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Effect of Mixing Method on Mechanical Properties of Fiber Reinforced Concrete

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Abstract

Fiber reinforced concrete (FRC) has been successfully used to enhance the flexural toughness of concrete. As fibers are randomly oriented in FRC, they sometimes produce clumps that reduce the mechanical performance, and a properly chosen mixing protocol can be a way to minimize this problem. In this research, the effects of mixing method on the mechanical properties of FRC were investigated. The compressive strength, flexural strength, and flexural toughness were measured using three different mixing methods. It was shown from the results that the compressive strength and peak flexural load were not affected by changes in mixing method. However, in terms of flexural toughness, the changes in mixing method clearly affected the flexural toughness of FRC. The truck-mixed FRC outperformed two pan-mixed FRCs.

Keywords : fiber reinforced concrete, mixing method, flexural toughness

1. Introduction

Fiber reinforced concrete (FRC) has been introduced in order to increase the mechanical properties (mostly flexural toughness) of concrete[1]. Li et al.[2,3,4,5,6] and other researchers[7,8,9] investigated numerous cases and showed that FRC is a valuable structural material that can be used for civil infrastructures. When producing FRC, the fibers are randomly oriented, which means that they sometimes become entangled with each other, producing clumps in the mixtures[1]. Clumping generally depends on the volume fraction of the fiber that is mixed within the concrete. Since the undistributed fiber clump is unlikely to provide the desired mechanical properties of FRC, breaking the clumps during the mixing procedure is essential. Therefore, proper control is necessary for the easy production of FRC.

It is well known that the rheological properties (such as yield stress and viscosity) of cement–based material are very important for the construction of buildings and civil engineering infrastructures[10]. The angularity and shape of aggregates, total solid contents (represented by water to cement ratio and the amount of aggregate), and the surface area (cement and aggregate fineness and the amount of hydration products) are the factors that affect the rheological properties most significantly[11]. However, with FRC, the presence of fibers often reduces workability due to their bridging effect between solid particles (including cement paste and aggregate). FRC with poor rheological properties often generates air–filled defects

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with entangled fibers, which eventually has adverse effects on the structural integrity of FRC. General approaches to modify such properties are to control the quality of the aggregate and to use retarder (reducing the speed of hydration) and/or superplasticizer (coating cement particle with the organic polymer to cause electric repelling force and/or to cause steric hindrance between particles)[11]. However, in the case of FRC, the retarder and superplasticizer are not able to successfully minimize the clumping of fibers because they mostly interact with cement particles, not with fibers or aggregates.

It is worth noting that the rheological properties can also be affected mechanically. Mechanical contribution to the rheology of concrete is related to the shear history of the fresh mixture[12,13]. Shear history includes the amount of shear force that is applied during mixing. The amount of mixing time, the presence of aggregates at the time of mixing, angularity of aggregates, the speed of mixing, etc. all affect the shear history of concrete. In general, a higher shear rate provides better distribution of solid particles in the fresh concrete, and the same thing can occur with reinforced fibers. Since the presence of entangled clumps in FRC can be effectively distributed with the proper shear history of the mixture[14], it is necessary to control such variables, and the selection of a proper mixing procedure is a way to achieve that goal.

In this research, the effects of the mixing method on the mechanical properties of FRC are investigated. The compressive strength and flexural toughness are measured depending on the changes in mixing method of FRC. The purpose is to compare the performance of the FRC produced using a standard laboratory mixing procedure with FRC being produced by a ready-mix truck. The testing results will help to illuminate the mechanical performance differences between FRC produced in a laboratory and FRC produced on a construction site.

2. Materials and Experimental Procedures

Table 1 shows the mixture proportions of the base concrete without fibers. ASTM type I Portland cement[15] was used to prepare concrete. Water to cement ratio (w/c) was 0.42. Base concrete (plain concrete without fibers) of 3.0 m^3 batch was provided by a local ready mix concrete company. Synthetic macro fibers from a commercial bender were used as fiber ingredient. Table 2 shows the properties of the fibers used. Fibers of 2.3kg/m^3 (volume fraction of 0.25%) were added separately to the base concrete using three different mixing methods.

