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INNOVATIVE USE OF AGRICULTURAL WASTES FOR ECO-FRIENDLY CONSTRUCTION

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Abstract
The inclusion of agricultural wastes in construction has drawn research attention in recent times. In this work, wastes including fibres obtained from different parts of the oil palm tree, chicken feather and sugarcane bagasse, are considered. Information is also provided on the properties, enhancement techniques, current and potential application of the wastes in construction. An extensive review on oil palm fibres is presented as well as the incorporation of sugarcane bagasse and chicken feathers, as additive, in the production of unfired clay bricks is reported. The clay mixes partially replaced (by volume) at 1, 3, and 5% of either of bagasse fibres and feather fibres were prepared and cube specimens of (5x5x5) cm^3 were made by moulding. Tests results reveal that the addition of the wastes leads to 13% and 3% reduction in brick density, each at 5% feather fibre and bagasse fibre inclusions respectively. Furthermore, improvement in compressive strength reached 78% while linear shrinkage in the clay samples is reduced. The use of agricultural wastes as cheap and environmentally-friendly construction materials is beneficial towards provision of affordable housing in developing countries.

Keywords: Agricultural wastes; Earthen bricks; Oil Palm Fibre; Chicken feathers; Sugarcane bagasse; Construction.

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1. INTRODUCTION

The continual increase in cost of infrastructure on one hand and global environmental concerns on the other hand, has favoured the inclusion of agricultural wastes in construction as beneficial additives or possible alternatives to conventional construction materials. Major raw materials used for construction include clay, timber, cement, aggregates and steel. Steel for example, has numerous advantages, but, it is expensive from both cost and environmental standpoints. The mining and processing of iron ore into steel and the process of employing steel in the construction and servicing of buildings contributes up to 50% of carbondioxide to the atmosphere [1]; this is subsequently responsible for global warming and environmental climate change.

Asides the attendant negative environmental impact of conventional materials in construction, economies of developing countries have found it difficult to provide decent housing for their citizens due to the ever-increasing cost in building materials. These same countries face the worst agricultural waste disposal problems. Therefore, there is the need to seek and employ agricultural wastes with potentials as either building materials or as beneficial additives. Examples of such agricultural wastes include; wheat straw, rice husk, Bambara nut husk, groundnut husk, chicken feathers, sugarcane bagasse, several fibres of vegetative origin and ash from these wastes. Their use in construction is sustainable, since they are readily available, considerably more economical to process and possess zero-carbon footprint.

Due to the afore-mentioned, the use of sustainable materials in the construction industry has become a key focus of engineers, researchers and scientists [1-9]. For instance, several studies have been carried out to incorporate several kinds of agricultural and industrial waste in bricks manufacturing. This include attempts such as analyzing the effect of inclusion of processed waste tea [10], vine shoots [11], wood ash [12], palm oil fly ash [13], rice husk ash [14], wheat straw residues [15], corn cob [16], sheep wool [17] crumb rubber [18] and polystyrene [19] in the production of clay bricks.

Numerous advantages are associated with the use of agricultural wastes for cement and soil composites. Most outstanding among these advantages include;

low-cost, zero-carbon footprint, light-weightiness, toughness, biodegradability, non-toxicity to the ecosystem, thermal insulation, improved acoustic insulation and high recyclability [9,20-28]. For instance, it has been shown that a 16kg bale of straw retains 32kg of carbon dioxide [29]. From this calculation a typical 3-bedroom house would require about 350 bales thereby retaining 11.2 tonnes of carbon dioxide, thus, leading to a more sustainable and environmentally friendly construction.

2. AGRICULTURAL WASTES

About 2 billion tonnes of agricultural wastes are produced annually. This quantity represents a production rate of 7 times more than the quantity of industrial wastes produced globally [29]. Some of these wastes are plant materials discarded in the form of seeds, empty husks, or animal material in the form of bones, shells, furs and feathers. It is estimated that the world's population shall grow by over 2.3 billion people by the year 2050, that is, over a third of the current population and much of this growth is expected to occur in the developing world [30]. The implication of this is a proportionate increase in agricultural activities. This means that, aside the anticipated increase in agricultural wastes [27,31], there will be attendant pressure on already-scarce infrastructure and hence the need to provide low cost housing by governments of these developing nations for the teeming population [20,24,32,33].

An example of a plant with huge waste generation is oil palm tree. Studies reveal that in developing countries, there have also been disposal problems with fibres of the oil palm origin [34]. These fibres are either by-products of the process of extracting palm oil from palm fruit, cultivation activities or remains of the trees at the end of their useful life. The wastes are usually disposed indiscriminately or used by the locals as cooking fuel, both of which are not environmentally friendly. For instance, it is deduced that total oil palm wastes worldwide which presently stands as 83 million tonnes per year (dry weight) is projected to experience a 40% rise by the year 2020 [35].

3. NATURAL FIBRES FROM AGRICULTURAL WASTES

Natural fibres can be defined as threads or filaments whose origins are from plants, animals or geological processes. These filaments have found diverse applications ranging from textile-making to construction. The use of wheat straw for reinforcing bricks dates back to ancient times. In recent times however, natural fibres have found applications in reinforcing civil engineering composites like soils, mortars and concrete. The aim of incorporating them in construction is to enhance the strength of the resulting composites. For example, natural fibres are incorporated in concrete to improve its ductility and tensile resistance.

