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Mechanical Properties of Fibre Reinforced Concrete - A Comparative Experimental Study

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***Abstract*—**This paper in essence presents comparative experimental data on the mechanical performance of steel and synthetic fibre-reinforced concrete under compression, tensile split and flexure. URW1050 steel fibre and HPP45 synthetic fibre, both with the same concrete design mix, have been used to make cube specimens for a compression test, cylinders for a tensile split test and beam specimens for a flexural test. The experimental data demonstrated steel fibre reinforced concrete to be stronger in flexure at early stages, whilst both fibre reinforced concrete types displayed comparatively the same performance in compression, tensile splitting and 28-day flexural strength. In terms of post-crack control HPP45 was preferable.

***Keywords*—**Steel Fibre, Synthetic Fibre, Fibre Reinforced Concrete, Failure, Ductility, Experimental Study.

I. Introduction

STEEL and synthetic fibres are the two most commonly used fibre concretes in the world [1]. Their mechanical properties have therefore become very important in light of the rapid transformation in their application. Various studies have covered different mix designs, fibre volumes and aspect ratios but still there is a considerable gap in knowledge about the behaviour of concrete reinforced with these types of fibres. This paper aims to address some experimental data to create a base for better understanding of the comparative performance of these types of structural materials. This study is therefore based on the comparative mechanical behaviour of the steel (URW1050) and the synthetic (HPP45) fibre concrete types in the same mix design and fibre weight after 7, 14 and 28 days with respect to their performance in flexure, compression and tensile splitting.

Concrete is the second most consumed construction material after water with twice as much concrete used across the world than all other construction materials put together [2]. Concrete meanwhile, in its unreinforced state, has certain common characteristics: strong in compression and weak in tension. As a result, steel rods are used to resist any tensile forces or to apply compressive forces to the concrete to be able to withstand the tensile forces [3]. There is therefore the need to do further studies with the aim of improving on the brittle nature of concrete in view of its huge benefit to society.

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Subject to the dispersal and orientation of fibres in the cement matrix, the inclusion of the fibres transforms the matrix from a brittle to a ductile material [4], [5]. It must be well noted however that the benefits of adding fibres to concrete in construction, which is principally to improve on the residual load-bearing capacity, is influenced by the content, orientation and type of fibres in use [6]. The world has a witnessed rapid increase in the use of fibre reinforced polymer (FRP) materials as a substitute for conventional steel bars in some concrete structures, due to the numerous benefits: high strength, improved toughness, resistance to post-crack propagation and light weight amongst others [7]. There have been extra efforts by researchers with respect to the various fibre concrete types. Different experimental and theoretical studies have reported on varied mechanical properties of steel, synthetic, natural and glass fibre reinforced concrete, in view of structural applications [8]. Therefore, the use of Fibre-Reinforced Concrete (FRC), derived by the combination of steel or synthetic fibres and plain-concrete, is gradually gaining ground in civil engineering and structural applications due to its beneficial mechanical properties [9]. The gap in knowledge relating to the behaviour of fibres (e.g. polypropylene and nylon) and their effect on concrete as reinforcement has restricted their application mainly to control the early cracking (plastic-shrinkage cracks) in slabs [10]. Unfortunately, even the experimental results reported conflict. According to Yazici, Inan and Tabak [11], the addition of steel or synthetic fibres in concrete mix improves upon the tensile, flexural, fatigue and wear strength, deformation resistivity, load bearing capacity after cracking and toughness properties of the resulting product. Some researches such as Bentur and Mindness [12], Tchrakian, O'Dwyer and West [13] and Kazemi and Lubell [8] report a significant improving effect on the peak strength and post-peak ductility in compression, flexure and direct shear as the fibre volume fraction increases. The information provided by other studies such as Casanova and Rossi [14], Zhang and Stang [15], Lok and Xiao [16] and Dhir et al. [17] indicates that the influence mentioned previously is negligible. Also, as explained in the 2007 edition of Technical Report No. 65 [18], the use of macro synthetic fibre does not have any significant structural effect on the concrete, which would be expected of traditional steel bar or fabric reinforcement. Various research papers have looked at how the introduction and dosage of fibres in a concrete mix affect the compressive strength of the hardened concrete. Richardson [19] suggested that a higher dosage of polypropylene fibres would lower the compressive strength.

Hasan, Afroz and Mahmud [20] found a mild increase in compressive strength in relation to fibre content and Richardson, Coventry and Landless [21] found no effect on compressive strength to record. These conflictions, as alluded to earlier, reveal a critical gap in knowledge which will be studied further in this paper.