The mixing methods were as follows: (#1) base concrete was poured into the pan, fibers were added, and regular mixing time was applied for the pan mixing, (#2) base concrete was poured into the pan, fibers were added, and triple mixing time was applied for the pan mixing, and (#3) fibers were directly added to the ready-mix truck for truck-mixing. Table 3 shows the details of the mixing methods. The fresh concrete properties, including unit weight, slump and air contents, were also measured for reference, according to ASTM C 138[16], ASTM C 143[17], and ASTM C231[18], respectively.

Four beam specimens (150×150×525mm) and three cylinders (100×200mm) were fabricated for each mixing method (mixture #1, #2, and #3) for flexural toughness measurements and uniaxial compressive strength tests, respectively. A vibration table was used to consolidate the concrete in the beam mold. The beams and cylinders were de-molded at the age of 1 day and stored in a 100% RH (relative humidity) moisture chamber for additional 6 days. After the age of 7 days, the specimens were moved out of the 100% RH chamber and stored in a laboratory until the age of 14 days for ambient curing.

Beam specimens per each mixing method were tested according to JCI–SF4[19] and ASTM C1018[20] standard test methods. Note that the ASTM C1018 was withdrawn as of 2006 but the flexural toughness index from this specification still provides meaningful information in evaluating the performance of FRC. These test procedures are basically similar but they differ in a way to derive flexural toughness indices. JCI–SF4 measures the energy absorption of the material up to a certain value of deflection (the area underneath of the load–deflection curve up to δ = L/150), and ASTM C1018 measures first crack toughness (the area underneath of load–deflection curve up to the point of first–crack deflection). The details of deriving flexural toughness indices are well presented in other research[21].

Table 1. Mixture proportions of plain concrete

Ingredient	Weights in SSD (kg/m^3)
Water	151
Type I Portland Cement	359
Limestone	1088
Sand	782

Table 2. Properties of fiber

Raw Material	Polypropylene+Polyethylene
Shape	Flat Rectangle
Length	40mm
Aspect ratio	90
Specific Gravity	0.92
Absorption	None
Modulus of Elasticity	9.5GPa
Tensile Strength	620MPa

Table 3. Mixing methods for FRC

Mixture	Mixing Method	Mixer
#1	3–3–2 *	Pan
#2	9–3–6 *	Pan
#3	125 **	Truck

* represents the (time in minutes for initial mixing) – (time in minutes for rest) – (time in minutes for final mixing).
** represents the revolution of drum of ready–mix truck with speed of 10 revolution/min.

The experimental test setup for flexural toughness is presented in Figure 1. The span length between supports was 450mm, and the vertical load was applied at the third points. The deflection was measured by the LVDT mounted on the yoke to avoid the influence caused by extraneous deformation (crushing at the load points).

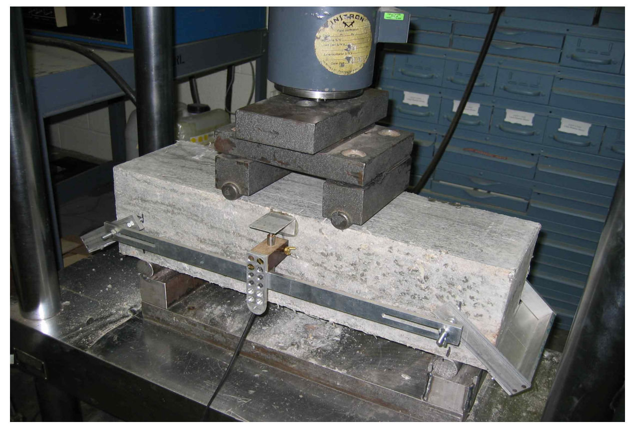


Figure 1. JCI–SF4 and ASTM C1018 testing setup

3. Results

3.1 Fresh Concrete Properties

The fresh concrete properties of FRC are presented in Table 4. It was shown from Table 4 that the unit weight, slump, and air content of mixtures #1, #2, and #3 were similar to each other. No significant differences in the fresh concrete properties of FRC were observed when the fiber mixing method was changed.

Table 4. Fresh concrete properties of FRC

Mixture	Unit Weight (kg/m^3)	Slump (mm)	Air Content (%)
#1	2419	89	1.3
#2	2419	76	1.3
#3	2403	89	1.4

3.2 Compressive Strength

Three cylindrical specimens of each mixture were tested for compressive strength at the age of 14 days. Measured compressive strength values of each specimen are shown in Table 5 and Figure 2. The average compressive strength of mixture #1 showed higher compressive strength than #2 and #3 specimens. However, the differences are within the range of standard deviation. In fact, as mixing method changes from #1 to #2 (#2 has longer mixing time), it reduced the standard deviation. When FRC was prepared in a ready-mix truck (mixture #3), the standard deviation decreased even more. These results indicate that mixing method #3 provided the most reliable test results in the test of compressive strength.