Numerous advantages of the use of natural fibres in cement composites have been reported. For example, A 10% reduction in weight, 80% reduction in energy required for production, and 5% reduction in cost of component used as compared to a fibre-glass reinforced component is reported [2]. However, the characteristic high water absorption capacity of natural fibres results in poor workability in fresh concrete, degradation in alkaline environment, and as a consequence, reduces desirable properties like tensile and bond strengths in the long term [20,36-39]. Several treatments such as alkalization, silane addition and non-permeable coating, can be adopted to overcome these setbacks [7,8,20,40,41]. On another note, the high water absorption of natural fibres can be beneficial for internal curing of the composite [42,43]. Use of natural fibres to reinforce cement composites in lieu of asbestos has been reported to eliminate the risks of exposure of human lives to diseases such as asbestosis, cancer, malignant pleural disease and tumours [44]. On these health grounds, some countries have in addition, ensured that the procedure for obtaining natural fibres is pollution free and environmentally sustainable. They are also available across the world and fibres domiciled in any region can be enhanced to suit applications for that climate thereby reducing material importation [9,32].

3.1 OIL PALM FIBRES

Although, investigation into reinforcing concrete with oil palm fibres started in the 1980's [2], the increasing level of awareness of the importance of environmental sustainability has led to increased research into the use of natural fibres. Fibres obtained from all parts of the oil palm have been studied for possible use in construction [33,35,46-54]. This includes investigations of the fibres' engineering properties [38,47-49,55-63]. However, there have been inconsistencies in the experimental methods employed, and reported values of fibre properties. Organised information on fibre properties will not only be useful for research, and design of oil palm fibre-cement composites, it will also aid researchers in making informed decisions when investigating the use of the fibres in construction.

Obtained oil palm wastes from plantation sites include, oil palm shell (OPS), empty fruit bunch (EFB) fibre, pressed fruit (or mesocarp) fibre, trunk fibres (OPTF), frond fibres (OPFF) and until recently, oil palm broom fibre (OPBF) [33,64].

Different types of oil palm wastes are discussed in sections 3.1.1-3.1.4.

3.1.1 Empty Fruit Bunch (EFB) Fibres

Fibre residues obtained after the removal of the fruit and processing of oil from the fruit bunch are called empty fruit bunch (EFB) fibres. EFB is different from the fruit fibres even though some studies [43,51,52] assumed otherwise and the fibre properties reported may be misleading for engineers wishing to employ them in construction . For example, Sreekala *et al.* [51] in their study used empty bunch fibres as a combination of the bunch fibres and the mesocarp fibres. The study reported an average yield of 400g of EFB fibres per fruit bunch. Kelly-Yong *et al.* [65] reported 4.4 tonnes of EFB fibres per hectare per year, as waste from oil palm refineries. They were either discarded as waste [22,51], or used as fuel in boilers for the generation of electricity for the oil palm plantation mills. Other uses of the fibre include, manure, mulching [66], and of recent, in polymer composites [50,67-70].

3.1.1.1 Extraction of EFB Fibres

EFB fibre is usually extracted by mechanical, chemical (immersion and boiling in chemicals), or microbial retting [66]. Firstly, palm oil is obtained by crushing the fruit bunches, which include fruit shells and husks, sieved to reduce impurities, loosened up, washed, dried and finally cut into the required lengths [61]. A decorticating machine for EFB fibre extraction was developed by Jayashree *et al.* [71] which separate the fibres through the beating action of the blades.

3.1.1.2 Morphology

The porous surface morphology of EFB fibres can be advantageous for fibre-matrix interlocking, therefore, previous studies have also investigated the surface topology of the fibres using a scanning electron microscope (SEM) in order to further understand its microstructure [45,51].

3.1.1.3 Chemical Composition

Palm fibres are mainly composed of cellulose, hemicellulose, hollocellulose, lignin and ash [72]. The EFB fibres is made up of lignin (19%), cellulose (65%) and ash (2%) while the mesocarp fibres is made up of lignin (11%), cellulose (60%) and ash (3%) [51]. Based on these values however, it is reasonable to classify the mesocarp fibres as EFB fibres. The chemical composition of oil palm EFB fibres obtained from literature is presented in Table 3.1. Despite attempts made to capture chemical composition of EFB fibre within a range [73], there are still discrepancies with the values reported by researchers.

3.1.1.4 Fibre Treatments/Enhancements

Several treatment methods for enhancing the strength of EFB fibres have been reported in literature [51]. Notable among them are alkalisation, acetylation and silane treatments. For alkali treatment, fibres are soaked in a solution of 5% NaOH for 48 hours, after which they are washed with fresh water and dried. However, this treatment could result in reduction of cross-sectional diameter for both EFB fibres and mesocarp fibres. Silane treatment usually results in fibre weight loss (up to 7%) and an increase in hydrophobicity by forming a protective monolayer on proton-bearing surfaces, thereby reducing water absorption. Silane treatment can be used for fibre surface treatment where hydrophobicity of fibre is the most desirable characteristic.

Thermal degradation is a key disadvantage of natural fibres since lignin, the binding agent for cellulosic fibres, begins to dissolve, at temperatures above 200 ^{0}C [44,51]. Table 3.2 presents weight loss of untreated and treated fibres, at varying temperatures. Degradation at elevated temperature is synonymous with strength loss and this might indicate poor structural resilience against fire.

