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Summary

The significance of energy absorption of the fiber reinforced concrete (FRC) for its performance in the structures motivates the attempts to determine the most proper test procedure for FRC toughness characterization. This paper presents the results of study on determination of correlation among various standards and recommended test methods for flexural behavior and primarily for flexural toughness of FRC . Compressive toughness behavior is of concern as well.

1. Introduction

The basic difference between the plain concrete and fiber reinforced concrete is found in their toughness performance. The significance of energy absorption capability for the materials and structural design motivates the further developments of various test procedures for better description of toughness performance. The toughness is considered as a compressive, tensile, flexural etc. toughness. Usually, the flexural toughness is determined according to ASTM requirements [1], JCI recommendations [2] and ACI recommendations [3]. The most recent studies proved that the obligatory determined I_5, I_{10} and $R_{5,10}$ are not sensitive to the fiber type and volume, and that is more valid for small size of test specimens (like 100x100x150 or 150x150x450 mm) [4]. The higher indices I_{20}, I_{30} etc. and JCI parameters are pointed out to be more descriptive for the improvement in flexural toughness due to fiber volume or type. Another test method describes very well the post-peak part of the load-deflection curve and therefore the toughness performance [5].

The importance of first crack deflection was shown and a new, more practical proposal for a determination of a flexural parameter was given in order to estimate first crack deflection influence on the toughness parameters. Very comprehensive research is done on the effect of seating and twisting of supports on the mid-span deflection [6,7] and most of the experiments considered that problem by using a special frame as described in [2,7,8,10]. The specimen geometry and size influence the toughness expressed through ASTM indices, which was reported in recent studies unless the specimens are in geometrical similarity [4]. In some of the analyses [4], it was stressed that more attention should be paid to residual strength factor like $R_{30,50}$ or $R_{80,100}$ which are more meaningful for the design because they would express the average load over a portion of load-deflection curve preceding the specified end-point deflection.

The properties of plain concrete are well studied in cases involving different temperatures, especially subzero ones [9] and thermal shock. In last decade, the studies on FRC behavior at low temperatures aimed to fill the gap in the knowledge for toughness behavior at low temperatures.

The objective of this study is to find and analyze how the different standard test methods and parameters describe the toughness behavior of FRC tested not only at normal (20deg) temperature as required in the specifications, but at low temperatures like -20 or -50 deg. The correlation among the toughness parameters of different test methods would explain to what degree those methods are applicable to different than specified test conditions.

2. Experimental Program and Reference Experiment Details

2.1 Details of Authors' Experiment

In the experiment conducted, the flexural toughness behavior was studied in terms of different fiber type, fiber volume and testing temperature. Steel fibers were applied in two types differed by shape and in 5 volumes (0.5; 1.0; 1.5; 2.0; 2.5%). Three test temperatures were chosen - +20; -20; -50 deg. The testing machine was a hydraulic type with a load control. The loading speed maintained a constant increase in the stress. The size of test specimens was 100x100x420 mm with a mid-span of 300mm. The load-deflection curves were measured and toughness parameters were determined according to ASTM (I_i and $R_{i,i+1}$) and JCI. More details on the experimental program are given in [10,11].

2.2 Details of Reference Experiments

2.2.1. Experiment by Horiguchi etc. [12]

The main objective of this experimental program was to study the compressive, pull-out and flexural toughness behavior of hybrid fiber reinforced concrete (HFRC) at different temperatures. Two fiber materials were applied: steel and vinylon. Steel fibers (S) were presented in 4 types which differed mainly in length, shape and aspect ratio. Vinylon fibers (V) were two types with different lengths. HFRC mixes with total 1% (.5S+.5V); 1.5% (.5S+1.0V); 1.5% (1.0S+.5V) fiber inclusion were produced. Compressive and flexural test were conducted both at +20; -20 deg. The loading machine in compression was with a load control and that in flexure - with a deflection control. The test specimens for flexural test were beams 100x100x400 mm in size and with a mid-span of 300 mm, and those for compressive test were cylinders 200x100 mm in size. The load-deflection curves in compression were measured and the toughness parameter according to JCI was calculated. The load-deflection curves in flexure were also recorded and based on the procedure described in ASTM [1] and ACI [3] both I_{30} and I_{075} were calculated respectively. Also the parameter FF, proposed in [5] and which should be independent of fiber amount for fiber types assuring good toughness, was determined.

