistently and steadily as the kraft pulp reinforcement content increases. Following this, the composite board's flexural strength gradually decreased. This was thought to be the result of excess kraft fibres in the composite that didn't react with cement particles, creating a weak point in the material that contributed to the observed decrease in flexural strength. According to research conducted by Khorami et al. [47], the proportion of fibres to cementitious matrix particles in the composite should be balanced. The authors investigated the impact of different residual waste cardboard contents (up to 14%) on the flexural behaviour of cementitious composites in their study on the utilisation of waste cardboard and nano-silica fume in the production of fibre cement board reinforced by glass fibres. They concluded that 8–10% of the cement matrix's mass should be the appropriate threshold for reinforcing fibres. Furthermore, it was discovered that the composite sample K5, which contained 5% kraft pulp fibre reinforcement, outperformed the control sample in terms of flexural strength, with values of 4.64 MPa and 5.45 MPa at 7 and 14 days, respectively. This represented

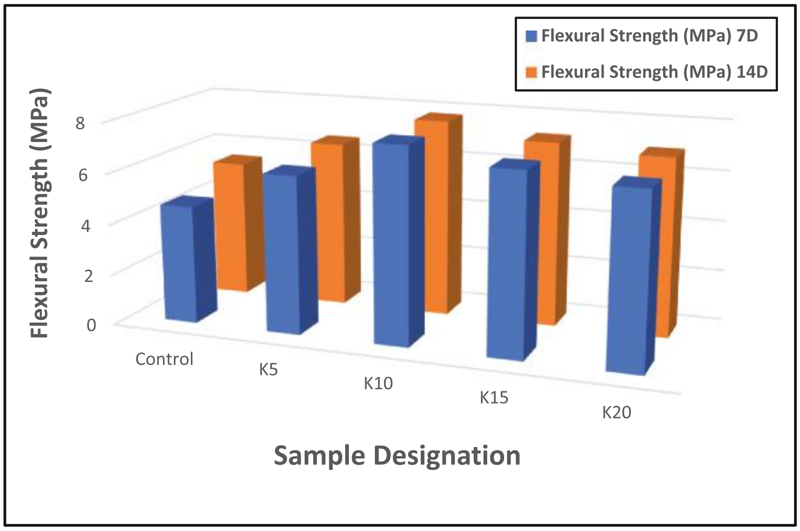

Figure 8. Flexural strength of composite boards reinforced with 5–20 wt.% of kraft fibre (7 & 14 days).

a 34% and 37% increase in strength. Similarly, at 7 and 14 days, the flexural strength values of the composite sample K10, which incorporated 10% kraft pulp fibre reinforcement, were 7.68 MPa and 7.78 MPa, respectively, showing a 65% and 43% improvement over the control sample. This showed that incorporating kraft pulp fibres into the cementitious matrix up to a maximum of 10% by weight can help the FCB achieve the optimum flexural strength.

Figure 9 shows the flexural strength of composite boards reinforced with 10 wt.% kraft pulp, and banana fibre at a varying percentage of 2–6 wt.%. It was noted that the inclusion of the banana fibres as a reinforcing agent produces a significant enhancement in the flexural strength of the composite boards even at the lowest reinforcement percentage. This could be traced to the intrinsic strength of the banana fibres as earlier recorded in Table 1. This inherent strength of the fibre will provide sufficient internal strength, coupled with the exceptionally high aspect ratio of the fibre which will provide a large surface area to allow adequate fibre-matrix interaction leading to the very high flexural strength recorded in the composite board. Furthermore, it was observed that a further increase in the reinforcement content also led to additional improvements in

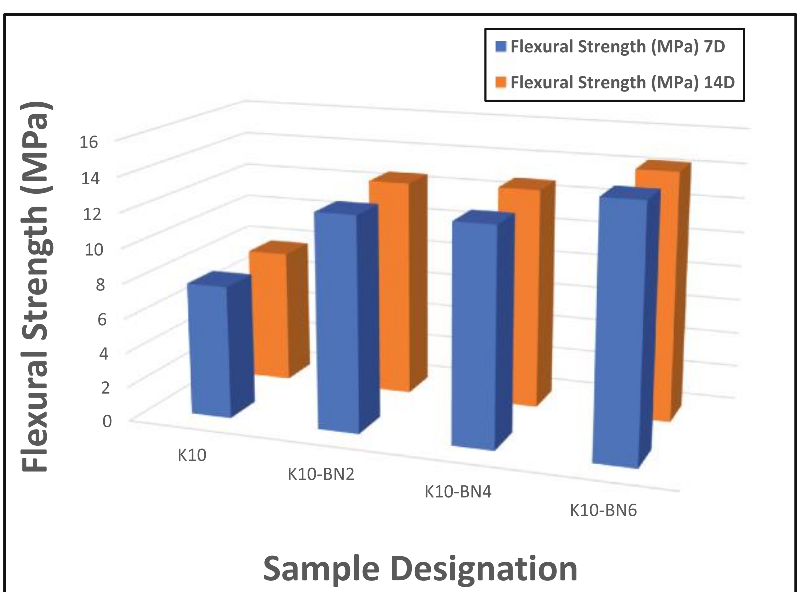

Figure 9. Flexural strength of composite boards reinforced by 10 wt.% of kraft pulp and 2–6 wt.% of banana fibre (7 & 14 days).

