



Enhancing the behaviour of broom-strands reinforced concrete using hose-clamps

Emmanuel Owoichoechi Momoh, Adelaja Israel Osofero*, Oleksandr Menshykov

University of Aberdeen, School of Engineering, King's College, Aberdeen AB24 3UE, United Kingdom

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ABSTRACT

Ever-increasing housing deficits, especially in developing countries, and concerns on environmental pollution have stimulated the use of indigenous environmentally friendly materials like oil palm broom fibres (OPBF) which is an abundant waste material from oil palm cultivation and processing activities. Research into the suitability of OPBF as a reinforcement material for concrete is recent with OPBF being reported to surpass steel as regards strength-to-weight ratio. However, a relatively low bond strength between the fibres and concrete has also been reported. This study, therefore, explores the possible bond enhancement of OPBF strands in concrete matrix with the aid of hose-clamps attached to the OPBF strands. Tests carried out include tensile strength test of the OPBF strands, bond pull-out test of the OPBF strands from concrete, and flexural strength test of the OPBF reinforced concrete. Concrete samples with 28 days compressive strength of 30 MPa were cast with a mix proportion of 1:1.5:3 of cement, fine and coarse aggregate respectively. A total of 22 concrete samples comprising of 2 unreinforced, 2 steel reinforced beams and 6 OPBF reinforced concrete beams of 100x100x500 mm singly reinforced with OPBF strands in three categories, in terms of cross-sectional areas of 96 mm², 192 mm² and 288 mm² and 12 bond pull-out samples were prepared. For each category of reinforcement, the strands were fitted with hose clamps spaced at either 45 mm or 85 mm to improve the bond strength between the concrete and the reinforcement. For bond pull-out strength, the 3 categories of OPBF strands with attached clamps were inserted in the freshly prepared concrete to an embedment length of 80 mm. Flexural tests on the concrete beams under 4-point loading and pull-out tests of strands from the concrete were carried out at 28 days of curing. An average tensile strength of 200 MPa was obtained for OPBF strands and results show improvements of over 35% and 500% in the bond and flexural strengths, respectively, due to increased slip resistance induced by the hose clamps. The developed hose-clamp enhanced palm fibre reinforced concrete can lead to a reduction in material costs as well as in the carbon footprint on the environment and can be used in lintel beams for low-cost residential housing.

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1. Introduction

An estimated 14.5 million people migrate yearly from rural areas to cities in developing countries across the world without having a roof over their heads [1]. The rapid urbanisation in these regions of the world together with other factors such as inflation, lack of housing finance, weak land tenure system and over-dependency on imported building materials, have made access to housing continuously difficult. Currently, the housing deficit is in

excess of 20 million units each for populous countries such as India and Nigeria [2,3]. These developing countries are also faced with huge amounts of solid wastes generation, in form of agricultural and industrial wastes, due to a high population growth rate and the attendant problems of waste management. For example, while the United Kingdom is projected to increase in urban population and in its generation of municipal solids wastes by 14% and 17% respectively by 2030, India is projected at 60.1% and 159% respectively with most of the latter burnt indiscriminately in an environmentally unfriendly attempt to manage the wastes [2,4]. A few examples of industrial wastes include: scrap-tyre (textile, rubber, steel fibres) [5,6], fly ash, silica fume, blast furnace slag, and sew-

* Corresponding author at: University of Aberdeen, School of Engineering, King's College Aberdeen, Fraser Noble Building, United Kingdom.

E-mail address: aiofero@abdn.ac.uk (A.I. Osofero).

age sludge, etc., whose incorporation as building materials have been reported to enhance the physical and mechanical properties of earthen and cementitious composites [7], improve waste management and reduce demand on already scarce conventional construction materials, thereby providing eco-friendly options [8].

On the other hand, agricultural wastes of about 600 million tonnes and 200 million tonnes are generated annually in India and Nigeria respectively – most of which are burnt openly in the fields [9]. Similar to industrial wastes, affordability in the provision of infrastructure can be achieved by developing building materials from agricultural wastes and adopting the locally available construction materials that are both renewable and environmentally friendly as an alternative [10]. On the economic side, studies have reported savings in cost by incorporating agricultural wastes in construction, for example, up to 26% savings in cost can be achieved by partially replacing stone chips with 10% crushed coconut shell to produce lightweight concrete [11]. Other agricultural wastes that have found popular use as reinforcement for cement composites include (but not limited to): sugarcane bagasse, coir, flax fibres, hemp fibres, sisal, jute, bamboo, chicken feathers and oil palm fibres.

Oil Palm Broom Fibres (OPBF) which are the ribs of the leaflets of oil palm tree have recently begun to attract research attention because of its relatively high strength/weight ratio (see Fig. 1 for an illustration of the location of OPBF on a palm frond) [12,13]. Momoh and Dahunsi [14] fabricated meshes from OPBF which were then embedded in 300x150x10 mm flat roof tiles made from laterite-cement mortar. An improvement of over 200% of flexural strength was reported for the samples incorporating the mesh reinforcement. Another study reported the feasibility of incorporating OPBF as random discrete reinforcement for concrete in which over 300% increase in energy absorption for the OPBF-concrete was reported, and hence making it a prospective building material for low-cost housing in seismic regions [12,15].

The use of plant fibres for longitudinal reinforcement in concrete has been so far limited to bamboo. Preliminary findings show that OPBF can be combined in the form of strands and used as flexural reinforcement like bamboo [16]. An attempt at combining the fibres into strands was also reported in a preliminary study [17] in which the fibres were wound around one another in the form of a helix and inserted in concrete to an embedment length of 80 mm. Bond pull-out test was carried out where the strands were pulled

out of the concrete matrix after being cured for 28, 56 and 112 days. A maximum bond strength of 1.16 MPa was reported in the study which is 40% of the bond strength value reported for reinforcing steel [17]. The drawback with the attempt at combining OPBF with the winding procedure is the difficulty in achieving rigidity of the strands and the repeatability of the procedure.

