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IMPACT RESISTANCE AND STRENGTH RELIABILITY OF FIBER-REINFORCED CONCRETE IN BENDING UNDER DROP WEIGHT IMPACT LOAD

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ABSTRACT

This paper presents an experimental investigation on the Impact failure energy and strength reliability of fiber reinforced concrete (FRC) by using a simple drop weight test which was based on the testing procedure recommended by ACI committee 544. Two different steel fibers were used as the reinforcing material in various volume fractions such as 0%, 0.5%, 1.0% and 1.5% with a water cement ratio of 0.42. Furthermore, the two-parameter weibull distribution was used to analyze the experimental data in order to sort out a variation of test results. Using the weibull distribution, the impact failure strength reliability, in other words, the probability distribution according to which the concrete will fail, was obtained. The results indicated that the concrete containing a 1.5% volume fraction of fiber gave the best performance followed by 1.0% and 0.5% under impact loading. It was proven that the probabilistic distributions of the impact failure energy of seven types of samples approximately follow two-parameter Weibull distribution.

Keywords: Fiber; Impact failure energy; Impact load; Linear regression; Reliability; Weibull distribution

1. INTRODUCTION

In the present scenario, impact resistance of concrete is recognized as one of the most important properties by the construction industry. It is accepted that the concrete having properties of strength, toughness, fatigue, resistance against impact and dynamic loads, ductility, durability, flexural strength, etc, can be achieved by incorporating various types of fibers in the cement mixtures (Cachim et al., 2002; Carpinteri & Brighenti, 2010; Mahmoud & Afroughsabet, 2010, 2010; Xu et al., 2012). The FRC is widely used nowadays in hydraulic structures, airport runway pavements, industrial flooring, bridges, military building and railway traversers, where the impact loads are enormous and hence these types of concrete are in great demand in the construction industry.

The fibers are mainly made of steel, carbon or polymer (Ghavami, 2005). Of all the types of fibers, steel fiber has attracted the most attention among researchers because of its low cost, outstanding impact resistance, capacity to arrest crack openings and crack propagation in concrete reinforced with this type of fiber (Nataraja et al., 2005; Song et al., 2004, 2005; Atef et al., 2006; Mahmoud & Afroughsabet, 2010).

A simple drop weight test is the popular and attractive method suggested by the ACI Committee 544, for determining the impact resistance of concrete.

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However, a greater deviation can be observed in the drop weight test results, which may be due to the following reasons (Song et al., 2004, 2005; Atef et al., 2006): (i) the test results are interpreted based on the recognition of first crack by visual means and this crack may occur in any direction; (ii) it is too precise to control the height of fall of drop hammer exactly, as it is being done manually; (iii) the impact resistance of concrete is determined by the impact occurring at a single point, which may be either, on a tough coarse aggregate or a fiber or a matrix; (iv) any variation occurring in the mix design of concrete would result in a change in its impact resistance; (v) the height of the fall of hammer is a handmade process and it becomes difficult to have an accurate control over it; (vi) the drop weight test is influenced by handmade work and hence the test results would also be greatly influenced by man-made errors. In the view of the features of the impact test results, the statistical analysis has emerged as a legitimate technique for resolving the variations in impact test results and determining the significance of steel fiber in concrete.

2. EXPERIMENTAL

2.1. Material properties

Ordinary Portland Cement (OPC) 53 grade corresponding to ASTM Type I cement with a specific gravity of 3.15 was used in concrete mixtures. Crushed granite gravel with a size of 12 and 20 mm, respectively and the specific gravity of 2.71 and 2.77, respectively were used as the coarse aggregate. The natural siliceous river sand having a specific gravity of 2.64 was used as a fine aggregate. Commercial high-performance polycarboxylic ether superplasticizer (SP) was used as high-range water-reducing agent to produce a workable fiber-reinforced concrete and true slump (25 to 50mm) was maintained for all the mixtures. The dosage of SP on mass basis varied from 0.3 to 1.0% of the cement content. Two different fibers, namely crimped fiber (CF) and hooked end fiber (HF) with an aspect ratio 50, and having a length of 50 mm and equivalent diameter of 1 mm were used. The density of both the fibers was 7.8 g/cm^3. Tensile strength of crimped and hooked end fiber was 1000 MPa and 1050 MPa, respectively. Concrete mix proportion used for casting the test specimens is shown in Table 1.

