Mechanical Properties and Fracture Behaviour of Coconut Fibre Reinforced Concrete (CFRC)

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Abstract The effect of coconut fibre content on the mechanical properties and fracture behavior of reinforced concrete was studied. The mix design used for the plain concrete and the coconut fibre reinforced concrete was based on 1:2:4 for cement: sand and coarse aggregate. Water/cement ratio used was 0.6. The coconut fibre was added as reinforcement principally to check the propagation of cracks. The composites developed by adding 6%, 8%, 10% and 12% coconut fibre (by weight), mixing and curing. Plain concrete was cast and cured and used as control. Composites were cured for 7, 14 and 28 days. It was observed that the composite with 6% of coconut fibre demonstrated the highest compressive, flexural and split tensile strengths when compared to the control.

Keywords: coconut fibre, cement, concrete, compressive strength, flexural strength, split tensile strength, workability, slump

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1. Introduction

Concrete primarily because of its low tensile strain capacity and fracture toughness is considered a brittle material.

Reinforcing concrete with fibres would not only improve on the compressive strength of concrete but also provide a significant improvement on the tensile strength, flexural strength, ductility, durability, toughness and also arrest cracks in concrete.

Several researchers have used plant fibres as an alternative of steel or synthetic fibres in composites such as cement paste, mortar and concrete [1-26].

These natural fibres include coconut, sisal, jute, hibiscus cannabinus, eucalyptus grandis pulp, malva, ramie bast, pineapple leaf, kenaf date, bamboo, palm, banana hemp, flax, cotton and sugarcane fibres [27].

Compared to steel fibres, they are also easy to use or handle because of their flexibility especially when high percentage of fibres is involved [27].

Coconut fibre is extracted from the outer shell of coconut. The common name, scientific name and plant family of coconut fibre are coir, *cocos nucifera* and arecaceae (palm), respectively. There are two types of coconut fibres, brown fibre extracted from matured coconuts and white fibres extracted from immature coconuts. Brown fibres are thick, string and have high abrasion resistance, while white fibres are smoother and finer, but also weaker [27].

1.1. Previous Works on Coconut Fibre Reinforced Composites

Slate [11] investigated compressive and flexural strength of coconut fibre reinforced mortar. Two cement-sand ratios by weight 1:2.75 with water cement ratio of 0.54 and 1:4 with water cement ratio of 0.82 were considered. Fibre content was 0.08%, 0.16% and 0.32% by total weight of cement, sand and water. The mortars for both design mixes without any fibres were also tested as reference. Cylinders of 50 mm diameter and 100 mm height and beams of 50 mm width, 50 mm depth and 200 mm length were tested. The curing was done for 8 days only. It was found that, compared to that of plain mortar of both mix designs, all strengths were increased in the case of fibre reinforced mortar with all considered fibre contents. However, a decrease in strength of mortar with an increase of fibre content was also observed.

Cook et. al. [12] reported the use of coconut fibre reinforced cement composites as low cost roofing materials. The parameters studied were fibre length (2.5, 3.75 and 6.35cm), fibre volumes (2.5%, 5, 7.5%, 10% and 15%) and casting pressure (from 1 to 2MPa with an increment of 0.33MPa). They concluded that the optimum composite consisted of fibres with a length of 3.75cm, a fibre volume of fraction of 7.5% and is casted under the pressure of 1.67MPa. A comparison revealed that this composite was much cheaper than locally available roofing materials.

Aziz et. al. [13] cited the work of Das Gupta et. al. [14,15] studied the mechanical properties of cement paste composites for different lengths and volume fractions of coconut fibres. Aziz et. al. concluded that the tensile strength and modulus of rupture of cement paste increased when fibres up to 38mm fibre length and 4% volume fraction were used. A further increase in length or volume fraction could reduce the strength of composite. The tensile strength of cement paste composite was 1.9, 2.5, 2.8, 2.2 and 1.5MPa when it was reinforced with 38mm long coconut fibre and the volume fractions of 2%, 3%, 4%, 5% and 6%, respectively. The corresponding modulus of rupture was 3.6, 4.9, 5.45, 5.4 and 4.6MPa, respectively. 4% volume fraction of coconut fibres gave the highest mechanical properties amongst all tested cases. With 4% volume fraction, they also studied the tensile strength of cement paste reinforced with different lengths of coconut fibres. With the fibre lengths of, 2.5, 3.8 and 2.7 MPa, respectively. The results indicated that coconut fibres with a length of 38mm and a volume fraction of 4% gave the maximum strength.