Alkali-treatment can increase pore sizes on the surface of the fibres by up to 200% and cause rough surface topography of fibres as a result of the removal of hemicellulose, lignin and waxes. The resulting rough surface topography could enhance fibre-to-

Table 3.1. Percentage dry weight composition of Oil Palm EFB fibres from literature

	Composition (%)							
References	Lertwattanaruk and Suntijitto (2015)	Mayowa and Chinwuba (2013)	Shibata *et al* 2008	Sreekala *et al* (1997)	Ismail and Yaacob (2011)	Bahari (2010)	Koba and Ishizaki (1990)	Khalil *et al* (2012)
Cellulose	-	0.62	65	38.3	59	-	-	43-65
Hemicellulose	-		-	35.3	2.1	24.0	20.8	17-33
Holocellulose	47.7	-	-	-	-	65.5	-	68-86
Lignin	24.5	58.8	19	22.1	25	21.2	28.5	13-37
Ash	6.99	-	2	1.6	3.2	3.5	5.6	1-6

microaggregate bonding in cement composites. This phenomenon is due to the pectinolytic community of bacteria that develops as a result of the treatment. It degrades the pectin which is the main cementing part of the hemicellulose that is responsible for binding the fibre together [74]. Other effects of alkali treatment on fibres include reduced diameter and increased aspect ratio [51]. Alkali treatment is regarded as the most effective and preferred treatment against thermal degradation of OPFs [41,51]. Therefore, in the likelihood of exposure of component to fire, OPFs could therefore be alkali-treated prior to inclusion in cement-based composites for fire resistant application.

3.1.1.5 Mechanical Properties

EFB fibres have cross sectional diameter of between $0.015x10^4$ - $0.05x10^4$ μm and fibre density is in the range of 0.7 - 1.55g/cm^3 [51]. This range of values leads to a large variation of mechanical properties in oil palm fibre-cement composites. Fibre treatment has no significant impact on the elongation of the fibres which was about 14% for the EFB fibres and 17% for mesocarp fibres. The reported strain result in Sreekala *et al.* [51] differ from the results of Shareef and Ramli [47] and Ismail and Yaacob [22] with untreated fibres strains of 4% and 30% respectively. The tensile strength of mesocarp fibres and EFB fibres were increased by 38.8% and 10% respectively as a result of silane treatment [51]. Some physical and mechanical properties of EFB fibres obtained from literature, are presented in Table 3.3.

3.1.1.6 EFB Fibres in Cement Composites

A study of the effect of EFB fibre inclusion on the compressive strength of 1:4 cement-sand mortar ratio, recommends an optimum fibre length of 12mm and optimum fibre content of 0.6% with compressive strength increase of up to 23% [59]. The resulting mortar is self-compacting and could find choice use in the repair and retrofitting of concrete structures.

EFB fibres are also used to reinforce concrete roof slates. The fibres are used for partial replacement of cement in the roof slates. Regardless of the reduced density, flexural strength of the roof slate increases with percentage fibre content. This flexural strength for 1% EFB fibre inclusion exceeds the ASTM requirement of 4MPa [48]. The study of Shareef and Ramli [47] who reported a 15.1% and 16% increase in compressive strength and flexural strength respectively using 1% fibre inclusion by volume is hence corroborated. Another study revealed an optimum fibre volume and length of 0.5% and 5cm respectively [75]. Longer fibres were reported to create balling effects in the concrete and made mixing difficult. Compressive strength increase of 39% was also recorded. EFB fibre volume of less than 1% can be used for controlling shrinkage cracking in concrete. For structural elements requiring enhanced energy absorption characteristics, 2% fibre volume inclusion is recommended with compressive and flexural strengths increases of up to 39%. Optimum fibre length reported for the study is 3cm [76].

Table 3.2. Weight loss of treated and untreated EFB fibres at various temperatures

Untreated	Alkali-treated	Acetylated	Silane-treated	Weight loss (%)
150	235	145	180	10
260	290	240	300	20
300	325	285	328	30
315	350	308	360	40
340	352	325	370	50
340	352	338	370	60
345	360	340	370	70
395	415	370	420	80
440	460	435	440	90
480	510	495	520	100

Source: [57]

Table 3.3. Some physical and mechanical properties of EFB fibres from literature

	Fibre Properties							
References	Danso (2017)	Shareef and Ramli (2009)	Ismail and Yaacob (2011)	Khalil *et al.* (2012)	Sreekala *et al* (1997)	Ahmad and Nurazuwa (2008)	Patel and Parsania (2018)	Yousif (2008)
Diameter (mm)	0.23	0.02	0.25-0.6	0.008-0.3	-	0.02-0.07	0.15-0.5	0.35
Length (mm)	17	30	100-280	0.89-142	-	-	-	20
Density (g/cm^3)	4.0	-	1.3	0.7-1.55	-	1.03	0.7-1.55	-
Moisture Content(%)	4.0	-	11	-	-	-	-	-
24hours Water absorption (%)	-	0.6	-	-	-	60	-	-
Specific Gravity	-	2.14	-	-	-	-	-	-
Breaking Elongation (%)	-	4	30	2.5-18	14	-	4-18	0.3-16.2
Tensile Strength (MPa)	19	21.2	21	50-400	248	-	50-500	50-55
Young's Modulus (GPa)	12	0.5-2	-	0.57-9	2.0	-	0.6-9	0.57-0.59

Other recommended use of EFB fibres are as reinforcement for clayey bricks and soil blocks for low cost housing construction. A comparison of water absorption characteristics between coir, sugarcane bagasse and EFB fibres shows minimal water absorption for EFB fibres [22,23,52]. Study on the suitability of the fibres as a natural acoustic material shows an average absorption coefficient of 0.9 for frequencies above 1 kHz, making the sound absorption performance of EFB fibres comparable to rock wool. Average noise absorption coefficient for coir and OPF was reported as 0.50 and 0.64 respectively. The higher noise absorption coefficient of OPF is due to its higher density [50,54].

The incorporation of EFB fibre in composites is also reported to enhance thermal stability, electrical conductivity and dielectric constants of such composites [45].