Table 1 Concrete mix proportions for 1m^3

Mix id	W/B	W (Kg/m^3)	Cement (Kg/m^3)	Fine Agg. (Kg/m^3)	Coarse Agg. (Kg/m^3)		Volume fraction of fiber V_f	Weight of fiber (Kg/m^3)	Sp (%)
					20 mm	12.5 mm			
PC	0.42	140	333	901	465	697	-	-	0.3
CF2	0.42	140	333	903	460	689	0.5	39	0.5
CF3	0.42	140	333	892	454	681	1.0	78	0.8
CF4	0.42	140	333	885	450	676	1.5	117	1.0
HF5	0.42	140	333	903	460	689	0.5	39	0.5
HF6	0.42	140	333	892	454	681	1.0	78	0.8
HF7	0.42	140	333	885	450	676	1.5	117	1.0

2.2. Mixing procedure and specimen molding

The fine aggregate and cement were mixed for 1 minute, following which half of the mixing water and SP were added to the mix and it was mixed for 2 minutes. The remaining water was then added to the mix along with coarse aggregate and mixing was done for 5 minutes. Finally, fibers were added in various proportions such as 0.5%, 1.0% and 1.5%, respectively to the mixture which was mixed for 5 minutes (Mahmoud & Afroughsabet, 2010, 2010; Alavi Nia et al., 2012). Each batch of freshly mixed concrete was then cast into prisms (500×100×100 mm) which were used in the three point bending and impact test.

2.3. Impact test

The impact resistance of the specimens was determined in accordance with the procedure proposed by the ACI Committee 544.2R-89. For this purpose, from each batch, six specimens were used and the specimens were supported on a 400 mm span. The impact load was applied with hammer onto a 4.45 kg ball of 60.2 mm diameter, dropped repeatedly from a 457 mm height on the center of the top surface of the specimens. The drop weight test arrangement was as shown in Figure 1. In each test, the number of blows (N_1) required to produce the initiation of crack was recorded as the initial crack strength, and the number of blows (N_2) needed to cause failure of the specimen was recorded as the failure strength; this method has been used by several researchers (Nataraja et al., 2005; Song et al., 2004, 2005; Atef et al., 2006; Mahmoud & Afroughsabet, 2010, 2010).

Figure 1 Drop-weight test arrangement

The energy absorption capacity of each specimen used in this test was calculated using Equation (1):

$$\text{Impact energy } U = \left(\frac{\text{n.m.V}^2}{2}\right) \tag{1}$$

$$H = \left(\frac{gt^2}{2}\right) \tag{2}$$

$$V = g.t \tag{3}$$

$$m = W/g \tag{4}$$

where, *V* is the velocity of the hammer at impact, *g* is acceleration due to gravity, and *t* is the time required for the hammer to fall from a height of 457 mm. *H* is the height of fall, *m* is the mass of hammer and *W* is the weight of hammer.

Substituting the relevant values in Equation (1) yields:

$$457 = \frac{9810t^2}{2}$$

$$t = 0.3052 \text{ s and } V = 9810 \times 0.3052 = 2994.01 \text{ mm/s}$$

The impact energy per blow, U, of the hammer can be obtained by substituting the values in Equation (1):

$$U = \frac{44.3\text{x}2994.01^2}{2\text{x}9810} = 20.345\ \text{kN mm}$$

Table 2 Statistical analysis of impact test results

S.No	N_1/N_2						
	PC	CF2	CF3	CF4	HF5	HF6	HF7
1	8/12	11/20	17/23	15/26	12/20	16/25	17/28
2	9/17	12/23	20/26	19/29	14/22	19/27	19/31
3	11/20	15/24	21/29	22/35	15/27	22/30	22/38
4	13/25	16/26	24/31	27/38	17/31	26/34	28/42
5	15/28	18/28	26/34	29/41	19/33	28/36	33/45
6	17/31	20/32	27/37	30/44	21/36	31/39	35/46
Mean	12/22	15/26	23/30	24/36	16/28	24/32	26/38
Standard deviation	6.18/ 12.05	7.24/ 11.28	10.39/ 13.49	12.23/ 16.73	7.57/ 13.86	11.77/ 14.71	13.28/ 18.38
Coefficient of variance	50.79/ 54.38	47.25/ 44.23	46.16/ 44.97	51.67/ 47.13	46.35/ 49.19	49.75/ 46.21	51.73/ 47.96

3. RESULTS AND DISCUSSION

Figure 2 presents the results of flexural strength versus fiber volume fraction testing carried out on seven different mixtures after 28 days. As expected, a higher flexural strength was obtained in 1.5% volume fraction of steel fiber. Introducing steel fiber into the concrete mixtures has led to significant increases in the flexural strength. For instance, the flexural strength increased by 13%, 33.6%, 50.7%, 17%, 38% and 55% (CF2, CF3, CF4, HF5, HF6 and HF7) respectively.