The use of the hose clamps was employed in this study for the purpose of enhancing the rigidity of the combined OPBF (strands) and to ensure that each strand acts like a typical reinforcing bar. In preliminary trial experiments by the authors, the fibres themselves were used to combine the OPBF into strands. A second attempt was the use of 1 mm aluminum wires to combine the fibres into strands. In both experiments, strand rigidity was not achieved, and the strand reinforced concrete showed inferior results. Therefore, hose clamps have been employed in combining the fibres into reinforcement strands as an attempt at mitigating this drawback. With the use of hose clamps, the parameters influencing the bond and flexural behaviour of OPBF reinforced concrete would be better understood and an attempt can be made on standardizing the procedure for making the reinforcement strands.

2. Materials and methods

2.1. Materials

The palm fibres were supplied by *Rice and Spice*, UK as broom units and already air-dried to a moisture content of between 7 and 11% with an average fibre density of 840 kg/m³. Hose clamps used in combining the fibres into strands were made of mild steel and were supplied by *RS-component*, UK. The hose clamps had a range of internal diameter and torque of 8 – 13 mm and of 3.5 – 5Nm respectively. Coarse and fine aggregate and general-purpose Portland cement were supplied by *Jewson Ltd*, UK. Specific gravities of 2.62, 2.55 and 3.15 were obtained for the coarse aggregate (pea gravel), fine aggregate (sharp sand), and cement respectively and in accordance with ASTM D854-14. The fine aggregate (with a range of particle size of 0.09 – 2 mm) was classified as medium sand while the gravel (with a range of particle size of 0.2 – 10 mm) was classified as fine gravel in accordance with ASTM D2487. The particle size gradation curves can be found in an earlier study by the authors [12]. By conducting trial mixes, a compressive

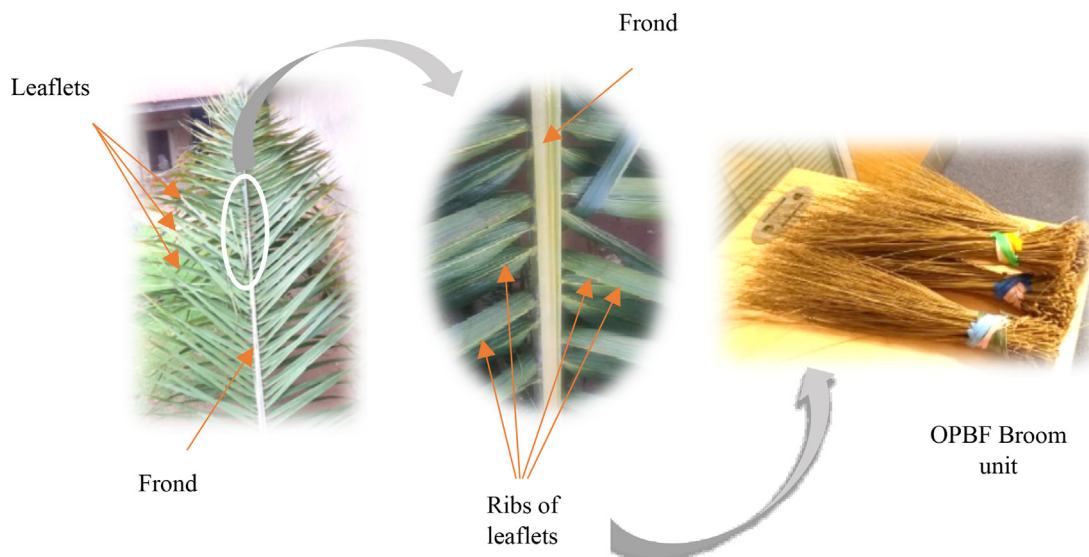


Fig. 1. Location of OPBF on an oil palm frond [7].

strength of 30 MPa was achieved for a concrete mix of 1:1.5:3 at 28 days and was adopted for this study. Water cement ratio of 0.52 was used with a target slump of between 80 and 100 mm. Araldite epoxy glue was supplied by RS-component UK for the purpose of hardening the ends of the OPBF strands to be placed into the jaw grip of the universal testing machine. The experiments in this study were performed at the concrete and materials laboratories of the University of Aberdeen, UK.

2.2. OPBF reinforcement

Blemish-free OPBF were chosen by visual inspection and cut into lengths of 480 mm. The fibres were held side-by-side longitudinally to form strands with the aid of hose clamps. A torque wrench was used to tighten the hose clamps on to the strands to a torque of 3.5 Nm. In terms of the number of fibres, three categories of fibres were investigated: 40 fibres-strand, 80 fibres-strand and 120 fibres-strand, while the hose clamps were spaced at 45 mm and 85 mm for all the categories of strands (see Fig. 2a and 2b). For sample identification, the following nomenclature was adopted: 040F-45s refers to a concrete prism reinforced with an OPBF strand consisting of 40 fibres, whose hose clamps are spaced at 45 mm. Table 2.1 presents an overview of the samples, sample description, sample identification and tests carried out.

