

Tensile Behaviour of High Content Steel and Polypropylene Fibre Reinforced Mortar

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Abstract

In this study, the behaviour of high content steel and polypropylene fibre reinforced concrete under direct tensile loading using dog-bone shaped specimens was studied. Two different fibres, steel and polypropylene, were used at 5 different volume fractions from 1% to 5%. It was found that the tensile properties of FRC depended mostly on the type and content of fibre. Steel Fibre Reinforced Concrete (SFRC) was found to behave in a single peak manner with peak load occurring at a very small deformation. In the case of Polypropylene Fibre Reinforced Concrete (PFRC), the response was mostly a double peak response with the occurrence of a second peak at large deformation. Steel fibre was believed to contribute more to strength while polypropylene fibre was believed to mainly contribute to the post-peak ductility.

Keywords: Steel fibre, Polypropylene fibre, Direct tensile loading, Double peak response, Toughness

1. Introduction

1.1 General

Fibres have been used to reinforce brittle materials since the Ancient Egyptian times. At that time, the fibres used were natural fibres, such as horsehair, straw, etc. In the early 1900s, the first commercialized asbestos fibres were introduced. Since then, there are numerous fibre types available for commercial use, the basic types being steel, glass, synthetic materials (polypropylene, carbon, nylon, etc.) and some natural fibres.

Generally, the bond strength of fibre is dependent upon the surface characteristics (shape, roughness) of fibres, and upon the aspect ratio (ratio of length to diameter of the fibre). The bond can be enhanced by increasing the mechanical anchorage or surface roughness of fibres, or by increasing the aspect ratio. The

typical fibres volume fraction of FRC is in the range of 0.5% to 2.0%. The use of fibres may reduce the slump by about 25 to 100 mm depending on the type, volume fraction, and shape of the fibre (1,2). Therefore, some adjustments to the fresh mix are required in order to obtain adequate workability with minimal segregation and bleeding, and to provide a uniform distribution of fibres. With higher fibre content (over 2.0%), special techniques for mixing and placing such as Slurry Infiltrating are required.

Even though it is possible to mix such a high content FRC in the lab, it is still not yet practical in the actual industry; this is because of its difficulty in mixing and placing. As a result of this, understanding of the properties of high content FRC is still very much far from completed. Therefore, in this study, we are trying to take one more step to complete the big

picture by carrying out tests with high fibre content up to about 5%. It is expected that with high fibre content, the tensile behaviour of concrete would be quite different from those with lower fibre content.

2. Experimental Program

2.1 Concrete Mix Proportion

The specimens were cast using the following materials:

- Cement: Type 1 Ordinary Portland Cement (ASTM Type I)
 Fine agg.: Clean river sand with a fineness modulus of about 2.7
 Fibers: Two different types of steel fibers were used (Table 1) at five different volume fractions, 1%, 2%, 3%, 4% and 5%

The mix proportions shown in Table 2 were used, providing an average compressive strength of 35 MPa at 28 days based on ACI standard.

2.2 Specimen preparation

The bone-shaped specimens were cast in the molds as shown in Fig. 1. The molds were made of steel with an opening at both ends. Prior to the casting, the molds were lubricated with oil in order to ease the removing process.

Two types of fibres were used: Steel and Polypropylene (Fig. 2) at 5 different volume fractions: 1%, 2%, 3%, 4% and 5%. Geometrical details for each type of fibre were given in Table 1. Two fibre systems were adopted: Single type and Hybrid type. In the hybrid system, the volume fractions were equally divided between these two types. The casting schedule is given in Table 3. After removing from the molds, the specimens were then placed in water for 28 days for curing (Fig. 3) before subjecting to test.

