BEHAVIOUR AND STRENGTH OF POLYPROPYLENE FIBRE REINFORCED CONCRETE BEAMS IN FLEXURE AND UNDER IMPACT LOADS

Shodolapo Oluyemi Franklin[1,a], Zibanani Koobakwa Thobane[2]

[1]Senior Lecturer, Department of Construction Engineering, Gaborone University College, Mmopane, Botswana. Formerly, Department of Civil Engineering, University of Botswana, Gaborone, Botswana
[2]Formerly, Department of Civil Engineering, University of Botswana, Gaborone, Botswana
[a]Corresponding Author

Abstract – *The present study forms part of a continuous investigation that seeks to evaluate the benefits of synthetic, or more specifically, polypropylene fibre reinforced concrete (PFRC) in the context of utilization of local raw materials in Botswana, and bring its attention to practitioners in the building and civil engineering industry in this part of Southern Africa. Towards this end, concrete containing GR05 synthetic polypropylene fibres with four different fibre contents – 0.5%, 1.0%, 1.5% and 2.0% by volume fraction of concrete was manufactured. The hardened concrete specimens comprising cubes and beams were subjected to compressive, flexural and impact strength tests after 7 and 28 days. It was found that the compressive strength increases steadily with increase in fibre fraction up to 1.5%, but thereafter showed a marked decrease. For the modulus of rupture tests, beams with increasing fibre fractions exhibited correspondingly greater resistance to flexural loading; furthermore the resulting crack patterns were increasingly more widespread and developed, prior to ultimate failure. In respect of the impact tests, it was observed that PFRC had greater resistance to impact loading than unreinforced beam specimens. Beams reinforced with higher percentages of fibre fractions (1.5%–2.0%) withstood the highest amount of impact loads from after the appearance of first cracking to just prior to ultimate failure.*

Key Words: Polypropylene, Fibres, Concrete, Compressive, Flexural, Impact, Strength, Tests

1. INTRODUCTION

Concrete made from Portland cement is arguably the most widely used building and construction material due amongst several other reasons to its relatively simple and inexpensive production process, coupled with its ability when fresh to be moulded into a variety of shapes. Furthermore in recent years newer applications and developments in concrete technology have arisen, such as self-compacting and high performance concretes. As a consequence, there is likely to be greater exploitation and consumption of concrete as a building material well into the foreseeable future.

Unfortunately in comparison to its compressive strength, concrete is relatively weak in tension and tends to be brittle with poor resistance to crack opening and propagation. This disability can be overcome by the adoption of conventional steel reinforcement and to some extent, by the utilization of sufficient volume fraction of fibre reinforcement. Fibre reinforced concrete (FRC) is a cement-based composite material that is reinforced with discrete but often randomly distributed fibres. The fibres come in various shapes and sizes, and a variety of materials may be employed. According to Zollo [1] based on the terminology chosen by the ACI Committee 544, Fibre Reinforced Concrete [2], there are four groups of FRC dependent on the type of fibre materials. These are SFRC for steel fibre FRC, GFRC for glass fibre FRC, SNFRC for synthetic fibre FRC including polypropylene and carbon fibres, and NFRC for natural fibre FRC. In the context of the present study, it is the SNFRC or more specifically polypropylene fibre reinforced concrete (PFRC) that is of interest.

1.1 Applications and Evolution

Synthetic fibres cannot be regarded as substitutes for the conventional steel reinforcement in concrete since their adoption results in only marginal strength increases. However normal steel rebars do not provide any benefits prior to the concrete hardening and furthermore, they suffer from corrosion of the steel by salts which may result in failure. Synthetic fibres on the other hand provide benefits while the concrete is still in its plastic state, and in addition may enhance some of the properties of the hardened concrete (Rai and Joshi [3]). The varieties of synthetic fibres have multiplied in recent years and include polypropylene, polyethylene and polyolefin, polyvinyl alcohol, etc. (Brandt [4]).