2.3. Tensile strength of OPBF strands

A total of 3 samples were also prepared to assess the tensile strength of the OPBF strands. For each strand, 80 OPBF were cut into lengths of 200 mm and combined with 2 hose clamps spaced at 90 mm (gauge length). Both ends of each strand were knitted with 1 mm steel wires starting from each hose clamp to the strand end (i.e., 50 mm length). The knitted ends were then dipped in the Araldite glue to a depth of 50 mm for 60 s and removed, after which three 20 mm steel o-clips immediately fitted on to each knitted end. A plier was then used to press the o-clips sideways to about 10 mm and left to set with the glue. This was done to prepare the ends of the strands for the grip of the testing machine (see Fig. 3). Tensile strength test was carried out at a displacement control rate of 5 mm/minute on an Instron 4483 universal testing machine with static test and dynamic test frame capacities of ± 150 kN and ± 50 kN respectively. The maximum rate limit for static testing in both tension and compression is 50 mm/min. A 5 kN drop-through static load cell was used for the bond pull-out test while a 100 kN cylindrical load cell was employed for the tensile and flexural tests with both load cells having a measurement error of about 0.025% of rated capacity of each load cell. See Table 2.1 for an overview of the samples, sample description, sample identification and tests carried out.

2.4. OPBF strands reinforced concrete

A total of 10 samples consisting of 2 unreinforced, 2 steel reinforced and 6 OPBF reinforced 100x100x500 mm were cast with varying OPBF reinforcement areas. All the samples were singly reinforced with areas of reinforcement varied by increasing the number of OPBF, i.e., in the three categories of 40F, 80F and 120F strands having cross-sectional areas of 96 mm², 192 mm² and 288 mm² respectively. Each reinforcement consisted of 2 strands and 5 single fibres used for connecting the strands (see Fig. 4). The effects of the reinforcement areas and spacings of the hose clamps on the flexural response of the reinforced concrete beams was investigated. For the steel reinforced samples, two 6 mm steel bars were embedded in the samples with a concrete cover of 10 mm. The metallic moulds were placed on a vibrating table after which the fresh concrete was poured into them to a depth of 10 mm and vibrated for about 20 s. The reinforcement was then placed on the concrete in the moulds. The rest of the concrete was then poured into the moulds to the full and vibrated for a further 60 s. After this, the sample surfaces were levelled with the aid of a hand trowel. The samples were then left to set for 24 h after which they were demoulded and covered with jute bags with tap water poured over the covering until it was wet. A covering of polyethene was then laid over the jute covering to minimise evaporation of water with the wetting procedure carried out every 2 days. See Table 2.1 for an overview of the samples, sample description, sample identification and tests carried out.

2.5. Flexural strength test

At 28 days of curing, the samples were removed from the curing area and left standing on a preparation table for about an hour to dry. The samples were then wiped clean using a toilet paper after which a marker was used to mark the points for the machine fixtures. A metallic bracket was attached to the side of the samples at midspan. A test frame was mounted accordingly on these markings before transferring the samples onto the test machine. An LVDT device was inserted on the provision made on the test frame and positioned onto the side bracket on the samples to measure midspan deflection. The samples were then subjected to 4-point flexure according to ASTM C1609/C1609M-12. See Fig. 5 for the flexural strength test set up. Also see Table 2.1 for an overview of the samples, sample description, sample identification and tests carried out.

2.6. Bond pull-out test

A total of 12 samples were also prepared to assess the bond pull-out strength of the OPBF strands from concrete at 28 days into

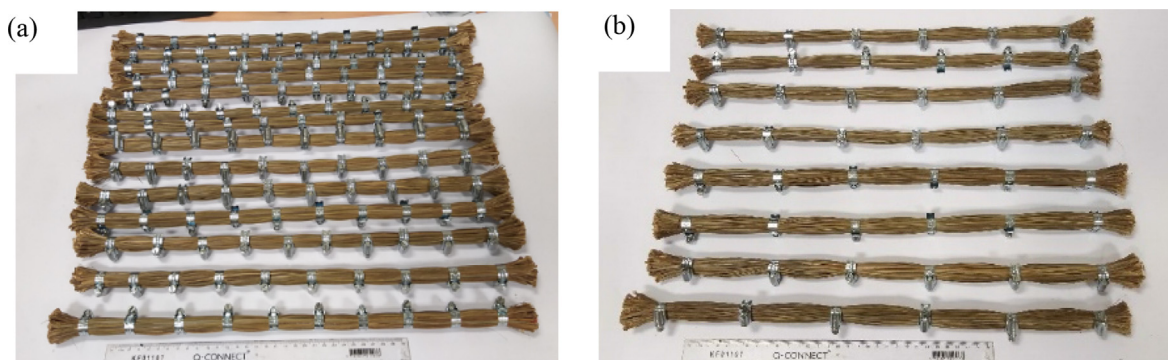


Fig. 2. OPBF strands with clamps spaced at (a) 45 mm (b) 85 mm.

Table 2.1
Overview of samples, tests and strand classification in terms of number of fibres and spacing of hose clamps.

Sample Description	Type of Test (Measured parameter)	Number of identical samples	Number of fibres per strand	Clamp spacing on strand (mm)	Sample ID
OPBF reinforcement strand OPBF strand embedded in concrete to a depth of 80 mm	Tensile strength of OPBF strand Bond pull-out strength of the strands from concrete	3	80	80 (gauge length)	NA
		2	40	45 (2 clamps embedded)	40F-45s
		2	40	85 (1 clamp embedded)	40F-85s
		2	80	45 (2 clamps embedded)	80F-45s
		2	80	85 (1 clamp embedded)	80F-85s
		2	120	45(2 clamps embedded)	120F-45s
		2	120	85 (1 clamp embedded)	120F-85s
		100x100x500 mm concrete prism singly reinforced with OPBF clamps	Flexural load capacity of OPBF strand reinforced concrete under 4-point bending	1	40
1	40	85		40F-85s	
1	80	45		80F-45s	
1	80	85		80F-85s	
1	120	45		120F-45s	
1	120	85		120F-85s	
100x100x500 mm concrete prism singly reinforced with 6 mm steel bars		2	NA	NA	Steel reinforced unreinforced
100x100x500 mm concrete prism unreinforced (control)		2	NA	NA	Steel reinforced unreinforced