However, it must be emphasised that user reasons for FRC and conventional reinforcement are unequivocally different. For instance, steel fibres are added to concrete mainly to influence the manner in which cracks develop as it fails, but do not provide the concrete with a meaningful post-cracking strength that can be taken into consideration during design. On the contrary, adequate quantities of conventional reinforcement are provided to ensure that the load-bearing ability of the cracked section exceeds the capacity of the plain concrete in structural uses. [22]

II. Methodology

The conduct of the research in view of the set aim and objectives calls for the detailed laboratory testing of specimens followed by a thorough analysis. This was fundamentally carried out at the civil engineering concrete laboratory at the University of Greenwich. The specimens were prepared in accordance with BS EN 12390-1:2009 [23]; Shape, dimensions and other requirements of specimens and moulds and with BS EN 12390-2:2009 [24]; making and curing specimens for strength tests.

The raw materials used include: tap water, Rugby cement BS EN 197-1-CEM Il / B-V 32, 5 N (which is environmentally friendly), Civil Marine GGBS conforming to BS EN 15167-1 or BS 6699, ground granulated blast furnace slag for use with Portland cement, coarse aggregates with diameters in the range of 10-20mm, medium graded with aggregate size within 4-10mm, fine sand and Sika Twin flow 05 super plasticiser.

The steel fibre used is the continuously deformed Novo con Steel fibre-URW1050 conforming to ASTM A820/A820M-04, type 1 cold drawn wire. The macro synthetic fibre is the ENDURO HPP45 complying with ASTM C III6 Type III 4.1.3. Tables I and II below detail their full physical and chemical properties, with Fig. 1 showing samples of the fibres.

TABLE I
Chemical and Physical Properties of the HPP45 Synthetic Fibres

Characteristics	Material properties
Fibre length and diameter	45mm and 1mm
Type/ shape	Macro/ monofilament
Aspect ratio	45
Specific gravity	0.91
Electrical conductivity	Low
Acid and salt resistance	High
Melting point	1640C
Ignition point	> 5500C
Thermal conductivity	Low
Alkaline resistance	Alkaline proof

TABLE II
Chemical and Physical Properties of the URW1050 Steel Fibres

Characteristics	Material Properties
Fibre length	50mm
Appearance	Bright and clean wire
Diameter	1mm
Aspect ratio	50
Tensile strength	1050 MPa

(a) HPP 45 fibre

(b) URW 1050 fibre

Fig. 1 Samples of fibres

The concrete mix was designed with respect to British Standards as per the expected Concrete class strength (C32/40). Fibre dosage of 7Kg/m^3 for both the steel and synthetic fibre concrete was used. Table III below shows the design mix ratios.

TABLE III
Details of the Design Mix as per the Expected Strength

No.	Component	Unit/ 0.100m3	Dosage
1	10/20mm aggregates	kg	74.700
2	4/10mm aggregates	kg	38.500
3	Sand	kg	83.100
4	Cement(Rugby)	kg	15.300
5	GGBS	kg	15.300
6	Super-plasticiser	Lt	110.000
7	Water (weight)	kg	16.500

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The HPP45 and URW1050 were added to the concrete during the mix at the rate of 0.7kg/0.1m3.

The concrete manufacturing process was based on controlled laboratory conditions. For accuracy and reliability of the results, 42 specimens were tested: cubes, cylinders and beams for the compressive, tensile splitting and flexural tests respectively. Table IV details the number of specimens tested on the 7th, 14th and 28th days. Cubes of size 150×150×150mm, cylinders of 300mm length and 150mm diameter and beams of 150×150×500mm were used.

TABLE IV
QUANTITY OF SPECIMENS TESTED FOR BOTH FIBRE CONCRETE TYPES AT RESPECTIVE AGES

Specimens	Tested specimens for synthetic and steel fibres /curing age			Total Quantity
	7 days	14 days	28 days	
Cubes	3*2	3*2	3*2	18
Cylinders	3*2	-	3*2	12
Beams	3*2	-	3*2	12

The compressive and tensile split tests were carried out using an Avery Denison testing machine Type 7226CB calibrated in accordance with BS 1610:Part 1:1992. The Universal Dartec testing machine with a loading capacity of 100kN on the other hand was used for the flexural tests, with reports in accordance with BS EN 14651:2007. [25]

III. EXPERIMENTAL RESULTS

This section presents the results obtained during the experimental studies. Compressive strengths were attained as a result of the compressive tests conducted on the cube specimens. Tensile splitting strengths were obtained as a result of the splitting tests conducted on the cylindrical specimens. The flexural strengths of the respective fibres have been obtained from the flexural tests performed on the beam specimens. The respective results for the compressive tests are summarised and presented in Fig. 2.

