Toughness Evaluation of Steel and Polypropylene Fibre Reinforced Concrete Beams under Bending

Piti Sukontasukkul
Assistant Professor Department of Civil Engineering,
Faculty of Engineering King Mongkut's Institute
of Technology-North Bangkok
1518 Pibulsongkram Road, Bang Sue, Bangkok 10800
Tel 02-913-2500 ext. 8621-29, Fax. 02-587-4337, Email: piti@kmitnb.ac.th

Abstract

Generally, the performance of most materials is characterized by parameters based on the mechanical properties such as strength, strain, or stiffness etc. However, in fibre reinforced concrete (FRC), unlike other materials, strength or stiffness alone is not sufficient to characterize its behaviour, and the value of toughness is often used instead. In this study, two different methods (ASTM C1018 and JSCE SF-4) are used to measure the toughness of steel and polypropylene fibre reinforced concrete subjected to bending. Results indicated that in the JSCE method, the information obtained by only one specified deflection toughness seemed to be insufficient in reflecting the characteristics of the load-deflection curves of both FRCs. On the other hand, in the ASTM method, the obtained information using the four toughness values at different deflections appeared to better clarify the characteristics of both FRCs.

Keywords: fibre reinforced concrete, toughness, ASTM C1018, JSCE SF-4

1. Introduction

Short fibres have been known and used for centuries to reinforced brittle materials like cement or masonry bricks. At that time, fibres were natural fibres, such as horse hair, straw, etc. Now, 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. As for steel fibres, wire and metal clips were used first in 1910s to improve the properties of concrete. Extensive research on steel fibres began in the 1960's [1,2], and since then a substantial amount of research, development, application and commercialization have occurred [3-7].

Typically, the fibre volume fraction in Steel Fibre Reinforced Concrete (SFRC) is in the range of 0.5% to 1.5. At the practical volume fraction used in SFRC (<1%), the increase in compressive, tensile, or flexural strength is small because the matrix cracks essentially at the same stress and strain as in plain concrete [8-11]. The real advantage of adding fibres is that, after matrix cracking, fibres bridge these cracks and restrain them. In order to further deflect the beam, additional forces and energies are required to pull out or fracture the fibres. This process, apart from preserving the integrity of concrete, improves the load-carrying capacity beyond cracking. This improvement creates a long post-peak descending portion in the load-deflection curve.

Since fibres do not significantly improve the properties of concrete or strength prior to the peak (concrete cracks) as they do on the post-peak response, it would be more practical to evaluate the performance of FRC based on the energy absorption (area under the load-deflection curve). The area under the load-deflection curve is usually referred to as the toughness obtained from a static test of a beam specimen up to a specified deformation (not to be confused with the fracture toughness, K_{IC}).

The two most common methods to determine flexural toughness are based ASTM C1018 and JSCE SF-4 [12]. In ASTM C1018, toughness is specified in terms of *toughness indices* (I_5 I_{10} and I_{20}), which refers to the area under the load-deflection curve calculated out to three different specified deflections. While, in the case of JSCE SF-4, the area under the load-deflection curve up to a specified deflection (L/150) is measured and referred to as the *toughness*.

In this study, both ASTM and JSCE standards were used to determine the toughness of plain concrete as well as steel and polypropylene reinforced concrete beams. Results from both methods were then compared and discussed.

2. Experimental Program

Plain and fibre reinforced concrete with the mix proportions of 1:0.45:1.7:2.7 (cement: water : fine : coarse) were cast in the form of beams (dimensions of 100 x 100 x 350 mm).

Two types of fibres were used: Steel and Polypropylene at 2 different volume fractions: 1% and 2%. Geometrical details and properties of each fibre are given in Table 1. The casting schedule is given in Table 2. After being removed from the molds, the specimens were then cured in water for 28 days before being subjected to test.

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. During the test, specimens were placed on a simple support with a clear span of 300 mm, and then subjected to a third-point loading at the rate 0.05 in/min (two point-loads at 1/3 of the clear span, Fig. 1). Results in terms of load-deflection curve were collected by a PC-based data acquisition system.