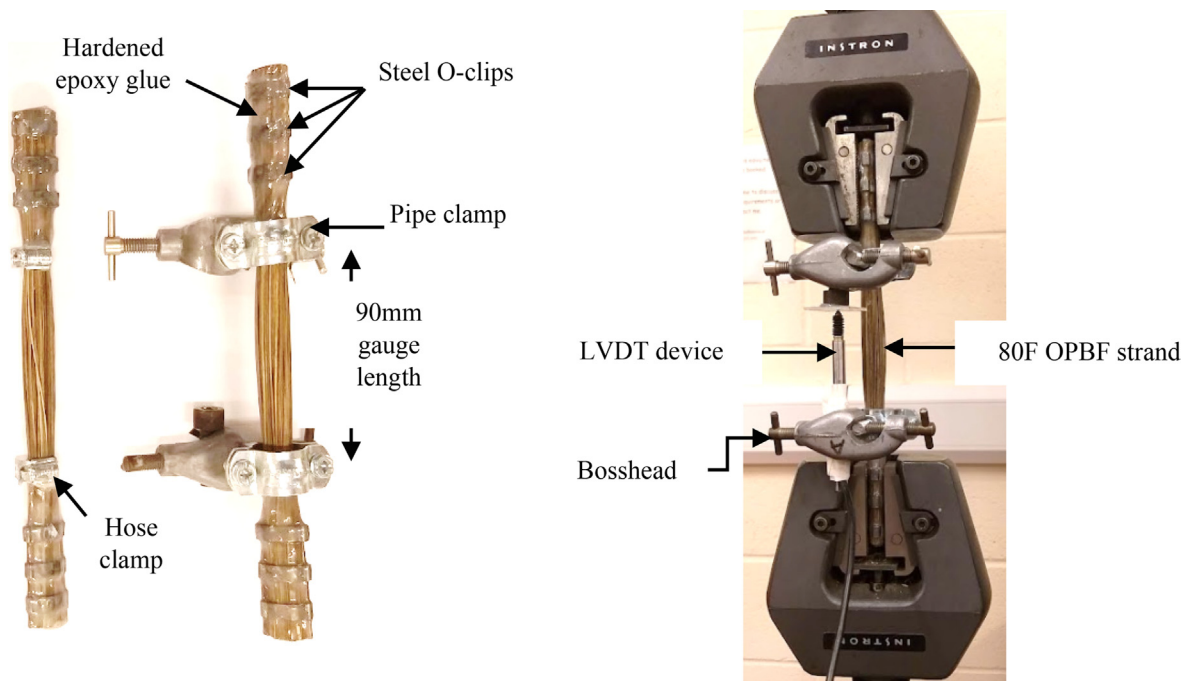


Fig. 3. Illustration of prepared tendon for tensile strength test and tensile strength set up.

lengths of 200 mm with one end of each strand knitted with 1 mm steel wires. The knitted ends were dipped in the Araldite glue to a depth of 50 mm for 60 s, removed, and two 20 mm steel o-clips immediately fitted on to the knitted end. A plier was then used to press the o-clips sideways to about 10 mm and left to set with the glue. This was done to prepare the pull-out end for the grip of the testing machine (see Fig. 6). After 72 h of setting of the glue, each strand was inserted into a 100 mm cubic mould. Concrete was poured into the mould to a depth of 20 mm, each strand was then

held by hand while the rest of the concrete was poured, vibrated for (60 s) and levelled (with a hand trowel) at the fullness of the mould. For the strands with 45 mm and 85 mm clamp spacing, 2 and 1 clamps (respectively) were embedded in the concrete blocks while embedment length of all strands was 80 mm (See Fig. 6 for the setup of the bond pull-out test). After 24 h, the samples were demoulded and placed in a curing basin with water level at 100 mm, same as height of the concrete block. At 28 days, the samples were removed from the curing tank after which the underside

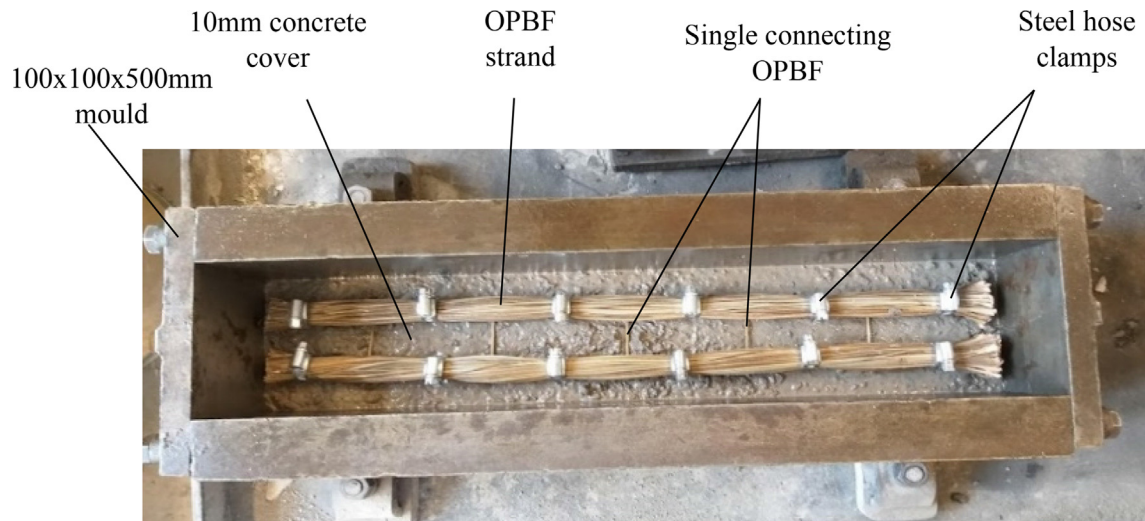


Fig. 4. A 120F-85 s reinforcement strand in 100x100x500mm mould.