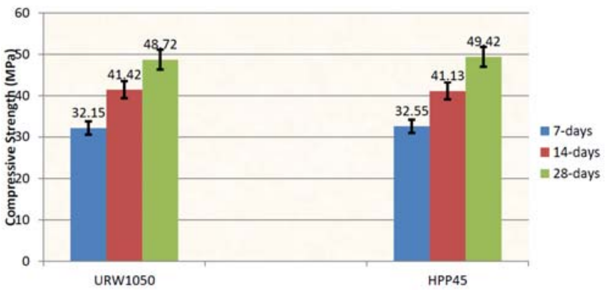


Fig. 2 Comparison between compressive strength of cube samples reinforced with URW1050 and HPP45 at 7, 14 and 28 days

Fig. 2 illustrates the comparative results of the two fibre reinforced concrete types and their behaviour in compression. Considering the average compressive strengths shown, there is ample evidence to suggest that the compressive strengths of both the fibre concrete types increase with age. There was a significant increase of an average of 9MPa between the 7 and 14 day old samples. Another increase from 41 to an average of 49MPa at the end of the 28 days was observed. However, the results also suggest little variation in terms of the strength of the steel and synthetic fibres.

The results provided in Table V show the seven day old specimens as having almost identical values in terms of the tensile splitting strength of the two fibres involved. The average tensile splitting strength values depict the fact that there is not much variation between the two fibre concrete types tested at the end of the seven days; however, the URW1050 has performed slightly better. The results for the 28day specimens however, as seen in Table V, also show a slight variation in the splitting strengths. The HPP45 has improved, considering the two values, by approximately 0.045N/mm2. This is just a slight difference, as compared to the 0.224N/mm2 for the URW1050 in the seven day old specimens. This suggests that there is little difference in terms of tensile strengths in this study.

TABLE V
SPLIT TENSILE STRENGTH RESULTS

Splitting strength (N/mm2) of	Cylinder 1	Cylinder 2	Cylinder 3	Average Value
URW 1050 at seven days	2.979	3.111	3.333	3.141
HPP45 at seven days	2.878	2.878	2.994	2.917
URW 1050 at 28days	4.107	4.124	3.665	3.965
HPP45 at 28days	3.596	4.193	4.254	4.010

Fig. 3 summarises the comparison between the results of seven and 28 day split tensile strengths for URW1050 and HPP45.

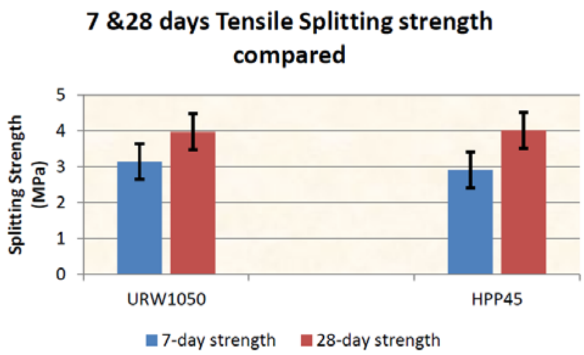
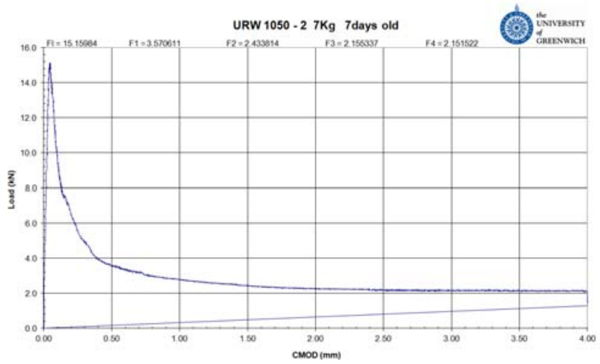


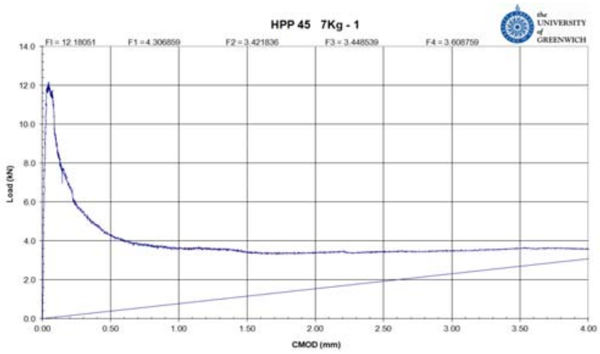
Fig. 3 Split tensile strength test results