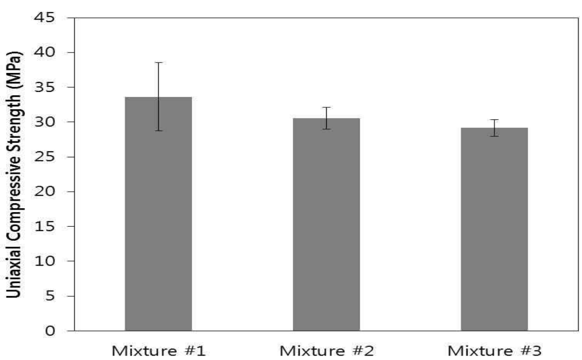


Figure 2. The compressive strength values of mixtures #1, #2, and #3; note that the coefficient of variation (standard deviation divided by average in percent) for mixtures #1, #2, and #3 is 14.5, 5.2, and 4.1%, respectively

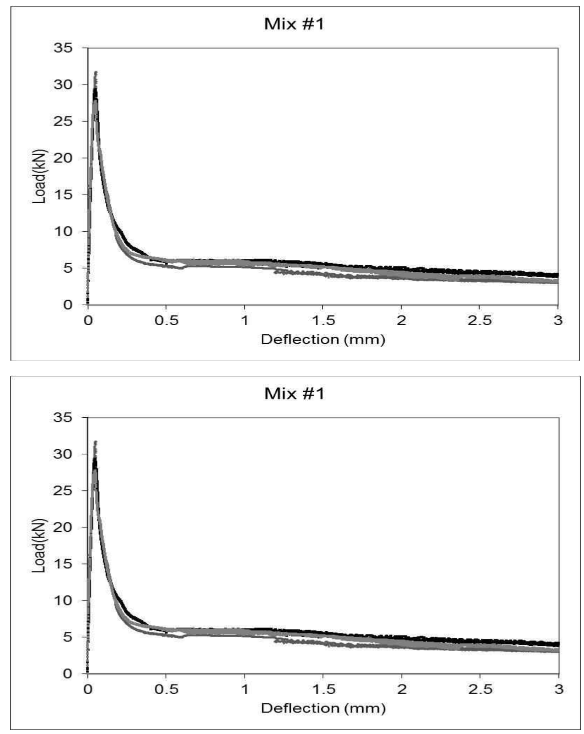
Table 5. Uniaxial compressive strength at14day

Mixture	Strength (MPa)			Average
#1	30.1	39.2	31.6	33.6
#2	28.8	31.0	31.8	30.5
#3	27.8	30.0	29.6	29.2

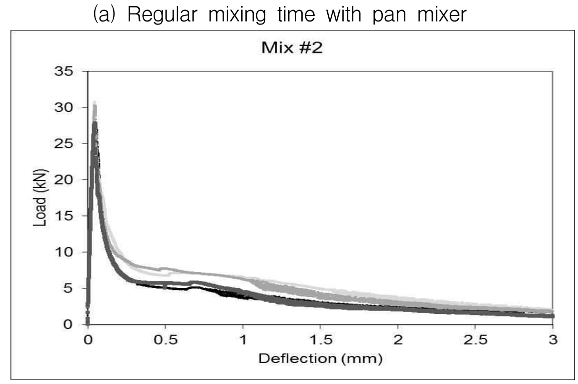
3.3 Load-Deflection Response of Flexural Test

Figure 3 shows the load-deflection curves for mixtures #1, #2, and #3. Load-deflection response was measured until the deflection of 3mm. The shape of load-deflection curves was similar for each specimen, indicating that they behaved similarly under flexural load.