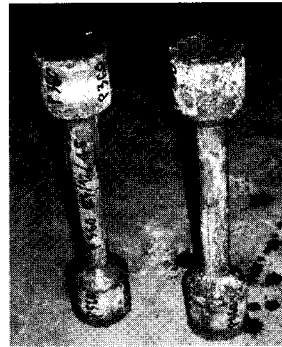


Fig. 1 Steel molds and Cast specimens

Table 1 Geometry of Fibres



Type	Material	Shape	Length (mm)	Section
Hooked End	Steel		60	Circle
Crimped	Polypropylene		58	Rectangle

Table 2 Mix Proportion

Cement (kg)	Water (kg)	Fine Agg. (kg)	Superplasticizer (ml/kg of cement)
1	0.5	3	12-15

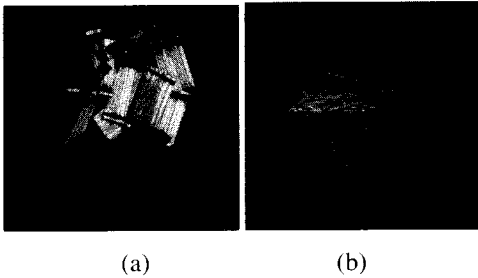


Fig. 2 Fibre used in this study (a) Steel fibres and (b) Polypropylene fibres

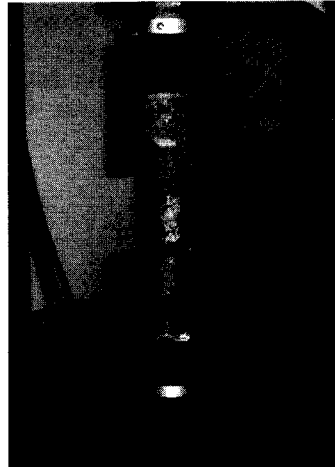


Fig. 4 Test Setup



Fig. 3 Curing process

All tests were carried out at the Department of Civil Engineering, King Mongkut's Institute of Technology-North Bangkok, using a 1500 kN universal testing machine^ψ. Specimens were held vertically at both ends of the machine by two slot grippers and the force was then applied directly at the rate of 0.05 in/min (Fig. 4). The data were collected by a PC-based data acquisition system.

3. Experimental Results

3.1 Failure Patterns

Typical failure patterns of the specimens were given in Fig. 5.

As expected, most FRC failed in more ductile manner with fibres partly pulled-out and partly fractured. There were signs of specimens being tortured during the fibres pulled-out process as seen by the occurrence of micro-cracks and uneven fractured surface. With fibres bridging across the cracks, more force needed to be applied in order to overcome the fibre bond strength, and pull-out or fracture the fibres. After failure, the pieces of concrete were still held together by the fibres.

Table 3 Casting schedule

Mortar type	Designation	% Volume fraction					Total	
		0	1	2	3	4		5
Plain Mortar	PLN	3						3
Steel FRC	SFRC		3	3	3	3	3	15
Polypropylene FRC	PFRC		3	3	3	3	3	15

^ψ Instron 'Fast-Track 8800'

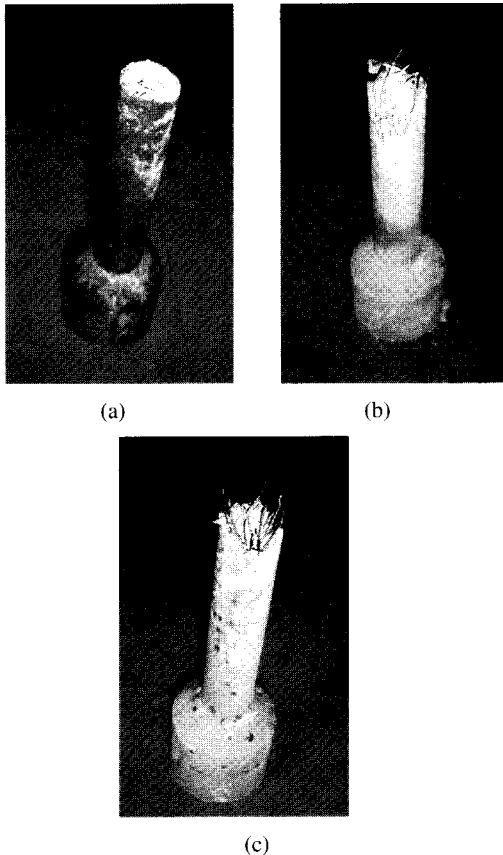


Fig. 5 Failure patterns of (a) Plain concrete, (b) Polypropylene FRC, and (c) Steel FRC,

On the other hand, plain concrete specimens were found to fail in a brittle manner. The fractured surface was flat and smooth with much less or no tortured sign because there was no fibre to prevent cracks from propagating. Once the applied load and energy are large enough to cause the cracks to self propagate, failure took place catastrophically.

