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Strength Characteristics of Recycled Polyethylene Fibre Reinforced Concrete

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Authors' contributions

This work was carried out in collaboration among all authors. Author AMG designed the study, performed the experimental analysis, wrote the protocol and wrote the first draft of the manuscript. Author CKK managed the analyses of the study and the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

This paper reports on the compressive strength and flexural tensile behavior of recycled polyethylene fibre reinforced concrete. Twelve concrete cubes of dimension 150 mm ×150 mm × 150 mm containing 0%, 0.25%, 0.50% and 1.0% of polyethylene fibres were cast and tested per BS 1881-part 116: 1983 to determine the compressive strength. Twelve concrete prisms measuring 100 mm×100 mm×300 mm containing 0%, 0.25%, 0.50% and 1.0% of polyethylene fibres were also cast and tested under a center-point loading system using an Avery Denison universal testing machine per the American Society for Testing and Materials, ASTM C78-2009 to investigate the flexural behavior of the polyethylene fibre concrete. Results of the tests showed that, the compressive strength fell from an average of 33.07 N/mm^2 for the plain concrete specimen to an average of 17.74 N/mm^2 for the 1.0% fibre concrete specimen. The drop in average compressive strength is 22% for the 0.25% fibre concrete, 36% for the 0.5% fibre concrete, and 46% for the 1.0% fibre concrete specimen. These drops in compressive strength of the polyethylene fibre concrete are quite significant compared to the plain concrete. The modulus of rupture which is an indication of the flexural tensile strength of the concrete however increased from 6.56 N/mm^2 for the plain concrete to 8.32 N/mm^2 for the 1.0% fibre concrete. The percentage

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increase is 3% for the 0.25% fibre concrete, 14% for the 0.5% fibre concrete, and 27% for the 1.0% fibre concrete specimen. The polyethylene fibres therefore have a generally positive effect on the flexural strength of concrete.

Keywords: Fibre reinforced concrete; modulus of rupture; flexural tensile strength; critical length; volume fraction; compressive strength; polyethylene fibre.

1. INTRODUCTION

Concrete is used twice as much in construction than all other building materials with an annual global production pegged at 5 billion cubic yards. Its properties like easy mouldability into any desired shape, easy availability of its constituent materials, and cost effectiveness makes it the most popular construction material. Concrete however have deficiencies such as brittleness, low tensile strength, and low ductility. Concrete is a strong material in compression but very weak in tension [1]. Reinforcement is therefore required in plain concrete to first, control cracking which will result in improved durability; and second, to resist tensile forces resulting from applied loads (ie increase load bearing capacity). Fibres are added to concrete to bridge discrete microcracks and thereby provide for increased control of the fracture process and also to increase the fracture energy thereby yielding a more ductile behavior. Fibre reinforced concrete (FRC) is a cement-based composite material reinforced with short, discrete, and usually random distributed fibres within a concrete matrix [2].

Theoretical studies into flexural behaviour of fibre reinforced concrete (FRC) can be obtained from the works of Lok and Pei [3] and Lok and Xiao [4]. Analytical models developed for depicting the flexural behavior of FRC can be found in Ezeldin and Shah [5] and Zhang and Stang [6]. Flexural strength provides two useful parameters, namely: “first crack strength, which is primarily controlled by the matrix”, and “the ultimate flexural strength or modulus of rupture, which is determined by the maximum load that can be attained’’ [7]. For unreinforced concrete structures such as roads and runways which rely on their flexural strengths to safely distribute concentrated loads over wide areas, flexural strength property of the concrete is particularly important hence, findings from this research will have great significance in providing relevant data for the analysis and design of such structures by consultants and practitioners in the construction industry.

The use of polyethylene products is widespread in the Ghanaian society. The country is estimated to generate about 4000 tonnes of plastic waste every month [8]. Most of the polyethylene products are however non-biodegradable, non-compactible, and non-destroyable hence their disposal presents a huge challenge to the Waste Management Authorities and the nation as a whole. Some of the dangers posed by the indiscriminate disposal of the polyethylene products include flooding as a result of choking of drainage ways, pollution of water bodies including ground water resources, upsetting the food chain, and causing land and air pollution. In Kumasi the second largest city, and other parts of the country, polyethylene products are collected by human scavengers, melted and recycled to produce tyres, bottles and sachet water bags but this alone is not adequate. There is the need for more recycling options. This research is therefore geared towards addressing the problems of concrete reinforcement and at the same time providing an avenue for recycling of the used polyethylene thereby solving the menace of polyethylene waste in the country.