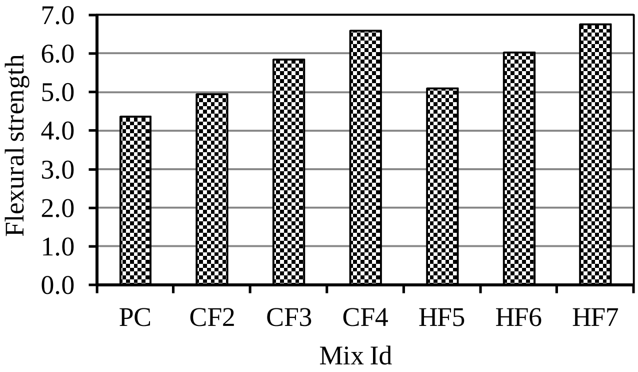

Figure 2 Flexural strength of concrete (N/mm^2)

By introducing steel fiber into the concrete, the failure mode was changed from a brittle to ductile behavior in both cases of the three point bending and impact test, which is shown in Figure 3.

(a) (b)

Figure 3 Failure pattern of specimen: (a) three point bending; (b) impact test

The number of blows required to cause the initiation of the first visible crack and the failure of PC, as well as FRC are shown in Table 2. It is obvious that, incorporation of steel fibers into the mixture shows a considerable increase in the number of blows required to cause the first crack and failure (Mahmoud & Afroughsabet, 2010, 2010; Alavi Nia et al., 2012). The mix that contained 0.5% CF and HF showed an increase in N_1 by 1.25 and 1.33 times respectively (CF2, HF5). This occurred due to an increase of the fiber volume fractions to 1%, N_1 by 1.91 and 2.0 times respectively (CF3, HF6). An additional increase in the fiber volume fraction to 1.5% showed an increase of 2.0 and 2.17 times respectively in N_1 (CF4, HF7) as compared to the PC. Similarly the mix that contained 0.5% CF and HF showed an increase in N_2 by 1.18 and 1.27 times respectively (CF2, HF5). By increasing the fiber volume fractions to 1%, N_2 increase by 1.36 and 1.45 times respectively (CF3, HF6). Further increase in the fiber volume fraction to 1.5% showed an increase of 1.63 and 1.72 times in N_2 in comparison with the PC (CF4, HF7).

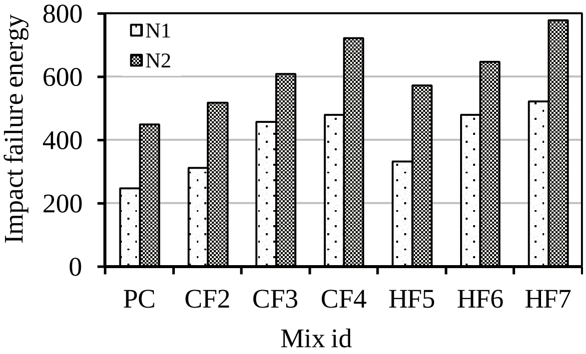

Figure 4 Impact failure energy at first crack and failure

Figure 4 shows an increase in impact energy at its first crack by, 26.03, 84.93 and 94.52% respectively for those concrete mixes (CF2-CF4) having the fiber volume fraction of 0.5, 1.0, 1.5% respectively. Similarly, concrete (HF5-HF7) that contains HF, increases the impact energy at first crack stage by 34.25, 94.52, and 110.96% with respect to the PC. The increase in impact failure energy was observed to be 27.07, 43.61 and 72.93% respectively in the case of HF (HF5-HF7) and 15.04, 35.34 and 60.15% respectively for CF (CF2-CF4). In general the best performance of FRC in terms of the first visible crack as well as impact failure energy was observed in the range of 1.5% volume fraction of fiber followed by 1.0% and 0.5%, respectively. Also, it is clear from Figure 3 that the impact energy of concrete, increased in both of the cases, i.e., HF and CF when compared to PC. This increase in energy was slightly greater in the case of HF when compared to CF. Furthermore, it can be concluded that the addition of steel fiber to concrete significantly increases its impact resistance (Chen Xiang et al., 2011; Alavi Nia et al., 2012).

3.1. Weibull distribution

The Weibull equation describes the relationship between the probabilities of failure of impact failure energy: It thus predicts the inherent dispersion in the failure strength of concrete. There are two simplified parameters in the Weibull equation.

It has been proven in several investigations that the two-parameter Weibull distribution is most commonly used for describing the fatigue life of concrete (Singh & Kaushik, 2009; Sakin & Irfan, 2008; Bedi & Chandra, 2009). Basically, the mechanism of the impact test is similar to that of the fatigue test; therefore, the two-parameter Weibull distribution is adopted and a graphical method is employed to clarify the distribution characteristics of the impact failure energy in seven groups of samples.