Polypropylene fibres were first introduced in 1965 by the United States Army of Engineers as admixtures in concrete for the construction of blast resistant buildings. Not surprisingly since this initial phase, the fibres have undergone further refinements and are presently used either as short discontinuous fibrillated material for the production of fibre reinforced concrete or as a continuous mat for the manufacture of thin sheet components (Singh [5]; Madhavi et al. [6]). Polypropylene fibres are made through an extrusion process by hot drawing the material through a die. This guarantees effective utilization of the inherent tensile and flexural strengths of the material together with appreciable reduction of plastic shrinkage cracking and minimization of thermal cracking (Ahmed et al. [7]).

1.2 Review of Mechanical Properties

The mechanical properties of PFRC have been studied by Ahmed et al. [7], Alhozaimy et al. [8], Yao [9], Patel et al. [10], Singh et al. [11], Parveen and Sharma [12], Ramujee [13], Dwivedi et al. [14] and Mohod [15] amongst others. However a distinguishing feature of the test results reported in the literature has been a lack of consistency in respect of the effects of polypropylene fibres on the compressive and flexural strengths of concrete. It has been suggested that this may be due in part to the different matrix composition, varying fabric types and volume fractions utilized in the investigations and undoubtedly the manufacturing conditions (Alhozaimy et al. [8]).

Results of impact strength tests on PFRC reported in the literature have been relatively meagre compared to compressive and flexural strength tests. The impact resistance tests have also displayed notable statistical variations. The latter has been discussed by Hwang et al. [16] who listed local variations in the fibre density at the interior of the mixes as one possible cause amongst others. From their statistical study they concluded that PFRC resisted on average 10% more impact blows for first cracking than normal strength concrete; the failure strength was 20% higher than that of normal strength concrete. Badr et al. [17] using the repeated drop weight impact test recommended by ACI Committee 544 [2] concluded that the impact resistance results had poor correlation with the normal distribution. More particularly, the observed coefficients of variation were about four times the recommended value for compressive strengths. They suggested that the drop weight impact test be modified or discarded completely in favour of a more reliable alternative.

The above apart, Nia et al. [18] using polypropylene fibres at 0.2%, 0.3% and 0.5% volume fractions, asserted that increasing the fibre volume fraction increased the impact resistance of concrete specimens regarding the initiation of first cracking and also final failure. Bothma [19] in his review reported that 40% enhancement of impact strength had been observed in drop hammer tests on PFRC beam specimens compared to plain concrete at a dosage of 0.5% fibre fraction. Additionally it was reported that failure mechanisms changed from fibre rupture to fibre pull-out as the volume fraction approached the region 0.5%–0.75%. Ambuvelan [20] examined the strength and behaviour of three grades of concrete having compressive strengths at 7 days of 21.4 MPa, 32.5 MPa and 48.3 MPa. The concretes had 0.1%, 0.2% and 0.3% dosage of polypropylene fibres. The impact tests were carried out using a drop hammer on cylindrical disc specimens. In general there was an increase in the number of blows required for first crack and for ultimate strength as the fibre percentage increased, although the results for the 32.5 MPa concrete showed a reverse trend in the 0.2%–0.3% dosage range.

A survey of the literature reveals that not much work has been carried out in Southern Africa in respect of PFRC although Walis [21] had reported on the progress and developments which had occurred in South Africa in relation to the utilization of steel fibres. In the Republic of Botswana, the growing economy and population coupled with the need for industrialization have necessitated urban developments and infrastructures including residential estates, bridges, high rise buildings, parking facilities and warehouses, etc. These have placed heavy demands on the importation of all types of conventional steel reinforcement. It is reasonable to expect that some of such applications could have been met by the adoption of non-conventional reinforcement. It is for this reason as well as to highlight the benefits of synthetic fibre FRC and bring its attention to practitioners in the building and civil engineering industry that the present study has been undertaken. However the emphasis here is specifically on the use of PFRC.