1.1 Strength of Brittle Materials

The tensile strength of concrete can be determined theoretically using Griffith theory [9] given by:

$$\sigma = \sqrt{\frac{2E\gamma}{\pi c}} \quad \text{Eq 1}$$

where σ denotes tensile strength of the concrete; c is size of crack; γ is unit weight of concrete; E is elastic modulus of concrete.

It can be seen from Equation 1 that the tensile strength is inversely proportional to square root the size of the crack. Concrete has a lower tensile strength due to the existence of large cracks in the matrix. The cement-based matrix is therefore reinforced with fibres to increase the tensile strength of the matrix by delaying the growth of cracks and also to increase the toughness by transmitting stress across the cracked section so that much larger deformation is possible beyond the peak stress.

1.2 Theoretical Flexural Strength

Theoretically, the flexural tensile strength or modulus of rupture of fibre reinforced brittle matrix composite can be calculated using the relation developed by Hannant [10] as follows:

$$\sigma_{fl} = 2.44\left(1 - \frac{l_c}{2l}\right)\sigma_{fu} \times V_f \qquad \text{Eq 2}$$

where σ_{fl} denotes flexural tensile strength or modulus of rupture; l_c denotes critical length of the fibre below which fibre pull-out will occur; l is length of fibre; σ_{fu} is ultimate tensile strength of the fibre; and V_f is volume fraction of the fibre in the composite.

The critical length of fibre l_c is given by:

$$l_c = \frac{\sigma_{fu} \times r}{\tau} \qquad \text{Eq 3}$$

where r denotes radius of the fibre and τ is the interfacial shear bond strength between fibre and matrix.

2. Experimental Method

2.1 Test Set-up and Instruments

The modulus of rupture was determined per the American Society for Testing and Materials, ASTM C78-2009 [11]. The test was conducted using a center-point loading system on an Avery Denison universal testing machine. The compressive strength was determined per British Standards, BS 1881-part 116: 1983 [12] using a digital DG-901 cube testing machine at a constant applied load rate of 0.2 M Pa/sec – 1.0 MPa/sec.

2.2 Specimen

A total of twelve concrete prisms measuring 100mm×100mm×300mm were cast with varying volume fraction of polyethylene fibres for the modulus of rupture test and a total of twelve concrete cubes measuring 150 mm × 150 mm × 150 mm were cast for the compressive strength test. Details of the test specimen are as shown in Table 1.

2.3 Materials

Medium strength concrete of nominal strength 30 N/mm^2 at 28 days was used. The component parts per m^3 of concrete were 340 kg of ordinary Portland cement (Diamond brand) obtained from local suppliers, 720 kg of river sand, 370 kg of 10 mm crushed granitic rock, and 720 kg of 20 mm crushed granitic rock with an optimum water cement ratio of 0.55. The aggregates were obtained from local quarries and potable water was used to mix the concrete. Low Density Polyethylene (LDPE) fibre with melt flow index of 7gm/10min, density of 0.922 g/cm^3, and low crystallinity (50-60% crystalline) was used [13] and is as shown in Fig. 1. The fibres were of dimensions 0.095mm×5mm×40mm.

2.4 Casting and Curing of Specimen

Batching of materials was done by weight using an electronic balance to the nearest 0.02 kg. A portable electric concrete mixer was used for the mixing to ensure an even, consistent concrete mixture Fig. 2a. All of the concrete was batched simultaneously, and the plain and fibre reinforced concretes were then re-mixed for four minutes to ensure the same mixing time was given to each batch. The specimens were compacted by extensive rodding and tamping and cured under water in curing tanks for 28 days Fig. 2b. The complete set of specimen for the experiment is shown in Fig. 3a and 3b.