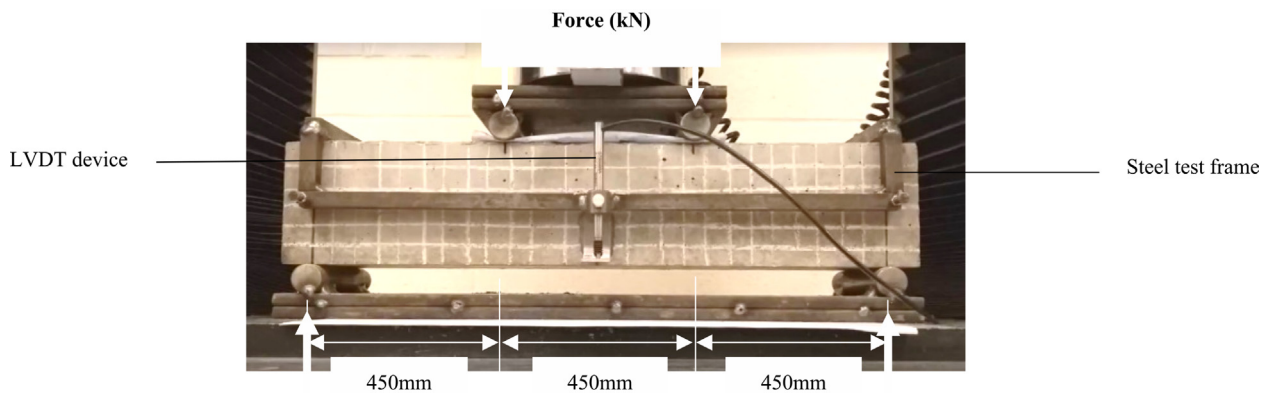


Fig. 5. Flexural strength test set up.

of the samples were bored open around the strand end and an LVDT mounted to measure slip from the underside of the strand end. The pull-out test was performed at displacement control (at 2.5 mm/minute) on an Instron 4483 universal testing machine.

3. Results and discussion

3.1. Tensile strength of OPBF strands

The tensile strength of the OPBF strands was characterised by an initial linear elastic response after which the individual fibres began to fail leading to a change in the gradient of the stress–strain curves of the strands (see Fig. 7). At the maximum tensile strength, there was sudden failure for all samples. An average maximum tensile strength of 200 MPa was obtained for the strands at a strain of about 0.02 while an average modulus of elasticity of 26 GPa was obtained at the initial elastic response. The strain at maximum strength of OPBF is about 3 times greater than the strain at yield strength for reinforcing steel which may imply higher deformations for OPBF-reinforced concrete as is typical with bamboo-reinforced concrete [18]. A marked difference in the tensile behaviour between the OPBF strands and other alternative reinforcement types such as bamboo and fibre-reinforced polymers is the shape of the tensile stress–strain curve. While the longitudinal tensile response of bamboo and related composites show an approximately linear elastic behaviour from the onset of testing to failure

under quasi-static loading [19–20], OPBF strands display pseudo-plastic behaviour due to the failures of individual fibres within the strand at different tensile stress levels during the tests. The gradual failure of individual fibres provides warning prior to the ultimate failure of the strand, and this could be used as a guide in determining a safe design tensile stress for the strands.

3.2. Bond pull-out strength

Fig. 8 presents the bond pull-out response of the natural fibre strands from the concrete which is characterised by pull-out of the strands from the concrete. The comparison between the samples with 1 clamp embedded and samples with 2 clamps embedded showed the latter having increased bond strength due to the greater shear connection between the matrix and the reinforcement. In other words, the 2 hose clamps provided better anchorage of the strands in the concrete, thereby providing a higher resistance to the pull-out force. A minimum bond strength of 1.02 MPa was recorded for the 40F-85s while a maximum bond strength of 1.6 MPa was recorded for the 120F-45s. Whereas the effect of Poisson ratio causes larger bars of steel or FRP to have lesser bond strength, the hose clamps (due to anchorage in the concrete) negates this effect for the strands such that the larger strands possessed greater bond strength. The maximum bond strength obtained from this study is about 55% and 89% of that of ribbed steel bars and non-ribbed mild steel bars, respectively, in