Paramasivam et. al [16] conducted a feasibility study of coconut fibre reinforced corrugated slabs of 915mm x 460mm x 10mm for low-cost housing. A cement-sand ratio of 1:0.5 and water-cement ratio of 0.35 were used. Test for flexural strength using third point loading was performed. For producing required slabs having a flexural strength of 22MPa, a fibre length of 2.5cm, a volume fraction of 3%, and a casting pressure of 0.15MPa were recommended. The thermal conductivity and absorption coefficient for low frequency sound were comparable with those of asbestos boards.

Agopyan et. al. [17] studied coir and sisal fibres as replacement of asbestos in roofing tiles. The dimensions of the tiles were 487mm x 263mm x 6mm. Three-point bend test specimen with 2% total fibre volume fraction, support span of 350mm, deflection rate of 3 mm/min was employed for determination of the maximum load. After the ageing periods of 16 and 60 months, the corresponding maximum load taken by coir tile were 235 and 248N., respectively while that by sisal tiles were 237 and 159n, respectively. The major benefit of reinforced tiles was their at least 22% higher energy absorption than that of the unreinforced tiles which could help to avoid fragile rupture of tiles during transportation or installation.

John et al [18] studied the coir fibre reinforced low alkaline cement mortar taken from the internal and external walls of a 12 year old house. The panel of the house was produced using 1:1.5:0.504 (cement:sand:water), by mass) mortar reinforced with 2% of coconut fibres by volume. Fibres removed from the old samples were reported to be undamaged. No significant difference was found in the lignin content of fibres removed from external and internal walls, confirming the durability of coconut fibres in cement composites.

Luisito et al [19] of PCA-Zamboana Research Centre in Philippines invented coconut fibre boards (CFB) for applications such as tiles, bricks, plywood and hollow blocks. It is used for internal and exterior walls, partitions and ceiling. CFB consisted of 70% cement and 30% fibre by weight. It has water absorption of 32%, water swelling of 4.2% and bending strength of 0.81MPa, respectively.

Mohammad [20] tested wall panels made of gypsum and cement as binder and coconut fibre as reinforcement. Bending and compressive strength, moisture content, density and water absorption were investigated. As expected, coconut fibres did not contribute to bending strength of the tested wall panels. Compressive strength increased with the addition of coconut fibres. There was no considerable change of moisture content with coconut fibres. However, moisture content increased with time. Water absorption of panels was not significantly affected with an increase in fibre content.

Ramakrishna and Sundararajan [21] carried out the experiments on impact resistance of slabs using falling weight of 0.475kg from a height of 200mm. The slabs consisted of 1:3 cement-sand mortar with the dimension of 300mm x 300mm x 20mm. They were reinforced with coconut, sisal, jute and hibiscus cannabinus fibres having four different fibre contents of 0.5%, 1.0%, 1.5% and 2.5% by weight of cement and three fibre lengths of 20, 30 and 40mm. A fibre content of 2% and a fibre content of 40mm of coconut fibre showed the best performance by absorbing 253.5J impact energy. At ultimate failure all fibres except coconut fibre, showed fibre fracture while coconut fibre showed fibre pull-out. The ultimate failure was determined based on the number of blows required to open a crack through the entire length of the specimen.

Li et al [22] studied untreated and alkalinized coconut fibres with the lengths of 20mm and 40mm as reinforcement in cementitious composites. Mortar was mixed in a laboratory mixer at a constant speed of 30 rpm, with cement: sand: water::super plasticizer ratio of 1:3:0.43:0.01 by weight, and fibres were slowly put into the running mixer. The resulting mortar had a better flexural strength (increased up to 12%), higher energy absorption ability (up to 1680%) and a higher ductility (up to 1740%), and is lighter than the conventional mortar.