the flexural strength of the composite boards, hence, an optimal strength of 14.31 MPa was recorded in the composite board at 6 wt.% reinforcement content after 14 days of hydration. This resulted in an unprecedented enhancement in the flexural strength of the cement composite board, recording an 84% increase in flexural strength compared to the reference sample (K10) without fibre addition. This exceptional enhancement in flexural strength of the composite board recorded in the current study was in contrast to the results reported by some other researchers [29,48], who conducted similar research on banana fibre-reinforced composite boards. For instance, Mugume et al. [29], reported in their study on the influence of adding banana fibres at various fibre lengths and content on the microstructural and mechanical properties of reinforced concrete. The authors explained that the addition of banana fibres having a length of 40 mm and fibre content of 0.25% to their concrete mix produces an adverse effect on the flexural strength of the composite. However, they ascribe this negative influence on flexural strength to two factors, namely, the fibre length which prevented homogeneous distribution of the reinforcing fibres and increased porosity caused by fibre volume-to-matrix ratio. In a similar vein, Elbehiry et al. [48] reported an analogous downward trend in the flexural strength of composite beams reinforced with banana fibre bars and/or bundles. In their study, the authors explained that the observed downward trend in flexural strength of composite beams could be attributed to fibre-debonding caused by insufficient interfacial bonding at the fibre-matrix interface leading to the inadequate load transfer mechanisms from the matrix to the fibre. The positive result recorded in the current study which contrasted with the findings of the aforementioned researchers could be attributed to the short and discrete length of the fibres used in this study. The short and discontinuous fibre length provided a platform for the homogeneity of fibre distribution as well as achieving optimum bonding with the cementitious-matrix interface. Hence, the short fibres are effective for hindering or reducing the propagation of cracks within the composite boards. Furthermore, the unique method employed for composite production in the current study was also advantageous as it ensures the adequate mixing of materials as well as producing successively layered composite boards with random fibre orientation as also reported in the work of Akhavan et al. [49].

The flexural responses of cement composite boards reinforced with kraft pulp, and banana fibres were recorded in Figure 10. It was observed that all the composite boards containing banana fibre addition show improved flexural stress and response to deflection when compared to the reference composite without fibre addition. Considering the area under the stress-deflection curves, it was noted that an increase in the reinforcement content from 2 to 6 wt.% produces a significant improvement in the flexural response of the composite board, as observed in the composite samples containing 4 wt.% and 6 wt.% fibre loading which shows a wider area compared to the composite board without any fibre addition. This improvement in flexural response is attributed to the fibres' high aspect ratio allowing the fibres to have maximum contact

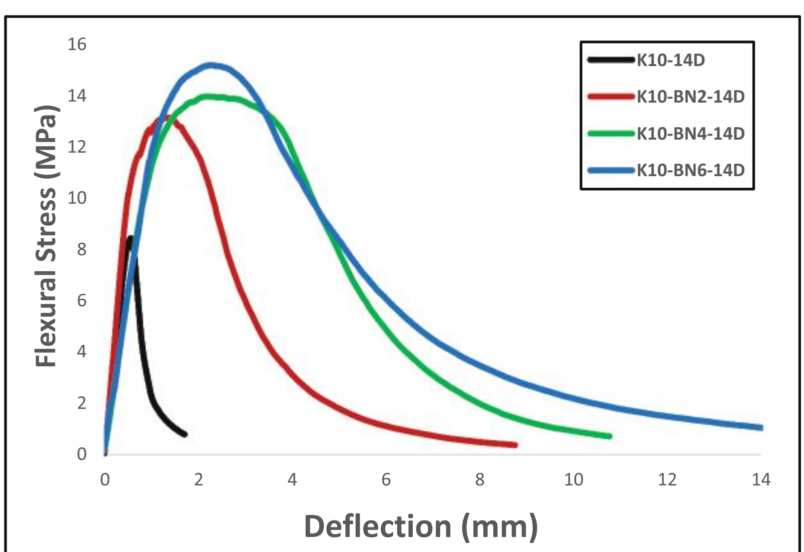

Figure 10. Flexural behaviour of composite boards reinforced by 10% of kraft pulp and 2–6 wt.% of banana fibre (14 days).

area with the cement matrix, leading to the formation of good interface bonding with the cementitious matrix. A similar observation was reported in the work of Khorami and Ganjian [50], when they compared the flexural behaviour of cement composites reinforced with wheat, bagasse, and eucalyptus fibres. The authors reported maximum flexural strength and improved ductility for bagasse fibre-reinforced composite boards due to the high aspect ratio of the bagasse fibres. In another study by Daneshfar et al. [51]; and Jadhav and Koli [52], the authors reported a substantial enhancement in the ductility of concrete composite reinforced with basalt and polypropylene fibres respectively. Both authors concluded that the improvement in ductility of the composite samples was due to the relatively high aspect ratios of the fibres. This proves that the addition of the banana fibre as reinforcement greatly improves the ductility and hence, the strain-hardening behaviour of the developed composite boards, permitting a slow and gradual failure of the composite boards as the stress values increases to a maximum level.

3.3. The influence of varying fibre content on the moisture movement characteristics of cement composite board

When the relative humidity of the environment around a cement composite board reinforced with natural cellulosic fibres rises, the composite boards may have an increased tendency to absorb moisture. This could alter the composite boards' dimensional stability, which could result in swelling. Nevertheless, the composite boards may desorb moisture as the surrounding relative humidity decreases, which could cause a corresponding shrinkage. However, to a considerable extent, a lot depends on the different components that make up the composite board as well as the period of exposure. This is because of the microstructural variations in the various elements that make up the cement board allowing them to absorb and desorb moisture at different rates. The moisture movement characteristics of the banana fibre-reinforced cement composite board depicted in Figure 11 followed a linear trend as the percentage of fibre reinforcement increased. A similar trend was reported in another study conducted by the authors [40]. It could be noted that the composite board containing lower fibre content shows a lesser extent of moisture movement when compared to those containing a higher percentage of fibre reinforcement. This is largely due to the intrinsic nature of the banana fibre being hydrophilic. Furthermore, it was observed that there is a commensurate change in the length of the composite boards as the percentage of fibre loading increases. This could be due to the existence of a higher percentage of fibre giving room for more moisture movement in the composite board containing higher fibre loading. Consequently, the difference in the percentage moisture movement or the change in length between composite boards containing 2 wt.% and 6 wt.% fibre loading is approximately 0.08%. Furthermore, according to related research authored by Wang et al. [53], and