The post failure shapes of the two split tensile strength test specimens show a slight difference. The URW1050 has a more visible crack as compared to the HPP45. This means the HPP45 was more able to resist the crack propagation than its counterpart. This could be attributed to the fibre count and distribution within the specimens. Definitely, the density of HPP45 which is almost eight times less than the density of URW1050 will result in a very high fibre count for synthetic fibre reinforced concrete. This will consequently generate a more uniform stress distribution in the synthetic fibre sample and the crack propagation will be more effectively controlled.

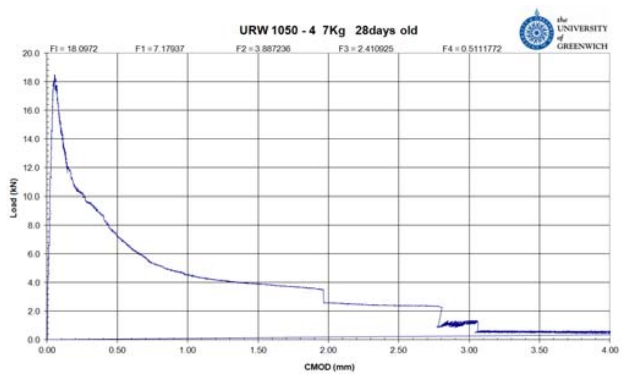
The flexural tests were conducted on 12 beam specimens, six for the HPP45 on the 7th and 28th days and six for the URW1050 on the 7th and 28th days- sample results are illustrated in Fig. 4.



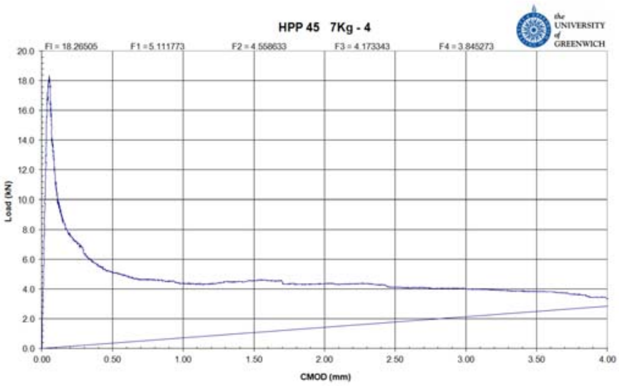
(a) Flexural strength for seven day HPP 45



(b) Flexural strength for seven day URW 1050



(c) Flexural strength for 28day HPP 45



(d) Flexural strength for 28day URW 1050

Fig. 4 Samples of flexural strength test results

The seven day flexural strength of samples reinforced with HPP45 has a maximum of 13.07kN. The relative maximum value for samples reinforced with URW1050 was 15.15kN. There was a sharp decrease in strength after the development of the first crack in the two situations. The residual strength for the HPP45 at 0.5mm crack mouth opening displacement (CMOD) is 3.50kN whilst the URW1050 at the same CMOD showed 3.57kN strength. There was meanwhile an increase in the residual flexural strength of the HPP45 at 2.00mm CMOD with the UWR1050 showing a consistent strength from 2.0mm to 4.0mm CMOD.

An average 28day flexural strength of 18kN was recorded for both specimens, meaning that, as far as this test is concerned, no significant difference in the flexural strength has been observed. The consistency in the residual flexural strength for the HPP45 after 0.5mm CMOD suggests a uniform presence of fibres within the crack opening, mainly due to the high fibre count, as opposed to the URW1050. The sudden rise and fall in the residual strength of the URW1050 in the CMOD range of 2.00 and 3.50mm, as seen in Fig. 4, could be attributed to the presence of few URW1050 fibres, due to the low fibre count. Comparatively, the URW1050 performed better in the seven day test and showed the same mechanical behaviour as the HPP45 in the 28day result.

According to the Concrete Society's Technical Report 63 [22], fibres have no mechanical implications on the material properties of unreinforced concrete before the appearance of first crack, unless the fibre dosage is above 80kg/m^3. This adds to the fact that fibres are basically playing the role of crack-control, mostly after the development of the first crack in concrete structures. The results seen in this study clearly attest to this fact. The respective composites displayed residual strengths after the first crack, thus preventing a sudden failure as seen in Figs. 5 and 6 for both the seven and 28 day results.