3.1.2 Oil Palm Trunk Fibres (OPTF)

Malaysia alone accounts for up to 7 million metric tonnes of oil palm tree trunks fell annually to make space for new plantings After the useful lifespan of oil palm trees which is about 25-30 years, the trees are fell and the trunks are usually left in the field to rot [60]

Oil palm tree trunks have cross-sectional diameter, between 45 to 65cm and they are about 700-1300cm tall [77]. Findings from studies differ on the oil palm biomass residue with the highest potential for exploitation on a commercial scale. A study by Dungani *et al.* [64], reports this part as the oil palm trunk while *Saka et al.* [78] reports that the trunk is not suitable for application as a structural material since the cell density is not consistent and possess small amount of cellulose.. Physical and mechanical properties of OPTF obtained from literature are presented in Table 3.4.

3.1.2.1 Extraction of OPTF

The recommended maturity age for harvesting oil palm

Table 3.4. Physical and mechanical properties of OPTF available in literature

	Properties					
References	Ahmad *et al* (2010)	Ahmad *et al* (2010)	Karade (2010)	Choowang and Hiziroglu (2015)	Dungani *et al* (2013)	Mahat et al (2010)
Diameter (mm)	-	0.3-0.6	-	-	0.0261	-
Length (mm)	-	-	-	-	2.04	-
Density (g/cm^3)	1.2	1.1	1.2	0.34	0.2-0.6	-
Moisture content (%)	-	-	-	-	-	2.3
Tensile Strength (MPa)	300-600	-	-	-	-	-
Young's Modulus (GPa)	15-32	-	-	-	3.0	-

trunks for the purpose of fibre extraction is 20-30 years [78]. The matured trees are usually fell by hand or by machines after which they are cut into lengths of about 1m. The trunks are beaten using hammer and then retted to loosen the mass of the trunk. The trunks are usually left for about 48 hours to dry naturally. The dried fibres are pulled out manually with local implements and cut into required lengths of about 2-3cm after which they are subjected to further washing to remove impurities. They are then boiled in a solution of NaCl and oven-dried for 24 hours at 45ºC. OPTF need to undergo some form of chemical treatment to improve its strength and compatibility with cement matrix [79].

3.1.2.2 Fibre Treatments/Enhancements

OPTF has low density and high porosity which limits its usage for structural application. To overcome this drawback, the fibres can be thermally compressed to improve their density. Compression of fibres was carried out at 140ºC, 180ºC and 220ºC with 2MPa pressure for 8 minutes in a study [80]. This caused up to 110% increase in oven-dry density of the fibres. Due to the temperature-sensitivity of the fibres, it is advised that they should be subjected to a temperature of not more than 220ºC since deterioration in fibre hardness sets in at higher temperature. According to literature, optimum temperature for pressing the fibres is 140ºC. Up to 120% increase in flexural strength and 315% increase in modulus of elasticity can be achieved by this treatment. However, thermal compression is reported to produce fibres with smooth surfaces which may reduce fibre-matrix bond strength [80].

3.1.2.3 Chemical Composition

A lot of variation can be noticed in values of the chemical contents of OPTF reported in literature which can be attributed to factors such as, climate of oil palm tree cultivation, fibre age, method of extraction of fibre, type of experimental method employed, level of expertise and the efficiency of the apparatus used for the study. An attempt was made to put the values of each chemical compound contained in OPTF in a range [73], however, values recorded in other studies [31,60,65,80-82] are not within this range. A summary of the chemical composition of OPTF obtained from literature is presented in Table 3.5.

3.1.2.4 OPTF in Cement Composites

It has been shown that oil palm stem (trunk) has the potential of being used as main reinforcement for concrete beams [46]. Other studies reports OPTF as possessing high tensile strength in the range of 300-600MPa [44,46,83]. This is more than double the tensile strength of EFB fibres [51]. In one study, the relatively high strength of the trunk fibres is reported to be due to its thick cell wall as observed in scanning electron microscopy (SEM) analysis [60]. In another study, 1% volume inclusion of OPTF in concrete, shows that the hardened concrete has better resistance against NaOH and NaCl attack. As OPTF is added to concrete, there is an increase in water absorption and surface area, reducing the amount of water available to the concrete and hence decreasing workability [53,84]. Flexural strength of concrete incorporating 1% of the fibre increases by 220% while tensile strength increases by 130%. Determination of tensile strength was carried out in accordance to recommendations in ACI 544.1R. There are differing reports from studies however on the optimum fibre volume of 1%. The reason being that, amount of fibre inclusion alone cannot be the only variable responsible for strength prediction. Other variables like fibre length, fibre moisture content, fibre water absorption and mixing method should be investigated before conclusions on optimum fibre volume can be made. From the study, compressive strength and flexural strength of concrete incorporating 1% OPTF can be improved by 13.22% and 18.35% respectively [53,84]

It can be said that the dominant failure mode of OPTF-reinforced concrete is fibre-pull-out as a result of the poor bond between fibres and surrounding concrete matrix. [83,60]. Chemical resistance of OPTF-reinforced concrete is also investigated by exposing specimens reinforced with 1-3% OPTF content to

Table 3.5. Chemical composition (% weight) of OPTF from literature

References	**Composition (%)**							
	Ahmad *et al.* (2010)	Kelly-Yong *et al.* (2007)	Hashima *et al.* (2017)	Tomimura (1992)	Choowang and Hiziroglu (2015)	Shibata *et al.* (2008)	Bahari *et al.* (2010)	Khalil *et al.* (2012)
Cellulose	-	30.4	40.7	-	39.9	30.6	-	29-37
Hemicellulose	-	40.4	26.1	-	21.2	33.2	25.3	12-17
Holocellulose	72.12	-	-	-	-	-	76.3	42-45
Lignin	23.03	21.7	26.2	15.7	22.6	28.5	18.1	18-23
Ash	-	5.8	1.8	2.9	1.9	4.1	1.1	2-3

Hydrochloric acid, NaOH, NaCl and water. After 30 days of immersion, specimen deterioration is highest in those exposed to HCl with higher OPTF content. Water absorption also increases with increase in OPTF content. Water absorption is less than 4% for concrete incorporating 3% OPTF by volume which is only 43% of the limit set in ASTM 208-12 for water absorption for cellulosic building boards [60]. The fibre composite could be adequate for lightweight sheets intended for use as building boards.