The cumulative distribution function $F_N(c)$ of the Weibull probability law may be expressed as:

$$F_N(c) = 1 - exp\left[-\left(\frac{c}{b}\right)^{\alpha}\right] \tag{5}$$

Where, c represents the specific value of the random variable N; b denotes the scale parameter; α denotes the shape parameter.

Taking natural logarithm twice on both sides of the Equation (5) gives:

$$ln\left[ln\left(\frac{1}{F_N(c)}\right)\right] = \propto \ln(c) - \propto \ln(b) \tag{6}$$

Thus, Equation (6) can be used to verify whether the statistical distribution of the impact failure energy in the seven groups of samples follows the two-parameter Weibull distribution. Two steps are adopted to conduct the verification. In the first step, the impact failure energy is arranged in ascending order, and then an empirical survivorship function can be analyzed.

Several predefined empirical survivorship functions have been used in different sets of literature for evaluating the value of L_N (Jayatilaka & De, 1979; Saghafi et al., 2009).

$$L_N = 1 - \frac{i - 0.3}{k + 0.4} \tag{7}$$

Where i is the failure order number and k is the total number of the samples for a given type of specimen. If an approximately linear relationship is observed between $\ln[\ln(l/L_N)]$ and ln (Impact failure energy, we can assume that the two-parameter Weibull distribution is a reasonable assumption for the statistical description of the impact resistance factor of the seven types of concrete samples.

The probability of survivorship function may be defined as:

$$R = 1 - F_N(c) \tag{8}$$

The probability of survival and U_{RN} denotes the Impact failure energy based on the reliability.

$$U_{RN} = b.((-\ln(R)^{\frac{1}{\propto}}) \tag{9}$$

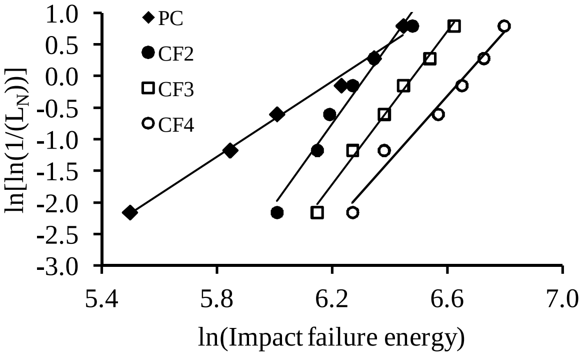

Figure 5 Linear regression of Impact failure energy in the Weibull distribution

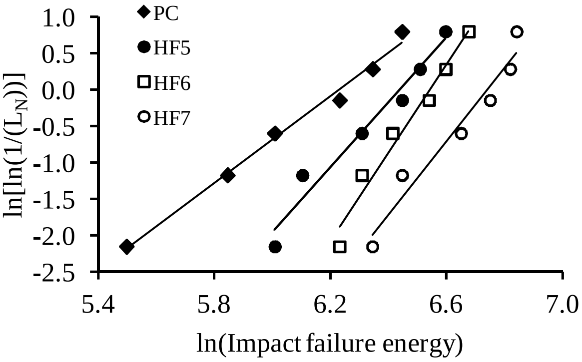

Figure 6 Linear regression of Impact failure energy in the Weibull distribution

The slope of the line for PC, CF2, CF3, CF4, HF5, HF6 and HF7 was 2.98, 6.39, 6.057, 5.138, 4.47, 6.04 and 5.05 respectively, which corresponds to the value of the shape parameter α, which was obtained from Figures 5 and 6. When the shape parameter ranges from $\alpha<1.0$, $\alpha=0$ and $\alpha>1.0$, it indicates that the material has a decreasing, constant and increasing failure rate respectively. The *u* value for PC, CF2, CF3, CF4, HF5, HF6 and HF7 was computed as u= 507.70, 554.60, 654.19, 782.21, 626.26, 694.83 and 846.60 respectively, using the points at which the line intersects the Y axis (-18.59, -40.38, -39.27, -34.23, -28.76, -39.55 and -34.05, respectively). Therefore, α indicates, an increasing failure rate of the material for every unit of increase in Impact failure energy. Based on this theoretical property, the reliability value of 0.368 is obtained from Eq. (8). Therefore, 36.8% of the tested PC and FRC specimens have an Impact failure energy value of at least 108.67, 270.01, 306.11, 319.52, 223.57, 324.59 and 340.53kN mm, respectively.