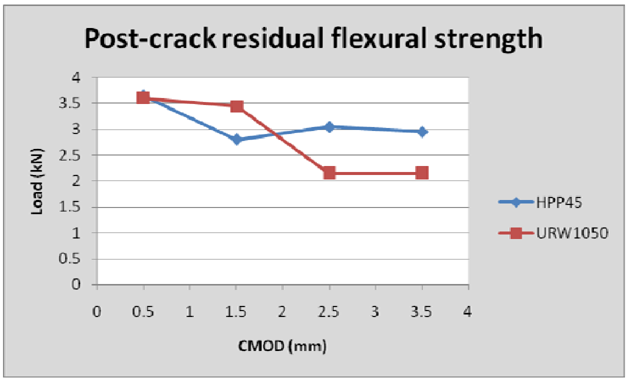


Fig. 5 Residual flexural strength for URW1050 and HPP45 compared on the7th day

The resistance of the HPP45 sample dropped from 13kN at its ultimate flexural strength to 3.61kN, corresponding to a crack mouth opening displacement (CMOD) of 0.5mm. It further dropped at a CMOD equal to 1.5mm and then increased again. The URW1050 on the other hand initially maintained a constant strength of 3kN over the CMOD range of 0.5mm to 1.5mm, before steadily dropping. The steady fall in strength of the URW1050 could be attributed to the lower fibre count in the mix as compared to the HPP45's higher fibre count.

Fig. 6 below shows a gradual but continuously downwards decreases in 28 day residual strength values of the URW1050 sample. The HPP45 again has displayed a relatively more consistent residual strength.

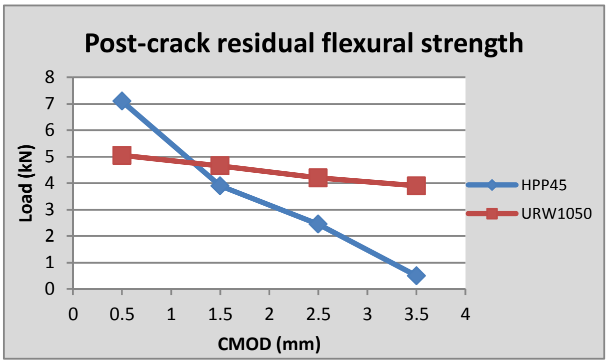


Fig. 6 Residual flexural strength for URW1050 and HPP45 compared on the 28th day

After the first crack, the residual flexural strength of the URW1050 sample dropped to 7kN and then decreased steadily and continuously up to the CMOD value of 3.5mm. This shows quite clearly that the samples reinforced with HPP45 are more reliable and ductile in the post-crack range.

IV. Conclusions

This manuscript sets out to compare the mechanical properties of concrete reinforced with steel fibre and macro synthetic fibre. The literature review identified a gap in knowledge on the mechanical properties when fibre type is varied. The mechanical behaviour of the URW1050 steel and the HPP45 synthetic fibres have been investigated in this study in the same design mix and fibre dosage of 7kg/m^3. The compressive strength was averaged from nine cube specimens, three tested at each age, on the 7th, 14th and 28th day. Tensile splitting strength was estimated from six cylindrical specimens, three tested on the 7th and the other three on the 28th day. The flexural strength was deduced from six beams, each set of three tested on either the 7th or 28th day.

In terms of the compressive strength, both concrete types revealed marginally the same mechanical behaviour.

The tensile splitting strength of the samples reinforced with URW1050 was superior to its counterpart by 7% at the early stages. However, the HPP45 marginally superseded the URW1050 by 3% on the 28th day. It can be concluded that the tensile splitting strength of concretes reinforced either by steel or synthetic fibre of the same fibre content based on weight is identical. It must be noted that, as the specific weight of steel fibre is considerably more than synthetic fibre, the fibre count for the URW1050 sample will be significantly less. This fact explains why the crack propagation is controlled better in the HPP45 sample beyond the ultimate capacity.

The URW1050 fibre concrete displayed an average flexural strength increase of 2.4N/mm2 on the 7th day. Nevertheless, both concrete types exposed the same maximum flexural strength in the 28 day test. Meanwhile, the HPP45 sample proved to be more efficient in post-crack development control and ductility.

It can be concluded that the ultimate strengths of concrete under compression and tension recorded in split and flexural tests are almost the same with similar synthetic and steel reinforcing fibres content, but the synthetic fibre produces a more ductile concrete.

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