Reis [23] performed third-point loading tests to investigate the flexural strength, fracture toughness and fracture energy of epoxy polymer concrete reinforced with coconut, sugarcane bagasse and banana fibres. The investigation revealed that fracture toughness and energy of coconut fibre reinforced polymer concrete were the highest, and an increase of flexural strength up to 25% was observed with coconut fibres.

Asasutjarit et al [24] determined the physical (density, moisture content, water absorption and thickness swelling), mechanical (modulus of elasticity, modulus of rupture and internal bond) and thermal properties of coir-based light weight cement board after 28 days of hydration. The physical and mechanical properties were measured by Japanese Industrial Standard JIS A 5908-1994 and the thermal properties according to JIS R 2618. The parameters studied were fibre length, coir pre-treatment and mixture ratio. 6cm long boiled and washed fibres with optimum cement:fibre:water weight ratio of 2:1:2 gave the highest modulus of rupture and internal bond amongst the tested specimens. The board also had a thermal conductivity lower than other commercial flake board composite.

Buruah and Talukdar [25] investigated the mechanical properties of plain concrete (PC) and fibre reinforced concrete (FRC) with different fibre volume fractions

ranging from 0.5% to 2%. Steel, synthetic jute and coconut fibres were used. Here the discussion is limited to the coconut fibres reinforced concrete (CFRC) only. The cement:sand:aggregate ratio for plain concrete was 0.535. Coconut fibres having length of 4cm and an average diameter of 0.4mm with volume fraction of 0.5%, 1%, 1.5% and 2% were added to prepare CFRC. The sizes of specimens were (1) 150mm depth and 300mm height for cylinders (2) 150mm width, 150mm depth and 700mm length for beams, and (3) 150mm cubes having a cut of 90mm x 60mm in cross-section and 150mm high for L-shaped shear test specimens. All specimens were cured for 28 days. The compressive strength q , splitting tensile strength (STS), modulus of rupture (MOR) using four point load test and shear strength T . It can be seen that CFRC with 2% fibres showed the best overall performance amongst all volume fractions. The compressive strength, splitting tensile strength, modulus of rupture and shear strength of coir fibre reinforced concrete with 2% fibres by volume fraction were increased up to 13.7%, 22.9%, 28.0% and 32.7%, respectively as compared to those of plain concrete. Their research indicated that all these properties were improved as well for CFRC with other fibre volume fractions of 0.5%, 1% and 1.5%. Even for CFRC with small fibre volume fraction of 0.5% the corresponding properties were increased up to 1.3%, 4.9%, 4.0% and 4.7%, respectively.

Li et al [26] studied fibre volume fraction and fibre surface treatment with a wetting agent for coir mesh reinforced mortar using nonwoven coir mesh matting. They performed a four-point bending test and concluded that cementitious composites, reinforced by three layers of coir mesh with a low fibre content of 1.8%, resulted in a 40% improvement in the maximum flexural strength. The composites were 25 times stronger in flexural toughness and about 20 times higher in flexural ductility.

To the best knowledge of the authors the only research [25] on the static CFRC properties is done with only one coir fibre length of 4cm. With regard to dynamic properties of CFRC, no study has been reported. Dynamic tests had been performed only for concrete reinforced by other fibres, e.g. polyolefin fibres [37] or rubber scrap [38]. To reveal the consequence of fibre lengths and other parameters are required in order to have reliable insights. To be able to apply CFRC in cheap housing in tropical earthquake regions, the knowledge of static and dynamic properties of CFRC is necessary.

Spadea, et al [28] investigated the strength and ductility properties of recycled PET fibre-reinforced concrete (RPETFC) with different mix design and PET filaments with variable mechanical geometric properties. Tests highlighted that the most relevant effect of the recycled PET for reinforced fibre concrete are concerned with material toughness and ductility.. In the case of strength test, significant compressive and flexural strength enhancements due to the addition of PET fibre are noticed..