2.5 Test Procedure

2.5.1 Modulus of rupture

The specimen was brushed clean, turned on its side with respect to the position in the formwork and simply supported at each end on the beam of the universal test frame. The load was then brought into contact with the upper surface of the prism via a bearing bar positioned centrally on the specimen. A slight force was applied to seat the specimen firmly in its supports and loading of the specimen continued via the lever pump at the rate of 2kN/s until the specimen could not support further load increment. The maximum load was then recorded as P. The modulus of rupture was calculated using the formula:

$$R = 1.5\left(\frac{Pl}{bd^2}\right) \qquad \text{Eq 4}$$

Where R denotes the modulus of rupture in N/mm^2; P is the maximum load on prism in N; l is the span between centers of lower supports in mm; b is the average width of prism in mm; and *d* is the average depth of prism in mm. The test setup is as shown in Fig. 4.

Table 1. Details of test specimen

Test	Standard	Specimen type & size (mm)	Number of specimen	Fibre volume fraction (%)
Compressive Strength	BS 1881-part116: 1983	Cubes 150×150×150	12	0, 0.25, 0.50, 1.0
Modulus of rupture	ASTM C78-2009 Center-point loading	Prisms 100×100×300		

Fig. 1. Low density polyethylene fibres

Fig. 2a. Mixing of concrete in electric mixer

Fig. 2b. Curing of specimen in curing tank

Fig. 3a. 100 mm × 100 mm × 300 mm prisms **Fig. 3b. 150 mm × 150 mm × 150 mm cubes**

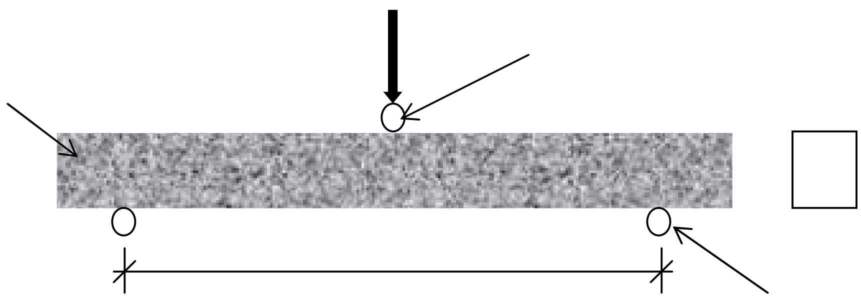


Fig. 4. Modulus of rupture test setup

2.5.2 Compressive Strength

The cubes were brushed clean, turned on their sides with respect to the position in the mould and placed centrally in the testing machine. The plates of the testing machine were brought into contact with the cast faces of the cube. Loading of the cube then continued at the rate of 1.0 M Pa/sec until the cube crushed. The cube compressive strength was then calculated using the formula:

$$f_{cu} = \left(\frac{P}{b^2}\right) \quad \text{Eq 5}$$

where f_{cu} denotes the cube compressive strength, in N/mm^2; P is the ultimate load at collapse, in N; and b is the average height/ width/ breadth of cube, in mm.

3. RESULTS AND DISCUSSION

3.1 Compressive Strength

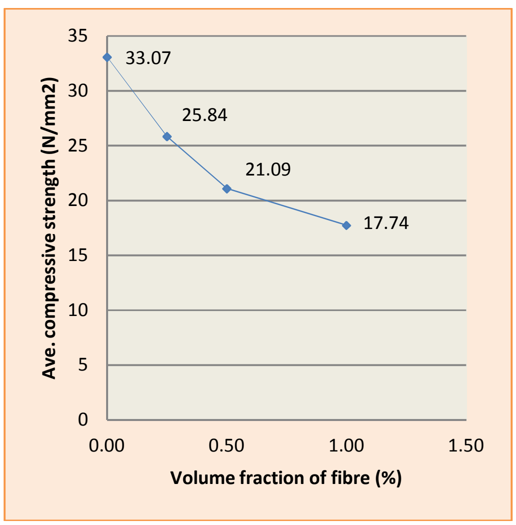
Results of the 28 days compressive strength test is presented in Table 2, the average 28 days compressive strength in Fig. 5 and the respective average concrete densities in Fig. 6. The percentage reduction in compressive strength and density is also presented in Table 3. It can be observed from Fig. 5 that there is a reduction in compressive strength from 33.07 N/mm^2 for the plain concrete to 17.74 N/mm^2 for the 1% fibre concrete. This reduction is consistent with the reduction in density of the fibre concrete as shown in Fig. 6.