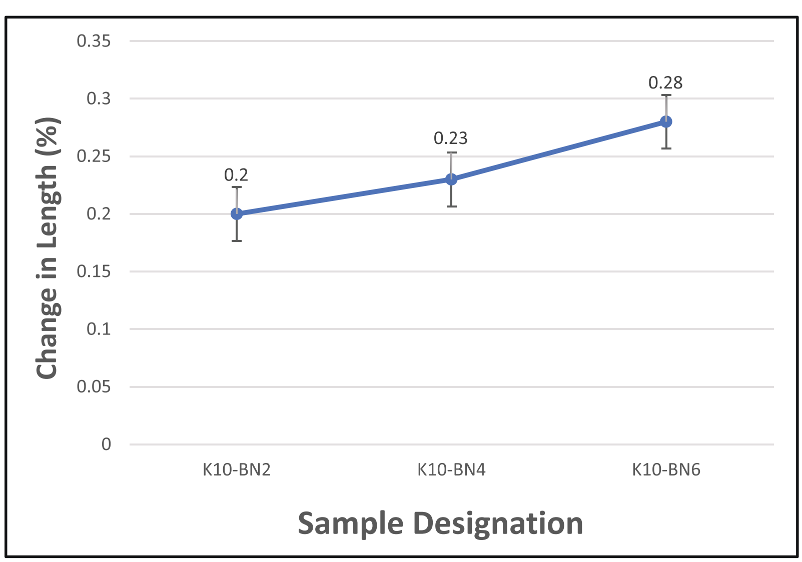

Figure 11. Percentage change in length of cement boards exposed to moisture movement.

Tonoli et al. [54], at typical air humidity and temperature, the equilibrium moisture content as a proportion of the oven dry weight is about 7%, but the moisture content required to thoroughly saturate the cement board is approximately 35%. This claim was further supported in detail by Maan's research [55], which examined the dimensional stability and moisture sensitivity of carbonated fibre-cement composites.

The Influence of Fibre Content on the Water Absorption Properties of Cement Composite Board

One of the very important physical qualities that should be assessed for a cement composite board is its water absorbency. This is because the water absorption property has a direct effect on the mechanical performance and dimensional stability of the composite board. Therefore, the water absorption properties of fibre-cement composite boards reinforced with 10 wt.% kraft pulp fibre and 2–6 wt.% banana fibre are presented in Figure 12. In another research conducted by the authors [40], the water transport mechanism in cement composite boards reinforced with natural cellulosic fibres was explained in detail. Furthermore, the water absorption property of the composite boards produced in the present study follows a similar trend that was reported in the literature by other researchers [56,57], who conducted similar investigations on fibre-cement composite boards reinforced with lignocellulosic fibre and stalk fibres, respectively. From Figure 12, it was observed that fibre content influenced the water absorption capability of the composite boards. This means that increasing the fibre content led to a subsequent increase in the water uptake potentials of the composite boards. According to the results of a study reported by Nassar et al. [58], as the fibre content rises, the water-to-binder ratio also rises, increasing the apparent void volume and, ultimately, the volume of water absorbed by the composite board. Moreover, a rise in fibre content causes a commensurate rise in porous fibre-matrix interfaces, which in turn increases the water absorption tendencies of the composite boards. Based on their research, the authors concluded that the water absorption capability of different types of fibres could also play an important role in defining the rate of increase in the water absorption capability of their corresponding cement composite board. Furthermore, it was believed that higher fibre content in the composite boards could mean several hydroxyl groups (OH^-) being made available for chemical reaction with the hydrogen (H^+) bond contained in the water molecules. A similar assertion was reported in the work of Ghofrani et al. [57]. Hence, the composite board containing the highest percentage of fibre reinforcement (K10-BN6) absorb the maximum volume of water with a value of 15.76% after 48 h of immersion in water. Producing an effective 17% increase in water absorption when compared to the reference sample K10 without banana fibre addition. This was followed by the composite samples K10-BN4 with a value of 13.93% and then K10-BN2 with a value of 13.76%. However, the reference sample K10 absorbs the minimum volume of water having a value of 13.4%, this was due to the absence of the banana fibre addition in the reference composite sample which has led to the sample absorbing the least volume of water.

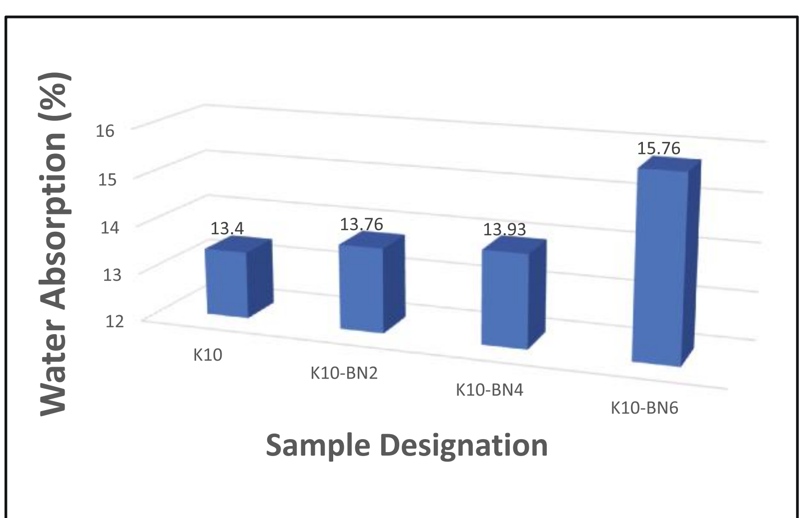

Figure 12. Percentage of water absorption of cement boards soaked in water for 48 hrs.