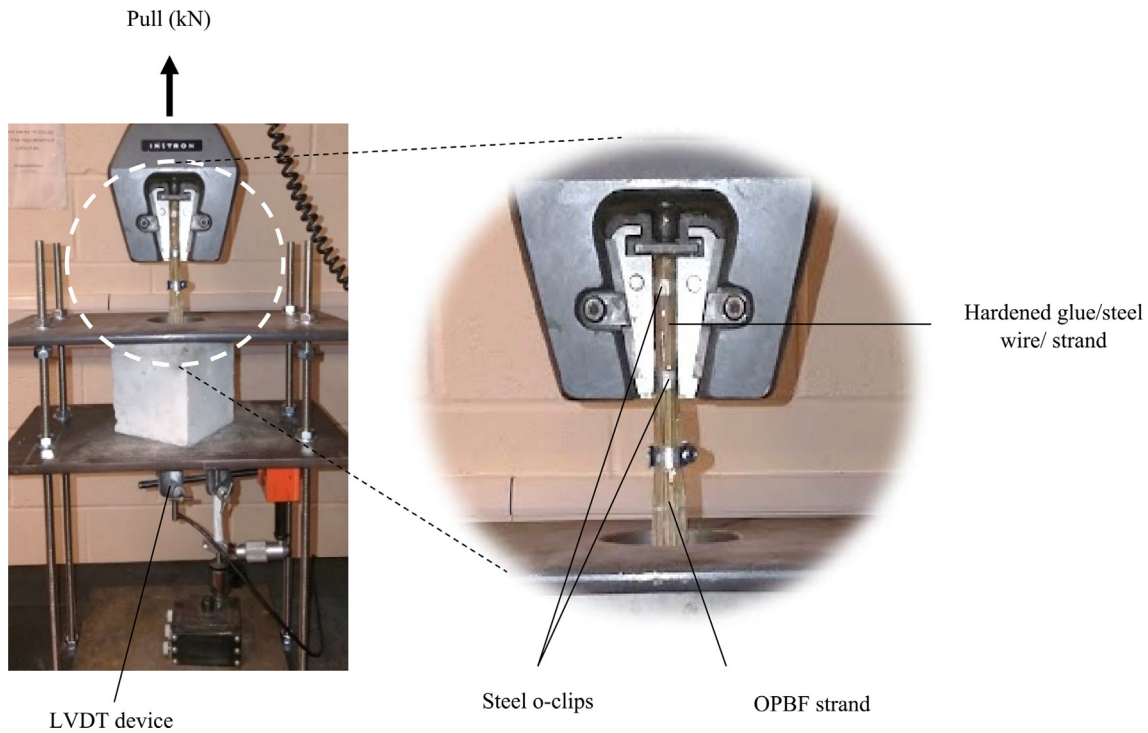


Fig. 6. Bond pull-out set up.

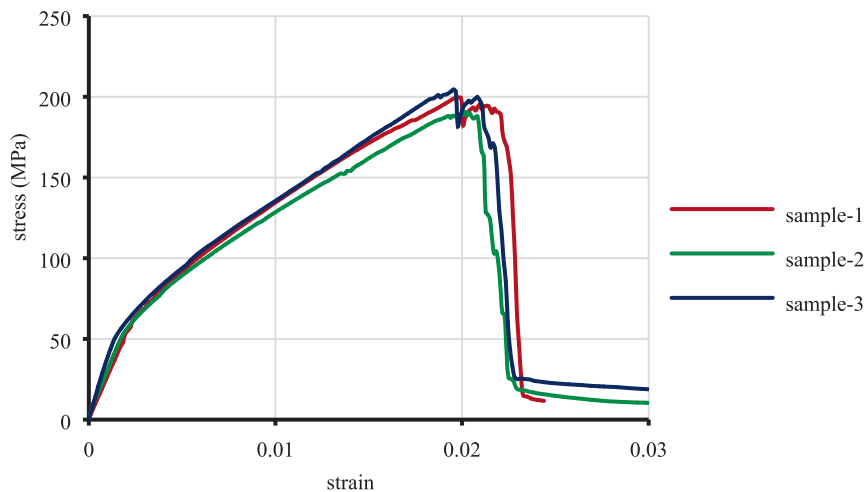


Fig. 7. Stress–strain curves of tensile tests of OPBF tendons.

concrete [17]. This shows some prospects of the OPBF strands being adequately employed in low load-bearing structural elements like lintels. Fig. 9 shows some strand pull-out from concrete after the bond pull-out test.

3.3. Flexural strength

The flexural response of the OPBF strand reinforced concrete presented in Fig. 10 can be divided into 3 regimes: an initial elastic regime, a post-crack regime, and failed regime. During loading, the tensile strength of the concrete was exceeded starting from the underside of the prisms, hence causing micro-cracks to develop which subsequently expanded into macro-cracks until failure.

The 120F-45s sample (having a reinforcement ratio of 3.49) showed a commensurate performance with the steel reinforced control sample (with reinforcement ratio of 0.56) in terms of maximum flexural load (see Fig. 11). However, at this maximum flexural load, the deflection of the natural fibre reinforced concrete is about 3 times that of the steel reinforced control prism. For the 40F-45s and 40F-85s samples (having a reinforcement ratio of 2.33), flexural strength curves showed a sharp drop after the initiation of the first crack in the concrete. This implies that the load was suddenly transferred to the reinforcement after the concrete cracked. A minimum reinforcement ratio of 2.33 is therefore recommended for OPBF strand reinforced concrete. As a result of the relatively low elastic modulus of natural fibres, a greater rein-

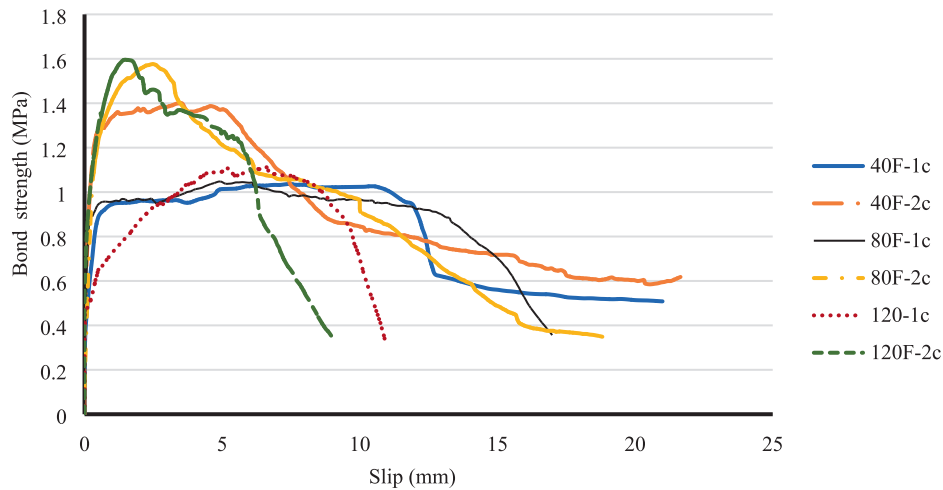


Fig. 8. Bond pull-out response of clamp enhanced OPBF strands at 28 days.