OPTF has a density of 1.1g/cm^3 and the inclusion of 1-4% volume trunk fibres in concrete can help to reduce drying shrinkage and crack development in concrete [83,78,85].

3.1.3 Oil Palm Broom Fibre (OPBF)

This new type of fibre from the oil palm tree has gained almost no research attention until recently [33]. Premiere findings on the fibre describe it as the ribs of the leaflets of the oil palm tree (Fig 3.1). OPBF is mainly used as sweeping brooms in many countries around the world. The fibres have cross-section diameter ranging between 1.5mm-2.5mm and length of between 0.5-1.0m.

3.1.3.1 Extraction of OPBF

In the rural areas of tropical regions, oil palm leaves find useful applications as sheds and roofs of mud huts or through the extraction of the ribs of the leaflets to make brooms. The leaflets are first detached from the petioles after which the leafy skins are peeled off from the ribs (see Fig. 3.1). This extraction process is mostly carried out by a machete or knife.

Only recently, have engineers developed and patented a palm frond broom peeling machine in a bid to reduce attendant drudgery and fatigue associated with the process of broom fibre extraction and also to make large scale extraction of the broom fibre possible [86]. Two models of this machine are currently available; the electric-powered broom peeler and the manually-powered broom peeler. The electric version extracts over 6000 broom fibres per hour with an efficiency of 88.33% while its manually-powered counterpart produces only about 2000 broom fibres per hour but with a higher efficiency of 91.7%. The recommended optimum moisture content of oil palm leaflets for effective peeling by the machine is 7% [87]. The broom fibres whose tensile strength are almost twice the yield strength of mild steel are only tied into broom units to be sold at local markets [33].

The average cost of one broom unit across developing countries is USD 0.11 and contains about 150-170 broom fibres, each of which is 700 mm long and about 1.2-2.5mm average cross sectional diameter. This implies that a USD 0.22 worth of broom fibres can probably reinforce a (225x300x1200) mm lintel beam thereby reducing reinforcement cost by over 90%. Average natural density of OPBF is 1.5 g/cm^3 making OPBF to be only 20% the density of reinforcing steel. Replacing steel bars with OPBF as main reinforcement in concrete will improve construction speed, reduce labour cost and also result in light-weightiness of the resulting concrete.

3.1.3.2 Chemical Composition

The chemical composition of the broom fibres is not available in literature as at the time of this study. The suitability of 1.13mm long oil palm leaves fibre for paper-based products has however been investigated. The report presents the following chemical composition for leaf fibres; cellulose - 43.8%, lignin - 19.7%, and hemicellulose - 36.4% [83]. Due to the size of OPBF, the method of improving the durability of bamboo fibres by coating of fibres with impermeable resins can be adopted for OPBF [8,88].

3.1.3.3 OPBF in Cement-based Composites

OPBF can be used for reinforcing laterite-based roof tiles. Instead of randomly dispersing the fibres in the (cement-latrite) matrix as is the case with other studies, the fibres can be fabricated in the form of meshes of

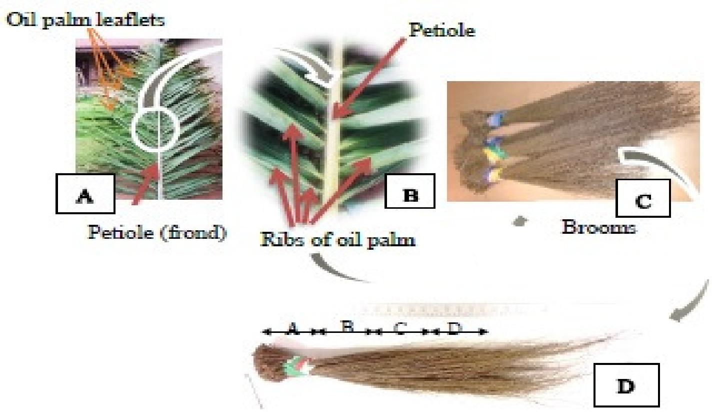

Fig 3.1. Illustration of OPBF (A) oil palm leaf (B) magnified image of oil palm leaf (C) OPBF tied into broom units (D) Categorization of OPBF

varying gauge sizes (of 10mm, 20mm, 30mm, 40mm and 50mm), embedded as reinforcements in 300x150x12mm laterite-cement matrices, and cured for 28 days [33]. For low cost construction, the broom fibres do not require treatment. Flexural strength increase of up to 130% can be achieved with the 10mm mesh size (calculated as 5% fibre volume inclusion). Average tensile strength of the broom fibres is about 1GPa and elastic modulus is over 70GPa which makes it as a potential alternative to steel. The authors of this chapter are presently investigating possibilities of grouping the fibres in the form of tendons in a bid to serve as main reinforcements for concrete elements.

3.1.4 Oil Palm Frond Fibres (OPFF)

OPFF is extracted from the fronds of the oil palm leaves which is usually sought after to feed livestock or are left to rot away in palm plantations as manure or as erosion cover. About 24 million tonnes of oil palm fronds are left to be discarded from oil palm factories every year in Malaysia. In other words, 10.88 tonnes per hectare of frond wastes are generated annually [73,65]. This represents significant amount of waste which if employed in construction will save costs both from economic and environmental perspectives.