Ali [29] studied the role of post-tensioned coconut-fibre ropes in mortar-free interlocking concrete construction during seismic loadings. It was observed that there is a percentage difference up to 35% in predicting the structures response which can be attributed towards the complicated nature of the structure versus the simple

approach developed. This can be of help in understudying the behavior of mortar-free interlocking structure having post-tension coconut-fibre rope in a systemic manner.

Wang et al [30] investigated the behavior of coconut fibre reinforced concrete (CFRC) under impact loading. This was with a view to prevent the damage resulting from impact loading and developing mitigating measures. Results from their experimental work showed that CFRC can absorb more impact energy than, while plain concrete shows brittle failure. The study also defined the influence factors that control the energy dissipation of the composite which will be used for developing future protection structures in earthquake regions.

Lumingkewas et al [31] carried out a study on the effect of fibres length and fibres content on the splitting tensile strength of coconut fibres reinforced concrete composite. They used fibre content of (1, 2, 3 and 4% by mass ratio of fibre per cement and the length of fibres (5, 20 and, 40mm) in the concrete. The results show that coconut fibre length of 5mm and fibre content of 3% in fibre concrete composite gave the composite 1.28 times higher splitting tensile strength than plain concrete. The density of the fibre concrete composite, decreases with the addition of coconut fibre content.

Prasad et al [32] investigated self compacting concrete beams strengthened with natural fibre under cyclic loading. They concluded that coconut fibre has the highest toughness amongst all fibres. A comparison was made between the cyclic and static loading of coconut fibre reinforced self compacting concrete. It was observed that (FRSCC) members from the test data obtained, hysteresis logs were obtained, same as comparison of envelope curve, energy dissipation, stiffness degradation to justify the use of coconut fibre in self compacting concrete.

An observation of the literature review above revealed that weight fraction and volume fraction of the coconut fibre added to the concrete was between (1-6%). This study was carried out using 6%, 8%, 10% and 12% weight fraction of coconut fibre. The gap being filled in this study is primarily in the area of increased coconut fibre content. Coconut fibre is an agricultural waste which is readily available in Nigeria.. Its use to improve the mechanical properties and fracture behavior of reinforced concrete will be of immense benefit in the environmental protection as well as an economic gain in the cost of production of reinforced concrete that could conveniently withstand crack propagation.

2. Materials and Methods

2.1. Materials

2.1.1. Cement

Ordinary Portland Cement (OPC) manufactured by DANGOTE INDUSTRIES Plc was used. The cement used in the study was (Grade 42.5). It conformed to [33].

2.1.2. Fine Aggregate

Naturally occurring river sand obtained from Imo River in Oyiabo Local Government Area of Rivers State was

used. The maximum size was 4.75mm. Impurities were removed and it conformed to the requirements of [34].

2.1.3. Coarse Aggregate

Coarse aggregate used is crushed angular and rough textured granite obtained from CRUSHED ROCK INDUSTRIES Plc at Isghiagu io Ebonyi State, South Eastern Nigeria. Maximum size was 20mm. It conformed to [34].

2.1.4. Coconut Fibre

The coconut fibre used for the project was obtained locally in Port Harcourt from local coconut traders. The fibres are usually obtained by manually extracting them from the outer coconut fruit shell. The fibres were washed properly to remove films of impurities attached to them, after which they were air dried for some few days under ambient temperature. The fibres were cut using scissors to lengths of approximately 25mm

2.1.5. Water

Potable water used was obtained from the Civil Engineering Laboratory of the Rivers State University, Port Harcourt. The water conformed to [35].

2.2. Method

Fibre lengths of 25mm and 0.03mm diameter and fibre contents by weight of cement of 0%, 6%, 8%, 10% and 12% were considered for the investigation. Of the mechanical properties and fracture behavior of CFRFC.