Slight decrease (less than 10%) in compressive strength has been reported when monofilament polypropylene fibres measuring 30mm long by 50 µm in diameter at low volume fractions (less than 0.5%) were added to concrete [14]. Singh et al. [15] also reported a 13% reduction in compressive strength as a result of a 1% volume fraction of fibrillated polypropylene fibre addition to concrete.

It is evident in the foregoing that polymer fibres when added to concrete result in a reduction in compressive strength of the concrete compared to a plain concrete. Normal weigh concrete has a bulk density of 2400 kg/m^3 whereas polyethylene has bulk density of 900 kg/m^3, this represent a density ratio of 2.7 to 1. The polyethylene is of a lower density and compressive strength compared to the surrounding concrete. It therefore follows that in the fibre concrete specimens, a certain volume fraction of the concrete is taken up by the polyethylene fibre which is a low-density material. This is partly responsible for the lower density and compressive strength of the fibre concrete. Secondly, the low bond strength of the fibres results in breaks in the Calcium Silicate Hydrate (C-S-H) bond between the cement and the surrounding aggregates, hence the lower compressive strength. Lastly, fibres have been shown [16] to contribute to problems of compacting in fibre reinforced concrete hence the reduced density.

Table 2. 28 days compressive strength test results

s/n	Specimen id	Specimen type	Load (KN)	Actual dimensions (mm)			Compressive strength (N/mm2)
1	CD1	1.0% fibre concrete	438	151	150	150	19.34
2	CD2	1.0% fibre concrete	374	150	150	150	16.62
3	CD3	1.0% fibre concrete	391	151	150	150	17.26
4	CC1	0.50% fibre concrete	472	149	150	150	21.12
5	CC2	0.50% fibre concrete	486	149	150	150	21.74
6	CC3	0.50% fibre concrete	456	149	150	150	20.40
7	CB1	0.25% fibre concrete	572	150	150	150	25.42
8	CB2	0.25% fibre concrete	534	151	150	150	23.58
9	CB3	0.25% fibre concrete	646	151	150	150	28.52
10	CA1	control-plain concrete	838	150	150	150	37.24
11	CA2	control-plain concrete	660	149	150	150	29.53
12	CA3	control-plain concrete	730	150	150	150	32.44



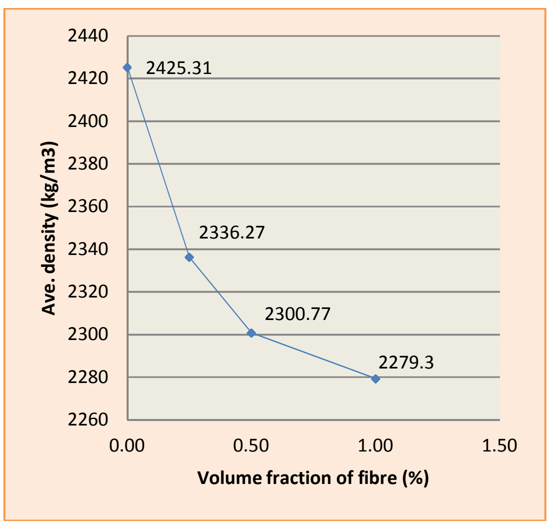


Fig. 6. Average concrete density values

Fig. 5. Average compressive strength values

Table 3. Percentage reduction in compressive strength and density

Concrete type	Reduction in compressive strength (%)	Reduction in density (%)
Plain concrete	0	0
0.25% fibre concrete	21.87	3.67
0.5% fibre concrete	36.24	5.13
1.0% fibre concrete	46.36	6.02

3.2 Flexural Tensile Strength

The results of the modulus of rupture test are presented in Table 4, the average values of the modulus of rupture in Fig. 7 and the percentage increase is presented in Table 5. The results show an increase in flexural tensile strength (modulus of rupture) as a result of fibre addition to concrete. MOR increased from 6.56 MPa for the plain concrete to 8.32 MPa for the 1% fibre concrete.

Kandasamy and Murugesan [17] recorded an increase in tensile strength of 1.63% due to addition of 0.5% polyethylene fibre to concrete. The tensile strength of concrete in this case was determined using the split tensile test on cylinders. Pelisser et al. [18] also recorded an increase in flexural tensile strength of concrete due to addition of polyethylene terephthalate (PET) fibres to concrete. The improvement in the flexural capacity can be attributed to the fibres slowing down crack propagation during loading through progressive bridging of micro-cracks in the concrete. The fibres are known to possess much higher ultimate tensile strength (500 MPa) compared to the more brittle concrete (4 - 8MPa); hence their inclusion is expected to improve the tensile strength of the concrete. The enhanced flexural strength of the fibre reinforced concrete is also evident on the test specimen after failure. Fig. 8 shows a complete separation of the plain concrete immediately after the first crack and therefore represents a typical brittle failure.