3.1.4.1 Extraction of OPFF

As is the case with other OPF, palm fronds are obtained by cutting using machete or cutlass. They are pruned in same manner, loaded into a decorticator and subjected to dew retting. The fibres are then separated by hand for drying and further processing [35]. The fibres can also be collected after fronds have been used for fermentable sugar production. After harvesting the fronds, they are pressed by a sugar machine, thereby removing its juice. They are then dried for about 3 days, shredded in pieces and sieved into particle sizes of less than 2mm. However, this method destroys the fibres and may not be advised if its mechanical properties are desirable [81]. Mechanical crushers like the Cheso Cresher Model-LCT10HP can be used to squeeze the fronds instead of the sugar machine [89].

3.1.4.2 Chemical Properties

Despite attempts to set the value of chemical constituents of OPFF reported by previous studies in a range [73], there is still a wide variation in the chemical properties reported in literature [31,82]. Factors responsible for this include, age of fibres, soil condition, climate, geography and extraction procedure [81]. The range of chemical composition of OPFF obtainable from literature, are presented in Table 3.6.

3.1.4.3 Fibre Treatments/Enhancements

One of the major problems of natural fibres is moisture-induced decay. Hence it is recommended that drying of the fronds (to below 10% moisture content) is necessary to prevent fungal attack [89]. To improve the resistance of fibres to the alkali environment provided by cementitious matrices, alkali treatment (also known as mercerization) is prescribed in order to have a consistent fibre-matrix bonding [45].

Table 3.6. Chemical composition of OPFF fibres from literature

	Composition (%)		
References	Khalil *et al* (2012)	Shibata *et al* (2008)	Bahari (2010)
Cellulose	40-50	39.5	46.6
Hemicellulose	34-38	29.8	33.9
Holocellulose	80-83	-	80.5
Lignin	20-21	23.3	18.3
Xylose	26-29	-	-
Glucose	62-67	-	-
Ash	2-3	5.7	2.5

The increase in cellulose after alkali treatment is believed to be due to distortions to the cell wall and the resulting exposure of the cellulose. This also leads to partial removal of hemicellulose and lignin, as a result of the disruption of the outer layer of the fibres [81].

A similar study on treatment of fan palm fibres recommends immersion of the fibres in 4% NaOH solution for 24 hours after which the fibres are then immersed in distilled water for one hour to remove residual NaOH. They are then dried and stored in plastic bags to protect them from environmental moisture [90]. This is done to prevent the fibres from absorbing moisture from the environment, thereby preventing moisture-induced decay.

3.1.5 Summary of Effects of Oil Palm Fibre in Cement Composites

3.1.5.1 Workability

The review of available literature on the incorporation of OPFs in cement composites has shown that, workability reduces with an increase in fibre content [27,28,41,51,53,60]. This is attributed to the increase in the surface area of the fresh mix and high water absorption of the fibres making less water available to the mix [76,79]. Engineers and designers wishing to employ OPF-reinforced cement composites in construction should make appropriate adjustments in mix design.

3.1.5.2 Setting Time

The setting time of the OPF-cement composites increases with increase in amount of OPF due to the presence of water-soluble compounds (e.g. pectin), in the fibres. This compound dissolves on contact with water in the fresh cement matrix and fastens to calcium ions, thereby inhibiting hydration through the prevention of C-S-H structure formation [91].

3.1.5.3 Chemical Composition

From available literature, the oil palm fibre with the highest amount of cellulose is EFB fibres, which by implication represents better strength and as a consequence, has received more research attention than other types of OPF. The range of chemical composition of oil palm fibres from literature is presented in Table 3.7

Table. 3.7. Chemical composition of OPF (%)

Composition	EFB	OPFF	OPTF
Cellulose	38-65	40-50	29-47
Hemicellulose	17-35	30-38	12-40
Holocellulose	65-86	80-83	42-76
Lignin	13-59	18-23	18-29
Ash	1-6	2-6	1-6

3.1.5.4 Treatment of Oil palm Fibres

It is reported that the strength of natural fibres can be improved by a factor of 3 through pyrolisis process [91]. However silane and alkali treatments were recorded as the most effective for enhancing the strength and thermal stability of OPFs [51,90]. On the effect of alkali, acetyl and silane treatments on the surface morphology of EFB fibres and mesocarp fibres, NaOH solution when in contact with the fibres dissolves impurities on fibre surface and a rough surface topography is created [51]. Although EFB fibres lose about 22% of initial weight, the resulting fibre surface roughness is desirable for good composite bonding. In general, all the above-mentioned treatment methods enhance oil palm fibre mechanical properties.

Similar treatment methods like the coating of bamboo strips with different types of polymeric adhesives before inserting them in concrete as reinforcements (to enhance bond strength) can be employed for OPBF. Test results recommended the "sikadur 32 gel" adhesive treatment. Another type of coating which can be used on OPBF is water-based epoxy coating. It is argued that when used on bamboo strips, fibre-matrix bond strength is not improved, but rather the already existing bond strength between the fibre and surrounding alkaline matrix is maintained as a result of the surface protection offered by the epoxy coating [85].

3.1.5.5 Strength in Cement Composites

Available literature sets limit of inclusion of OPTF in cement composites as 3% by volume, since strength reductions are likely beyond this amount [22,79,92]. A 5% inclusion of OPBF is however recommended. Chemical composition for OPBF is unavailable at the moment, but it is reported to be the stiffest of the oil palm fibres with tensile strength and Young's modulus in excess of 1GPa and 70GPa respectively [33].

Natural fibre-reinforced concrete is a lightweight composite due to the light weightiness of the natural fibres. Significant savings in the total cost of the structure is therefore possible. For developing countries with seismic disturbances, this type of composite is beneficial as the inertial forces generated during earthquake ground vibrations are proportional to the mass of the buildings.