2.2.2. Experiment by Banthia etc. [13]

The main purpose of this experimental program was to extend the limited data for FRC behavior at low temperatures. Here again two fiber materials were applied: steel and carbon. Steel fibers were described as macro (SMa) and micro (SMi) fibers, and carbon fibers (C) were only micro one. Fiber volumes used were 1%SMa; 2% (1.0SMa+1.0SMi); 2% (1.0SMa+1.0C). Testing temperatures were set at 22 and -50 deg. A deflection control type loading machine was used. The flexural test specimens were beams 50x50x450 mm in size with a mid-span of 300 mm. The load-deflection curves were recorded and the flexural toughness according to JCI [2] was provided and I_{30} indices calculated. All details mentioned above are summarized in Table 1.

Refer-ences	Fiber Material	Fiber Type	Type of Concret e	Fiber Volumes, %	Specimen' Size, mm	Loading Type	Temperature Range, deg
Authors [10,11]	Steel	2	SFRC	5(0.5;1;1.5; 2;2.5)	100/100/300	Load control	20; -20; -50
[12]	Steel; Vinylon	6	HFRC VFRC	2 (1; 1.5)	100/100/300	Deflection control	20; -20
[13]	Steel; Carbon	3	SFRC CFRC	2(1; 2)	50/50/450	Deflection control	20; -50
Compressive Test							
[12]	Steel; Vinylon	6	HFRC	2 (1; 1.5)	100/200	Load control	20; -20

Table 1 Details of the experiments in consideration

3. Results and Discussion

3.1 Compressive Toughness Parameters

The compressive test results of [12] are considered through JCI recommendations [2] for a compressive toughness , which is the area under load-deflection curve up to 0.75% of the deflection measured. Also, an average compressive strength was calculated at 0.75% change of the specimen height. Both were determined at normal and low (-20 deg) temperatures. The plotted results and a function of compressive strength and toughness correlation are shown in Fig. 1. The compressive strength at 20 deg and at -20 deg are in a linear relationship and an increase in the strength at 20 deg is maintained as an increase in the strength at -20 deg as well. The compressive toughness at both temperatures does not show high correlation. While the toughness at normal temperature increase with the fiber inclusion, the toughness at low temperature did not change significantly and kept almost the constant value. The hybrid fiber inclusion benefits the toughness at normal conditions, but concrete matrix behavior at low temperature still influenced strongly the hybrid FRC compressive toughness at those conditions.

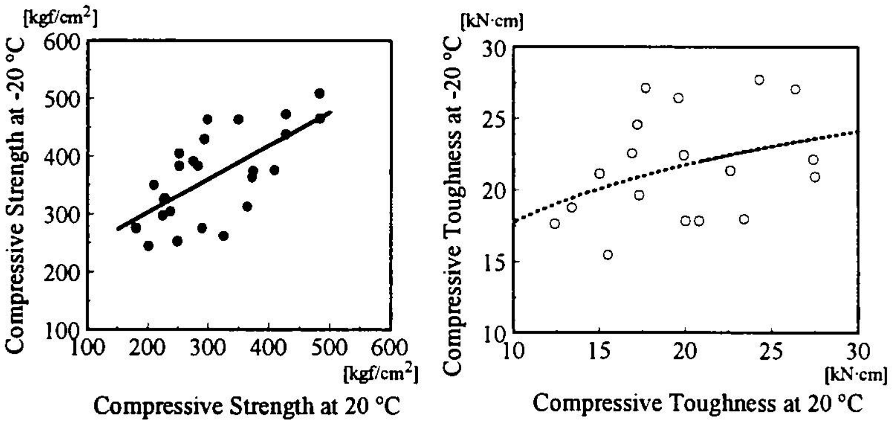

Fig.1 Compressive strength and toughness at 20 and -20 deg

Knowing the compressive strength at normal conditions, it is likely to predict it at low temperature, which is not valid for the compressive toughness because of the low correlation found. No correlation was found between ASTM I_{30} and compressive toughness at all temperatures either.