Fig. 9. Some bond pull-out samples showing strand pull-out from concrete matrix.

forcement area is needed to mobilise a section capacity commensurate to a steel reinforced concrete section.

Eurocode [21] specifies a minimum reinforcement ratio of 0.13% for reinforced concrete sections. By direct proportion, the minimum reinforcement section for OPBF concrete would translate to 0.81% which is almost one-third of the minimum recommended for OPBF strand reinforced concrete in this study. The difference between the minimum reinforcement ratio by direct proportion and the recommendation from this study can be traced to the relatively low bond stress between the OPBF reinforcement and concrete. In a comparison presented in the study of Momoh et al. [17], bond strength between plain OPBF strands embedded to 80 mm at 28 days was about 40% of TMT steel at same age but embedded to 150 mm. For the clamp enhanced OPBF strands reported in this study, results show a maximum bond strength of 1.6 MPa for an embedded length of 80 mm which is about 55.7% of that of TMT steel. Clearly, the reduced bond strength would require larger area of OPBF reinforcement if the flexural capacity of the section, in terms of serviceability, is to match the flexural capacity of an equivalent steel reinforced section. Concerns around bond stress also imply that the usual strain compatibility conditions assumed for steel-reinforced concrete may not apply. Hence, an allowable

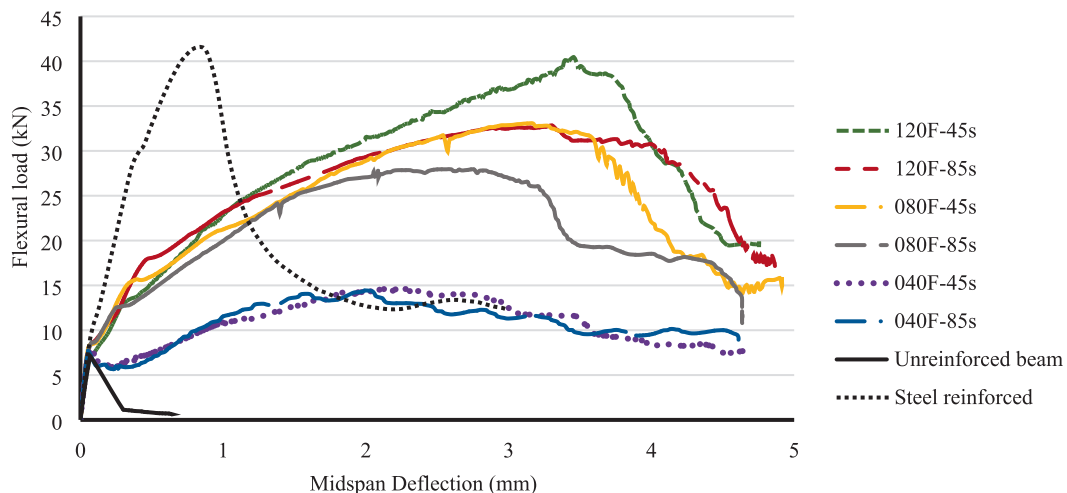


Fig. 10. Flexural response of clamp enhanced OPBF reinforced concrete at 28 days.

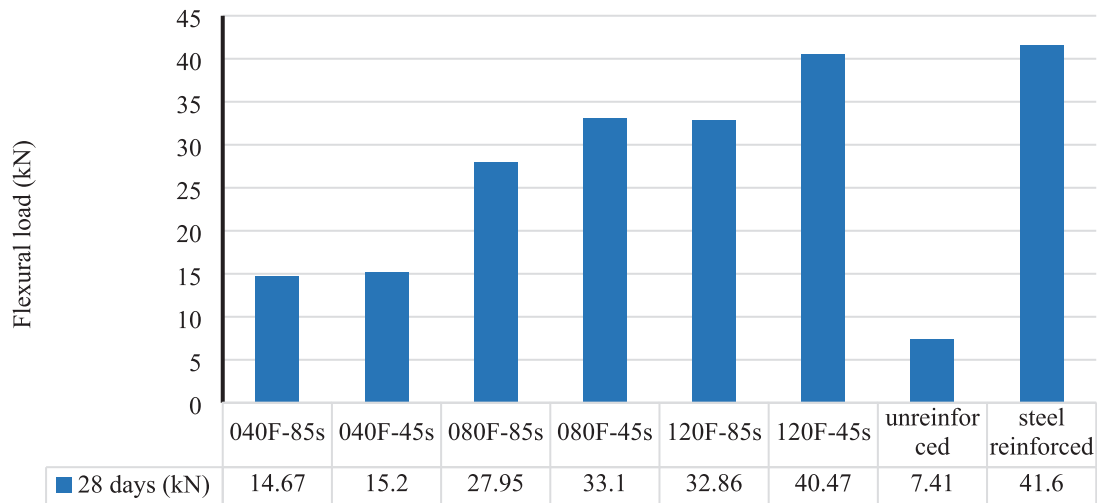


Fig. 11. Maximum flexural capacity of clamp enhanced OPBF reinforced concrete.

stress design methodology for the OPBF strand reinforced concrete may suffice.