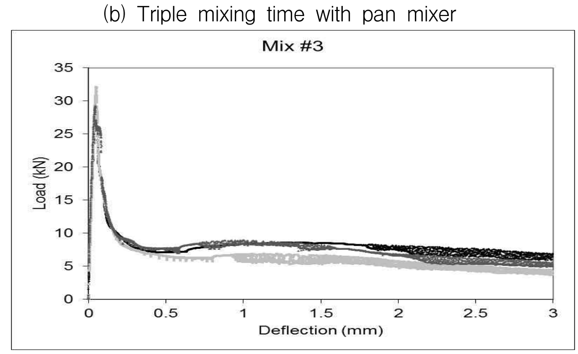
The peak loads of mixtures #1, #2, and #3 were observed at the deflection of around 0.05mm. Measured peak load values shown in Table 6 varied from about 27 to 32kN, and the average peak loads of each mixture are presented in Figure 4.



(a) Regular mixing time with pan mixer



(b) Triple mixing time with pan mixer



(c) Truck mix

Figure 3. Load-deflection curves of mixtures #1, #2, and #3

The peak loads of each specimen were within the range of standard deviation, indicating that there was no difference in peak load even though different mixing protocols were applied.

Table 6. Peak-Load of FRC

Mixture	Peak load (kN)				Average
#1	27.8	31.7	29.3	-	29.6
#2	27.8	30.2	28.1	30.7	29.2
#3	29.2	28.8	32.1	-	30.0

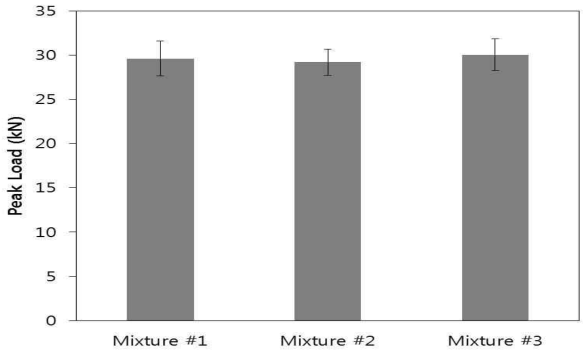


Figure 4. Peak loads of each specimen; note that the coefficient of variation for mixtures #1, #2, and #3 is 6.68, 5.07, and 5.95%, respectively)

3.4 Flexural toughness

The flexural toughness values can be calculated using the load-deflection curves shown in Figure 3. The calculated JCI-SF4 Flexural Toughness of FRC specimens are listed in Table 7 and presented in Figure 5. According to Figure 5, the flexural toughness values of pan-mixed specimens (mixture #1 and #2) were not greatly different from each other, but specimens mixed in a drum-type mixer (ready-mix truck) showed higher flexural toughness values. The differences in flexural toughness between pan-mixed specimens and truck-mixed specimens were above the range of standard deviation (shown as the error bars in Figures 5), and thus the mixture #3 (mixed in ready-mix truck) clearly showed higher flexural toughness than pan-mixed specimens.

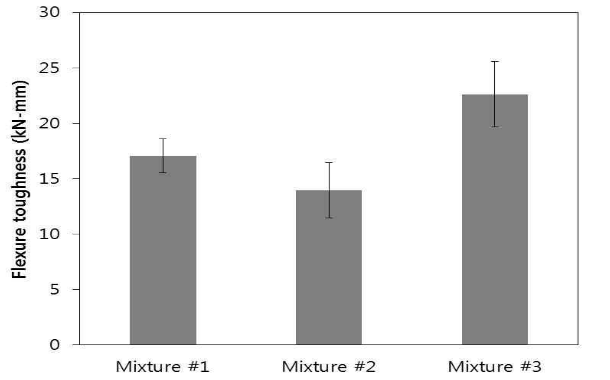


Figure 5. JCI-SF4 Flexural toughness of each specimen; note that the coefficient of variation for mixtures #1, #2, and #3 are 9.02, 17.97, and 12.95%, respectively

Table 7. JCI-SF4 Flexural Toughness

Mixture	Flexural Toughness (kN-mm)				Average
#1	17.5	15.4	18.4	-	17.0
#2	11.6	15.5	12.0	16.7	14.0
#3	23.7	24.9	19.3	-	22.6

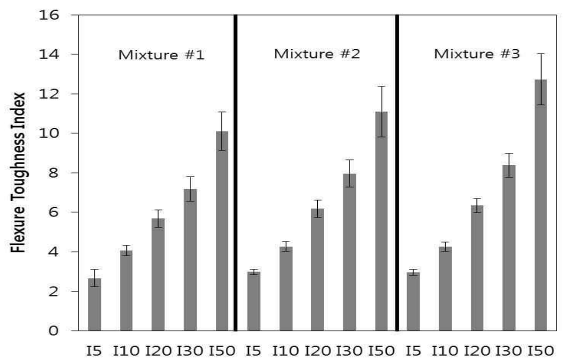


Figure 6. Flexural toughness indices of each specimen; note that the results were obtained using ASTM C 1018 procedure