2. METHODOLOGY

In this section a description is given of the different materials employed in the current study and how the mix proportions were arrived at. The procedure for casting of the concrete specimens as well as the methods employed for the various tests subsequently carried out on the hardened concrete are outlined.

2.1 Materials, Mix proportions and Casting

The cement utilized was 42.5 N Grade Ordinary Portland Cement with specific gravity 2.65, initial setting time ≥ 60 minutes and final setting time of approximately 110 minutes, with a 7 day compressive strength of 29 MPa and 28 day compressive strength of 42.5 MPa. Locally available coarse aggregates of 13 mm maximum size, having specific gravity 2.74 were employed. The fine aggregate was locally available sand with specific gravity 2.67. For the reinforcement, GR05 synthetic polypropylene fibres which were purchased from Randfontein in South Africa were used. These fibres had dimensions of 0.75 mm and lengths of 60 mm, and possessed an aspect ratio of 80. Batch samples of the aggregates and fibres utilized are shown in Figures 1 to 3 respectively.

Fig. 1: 13.2 mm maximum size coarse aggregates

Fig. 2: Natural fine aggregates used for investigation

Fig. 3: Batch sample of polypropylene fibres

The mix design methodology was basically that recommended by the Department of Environment (DoE) revised procedure described by Teychenne et al. [22]. The major factors considered in the determination of a suitable mix were the water-cement ratio, the cement content or the aggregate-cement ratio, the gradation of the aggregates and the consistency of the mix. The targeted compressive strength at 28 days was 40 MPa. Calculated mix proportions were ascertained using trial mixes with slight adjustments being introduced as deemed necessary. The final mix proportions are shown in Table 1.

Table 1: Mix quantities for 1 m^3 of fresh concrete

Fraction of fibre (%)	Cement quantity (kg)	Water quantity (kg)	Fine aggregate (kg)	Coarse aggregate (kg)
0	360	180	584	1224
0.5	358.2	179.1	584	1224
1.0	356.4	178.2	584	1224
1.5	354.6	177.3	584	1224
2.0	352.8	176.4	584	1224

Mixing was carried out via a conventional rotary drum concrete mixer in the Materials Laboratory of the University of Botswana's Civil Engineering Department. The mixer was firstly loaded with the coarse and fine aggregates and a proportion of the mixing water. After mixing for a specified period, the cement was added together with the rest of the mixing water and mixed for a set period. Subsequently the polypropylene fibres were added uniformly and final mixing was effected for about 2–3 minutes. This procedure was deemed acceptable since polypropylene fibres are not hydrophilic and consequently do not absorb water. During mixing, no shredding of the fibres was observed. A total of twenty 100 mm cubes were cast for the compression tests, while a total of forty 150 mm x 150 mm x 750 mm beams were cast for the flexural and impact tests. Both cube and beam specimens were de-moulded after 24 hours and immersed in a temperature regulated water bath using clean potable water. Ten cubes were cured for the 7 days test and the remaining ten were cured for the 28 days test. The same breakdown was applicable to the beam specimens; half were cured for 7 days while the balance was reserved for the 28 days tests.

2.2 Testing Procedures

The compression test was carried out using a 3,000kN compression testing machine on standard 100 mm cubes after 7 days and 28 days curing periods. The flexural strength was evaluated using a standard flexural strength test machine for beams of sizes 150 mm x 150 mm x 750 mm, after 7 days and 28 days curing periods. The impact strength was assessed using beams of 150 mm x 150 mm x 750 mm. For this latter test a standard compaction hammer weighing 6.51 kg was employed. The hammer was dropped from a height of 0.650 metres unto the beam specimens. The number of blows to initiate the initial cracking and the number of blows to cause ultimate failure were recorded. Thereafter the energy absorbed was calculated for both the first crack appearance and at ultimate failure, and subsequently, the residual strength impact ratio was computed. The basic set up for the compressive, flexural and impact strength tests are shown in Figures 4, 5 and 6 respectively.