The large area of reinforcement usually required for natural fibre reinforced concrete is corroborated in a similar study [18] that reported 4% bamboo reinforcement to be commensurate in flexural capacity to 0.89% steel reinforcement for a concrete beam of 150x75x1000 mm. In another study, the axial and lateral capacity of 8% bamboo reinforcement ratio for a 150x150x1000 mm concrete column was equivalent to 0.89% steel reinforcement ratio for the same column dimension [22]. A comparison in crack pattern between the steel reinforced and the OPBF reinforced concrete shows predominant shear cracks and flexural cracks respectively (see Fig. 12). This is due to the differences in the elastic modulus of the reinforcements. For the OPBF sample, the matrix possessed the stiffer path (than the reinforcement) for load travel which is vice versa for the steel reinforced concrete. Hence the maximum flexural capacity is achieved at a lesser deflection for the steel reinforced concrete but at a greater deflection for the OPBF reinforced concrete. Higher deflections characterizing natural fibre reinforced concrete therefore requires careful considerations for the satisfac-

tion of serviceability (deflection) limit state. However, it is noteworthy that the maximum flexural load of 41 kN for the reinforced samples is about 500% greater than the flexural capacity of the unreinforced sample.

Flexural toughness of the samples was determined from Fig. 10 by calculating the respective areas between the curve and the horizontal (midspan deflection) axis. The highest value of energy absorbed (131.97 Joules) was obtained for the 120F-45s which is about 730% and 220% greater than the energy absorbed by the unreinforced sample and the steel reinforced sample respectively. Relative higher toughness is characteristic of natural fibre reinforced concrete, and this makes them a promising building material in developing countries in seismic regions [12] although a long-term performance investigation would be necessary to confirm this.

4. Conclusions

The study has used broom fibres (OPBF) obtained from oil palm trees in the form of strands held together by steel hose clamps as

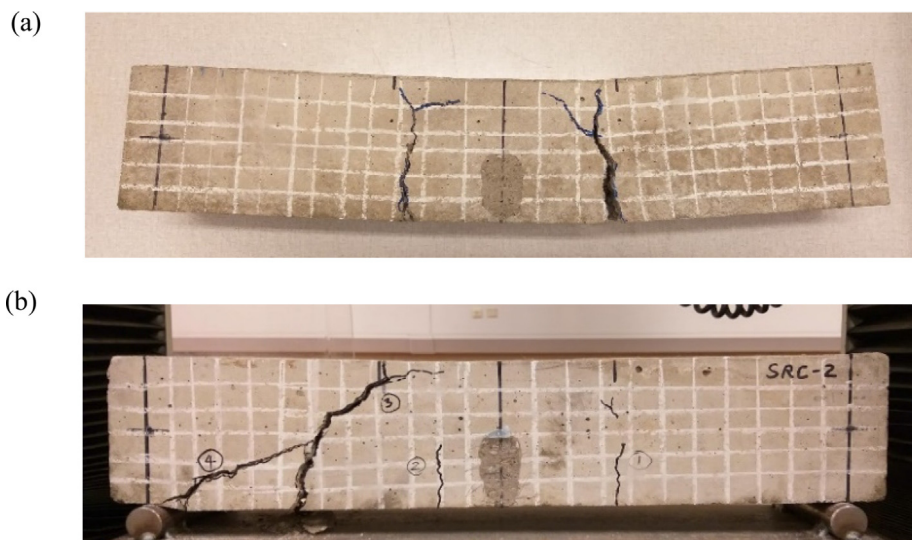


Fig. 12. Comparison of crack developments between (a) OPBF reinforced concrete and (b) steel reinforced concrete.

longitudinal reinforcement for concrete. For a given clamp enhanced OPBF strand reinforced concrete section to mobilise an equivalent flexural resistance like a conventional steel reinforced concrete, a bigger area of OPBF strand reinforcement would be required. Consequently, practicality in construction such as reinforcement detailing need to be considered. Effective crack control may also need to be investigated, especially since OPBF possesses a lower modulus of elasticity than concrete, thereby implying that concrete would firstly crack before stress is transferred onto the reinforcing OPBF strands. Excessive cracks may be mitigated by incorporating conventional steel stirrups to provide effective resistance against shear cracks.

In summary, the tensile strength of the OPBF strands was obtained while bond strength between the strands and the concrete was assessed, as well as the flexural capacities of the OPBF reinforced concrete, and the following conclusions have been made:

- An average tensile strength of 200 MPa was obtained for the OPBF strands,
- Bond strength increased with strand diameter and with clamps due to better anchorage,
- A maximum bond strength of 1.6 MPa was obtained for the pull-out of 120 fibres strand with embedded double clamps.
- The 28 days flexural capacity of an OPBF reinforced concrete beam having a reinforcement ratio of 3.49% is equivalent to 0.56% of steel reinforced concrete,
- A minimum limit of reinforcement ratio for OPBF reinforced concrete of 2.33 is recommended,
- Long term performance of the natural fibre reinforced concrete should be investigated,
- OPBF reinforced concrete can be used in building elements with light structural demands such as lintels.

CRedit authorship contribution statement

Emmanuel Owoichoehi Momoh: Funding acquisition, Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Adelaja Israel Osofero:** Funding acquisition, Investigation, Project administration, Conceptualization, Supervision, Writing – review & editing. **Oleksandr Menshykov:** Project administration, Investigation, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

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