Table 1: Fibre Geometry

Type	Material	Shape	Length (mm)	Section Shape and Dimension (mm)		Tensile Strength (MPa)
Hooked End	Steel		60	Circle	Dia. 0.50	1000
Crimped	Polypropylene		58	Rectangle	1.0 x 0.5	450

Table 2: Casting Schedule

Concrete type	Designation	Volume Fraction (%)	No. of Sample
Plain concrete	PLN	-	5
Steel FRC	1SFRC	1%	5
Steel FRC	2SFRC	2%	5
Polypropylene FRC	1PFRC	1%	5
Polypropylene FRC	2PFRC	2%	5

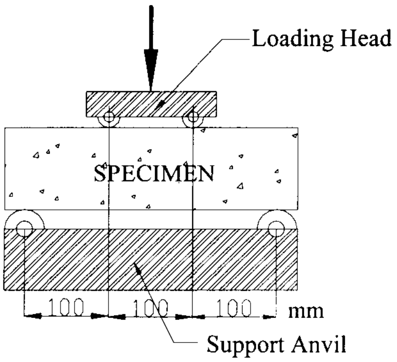

Fig 1: Test Setup

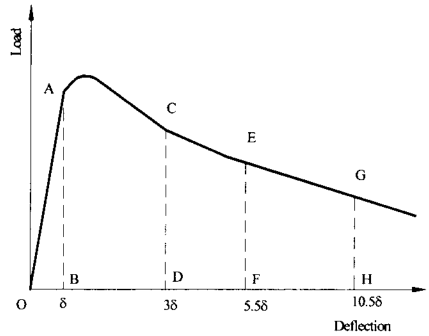

Fig. 2: Fracture toughness and Indices according to ASTM C1018

3. Determining Fracture Toughness

Two methods were used for determining the flexural toughness namely: ASTM C1018 and JSCE SF-4.

3.1 ASTM C1018

In ASTM C1018, toughness (or energy absorption defined as the area under the load-deflection curve) is calculated out at 4 specified deflections (δ, 3δ, 5.5δ and 10.5δ, Fig. 2). The toughness is calculated at the deflection δ which is considered the elastic or pre-peak toughness (first-crack toughness), while the other three (at 3δ, 5.5δ and 10.5δ) are considered the post-peak toughness.

Area OAB = Toughness corresponding to a deflection of δ, (T_δ)

Area OACD = Toughness corresponding to a deflection of 3δ, ($T_{3\delta}$)

Area OAEF = Toughness corresponding to a deflection of 5.5δ, ($T_{5.5\delta}$)

Area OAGH = Toughness corresponding to a deflection of 10.5δ ($T_{10.5\delta}$)

where δ = The deflection at the linear elastic limit

In addition, the terms of toughness indices (I_5, I_{10} and I_{20}) are also calculated. Each index is the ratio between the post-peak toughness and the pre-peak (elastic) toughness (Fig. 2).

I_5 = Area OACD/Area OAB

I_{10} = Area OAEF/Area OAB

I_{20} = Area OAGH/Area OAB

The residual strength represented by the average post-cracking load that the specimen may carry over a specific deflection interval, are usually determined as follows:

$$R_{5,10} = 20(I_{10} - I_5)$$

$$R_{10,20} = 10(I_{20} - I_{10})$$

3.2 JSCE SF-4

Unlike the ASTM C1018, JSCE SF-4 provides just a single value of toughness. For a given load-deflection curve, toughness is the area under the load deflection curve measured up to a specified deflection, δ_{tb} = L/150, as referred to Area OABC in Fig. 3.

The toughness factor (equivalent to the average residual strength) can also be determined as:

Toughness factor = toughness x $L/(BH^2 \times \delta_{tb})$

where L = Span length

B = Width of the specimen

H = Height of the specimen

δ_{tb} = Deflection at *L/150*

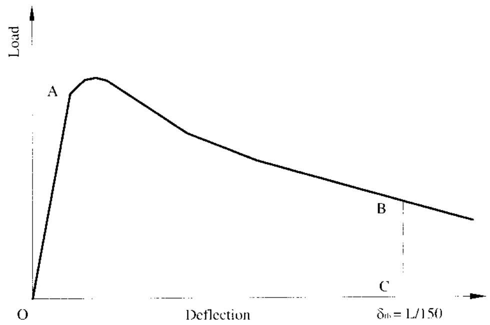

Fig. 3: Fracture toughness according to JSCE SF-4

4. Results and Discussion

4.1 Load-Deflection Response

Typical load-deflection responses of plain concrete, SFRC and PFRC beams are given in Figs. 4 and 5.

Comparing between plain concrete and FRC, it was the post-peak response that really differentiated the plain concrete from the FRC. For plain concrete, the behaviour was more in a brittle manner. Once the strain energy was high enough to cause the crack to self-propagate, fracture occurred almost instantaneously once the peak load was reached, due to the tremendous amount of energy being released. For FRC, the fibre bridging effect helped to control the rate of energy release. Thus, FRC maintained its ability to carry load after the peak.