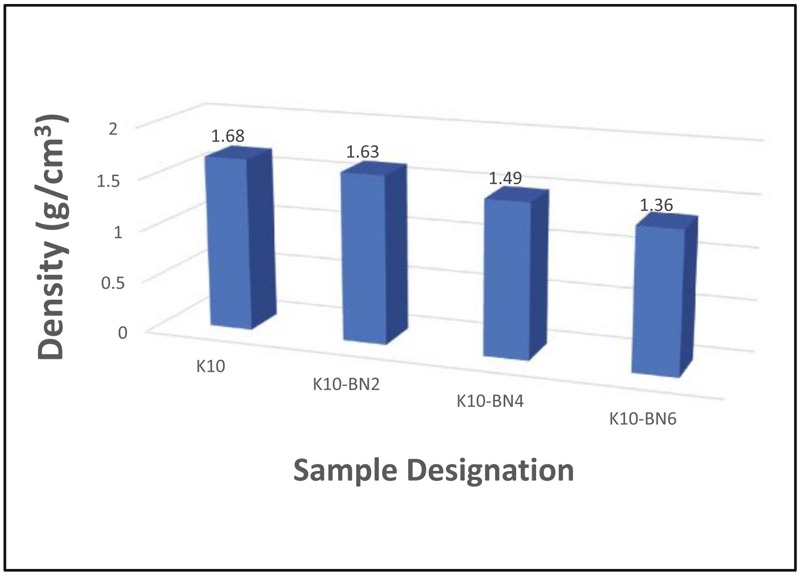

Figure 13. The density of FCB reinforced with kraft pulp and bamboo fibres.

3.4. The influence of fibre content on the density of cement composite board

The importance of lightweight structural materials for building constructions cannot be overemphasised in terms of their relevance in saving energy and overall cost (production, materials, and transportation costs) [40]. The effect of an increase in fibre reinforcement content with respect to the density of the cement composite board is presented in Figure 13. From the graph, it was observed that increasing the fibre content produces a gradual but effective reduction in the density of the composite boards. Several reasons such as the effective reduction in the percentage of cementitious matrix, as well as the inherent lightweight characteristics nature of the reinforcing fibre could be responsible for this observation. However, in the case of the current study, the effective reduction in the composite board's densities with respect to the increase in fibre reinforcement content could be traced to several factors such as the density of the matrix material and that of the individual reinforcing fibres including those mentioned above. Additionally, it was noted that the immediate presence of the banana fibre reinforcement in the composite board produces a small but noticeable change in the density of the composite board as observed in the composite sample K10-BN2 containing 2 wt.% banana fibre reinforcement with a density value of 1.63 g/cm^3 compared to the reference sample K10 with a value of 1.68 g/cm^3. A further increase in the fibre reinforcement content from 4 to 6 wt.% produces a significant reduction in the density of the corresponding composite boards, this implies that the percentage of fibre content in the composite board could have a direct influence on the ensuing density property of the cement board. Hence, the composite sample K10-BN4 containing 4 wt.% banana fibre reinforcement with a density value of 1.49 g/cm^3 showed a 13% reduction in density compared to the reference sample K10. In the same vein, the composite sample K10-BN6 with a 6 wt.% banana fibre reinforcement content and a density value of 1.36 g/cm^3 produces a 24% reduction in density as compared to the reference sample K10 having no banana fibre addition. The various density values reported in the current research suggested that the addition of up to 6 wt.% banana fibre as reinforcement in producing fibre-reinforced cement composite board could result in reducing the density of the composite board by twice its initial value. This means that by utilising banana fibres as a reinforcement in cement composite boards, lightweight structural materials with acceptable mechanical characteristics in terms of flexural strength and ductility (as discussed earlier in the study) could be produced for low-cost building applications in developing countries.

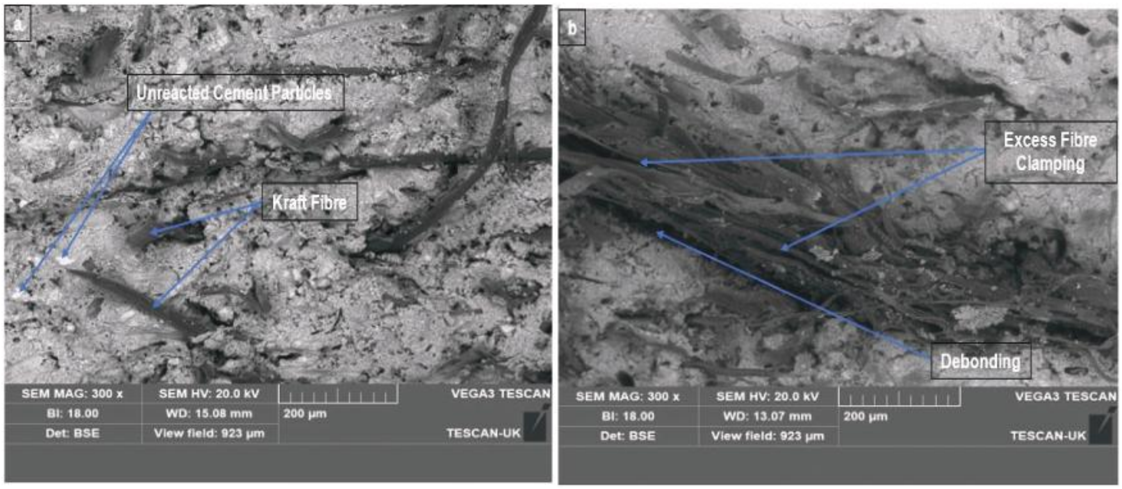

Figure 14. SEM morphology of the specimen reinforced with (a) 10 wt.% kraft pulp fibre (b) 20 wt.% kraft pulp fibre.