Table 4. Modulus of rupture test results

S/N	Specimen id	Specimen type	Load (kN)	Actual dimensions (mm)			Effective span (mm)	Modulus of rupture, R (Mpa)
1	PD1	1.0% fibre concrete	28	100	101	300	200	8.23
2	PD2	1.0% fibre concrete	28	100	102	300	200	8.07
3	PD3	1.0% fibre concrete	30	100	102	300	200	8.65
4	PC1	0.50% fibre concrete	25	101	101	300	200	7.28
5	PC2	0.50% fibre concrete	26	100	100	300	200	7.80
6	PC3	0.50% fibre concrete	25	100	101	300	200	7.35
7	PB1	0.25% fibre concrete	23	100	102	300	200	6.63
8	PB2	0.25% fibre concrete	23	100	102	300	200	6.63
9	PB3	0.25% fibre concrete	23	100	100	298	200	6.90
10	PA1	control-plain concrete	22	100	100	300	200	6.60
11	PA2	control-plain concrete	22	100	100	298	200	6.60
12	PA3	control-plain concrete	22	100	101	298	200	6.47

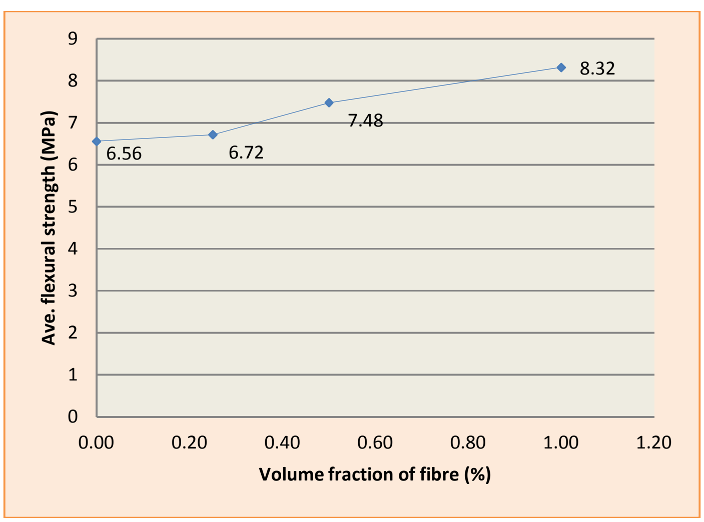


Fig. 7. Percentage reduction in flexural strength

Fig. 8. Plain concrete prisms after failure **Fig. 9. Polyethylene fibre concrete after failure**

Table 5. Average modulus of rupture values

Concrete type	Increase in flexural strength (%)
Plain	0
0.25% fibre	2.51
0.50% fibre	14.04
1.00% fibre	26.89

The fibre reinforced concrete specimens Fig. 9, however, showed a more ductile behavior at failure with fibres visibly seen spanning the cracked section and therefore preventing the complete separation of the member.

4. CONCLUSION

This research investigated the strength characteristics of concrete reinforced with various volume fractions of polyethylene fibre. Twelve concrete prisms measuring 100×100×300 mm were tested under a center-point loading system using a Universal Test Frame at constant load increments of 2kN to determine the flexural tensile strength. The compressive strength was also determined by crushing twelve concrete cubes per BS 1881-part116:1983. Findings of the research points to the fact that compressive strength of the polyethylene fibre concretes reduced significantly compared to those for normal concrete. Hence, the volume fraction of polyethylene fibre in concrete should be kept as minimum as possible to minimize the loss in compressive strength. Superplasticizers could also be used in polyethylene fibre concretes to help bring down the water cement ratio. The flexural tensile strength however increased with increase in polyethylene fibre content. Further work is required to acquire data on long-term strength characteristics and other structural properties of the experimental concrete. These include: shear strength, durability, resistance to impact, creep, etc. These will assist engineers and designers when using the materials for construction works.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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