Discrepancies noticed in the values of chemical and mechanical properties of oil palm fibres reported in literature could be due to a variety of factors such as age of the fibre source, varying experimental techniques, level of expertise, varying fibre sources, fibre treatments and age of the source plant. Development of a standard characterisation guideline for oil palm fibres requires attention.

The extraction and processing of fibres from oil palm biomass for incorporation in cement composites could create jobs which were hitherto non-existent. Environmental conservation would be enhanced and construction cost will also be reduced.

3.2 SUGARCANE BAGASSE AND CHICKEN FEATHERS

Research attention has also been drawn to the use of sugarcane bagasse and chicken feathers in construction due to their availability particularly in developing countries. Due to indiscriminate disposal of the waste, they create several environmental problems such as land contamination and air pollution in the form of excessive dust in the air [93].

3.2.1 Sugarcane Bagasse

The fibrous waste generated from sugarcane plant after the extraction of the juice is referred to as sugarcane bagasse. Annual production of sugarcane bagasse globally is over 54 million metric tonnes [94]. Asides the larger bulk being discarded as wastes from sugar factories, sugarcane bagasse finds useful application ranging from animal feed to paper production [95] and until recently, in its inclusion in unfired clay bricks. Results reported, indicated that the bagasse fibre-reinforced bricks showed enhanced strength, durability and stability [96-98]. Like other natural fibres, sugarcane bagasse is lightweight with an average dry density of 0.91g/cm^3.

3.2.2 Chicken Feathers

Annual production of chicken feathers is reported to be about 4 million metric tonnes globally [99].The major parts of the feather of interest to this study are the rachis, the barbs, and the barbules. The feathers have a unique structure and properties, distinguishing them from other natural or synthetic fibres. A detailed diagram of a feather is shown in Fig 3.2. Moreover, feather fibres are inexpensive, lightweight, continuously renewable, resilient, possess excellent compressibility and thermal insulation, and is a global waste [100]. Possible applications of chicken feathers in the textile industry [101], bioplastics [102], and wastewater treatment [103] have been investigated.

Studies are also ongoing on the possibility of utilizing chicken feathers and sugarcane bagasse in unfired clay bricks.

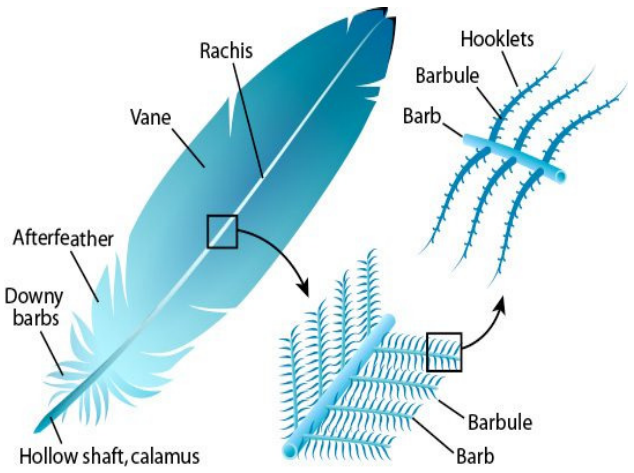

Fig 3.2. Annotated diagram of a chicken feather [104]

4. INCORPORATING SUGARCANE BAGGASE AND CHICKEN FEATHERS IN CLAY BRICKS

In a bid to determine the suitability of chicken feather fibres and bagasse fibres inclusion in unfired clay bricks, preliminary investigation of some mechanical properties where carried out on 5x5x5cm clay specimens incorporating the waste fibres.

Fibres from chicken feathers with density 0.8 g/cm^3 were obtained by cutting the barbs from the rachis using a pair of scissor. Average length and diameter of the fibres was 20mm and 50µm respectively. Sugarcane bagasse with a density of 0.91 g/cm^3 was also obtained and was prepared into fibres with average length and diameter of 20mm and 70µm respectively.

Fire clay with density of 1.31 g/cm^3, was used for the production of clay cubes with the clay being partially replaced by either chicken feathers or baggase fibres at 1%, 3% and 5% replacement levels. The percentage replacements were carried out by volume of the clay specimen. The mixes were moulded into (5x5x5) cm^3 cubes after which they were air-dried under room temperature for 7 days until constant weight was recorded. At the ed of the drying period, the moulded samples were tested for dry density, compressive strength and linear shrinkage. Control samples, i. e., samples with no fibre content were also tested.

4.1 Linear Shrinkage

Linear shrinkage was assessed by observing the decrease in one dimension of the cube (brick) specimens as it loses moisture through evaporation. This parameter is important because the major cause of cracks and dislocation defects in structural members made of clay bricks is moisture-dependent changes in member dimension [15,105,106]. Test results (Fig 3.3) reveal that linear shrinkage increased with increase in bagasse fibre inclusion, while increase in chicken feathers decreased linear shrinkage. Chicken feathers have a semi-crystalline morphology with high elastic modulus and low water absorption characteristics [99]. Its increased inclusion in clay at higher replacement levels leaves less amount of clay available to absorb water. Consequently, global water intake by the clay matrix is reduced and less shrinkage is observed as water is lost during hardening of matrix. However, bagasse fibres on one hand are natural (cellulosic) fibres with characteristic high water absorption capacity. On the other hand, mechanical crushing which the parent sugarcane is subjected to during juice extraction, damages the fibres. The crushing process alters the fibre morphology by increasing the surface areas of individual fibres. As a consequence, moisture absorption tendency is increased. At higher replacement levels of bagasse fibres, more water is absorbed by the matrix which is lost during hardening of clay matrix and hence causes specimens to undergo larger dimensional shrinkage.