Table 8. ASTM C1018 Flexural Toughness

Mixture		Flexural Toughness				Average
#1	I5	2.85	2.18	3.00	-	2.89
	I10	3.97	3.85	4.36	-	4.06
	I20	5.62	5.27	6.17	-	5.69
	I30	7.14	6.60	7.83	-	7.19
	I50	10.1	9.13	11.1	-	10.10
#2	I5	2.83	2.92	3.09	3.10	2.99
	I10	3.99	4.27	4.23	4.59	4.27
	I20	5.74	6.49	5.85	6.64	6.18
	I30	7.44	8.55	7.29	8.59	7.97
	I50	10.1	12.1	9.76	12.3	11.1
#3	I5	3.13	2.93	2.83	-	2.97
	I10	4.47	4.31	4.02	-	4.27
	I20	6.64	6.47	5.94	-	6.35
	I30	8.79	8.68	7.69	-	8.39
	I50	13.4	13.6	11.3	-	12.7

ASTM C1018 toughness indices were also calculated using the load–deflection curves shown in Figure 3. The calculated toughness indices are listed in Table 7 and presented in Figure 6. According to Figure 6 (the ASTM C1018 method), the I_5 values for all three materials are very similar, yet the I_{20}, I_{30}, and I_{50} diverged somewhat. According to the ASTM C1018 I_{50} toughness index, the #2 mix with longer mix times slightly outperformed the #1 mix. The #3 mix (truck–mix) showed the highest flexural toughness indices, outperforming the other two mixtures.

It is worth noting that the ASTM C1018 and JCI parameters provided somewhat different perspectives on the performance differences. In the JCI–SF4 flexural toughness index, the #2 pan–mixed FRC was a little lower than the #1 mix. This apparent contradiction results from the way the parameters are calculated. ASTM C1018 I_{50} index requires a load–deflection curve up to a deflection of 25.5 times the first–crack deflection (approximately 1.25mm for our case). On the other hand, JCI–SF4 index requires the load–deflection curve up to a deflection of L/150 (3mm for our case), where L= the span length. Mixture #2 showed a relatively higher load resistance than Mixture #1, up to the deflection of 0.05 in. Therefore the ASTM C1018 I_{50} index of Mixture #2 showed a higher number than that of Mixture #1. However, after the deflection of 1.25mm, the load resistance of Mixture #2 rapidly decreased compared to Mixture #1. Consequently, the area under the load–deflection curve of Mixture #2 became smaller than that of Mixture #1. Therefore, the JCI–SF4 index of Mixture #2 was lower than that of Mixture #1.

4. Discussion

The findings of this research indicated that the fresh concrete properties (unit weight, slump, and air content), the cylinder compressive strengths, and beam peak loads of all three materials were about the same, but the flexural toughness of the three materials differed depending on the mixing method. Although these mixed results prevent us from reaching a clear conclusion on whether the long pan mixing time had any significant impact, they clearly demonstrated the difference between the truck–mixed FRC and the pan–mixed FRC. Both the ASTM C1018 and JCI analyses found that the truck–mixed FRC (Mixture #3) outperformed the two pan–mixed FRC by 20–30% of the index values. Presumably, this advantage in flexural toughness occurs because the mixing action in the truck more effectively dispersed fiber clumps. It is also possible to consider that the truck mixing method can abrade the surface of fiber, creating rougher fiber surfaces that sustain higher loads during the fiber–pull–out stage of the test.

5. Conclusions

The flexural toughness of three FRC mixtures was tested in accordance with JCI–SF4 and ASTM C1018 standard testing method. Unit weight, slump, air content (fresh properties), and compressive strength were also measured. Load–deflection diagrams were prepared and toughness indices were calculated to allow comparison of the performance of these mixtures. The following conclusions can be drawn from the results.

1) No significant differences among the FRC mixtures were observed in freshness properties, compressive strength, or peak load.
2) Truck–mixed FRC outperformed pan–mixed FRC in terms of flexural toughness.