Comparing between each type of FRC, it could be seen clearly that the flexural responses of both FRCs were quite different. In the case of steel fibre reinforced concrete (Fig.4), the response was a so-called 'single-peak' response. Prior to the peak, the load increased proportionally with the increasing deflection, and then at the peak (concrete cracking), there was a slight drop of load before fibres began to take over and this led to a gradually drop of load. Unlike plain concrete where the point of concrete cracking indicated the point of failure, in FRC, with the effect of fibres bridging across the crack surface, FRC was able to maintain the load carrying ability even after the concrete had been cracked as shown in the descending long post peak response.

In the case of polypropylene fibre reinforced concrete (PFRC) as shown in Fig. 5, the response found here was a typical 'double-peak' response. The first response was a typical response of concrete under bending. The load increased proportionally with the deflection up to the peak, and then the failure occurred due to the matrix cracking. The second response was the load recovery due to the effect of fibre bridging.

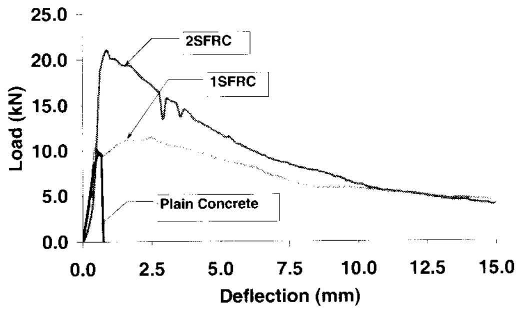

Fig. 4: Typical Load-Deflection Responses of Plain and Steel Fibre Reinforced Concrete

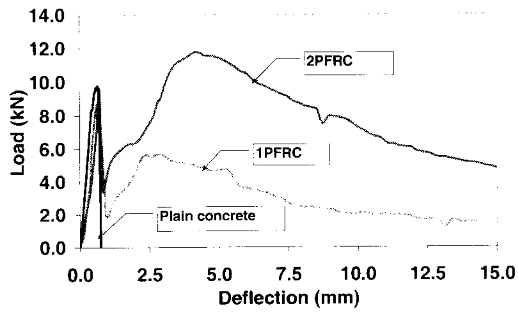

Fig. 5: Typical Load-Deflection Responses of Plain and Polypropylene Fibre Reinforced Concrete

The differences in the load-deflection responses of both fibres were essentially due to the properties of the fibres themselves. In SFRC, because of its high strength and stiffness, the fibres were highly effective in terms of bridging instantaneously over the cracks at a very small deformation or crack opening once the crack started to form. However, in the case of the polypropylene fibres which were low in strength and stiffness, they required much larger deformation or crack opening before the fibres could respond to the load. As a result of this, the recovery of load was found late in the post-peak response of PFRC (13).

4.2 Toughness

In this section, toughnesses for both FRCs were measured according to the methods described before; the results are compared and discussed.

4.2.1 ASTM C1018

According to this method, the toughness is measured at four different deflections: one prior to the peak (T_δ) and three after the peak ($T_{3\delta}$, $T_{5.5\delta}$ and $T_{10.5\delta}$) (Table 3). Once obtained, they were then used to determine the toughness indices as shown in Table 3 and Fig. 6.

Table 3: Toughness According to ASTM

Concrete Type	Toughness (N-m)				Toughness Indices		
	δ	3d	5.5δ	10.5δ	I_5	I_{10}	I_{20}
1PFRC	2.7	8.3	16.3	30.7	3.1	6.1	11.6
2PFRC	2.6	11.2	27.2	65.4	4.2	10.3	24.7
1SFRC	2.3	12.9	24.2	49.9	5.5	10.4	21.3
2SFRC	3.5	28.4	55.5	92.6	8.2	15.9	26.6

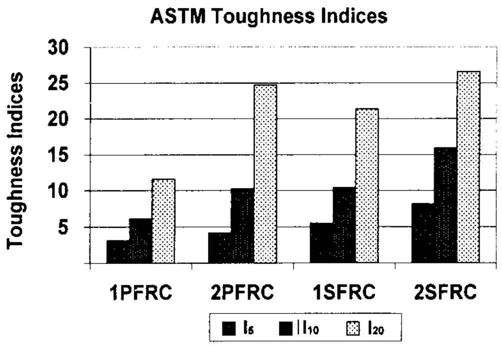

Fig. 6: Toughness Indices according to ASTM C1018

Consider the pre-peak (or elastic) toughness (T_δ). In the case of the polypropylene fibre, the pre-peak toughness (T_δ) of PFRC was found to be similar to that of plain concrete and remained constant even with the increasing fibre content from 1% to 2%. The reason for this performance was partly due to the material properties of the polypropylene fibre itself. With low strength and elastic modulus, after the first concrete crack, polypropylene did not take action immediately and this resulted in a large drop of strength in the load-deflection curve. Thus, the first peak response prior to the low recovery of PFRC got no action from the fibre and was, in fact, the response of the plain concrete.