2.2.1. Laboratory Preparation of the Coconut Fibre and Coconut Fibre Reinforced Cement

The CFRFC used had constituent materials made of fine and coarse aggregates, OPC, water and coconut fibre. The coconut fibres were washed, dried and cut into sizes of 25mm length and 0.03 mm diameter. The arrangement of the fibres in the concrete is still a subject of controversy in the sense that the fibres cannot be expected to remain straight in the concrete cubes during mixing, casting and curing. The random distribution of the fibers and their ability to add strength and mitigate crack propagation is more important. Coarse aggregates were 5mm or larger in size, while fine aggregates were less than 5mm in size.

Concrete cubes, beams and cylinders were prepared of sizes 150mm x 150mm x 150mm, 100mm x 100mm x 500mm and 150mm x 300mm respectively. They were cast for the plain concrete as well as for the CFRFC. Preparation of the CFRFC was done in accordance with [27], as stated as follows. A layer of coconut fibre was spread in the pan, followed by spreading of aggregate, sand and cement. The first layer of fibres was hidden under the dry concrete materials with the help of a spade. Then, another layer of coconut fibre followed by layers of aggregate, sand and cement was spread. This process is repeated until the rest materials were put into the mixer pan. Approximately three quarters of the water (according to water/cement ratio which was the same as that of plain concrete) was added and the mixer was rotated for 2min. All the cast specimens were given a 24 hour period to set under ambient temperature in their respective moulds

before being transferred to a curing tank for the appropriate curing days to their final tests.

2.2.2. Mix Design of the CFRFC

The control was plain concrete. The mix design ration for cement:sand:aggregate was 1:2:4 respectively, while the water cement ratio was 0.6. The same mix ratio and water cement ratio was used for the CFRFC. The various constituents of the CFRFC fine aggregate, coarse aggregates, water and coconut fibre were calculated by mass of cement.

2.2.3. Particle Size Distribution Test

The particle size distribution of both fine and coarse aggregates was carried out in accordance with [36].

2.2.4. Compressive Strength

Compressive strength test was carried out at 7, 14 and 28 days for CFRFC cubes in accordance with [37]. For each replacement level, 3 cubes were prepared, cured and crushed and the average value of the 3 results was used.

2.2.5. Flexural Strength

The flexural strength tests was carried out of plain beam CFRFC specimens of size 100mm x 100mm x 500mm loaded at one- third of its length from the extreme sides. Equal loads were applied at these points from sides of the beam support and an equal reaction is induced also. The flexural strengths were determined at 7, 14 and 28days. The test was performed in accordance with [38].

2.2.6. Split Tensile Strength

The split Tensile strength was carried out with cylindrical specimens measuring 150mm (dia) and 300mm (length). The split tensile strength was determined at 7, 14 and 28 days in accordance with [39].

2.2.7. Setting Time

The initial and final setting times of the specimen cubes with 0%, 6%, 8%, 10% and 12% were carried out in accordance with [40].

2.2.8. Workability

The workability of fresh concrete determines the ease with which it can be mixed, placed and transferred into its final location and compacted. The slump of the CFRFC with, 0%, 6%, 8%, 10% and 12% were determined in accordance with [41].

3. Results and Discussion

3.1. Particle Size Distribution

The particle size distributions of the coarse and fine aggregates are shown in Figure 1 and Figure 2. These charts show the behavioral pattern of the varied aggregate sizes, It can be observed that for the coarse aggregate size, the envelope for the coarse aggregate was that of the nominal size and for the fine aggregates the distribution is within the sand zone.

Figure 1. Particle Size Distribution for Fine Aggregates

Figure 2. Particle Size Distribution for Coarse Aggregate

3.2. Compressive Strength

Figure 3 shows the the plot of the compressive strength at 7, 14 and 28 days for CFRC with coconut fibre content of 0%, 6%, 8%, 10%, and 12%. In all cases, the compressive strength decreased as the quantity of the coconut fibre was increased. However, it is important to point out that up till 6% coconut fibre content, the compressive strength achieved for the 7, 14 and 28 days was not remarkably different from that of normal plain concrete, (21.0 N/mm², 22.22N/mm² and 23,.77N/mm²) for 7, 14 and 28 days. Since the coconut fibre assisted in resisting cracks, it could be safely stated that a maximum of 6% coconut fibre content added to concrete will resist crack propagation and still produce adequate compressive strength. The decrease in compressive strength as the content iof coconut fibre is increased is due to the resistance provided by the fibre via their surface areas and rigidity offered to the stresses induced in the walls [27].