3.2 Flexural Toughness Parameters

The results reported in [10,11] and their analysis showed that the toughness increased while fiber volume increased at all temperatures tested. Also that was indicated by all test methods - JCI, ASTM. A some contradictions appeared when comparing the overall performance in flexural toughness of SFRC at all temperatures. The toughness factor T according to JCI, showed an improvement in the performance while temperature was changed from 20 deg to -50 deg. On the other hand, ASTM I_{20}, I_{30}, I_{50} and I_{100} indices showed a decrease in the performance at the same conditions. The I_i lines presented in Fig. 2 show that I_5 and I_{10} could not be used for a precise description of the toughness at -20, -50 deg. A better description can be achieved by using higher indices I_{30} and more, at -20, -50 deg. The difference in the flexural performance expressed through I_{20}, I_{30}, I_{50} and I_{100} is more obvious when comparing 20 and -20 deg and very slight between -20 and -50 deg. When plotted, the results of [13] which are for different type fibers fitted well with the I_{30} results of [10,11].

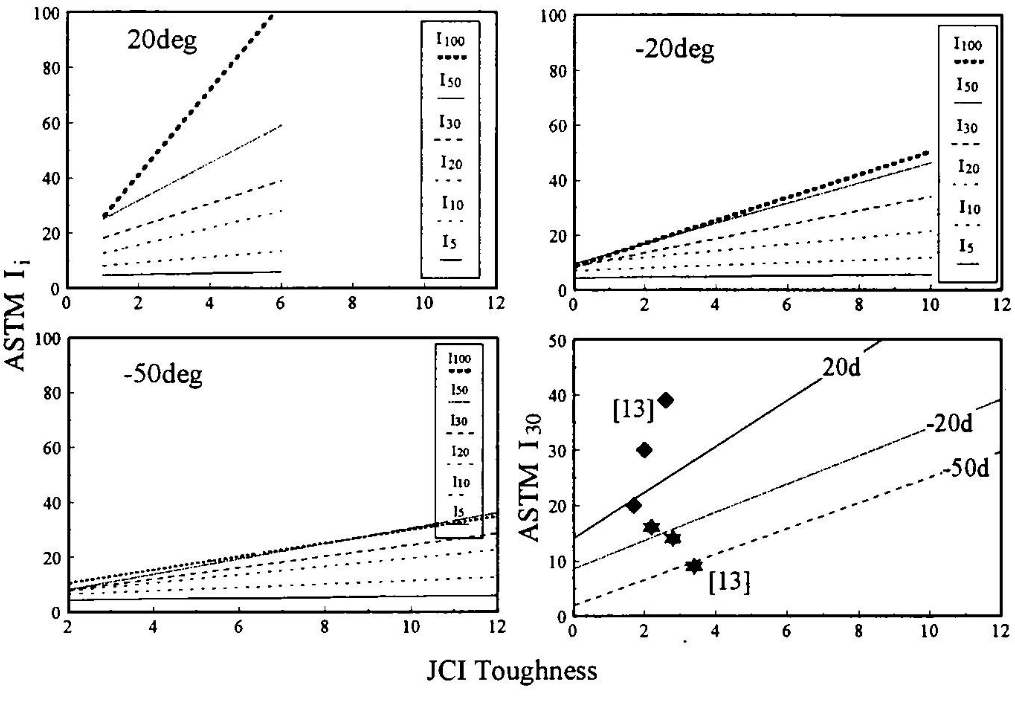

Fig. 2 Toughness correlation of T and I_i at different temperatures

The analysis of results of [12] is shown as a I_{075}-I_{30} relationship. It was reported previously that a linear relationship was found at low temperature, and a quadratic relationship at normal temperature. Therefore, the both procedures [1,3] equally describe the flexural toughness at low temperature, but I_{30} is a better measure at normal temperature, as shown in Fig. 3. On the other hand, it was not found any pronounced correlation between I_{30} and FF, where FF is a parameter which describes the post-peak part of load-deflection curve at a deflection with crack width of 1mm, at both temperatures considered. The possible explanation for this result is the small test specimen size used. Further study on different sizes and at low temperature is necessary for an identifying FF parameter usefulness.