3.5. SEM micrographs of cement composite boards reinforced with kraft pulp and 2–6 wt.% of Banana Fibre

Figure 14(a,b) depicts the SEM morphology of composite boards reinforced with 10 wt.% and 20 wt.% of kraft pulp fibres, respectively. From the SEM micrograph in Figure 14(a), it was observed that the kraft pulp fibre had a good interface bonding with the cement matrix. This was attributed to the kraft fibres rough surface and its excellent aspect ratio, which has contributed to the fibres forming good mechanical interlocking with the cement-matrix. As a result of the sufficiently good mechanical bonding at the fibre-matrix interface in this composite, there was no evidence of the kraft fibres pulling out of the composite. This was evidenced in the flexural behaviour of the composite board as described previously in Figure 8. However, there were traces of unreacted cement particles, which could be due to the continuous progression of the cement hydration process. In Figure 14(b), which depicts the SEM micrograph of a composite board reinforced with 20 wt.% of kraft pulp fibre. Fibre-to-fibre clamping, balling effect, and agglomeration of the fibres was observed in this composite sample. All these effects could be caused by the presence of excess fibres, which had little to no cement particles to react with, because according to an investigation performed by Khorami et al. [47], the proportion of fibres to cementitious matrix particles in the composite should be balanced. Furthermore, evidence of fibre debonding was also noted in the fractured morphology of the composite board. Hence, all these effects could be responsible for the gradual reduction noted in the flexural strength of this composite sample as described previously in Figure 8.

Figure 15(a–c) presented the SEM micrographs of composite boards reinforced with kraft pulp and 2, 4, and 6 wt.% banana fibres, respectively. Fibre fracture and pull-out were observed in all the SEM micrographs of these composite boards, this confirmed that this set of composite samples reinforced with kraft pulp and banana fibres failed by a combined effect of fibre pull-out and fracture, an evidence that the composite boards showed a desirable level of flexural strength and ductility before failure. A similar evidence and observation were reported in the work of Nassar et al. [58]. A further justification for this was seen in the result of the flexural behaviour of this set of composite samples as earlier discussed and depicted in Figure 10. Additionally, in the SEM morphology of the composite board reinforced with 4 wt.% banana fibre (Figure 15(b)), the presence of the short and discrete length of the banana fibre was seen blocking the progression of crack propagation in a particular direction within the composite board. This shows that the randomly dispersed short banana fibres were able to arrest and/or impede the movement of crack propagation within the composite board. Furthermore, fibre gliding and effective bonding at the fibre-matrix interface were observed in the SEM morphology of the composite board reinforced with 6 wt.% banana fibre (Figure 15(c)). This could justify the reason behind the optimum flexural strength and high level of ductility shown by this composite sample as discussed previously in this report in Figures 9 and 10. In all the SEM micrographs presented in this report, there was no indication that cement hydration products had migrated into the fibres' lumen or

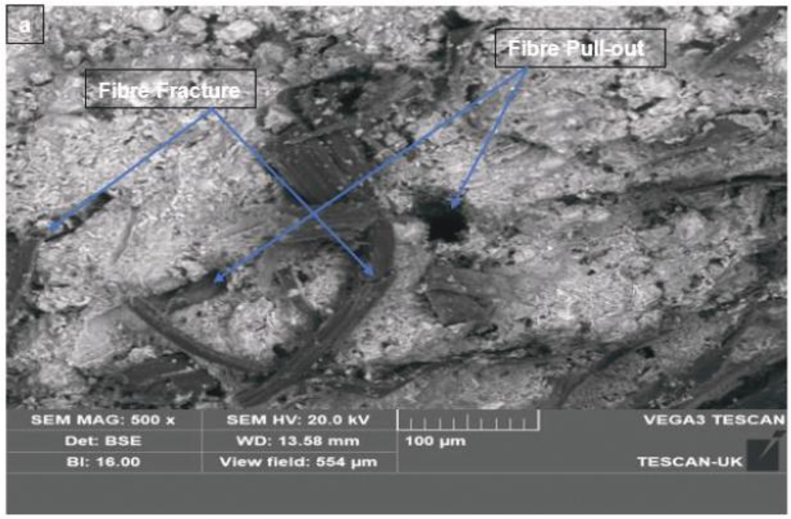

Figure 15a. SEM morphology of specimen reinforced with kraft and 2 wt.% banana fibre.

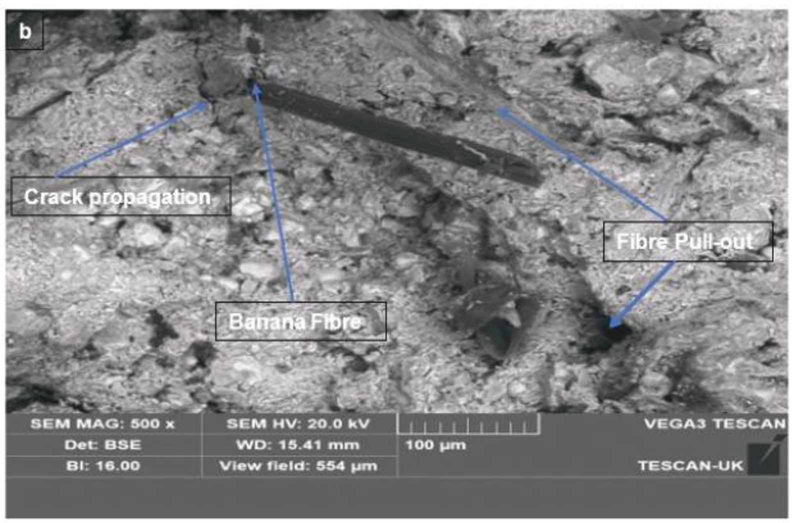

Figure 15b. SEM morphology of specimen reinforced with kraft and 4 wt.% banana fibre.