3.1 Load-Deformation Responses

3.1.1 Steel Fibre Reinforced Concrete (SFRC)

Typical Load-Deformation responses of the single-type steel fibre reinforced concrete (SFRC) are as shown in Figure 6.

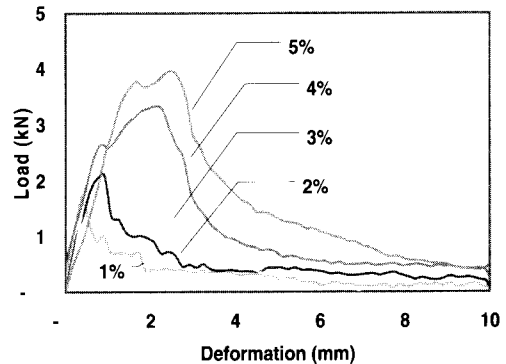


Fig. 6 Load-Deformation responses of steel fibre reinforced concrete specimen subjected direct tension

Considering the response, the single typed-steel fibre reinforced concrete (SFRC) appeared to behave in similar manner under load. The deformation was found to increase linearly with load at the beginning, and then followed by the non-linearity up until the peak. Increasing fibre content did not significantly effect the pre-peak behaviour as they were found to increase at a similar rate with respect to their corresponding deformation. In the case of the post peak response, increasing fibre was found to improve both toughness and ductility as seen by the larger and longer response. Overall, the responses of SFRC behaved in a more ductile manner with the increasing fibre content.

In terms of strength, it was found to increase with increasing fibre content. With high strength and stiffness of steel fibres, steel fibres were capable of bridging over the cracks instantaneously once the crack started to form (at small deformation). By bridging over the crack, the load was believed to be carried solely by fibres. The ability of fibre bridging was, of course, increased with the number of fibres intercepted at the crack surface. With increasing fibre content, the number of fibres also increased. As a result of this, the peak strength was found to increase dramatically from around 1.7 kN to 4.0 kN with increasing fibre content from 1.0% to 5.0% V_f .

3.2.2 Polypropylene Fibre Reinforced Concrete (PFRC)

Typical load-deflection response of the single typed-polypropylene FRC is as shown in Fig. 7.

PFRC specimens seemed to behave differently depending on the fibre content. At the lowest content used in this study (1%), the response of PFRC was essentially a single peak response with load increasing up to the peak followed by a fast drop in load carrying capacity. There was a sign of load recovering, though very small and can simply be ignored. With the increasing fibre content (2% to 4%), the behaviour of PFRC changed to a double peak response with the recovery response becoming more obvious. After a fast drop of load after the first concrete crack, the load started to pick up slowly and recovered back to create another peak. In some cases (3% and 4%), the recovery was so significant that the second peak was even larger than the first peak. The recovery was solely due to the properties of the polypropylene fibre which will be discussed later.

In the case of the first peak load, it was found to be unchanged (or increase slightly) with the increasing fibre. This was because of the low stiffness (high elasticity) of polypropylene fibres; it seemed to contribute very little to the first peak strength. In this case, once the load reached the flexural strength, cracks started to occur and this is then followed by a drop in loading. As a result, the first peak of PFRC was, in fact, representing the concrete tensile strength with little influence from fibres.

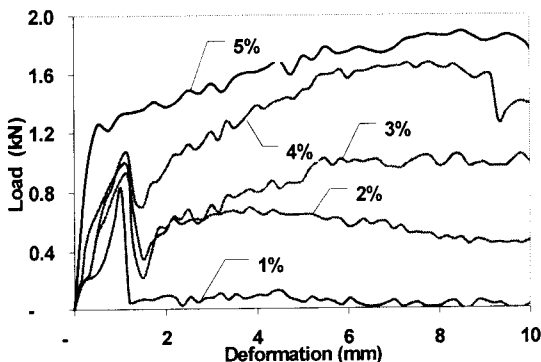


Fig. 7 Load-Deflection responses of polypropylene fibre reinforced concrete specimen subjected to direct tension

Even though the polypropylene fibre possessed low stiffness, it was highly elastic and ductile. Unlike steel fibres which reacted immediately to the load at a very small deformation or crack opening, the highly elastic properties of PE fibre required much larger deformation or crack opening before the fibres can be strengthened and stiffened enough to respond to the load. As a result of this, the recovering of load was found late in the post-peak response of SP-FRC.