3.3. Flexural Strength

Figure 4 shows a plot of the flexural strength of the CRFC against the percentage of the coconut fibre content. The result is a mirror image of that of the compressive strength. Flexural strength decreased as the content of the coconut fibre in the CFRC was increased. Similarly, up till 6% coconut fibre content, there was no appreciable decrease in flexural strength at 7, 14 and 28 days when compared to the plain concrete. Flexural strength at 6% coconut fibre content was (6.0N/mm², 8.3N/mm² and 10.5N/mm²) as against values of (7.0N/mm², 9.0N/mm² and 12.0N/mm²) for 0% coconut fibre content at 7, 14, and 28 Days respectively.

The bond strength between fibres and the concrete ingredients was not very efficient and as such the tensile stress could not be resisted, in addition to this, the fibre was rather too flexible to resist the bending stresses [27].

Figure 3. Compressive strength versus percentage coconut fibre

Figure 4. Flexural strength versus percentage of coconut fibre content

Figure 5. Split tensile strength versus coconut fibre content

3.4. Split Tensile Strength

The trend of reduction noticed in the compressive and flexural strength was also noticed in the split tensile strength result as can be observed from Figure 5. The same reason adduced for the compressive and flexural strength is applicable.

Up till 6% coconut fibre content split tensile strength of (2.33N/mm^2 , 2.55N/mm^2 and 2.55N/mm^2) were obtained as against (2.40N/mm^2 , 2.62N/mm^2 and 2.69N/mm^2) for 0% coconut fibre content at 7, 14 and 28 days respectively. There is no appreciable different in split tensile strength between 0% and 6% coconut fibre content in concrete.

3.5. Setting Time

Figure 6 is a graph of the setting time against the CFRC

with varying percentages of coconut fibre. The initial and final setting times decreased as the content of the coconut fibre is increased. As in other properties, up till 6%, there was no change in setting time between the plain concrete and CFRC. The addition of fibre reduces the hydration process and as such both plastic and solid state were attained faster by the concrete.

3.6. Workability

Figure 7 is a plot of the slump values in (mm) against the percentage of coconut fibre. The workability decreased as the quantity of the coconut fibre increases. The rate of water absorption increases with increasing content of the coconut fibre. At 12% coconut fibre, the lowest slump value of 3mm was observed.

Figure 6. Setting time versus percentage coconut fibre content

Figure 7. Slump value (mm) versus percentage coconut content

4. Conclusion

The following conclusions were drawn from the result of the experiments.

(i) The compressive, flexural, split tensile strength, workability and setting time decreased as the coconut fibre content was increased in the CFRC.

(ii) Up till 6% coconut fibre content there was no appreciable change in the values of the compressive, flexural, split tensile strength, workability and setting time. It can therefore be concluded that the optimum coconut fibre content to produce concrete with strength values close to normal plain concrete but with ability to resist crack propagation is 6% of coconut fibre content.

(iii) 6% coconut fibre in concrete can act as an admixture (accelerator) while still retaining compressive, flexural and split tensile strength comparable to those of normal concrete.

Abbreviations

BS – British Standard
CFB – Concrete Fibre Board
CRCF – Coconut Fibre Reinforced Concrete
FRC – Fibre Reinforced Concrete
FRSCC – Fibre Reinforced Self Compacting Concrete
MOR – Modulus of Rupture
OPC – Ordinary Portland Cement
PC – Plain Concrete
PET – Polyethylene Teraphthalate
RPETFRC – Recycled PET Fibre Reinforced Concrete.
STS – Split Tensile Strength

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