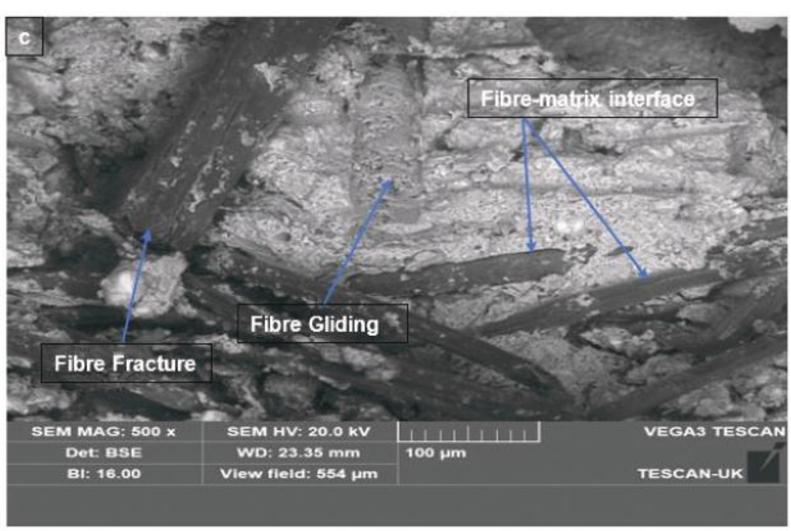

Figure 15c. SEM morphology of specimen reinforced with kraft and 6 wt.% banana fibre.

inner cell wall. Hence, the fibres retained their reinforcing capacity within the cement boards regardless of their interaction with the alkali environment of the cementitious matrix. This behaviour contradicts the observations reported by Ardanuy et al. [59] when they investigated fibre-matrix interactions in cement mortar reinforced with cellulosic fibres. However, the different behaviour detected in the current study could be explained, perhaps due to the degree of hornification and purity of the fibre studied in this research. Although the authors have reported a similar observation in one of their previous research projects [40].

4. Conclusion

The current research presented a critical evaluation of the mechanical, durability, and morphological properties of kraft pulp and banana fibre-reinforced cement composite boards. At the end of the experimental investigations carried out on the fibre-cement composite boards produced in the present study, the conclusions outlined below were drawn.

- The experimental result obtained from the thermogravimetric analysis study of the fibre proved that the banana fibre is stable thermally and will not decompose during the curing and/or hydration process of the cement matrix.
- Achieving optimal flexural strength and ductility in the composite boards requires a balance between the proportion of reinforcing fibres and the cement matrix; hence, an optimum percentage of 10 wt.% kraft pulp and 6 wt.% banana fibre is recommended for use in the composite development.
- The durability study of the different composite boards produced in this research proved that lightweight structural materials for exterior and/or roofing applications can be manufactured by combining 10 wt.% and 6 wt.% of kraft pulp and banana fibres, respectively, by weight of the composite composition.
- The SEM micrograph of the different composite boards showed that optimum bonding and/or good mechanical interlocking was achieved between the fibres and the cement matrix at the fibre-matrix interfacial zones. The composite boards produced from this research showed a combined effect of fibre pull-out and fracture as the primary means of failure.

To conclude, the banana fibre-reinforced cement composite boards produced in the current research exhibited flexural strength and flexural behaviour attributes that are highly suitable for fibre cement flat sheets under applicable standards (such as BS EN 12,467). Therefore, the composite boards produced in this study could be suitably recommended for external building construction applications in affordable housing in many developing nations.

Disclosure statement

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Data availability statement

All the data associated with the results presented in this paper are available from the authors on reasonable request.

References

[1] Savastano H, Warden PG, Coutts RSP. Potential of alternative fibre cement as building materials for developing areas. Cem Concr Compos. 2003;25(6):585–592. doi: 10.1016/S0958-9465(02)00071-9

[2] Moda HM, Sawyerr H, Clayson A. What will go wrong has gone wrong: asbestos exposure risk among construction workers in Nigeria. Polic Pract Health Saf. 2018;16(2):212–223. doi: 10.1080/14773996.2018.1492239

[3] Taiwo AS, Egbodion EO, Adediran AA, et al. Mechanical properties and water-absorption characteristics of selected natural fibers as a replacement for asbestos. J Mats Tech. 2021;55(1):97–104. doi: 10.17222/mit.2020.118

[4] Cook WE. Fibrosis of the lungs due to the inhalation of asbestos dust. Br Med J. 1924;2(3317):140–147.

[5] Gloyne SR, Merewether ER. Asbestos - occupation and health. In: Encyclopaedia of hygiene, pathology, and social welfare. Gineva: International Labour Office; 1938.

[6] Doll R. Mortality from lung cancer in asbestos workers. Br J Ind Med. 1955;12(2):81–86. doi: 10.1136/oem.12.2.81

[7] Thomson JG, Graves WM. Asbestos as an urban air contaminant. Arch Pathol. 1966;81(5):458–464.

[8] Allen L, Baez J, Stern M, et al. Trends and the economic effect of asbestos bans and decline in asbestos consumption and production worldwide. Int J Environ Res Public Health. 2018;15(3):531. doi: 10.3390/ijerph15030531

[9] Ganjian E, Khorami M, Sadeghi-Pouya H. Application of kraft and acrylic fibres to replace asbestos in composite cement board. In: Blanco A, de la Fuente E, Concepción Monte M, editors. The 11th International Inorganic Bonded Composite Conference; Madrid, Spain; Curran Associates, Inc, 2008. p. 52–61.

[10] Khorami M, Ganjian E, Srivastav A. Feasibility study on production of fiber cement board using waste kraft pulp in corporation with polypropylene and acrylic fibers. Mater Today. 2016;3(2):376–380. doi: 10.1016/j.matpr.2016.01.023

[11] Khorami M. Application of natural and synthetic fibres as a replacement for asbestos fibres in cement boards [Doctoral thesis]. United Kingdom: Coventry University; 2011.