Fig. 4: Compression test for concrete cube specimens

Fig. 5: Flexural strength test for beam specimens

Fig. 6: Impact strength test set up for beam specimens

3. RESULTS AND DISCUSSION

In this section the detailed results of the compressive, flexural and impact strength tests conducted on cubes and beams are presented in addition to the development of crack patterns observed during the respective tests. An attempt is also made to correlate the observations described herein with previous findings presented in the literature.

3.1 Compressive Strength Tests

The variation of compressive strength with different percentages of polypropylene fibre fraction is shown in Figure 7 for both the 7 days and 28 days compressive strengths. It is apparent that for both periods the compressive strength increases with increasing fibre content up to 1.5 % but thereafter, the strength decreases quite substantially. This may be due to the fact that the addition of higher percentage of fibres may lead to congestion of fibres causing balling effects and improper bonding with concrete (Gao et al. [23]). The addition of 1.5 % volume fraction of polypropylene fibres result in 10 % and 6 % increase in 7 days and 28 days compressive strengths respectively, in contrast to the control values. The maximum compressive strength recorded after 7 days curing was 28.7 MPa. For the 28 days period, the compressive strength was 42.1 MPa which was just 2.1 MPa higher than the targeted grade strength of 40 MPa.

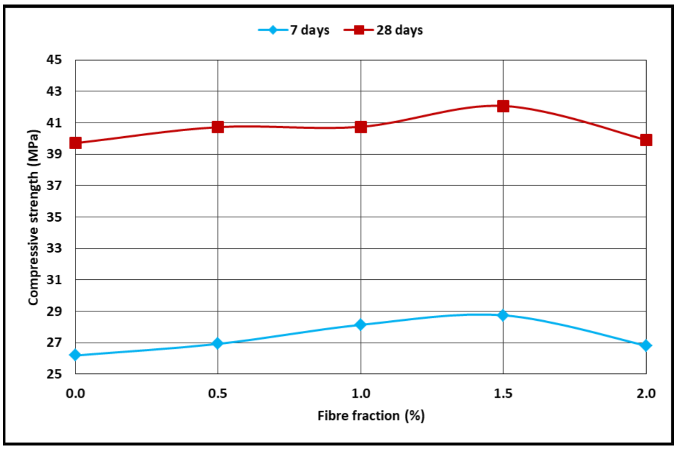

Fig. 7: Variation of compressive strength with fibre fraction

3.2 Flexural Strength Tests

The variation of flexural strength with different proportions of polypropylene fibre fractions after 7 days and 28 days curing periods is shown in Figure 8. The flexural strength increases as the percentage of polypropylene increases. For the 2.0 % volume fraction of fibres, flexural strength increases of 46 % and 56 % for 7 days and 28 days curing period respectively occur with reference to the control strengths. These pronounced increases are due to the beneficial effects of the fibres in curbing the formation, propagation and widening of the cracks more effectively (Balasubramanian et al. [24]). In addition the effective bridging action of fibres across the cracks enhances the ductility of fibre reinforced concrete beams (Baruah and Talukdar [25]). These fibres accommodate the crack face separation through the process of stretching the fibres, thus providing additional energy absorbing capacity (Aulia [26]).

The crack patterns in the flexural strength tests were similar for all beam specimens although the magnitude of cracks or crack openings at failure was different. The control or unreinforced beams showed larger and more visible cracks compared to beams with polypropylene fibres. The magnitude and length of cracks decrease with increasing fibre content. First cracking occurred at the centre of the beam specimens. The flexural cracks consist of vertical cracks perpendicular to the direction of the principal tensile stress and appeared in the early loading stages at mid-span, as noted by Aulia [26]. With increasing loading, more vertical flexural cracks spread horizontally from mid-span to the supports.