As for the steel fibre, the elastic toughness (T_δ) of SFRC changed and depended on the content of the fibre as seen by the increasing T_δ with the increasing fibre content. Because of the high strength and elastic modulus of steel fibre, immediately after the concrete first cracked, fibres started to take action. At low fibre content (1%), a small drop of load was found, and then followed by a quick recovery of load almost immediately. With the volume fraction of 2%, larger (twice) numbers of fibres were intercepted at the crack surface. This allowed fibres to pick up the load as soon as the concrete cracked, achieving no sign of strength drop.

Consider the post-peak toughness (3δ, 5.5δ and 10.5δ) by looking at the toughness indices, at small deflection (3δ and 5.5δ), SFRC seemed to be tougher than PFRC at both volume fractions as indicated by the larger values of I_5 and I_{10}. This was because, in PFRC, with a large drop of load immediately after the peak, the area under the curve (as well as toughness) of the PFRC became smaller than that of SFRC. However, at large deflection (10.5δ), once the polypropylene fibres in the PFRC came into play, the load started to recover and the toughness of the PFRC was found to be significantly increased, especially at 2% volume fractions where the toughness index of 2PFRC increased to almost the same level as that of 2SFRC.

4.2.2 JSCE SF-4

The toughness values and factor according to JSCE SF-4 of both FRCs are given in Table 4 and Fig. 7.

Table 4: Toughness according to JSCESF-4

Concrete Type	Toughness (N-m)	Toughness Factor
1PFRC	8.3	1.24
2PFRC	9.8	1.47
1SFRC	18.5	2.78
2SFRC	30.8	4.62

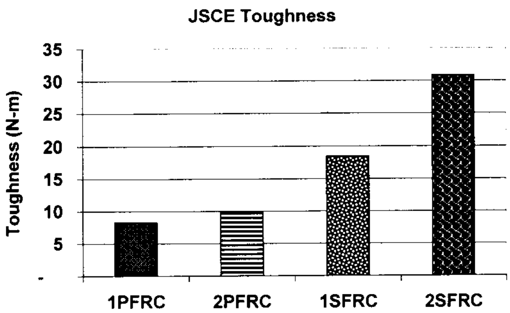

Fig. 7: Toughness according to JSCE SF-4

Based on this method, for a given load-deflection curve, a value of toughness measured up to a deflection of L/150 (2 mm) is calculated and then used to determine the toughness factor. The obtained results indicated that the performance of SFRC is more superior than that of PFRC at both volume fractions.

4.2.3 ASTM C1018 vs. JSCE SF-4

Comparing between these two methods, single value toughness measured using the JSCE method did not have any difficulty reflecting the toughness property of the SFRC. However, in the case of PFRC, JSCE did not seem to be sufficient to reflect the true toughness property. For instance, if the toughness value provided by JSCE is considered alone without looking at the load-deflection curve, it will lead to the conclusion that the performance of PFRC was much poorer than that of SFRC which was not quite right. It is true that the toughness of PFRC at small deflection was poorer than that of SFRC, but, at the larger deflection, the performance of PFRC was increased to almost the same as that of SFRC.

On the other hand, the toughness provided by ASTM at different deflections seemed to work out well in term of capturing and reflecting the true toughness properties of both SFRC and PFRC. By considering the toughness indices alone without looking at the load-deflection curve, rough descriptions of the behaviour of both FRCs could be achieved. For example, the small value of I_5 of the PFRC indicated that the PFRC did not perform well at the small deflection. However, the increase value of I_{20} of the PFRC to almost the same level as that of SFRC indicated that the performance of the PFRC was quite well at larger deformation.

5. Conclusions

From this study, the conclusions can be drawn as follows:

5.1 Both SFRC and PFRC behaved differently under bending. Due to the properties of the fibres, the behaviour of PFRC was clearly a double-peak response while the behaviour of the SFRC was a single-peak response.
5.2 Because of the way each FRC behaved differently, the toughness of each FRC was also different.
5.3 According to the ASTM method, with toughness measured out at 4 different deflections, the obtained information seemed to capture and reflect the true toughness properties of both SFRC and PFRC quite well.
5.4 On the other hand, the JSCE method, with a single value toughness, was not quite sufficient in reflecting the real toughness properties of the PFRC.

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