Nonetheless, at 5% levels of inclusion of both fibres, the specimens meet the requirements of ASTM C3260-9 (2014) which pegs the maximum limit of linear shrinkage for unfired clay bricks at 8%. In general, lower shrinkage indicates better physical and mechanical properties.

4.2 Dry Density

Fig 3.4 show that dry density of unfired clay bricks decreases with increasing amount of feather fibres and bagasse fibres. This is attributed to the lower density of chicken feathers and sugarcane bagasse compared to that of clay, resulting to lightweight bricks [107]. Generally, specimens with feather fibre were lighter than specimens with bagasse fibres for all mixes as a result of the relative lower density of the feather fibres. At 5% replacement levels, percentage reductions in the dry density for feather fibres and bagasse fibres were

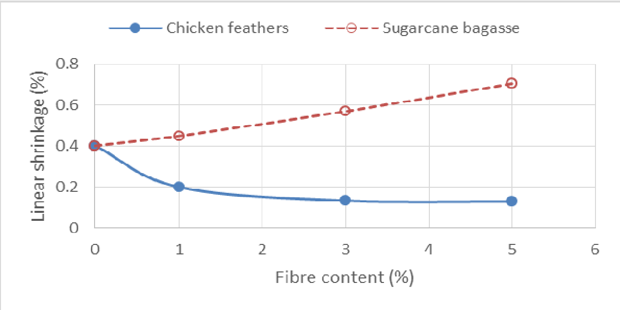

Fig 3.3. Mean values of the linear shrinkage of the

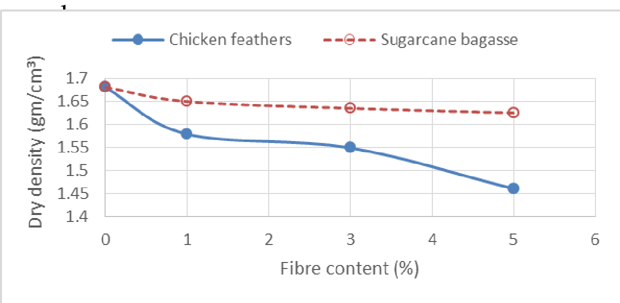

Fig 3.4. Mean values of the dry density of the samples.

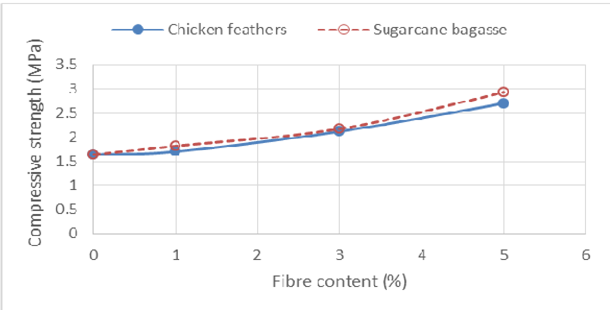

Fig 3.5. Mean values of the compressive strength of the samples.

recorded as 13% and 3% respectively. The body density reducing index (BDRI) defined as the ratio of the reduction in the brick density to the dry matter content of added fibre [105], varies from 0 - 10.181kg and 0 - 3.053 kg/3/% dry matter for feather fibres and bagasse fibres, respectively, thereby indicating that weight loss is more associated with feather fibre inclusion.

All samples satisfy the requirements of the British Standard Methods of Test for Masonry Units (Part 13: Determination of Net and Gross Dry Density of Masonry Units BS EN 772-13:2000)

4.3 Compressive Strength

Compressive strength is one of the most important parameters for construction materials because a higher compressive strength implies better structural stability. The compressive strength increased steadily with increase in feather fibre and bagasse fibre content (Fig 3.5). This is mainly attributable to improved matrix adhesion resulting from fibre-aggregate interlocking. The incorporation of the fibres also enhanced densification and compactness of the bricks. Maximum increase in compressive strength of 64.6%, and 78.5% were recorded for feather fibres and bagasse fibres respectively. Surface roughness of bagasse fibres implies better fibre-matrix bonding and hence explains the relative higher compressive strength noticed. Although the compressive strength tests were carried out on the specimens at a pre-mature age of 7 days, all the samples satisfied the requirements of BS EN 1052-2:2016 (1-8 MPa) for unfired clay bricks.

Thermal insulation is also expected to improve as a result of the characteristic insulation properties of the fibres and alteration in brick porosity. Even though preliminary findings highlight the potential of developing new type of construction materials from these agricultural wastes, more detailed research is on-going to fully understand their mechanical properties and possible usage in construction.

5. CONCLUSION

The following conclusions have been made;

- Inclusion of oil palm fibres in cement composites reduces workability of fresh cement mixtures and increases its setting time,
- EFB fibre has the highest amount of cellulose and has received more attention than other types of oil palm fibres,
- Alkali-treatment is the most preferred for enhancing the mechanical properties of oil palm fibres,
- The recommended optimal amount of oil palm fibre in cement composites is 3% by volume,
- OPBF is the stiffest amongst oil palm fibres with tensile strength and Young's modulus in excess of 1000 MPa and 70GPa respectively,
- Discrepancies in reported fibre properties make it difficult to make sound engineering decisions when dealing with oil palm fibres,
- Linear shrinkage of unfired clay bricks declines with increase of chicken feather content but increases with increase in sugarcane bagasse inclusion.
- The addition of chicken feathers and sugarcane bagasse reduces brick density and does not create problems during mixing, moulding, extrusion and drying,
- Compressive strength capacity of unfired clay bricks can be improved by incorporating agricultural wastes.

The incorporation of agricultural wastes in construction is an eco-friendly approach to sustainability and affordability.

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