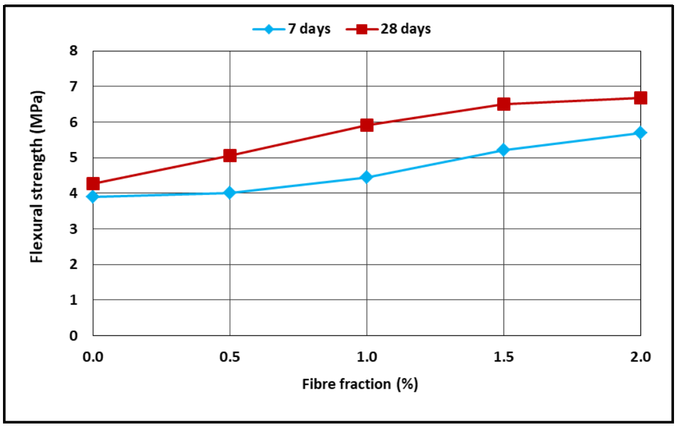

Fig. 8: Variation of flexural strength with fibre fraction

3.3 Impact Strength Tests

The relationship between the number of blows for initial or first cracking and for ultimate failure at 7 and 28 days as against increasing percentages of PFRC is shown in Figure 9. On average, 5 to 6 blows of the standard compactor hammer caused ultimate failure on the unreinforced beam (or 0 % fibre fraction) for the 7 days test. A longer curing period of 28 days resulted in very little increase in resistance to impact loading as only 8 to 9 blows on average were needed to cause ultimate failure. The number of blows between the appearance of first cracking and ultimate failure for the unreinforced beam was a meagre 3. This implies that the unreinforced beam has relatively very low resistance to impact loading.

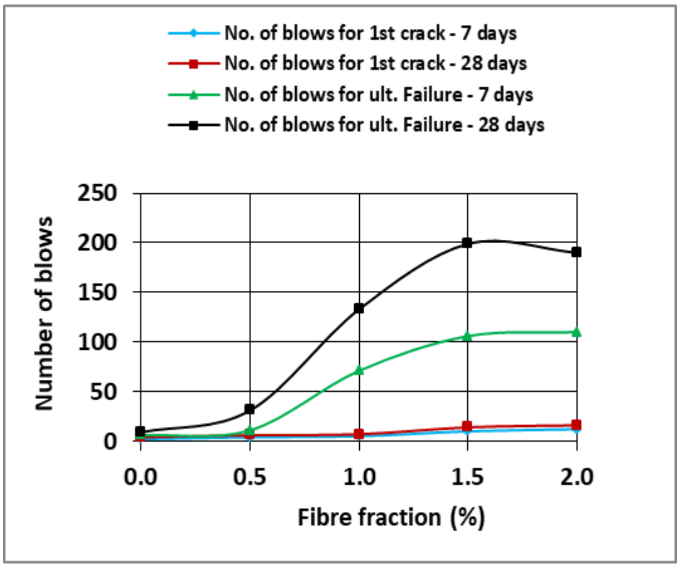

Fig. 9: Relationships between blow number and fibre fraction

The introduction of polypropylene fibres certainly enhanced the impact strength as 2.0 % fibre fraction resulted in about 12 blows of the hammer after 7 days curing and 16 blows after 28 days curing period for initiation of first cracking. In order to produce ultimate failure, a total of 110 blows for the 7 days test and 190 blows for the 28 days test was required for the 2.0 % fibre fraction. The number of blows to cause ultimate failure increased with the percentage of fibre fraction in the concrete mix. Aulia [26] suggested that this was due to the matrix the fibres create when properly mixed into the concrete. The fibres assist in holding the mortar together by distributing the shock loading evenly through the beam.