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References

1. Bentur A, Mindess S. Fiber Reinforced Cementitious Composites. London: Spoon Press; 2002. 449 p.
2. Chan YW, Li VC. Age Effect on the Characteristics of Fiber/Cement Interfacial Properties. Journal of Material Science. 1997 Oct;32(19):5287–92.
3. Li VC, Chan YW. Determination of Interfacial Debond Mode for Fiber–Reinforced Cementitious Composites. ASCE Journal of Engineering Mechanics. 1994 Apr;120(4):707–19.
4. Li VC. Postcrack Scaling Relations for Fiber Reinforced Cementitious Composites. ASCE Journal of Materials in Civil Engineering. 1992 Feb;4(1):41–57.
5. Li VC, Stang H, Krenchel H. Micromechanics of Crack Bridging in Fiber–Reinforced Concrete. Materials and Structures. 1993 Oct;26(8):486–94.
6. Li VC, Wu H-C, Maalej M, Mishra DK, Hashida T. Tensile Behavior of Cement–Based Composites with Random Discontinuous Steel Fibers. Journal of American Ceramic Society. 1996 Jan; 79(1):74–8.
7. Ding Y, Kusterle W. Compressive Stress–Strain Relationship of Steel Fiber–Reinforced Concrete at Early Age. Cement and Concrete Research. 2000 Oct;30(10):1573–79.
8. Gopalaratnam VS, Shah SP, Batson GB, Criswell ME, Ramakrishnan V, Wecharatana M. Fracture Toughness of Fiber Reinforced Concrete. ACI Materials Journal. 1991 Jul;88 (4):339–53.
9. Gopalaratnam VS, Gettu R. On the Characterization of Flexural Toughness in Fiber Reinforced Concretes. Cement and Concrete Composites. 1995 Jul;173:239–54.
10. Taylor HFW. Cement Chemistry. 2nd ed. London: Thomas Telford Publishing; 1997. 459 p.
11. Ferraris C, Francois de Larrard. Testing and Modeling of Fresh Concrete Rheology. Gaithersburg (MD): National Institute of Standards and Technology (US); 1998 Feb. 61p. Report No.: NISTIR 6094.
12. Ferraris C. Measurement of the Rheological Properties of Cement Paste: A New Approach. In: Cabrera JG, Rivera–Villarreal RR., editors. Role of Admixtures in High Performance Concrete. RILEM international symposium; 1999 Mar 21–26; Monterrey Mexico. RILEM Publications S.A.R.L.; 1999. p. 333–342.
13. Ferraris C. Measurement of the Rheological Properties of High Performance Concrete: A State of the Art Report. Journal of Research of the National Institute of Standards and Technology. 1999 (Oct);104(5): 461–478.
14. Soroushian P, Lee C-D. Distribution and Orientation of Fibers in Steel Fiber Reinforced Concrete. ACI Materials Journal. 1990 (Sep);87(5):433–9.
15. American Society for Testing and Materials. Annual Book of ASTM Standards. West Conshohocken; ASTM International; c2012. Vol. 04. 01. (C 150) ASTM Standard Specification for Portland Cement.
16. American Society for Testing and Materials. Annual Book of ASTM Standards. West Conshohocken; ASTM International; c2012. Vol. 04. 02. (C 138) ASTM Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravvimetric) of Concrete.
17. American Society for Testing and Materials. Annual Book of ASTM Standards. West Conshohocken; ASTM International; c2012. Vol. 04. 02. ASTM Standard Test Method for Slump of Hydraulic–Cement Concrete.
18. American Society for Testing and Materials. Annual Book of ASTM Standards. West Conshohocken; ASTM International; c2012. Vol. 04. 02. ASTM Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.
19. Japan Concrete Institute. JCI Standards for Test Methods of Fibre Reinforced Concrete; Tokyo; Japan Concrete Institute; c1983. SF4 Method of Test for Flexural Strength and Flexural Toughness of Fibre Reinforced Concrete.
20. American Society for Testing and Materials. Annual Book of ASTM Standards. West Conshohocken; ASTM International; c1997. Vol. 04. 01. ASTM Standard Test Method for Flexural toughness and First–Crack Strength of Fiber–Reinforced Concrete (Using Beam with Third–Point Loading.
21. Lee CJ, Lange DA, Lee JY, Shin SW. Effects of Fiber Volume Fraction and Water/Cement Ratio on Toughness Development of Steel Fiber Reinforced Concrete. Journal of the Korea Institute of Building Construction. 2013 (Feb); 13(1):20–8.