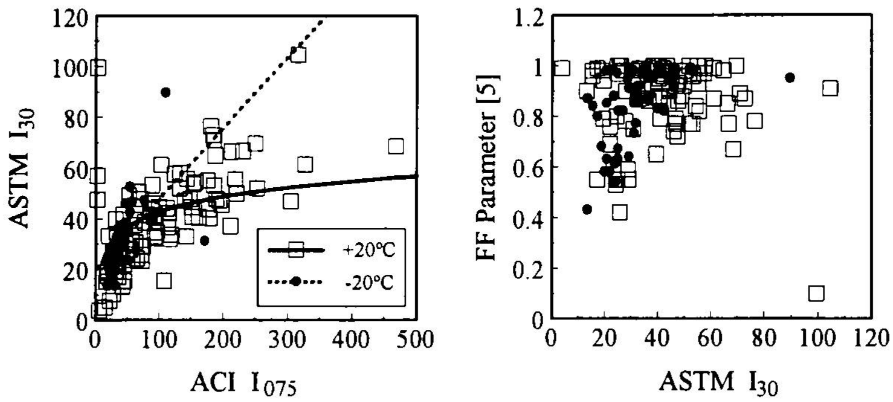

Fig.3 Toughness indices I_{075} - I_{30}, and I_{30} - FF relationships

Next, the toughness factor [2] and residual factors $R_{5,10}$, $R_{10,20}$, $R_{20,30}$ and $R_{30,50}$ relationships are shown in Fig.4. With the decrease of the temperature, residual strengths decrease and the area between $R_{5,10}$ and $R_{30,50}$ increases with the decrease of the temperature. Then the residual strength factor becomes more sensitive to low temperature and therefore good way for a description of flexural toughness performance of FRC.

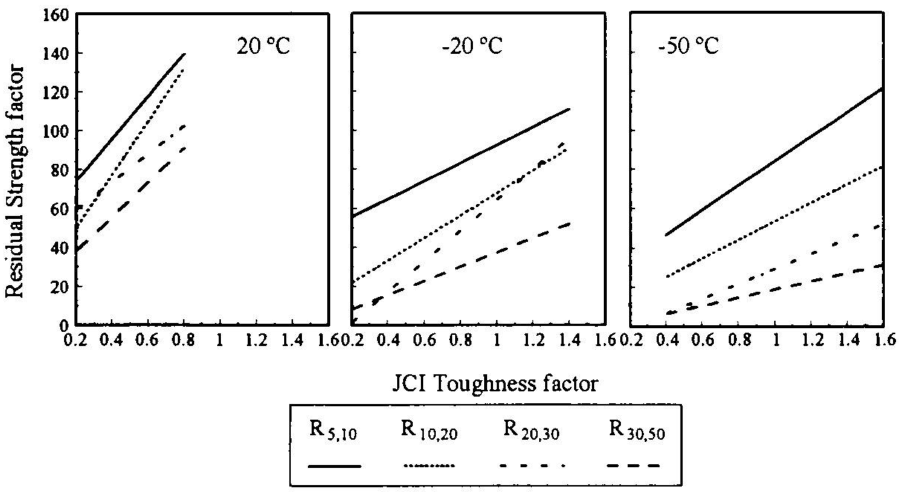

Fig.4 Residual strength factors at different temperatures

4. Conclusion

Next conclusions can be drawn based on the results and their analysis.

- The compressive strength at low temperature does not show an improvement and no correlation is found between the compressive toughness at both temperatures.
- It is confirmed that I_5, I_{10} and $R_{5,10}$ are not sensitive for a distinction of flexural

toughness at different temperatures, but using the indices I_{30} and higher, residual strength factors $R_{20,30}$ and higher would be a better way for flexural toughness characterization.

- ACI I_{075} index could be used for describing flexural toughness performance in the same order as ASTM I_{30} at low temperatures.

- The toughness factor T according to JCI is not very appropriate measure when considering low temperatures.

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