It can be seen from Table 2 that the residual impact ratio increases significantly with increase in the percentage fibre fraction. The residual impact ratio for the unreinforced beam was below 1.15 for both the 7 days and 28 days tests. This implies that very little energy was needed after initiation of first cracking to cause ultimate failure. In the present study, only 1.32 Joules was required. In contrast, the residual impact ratios for the 1.5 % polypropylene fibre fraction demonstrates that 144.6 Joules and 139.0 Joules were required immediately after the appearance of first cracking to cause ultimate failure at 7 days and 28 days respectively.

Table 2: Residual impact ratios for various fibre fractions

Days	Fibre content (%)	Energy absorbed (Joules)		Residual strength impact ratio
		First cracking	Ultimate failure	
7	0	9.92	11.24	1.133
	0.5	15.28	129.2	8.455
	1.0	17.89	151.6	8.474
	1.5	18.21	162.8	8.940
	2.0	14.54	138.0	9.491
28	0	11.23	12.56	1.118
	0.5	14.76	17.97	1.217
	1.0	19.41	25.19	1.301
	1.5	34.12	173.07	5.072
	2.0	29.20	165.2	5.658

Figures 10 to 15 show the first crack appearance and the ultimate failure patterns for the unreinforced beams, the PFRC beam with 1.0 % fibre fraction and the PFRC beam with 2.0 % fibre fraction in that order. For the unreinforced beams the initial crack line appeared across the beam specimens at the bottom. This spread and widened with further application of the impact loading until it went through the beam causing ultimate failure; the beam would have broken into two pieces at this stage. However with the PFRC specimens the initial cracks were relatively very small and short in length. For the 2.0 % fibre fraction reinforced beam, a careful visual inspection was required to spot or identify the initial crack. For all PFRC beams, the first cracking appeared at the bottom face; with further impact loading, multiple cracks formed at the struck point and meandered towards the beam edges. These cracks widened as further impact loading was applied at the same location. The magnitude of the cracks and their lengths decreased with increasing polypropylene fibre contents of the beams.

Fig. 10: First crack appearance for unreinforced beam

Fig. 11: Ultimate failure of unreinforced beam

Fig. 12: First crack appearance for 1.0 % PFRC beam

Fig. 13: Ultimate failure for 1.0 % PFRC beam

Fig. 14: First crack appearance for 2.0 % PFRC beam

Fig. 15: Ultimate failure for 2.0 % PFRC beam

4. CONCLUSIONS

The work contained in the present study was carried out to evaluate the influence of increasing percentage of fibre fractions on the behaviour of PFRC beams in regards to the compressive, flexural and impact strengths, using locally sourced aggregates. An additional objective was to highlight and bring to the attention of the engineering community in Botswana the benefits inherent in the adoption of synthetic fibre reinforced concrete, more especially PFRC, for certain applications within the context of building and civil engineering. Based on the study carried out, the following conclusions have been drawn.

(1) The addition of progressively higher proportions of polypropylene to a concrete mix up to a maximum level of 1.5 % volume fraction results in higher compressive strengths at 7 and 28 days compared to the unreinforced concrete. Further increase in fibre content leads to a marked decrease in compressive strength, due to congestion of fibres causing balling effects and improper bond with the concrete.
(2) The flexural strength increases as the percentage of polypropylene fibres in the concrete mix increases. This is true for the 7 and 28 days strengths. The 2.0 % fibre fraction PFRC beams showed an increase of 46 % and 56 % for the 7 and 28 days strengths respectively, in relation to the unreinforced concrete.
(3) The impact strength increases with progressively higher percentages of polypropylene fibres in the concrete. Beams reinforced with 2.0 % fibre fractions withstood the highest number of impact blows required for the initiation of first cracking right up to ultimate failure.
(4) The addition of polypropylene fibres in the range 0.5 % to 2.0 % by volume fraction is beneficial in controlling

the widening and lengthening of cracks, by effective bridging action, enhancement of ductility, as well as providing additional energy absorbing capacity.

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