Another important point that should be noted here was that the rate of load recovery after the peak was found to be quicker with increasing fibre content. This is because larger fibre content increased the number of fibres intercepted at the fracture surface.

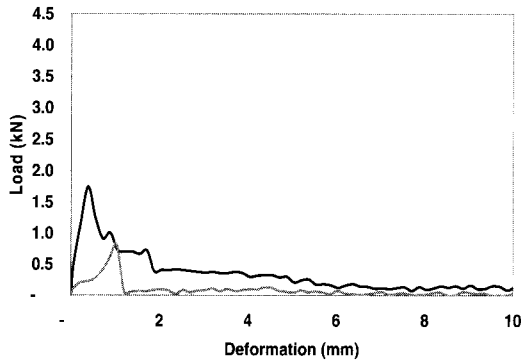
Comparison between steel and Polypropylene FRC is given in Fig. 8. Because of the difference in the properties of materials, steel fibres seemed to contribute mostly to the strength (peak load) while the polypropylene fibres were likely to contribute more to the ductility (toughness) of the post peak response.

3.3 Fracture Energy (Toughness)

Theoretically, fracture energy is defined as the amount of energy absorbed by the specimen up to fracture or a certain reference point (deflection or deformation). For a given load-deflection curve, the fracture energy can simply be calculated by the area under the curve.

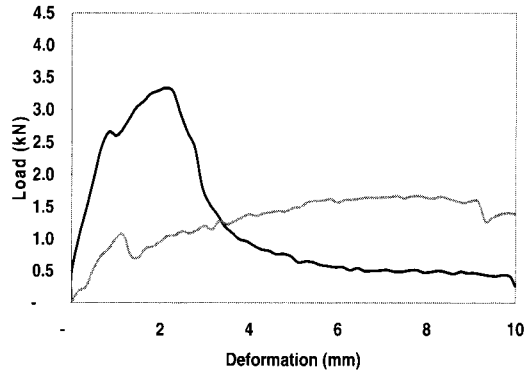
In this study, the fracture energy up to 2, 5, and 10 mm of deformation (FE-2, FE-5, and FE-10, respectively) was calculated; the results are given in Fig. 9.

Comparing between SFRC and PFRC, the fracture energy at the small deflections (i.e., 2 and 5 mm) of SFRC appeared to be much larger than that of PFRC for all fibre contents. This was because of the high strength and stiffness of steel fibres that made them highly effective in bridging over the cracks at a very small deformation or crack opening (as seen by the occurrence of peak load at a very small deflection), thus SFRC was able to absorb larger energy at small deformation.



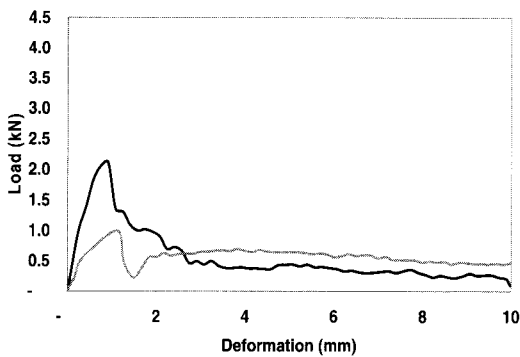
— SFRC 1% — PFRC 1%

(a)



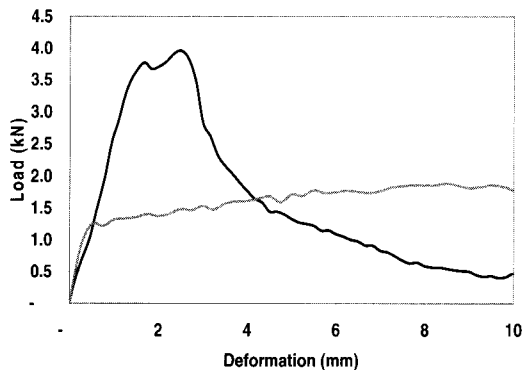
— SFRC 4% — PFRC 4%

(d)