[12] Ganjian E, Khorami M, Parhizkar T. Production of cement composite board using cellulose fibre. In: Zachar J, Claisse P, Naik TRanjian, E, editors. 2nd International Conference on Sustainable Construction Materials and Technologies; Ancona; UWM Center for By-Products Utilization, Milwaukee, WI, USA: UWM Center for By-Products Utilization, 2010. p. 145–152.

[13] Zephaniah HS, Aremu SO. Asbestos: a silent potent killer. Eur J Environ Public Health. 2019;3(2):2–7. doi: 10.29333/ejeph/5906

[14] Sangmesh B, Patil N, Jaiswal KK, et al. Development of sustainable alternative materials for the construction of green buildings using agricultural residues: a review. Constr Build Mater. 2023;368:130457. doi: 10.1016/j.conbuildmat.2023.130457

[15] Maghfouri M, Alimohammadi V, Azarsa P, et al. Impact of fly ash on time-dependent properties of agro-waste lightweight aggregate concrete. J Compos Sci. 2021;5(6):156. doi: 10.3390/jcs5060156

[16] Liuzzi S, Rubino C, Stefanizzi P, et al. The agro-waste production in selected EUSAIR regions and its potential use for building applications: a review. Sustainability. 2022;14(2):670. doi: 10.3390/su14020670

[17] Yaras A, Sutcu M, Gencel O, et al. Use of carbonation sludge in clay-based building materials processing for eco-friendly, lightweight, and thermal insulation. Constr Build Mater. 2019;224:57–65. doi: 10.1016/j.conbuildmat.2019.07.080

[18] Afolalu AS, Salawu EY, Ogedengbe TS, et al. Bio-agro waste valorization and its sustainability in the industry: a review. In: Iop Conf Series: Materials Science and Engineering. Bristol: IOP Publishing; 2021. p. 1170.

[19] Thomas BC, Jose YS. A study on characteristics of sisal fiber and its performance in fiber reinforced concrete. Mater Today Proc. 2022;51(1):1238–1242. doi: 10.1016/j.matpr.2021.07.312

[20] Long W, Wang Y. Effect of pine needle fibre reinforcement on the mechanical properties of concrete. Constr Build Mater. 2021;278:122333. doi: 10.1016/j.conbuildmat.2021.122333

[21] Krishna NK, Prasanth M, Gowtham R, et al. Enhancement of properties of concrete using natural fibers. Mater Today Proc. 2018;5(11):23816–23823. doi: 10.1016/j.matpr.2018.10.173

[22] Asim M, Uddin GM, Jamshaid H, et al. Comparative experimental investigation of natural fibers reinforced light weight concrete as thermally efficient building materials. J Building Eng. 2020;31:101411. doi: 10.1016/j.jobe.2020.101411

[23] Tian H, Zhang Y, Yang C, et al. Recent advances in experimental studies of the mechanical behaviour of natural fibre-reinforced cementitious composites. Struct Concr J Of The Fib. 2016;17(4):564–575. doi: 10.1002/suco.201500177

[24] Ferrara L, Ferreira SR, Krelani V, et al. Cementitious composites reinforced with natural fibres. Cementitious composites reinforced with natural fibres. In: Barros J, Ferrara L, Martinelli E, editors. Recent advances on green concrete for structural purposes. Research for development. Cham: Springer; 2017. p. 197–331. doi: 10.1007/978-3-319-56797-6_9

[25] Khorami M, Khalilitabas A, Noorbakhsh A. Increasing the flexural strength capacity of cement composite with natural fibres. Iran J Wood Paper Sci Res. 2009;24(2):206–218.