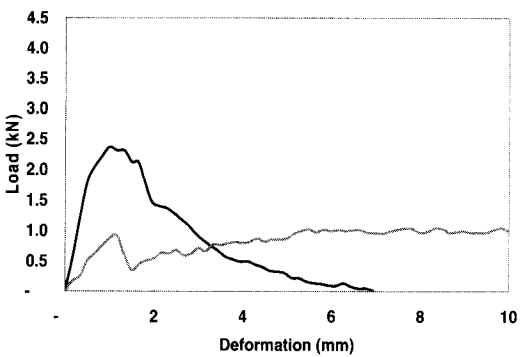
— SFRC 2% — PFRC 2%

(b)



— SFRC 5% — PFRC 5%

(e)



— SFRC 3% — PFRC 3%

(c)

Fig. 8 Comparison between the responses of PFRC and SFRC at (a) 1%, (b) 2%, (c) 3%, (d) 4% and (e) 5%

On the other hand, polypropylene fibres because of their high elasticity, seemed to react to the load slower. This meant that the specimens were required to have quite a bit of deformation before the fibres could be strengthened and stiffened enough to react with the load. As the result of this, PFRC was not quite effective in absorbing energy at the small deflection and hence, the fracture energy was found to be similar to plain concrete.

However, at the large deformation (i.e., 10 mm), the PFRC appeared be more effective in term of absorbing the energy. For steel fibres, most of the fibres were basically pulled out or fractured at the peak load, therefore there was not enough bond strength to carry out the load and this led to a continuous drop of load after the peak. However, this was not the case in the

polypropylene fibres. Even at large deformation, most fibres were still in position. Once the elongation was sufficient enough, the fibre then started to react and began to absorb energy.

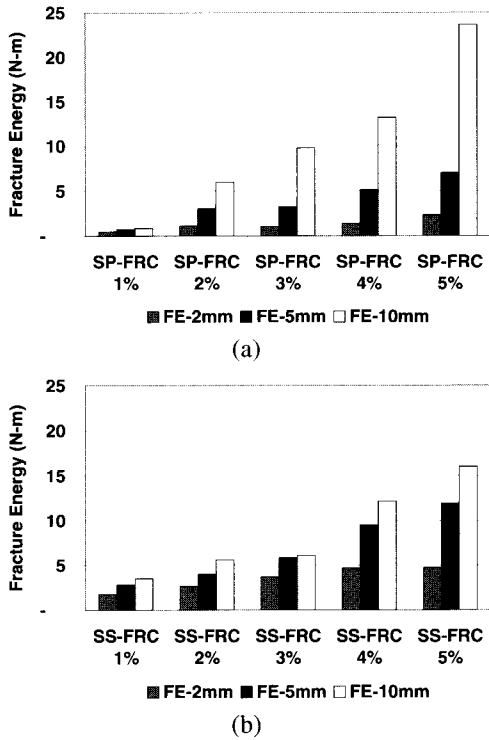


Fig. 9 Fracture energy of (a) PFRC, and (b) SFRC,

4. Conclusions

1. The tensile behaviour of FRC was found to be different depending on the type and content of fibre.
2. Steel fibres were found to contribute mostly to the strength of FRC; this was because of its high strength and stiffness. It was also able to react with the load quicker than the polypropylene fibre, as seen by the existing of peak load and larger fracture energy at the small deflection. However, in the case of steel fibre, once the load is past its peak, most fibres were either pulled out or fractured. As a result of this, a continuous

drop of load and fracture energy was found at larger deformation.

3. For Polypropylene fibre, because of its low stiffness, it seemed to react to the load slower than the steel fibres. The deformation had to be large enough for the polypropylene fibre to start gaining some loads. As a result, PFRC was not quite effective in term of carrying load at small deformation. However, later at large deformation, with sufficient crack opening, the fibres started to get strengthened, and led to the recovery of load. Therefore, the typical responses of most PFRC were found to be a double-peak response. The second peak happening late at large deformation was solely contributed by the fibres. Polypropylene fibres appeared to contribute more to the ductility (toughness) at large deformation after peak.

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