[26] Akers SAS, Studinka JB. Ageing behaviour of cellulose fibre cement composites in natural weathering and accelerated tests. Int J Of Cem Compos Lightweight Concr. 1989;11(2):93–97. doi: 10.1016/0262-5075(89)90119-X
[27] Sharma NK, Kumar V. Studies on properties of banana fiber reinforced green composite. J Reinf Plastics Compos. 2013 15;32(8):525–532. doi: 10.1177/0731684412473005
[28] Balda S, Sharma A, Capalash N, et al. Banana fibre: a natural and sustainable bioresource for eco-friendly applications. Clean Techn Environ Policy. 2021;23(5):1389–1401. doi: 10.1007/s10098-021-02041-y
[29] Mugume RB, Karubanga A, Kyakula M. Impact of addition of banana fibres at varying fibre length and content on mechanical and microstructural properties of concrete. Adv Civ Eng. 2021;2021(1):1–15. doi: 10.1155/2021%2F9422352
[30] Solomon IA, Olorunmeye FJ. Influence of lengths and volume fractions of fibre on mechanical properties of banana fibre-reinforced concrete. Int J Recent Innov Eng Res. 2017;2(6):49–58.
[31] Kübra EB, Leyla T. Production of banana waste fiber cement composite. In: Jideani IO, Anyasi A, editors. International Civil Engineering & Architecture Conference; Turkey; IntechOpen, 2019. p. 258–266.
[32] Zainal SI, Abel M, Durai D, et al. Experimental investigation on the mechanical properties of cement mortar containing recycled tire crumbs reinforced with polypropylene, oil palm and banana fibers. J Building Eng. 2024;92:109728. doi: 10.1016/j.jobe.2024.109728
[33] Zhu WH, Tobias BC, Coutts RSP, et al. Air-cured banana-fibre-reinforced cement composites. Cem Concr Compos. 1994;16(1):3–8. doi: 10.1016/0958-9465(94)90024-8
[34] Subagyo A, Chafidz A. Banana pseudo-stem fiber: preparation, characteristics, and applications. In: Afam, IOJ, Tonna, AA editors. Banana nutrition - function and processing kinetics. London, UK: Intech Open; 2020. p. 1–19. doi: 10.5772/intechopen.82204
[35] Workman D. Bananas exports by country. 2016. Available from: http://www.worldstopexports.com/bananas-exports-country/3363
[36] Food and Agricultural Organization of the United Nations (FAO). Banana market review. Rome; 2020. cited 2023 Oct 14th from https://www.fao.org/documents/card/en?details=CB6639EN
[37] Evans E, Ballen F. Banana market, IFAS. University of Florida; 2015 [cited 2023 Jul 4]. Available from: http://edis.ifas.ufl.edu/fe901
[38] Saxena T, Chawla VK. Banana leaf fiber-based green composite: an explicit review report. Mater Today Proc. 2021;46(28):6618–6624. doi: 10.1016/j.matpr.2021.04.099
[39] ASTM D3822-07. Standard test method for tensile properties of single textile fibers. ASTM International, West Conshohocken. West Conshohocken: ASTM International; 2007.
[40] Taiwo AS, Ayre DS, Khorami M, et al. Optimizing the mechanical properties of cement composite boards reinforced with cellulose pulp and bamboo fibers for building applications in low-cost housing estates. Materials. 2024;17(3):646. doi: 10.3390/ma17030646
[41] BS EN 12467. Fibre cement flat sheets – product specification and test methods. London: British Standards Institution; 2012.
[42] ASTM C1185-08. Standard test methods for sampling and testing non-asbestos fibre cement flat sheet, roofing and siding shingles, and clapboards. West Conshohocken: ASTM International; 2016.
[43] Komal UK, Verma V, Ashwani T, et al. Effect of chemical treatment on thermal, mechanical and degradation behavior of banana fiber reinforced polymer composites. J Nat Fiber. 2020;17(7):1026–1038. doi: 10.1080/15440478.2018.1550461
[44] Correia VC, Santos SF, Savastano Jr H, et al. Utilization of vegetable fibers for production of reinforced cementitious materials. RILEM Tech Lett. 2018;2:145–154. doi: 10.21809/rilemtechlett.2017.48
[45] Santos SF, Tonoli GHD, Mejia JEB, et al. Non-conventional cement-based composites reinforced with vegetable fibers: a review of strategies to improve durability. Mater Constr. 2015;65(317):1–20. doi: 10.3989/mc.2015.05514
[46] Bezerra EM, Joaquim AP, Savastano H, et al. The effect of different mineral additions and synthetic fiber contents on properties of cement-based composites. Cem Concr Compos. 2006;28(6):555–563. doi: 10.1016/j.cemconcomp.2006.02.001
[47] Khorami M, Ganjian E, Mortazavi A, et al. Utilisation of waste cardboard and nano silica fume in the production of fibre cement board reinforced by glass fibres. Const Building Mater. 2017;152:746–755. doi: 10.1016/j.conbuildmat.2017.07.061
[48] Elbehiry A, Elnawawy O, Kassem M, et al. Performance of concrete beams reinforced using banana fiber bars. Case Stud Construct Mater. 2020;13:e00361. doi: 10.1016/j.cscm.2020.e00361
[49] Akhavan A, Catchmark J, Rajabipour F. Ductility enhancement of autoclaved cellulose fiber reinforced cement boards manufactured using a laboratory method simulating the Hatschek process. Constr Build Mater. 2017;135:251–259. doi: 10.1016/j.conbuildmat.2017.01.001
[50] Khorami M, Ganjian E. Comparing flexural behaviour of fibre–cement composites reinforced bagasse: wheat and eucalyptus. Constr Build Mater. 2011;25(9):3661–3667. doi: 10.1016/j.conbuildmat.2011.03.052
[51] Daneshfar M, Hassani A, Aliha MRM, et al. Investigating flexural performance of fiber-reinforced concrete with different contents and types of macrosynthetic fiber. Strength Mater. 2022;54(10):1–12. doi: 10.1007/s11223-022-00443-x

[52] Jadhav HS, Koli MD. Flexural behavior of hybrid fiber reinforced concrete beams. Int J Struct Civ Eng Res. 2013;2(3):210–218. Available from: www.ijscer.com
[53] Wang Q, Banthia N, Sun W, et al. Water permeability of eco-friendly ductile cementitious composites (EDCC) under an applied compressive stress. Cem Concr Compos. 2019;107:103500. doi: 10.1016/j.cemconcomp.2019.103500
[54] Tonoli GHD, Belgacem MN, Siqueira G, et al. Processing and dimensional changes of cement based composites reinforced with surface-treated cellulose fibres. Cem Concr Compos. 2013;37:68–75. doi: 10.1016/2Fj.cemconcomp.2012.12.004
[55] Hassan MS. Moisture sensitivity and dimensional stability of carbonated fibre–cement composites. Adv Cem Res. 2018;30(9):413–426. doi: 10.1680/jadcr.17.00141
[56] Hasan KMF, Horváth PG, Alpár T. Development of lignocellulosic fiber reinforced cement composite panels using semi-dry technology. Cellul. 2021;28(6):3631–3645. doi: 10.1007/s10570-021-03755-4
[57] Ghofrani M, Mokaram KN, Ashori A, et al. Fiber-cement composite using rice stalk fiber and rice husk ash: mechanical and physical properties. J Compos Mater. 2015;49(26):3317–3322. doi: 10.1177/0021998314561813
[58] Nassar RUD, Soroushian P, Balachandra A, et al. Effect of fiber type and content on the performance of extruded wood fiber cement products. Case Stud Construct Mater. 2022;16:e00968. doi: 10.1016/j.cscm.2022.e00968
[59] Ardanuy M, Claramunt J, García-Hortal JA, et al. Fiber-matrix interactions in cement mortar composites reinforced with cellulosic fibers. Cellul. 2011;18(2):281–289. doi: 10.1007/S10570-011-9493-3

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