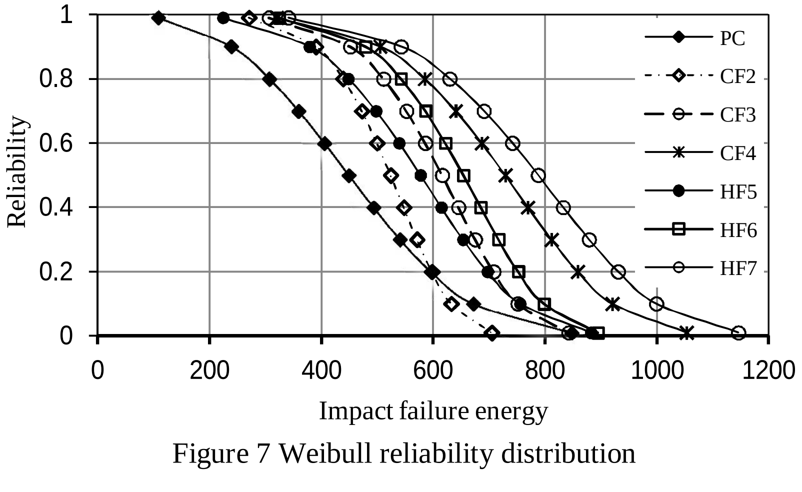

Figure 7 Weibull reliability distribution

The plot of reliability, also known as the probability of survival versus the Impact failure energy is shown in Figure 7. The 0.99 reliability in Figure 7 shows the Impact failure energy values of PC, CF2, CF3, CF4, HF5, HF6 and HF7 at failure stage that were approximately equal to 108, 223, 325, 340, 270, 306, 319 kN mm, respectively which offers a high reliability rate. In other words, the 0.9 reliability level was considered and value 0.9 was substituted in Eq. (9). The corresponding impact energy values for PC, CF2, CF3, CF4, HF5, HF6 and HF7 were 239, 378, 478, 542, 390, 451, 505 kN mm respectively. As the reliability curve of the plain concrete (PC) and FRC predicts accurately the experimental values, the additional costs involved to conduct further experiments can be avoided.

Subsequently, the regression coefficients about α, $\alpha \ln b$ and the correlation coefficient R^2 can be obtained by linear analysis, respectively. The regression coefficients about α, $\alpha \ln b$ and the correlation coefficient R^2 corresponding to seven types of concrete samples are demonstrated in Table 3.

Table 3 Linear regression coefficients of impact resistance in the Weibull distribution

Concrete type	Regression coefficient, α	Regression coefficient, $\alpha \ln b$	Correlation coefficient, R^2
PC	2.98	18.59	0.990
CF2	6.39	40.38	0.969
CF3	6.05	39.27	0.992
CF4	5.13	34.23	0.976
HF5	4.46	28.76	0.964
HF6	6.04	39.55	0.967
HF7	5.05	34.05	0.951

As an example, the test results of Mohammadi et al. (2008) for a different volume fraction of steel fibres are also reinvestigated numerically by using the same linear analysis and given in Table 4, and the regression coefficients of α, α ln b and the correlation coefficient R^2 corresponding to the test results of Mohammadi et al. (2008) are listed in Table 5.

From the above discussion, it can be seen that a linear relationship exists well between $\ln[\ln(1/L_N)]$ and ln Impact failure energy. This demonstrates that the two-parameter Weibull distribution is a reasonable analysis tool for the description of the impact failure energy.

Table 4 Drop-weight test results of Mohammadi *et al.*, (2008)

Specimen No.	Impact failure energy for 0.5% volume fraction of fiber $Vf_{0.5}$	Impact failure energy for 0.5% volume fraction of fiber $Vf_{1.0}$
1	609.20	685.4
2	647.30	761.6
3	723.50	856.8
4	742.50	875.8
5	761.60	952.0
6	856.80	1047.1
7	-	1085.2

Table 5 Linear regression coefficients of impact resistance of Mohammadi et al. (2008) results in Weibull distribution

Concrete type	Regression coefficient, α	Regression coefficient, $\alpha \ln b$	Correlation coefficient, R^2
$Vf_{0.5}$	8.528	56.60	0.953
$Vf_{1.0}$	6.453	44.29	0.981

4. CONCLUSION

The Impact failure energy values of concrete, increased in both the cases, i.e., HF and CF when compared to PC and this increase in energy is slightly greater in case of HF when compared to CF. Furthermore, it can be concluded that the addition of steel fiber to concrete significantly increases its impact resistance.

The best performance of concrete under impact loading was given by concrete containing 1.5 % volume fraction of fiber followed by 1% and 0.5% respectively. Furthermore, the impact resistance also increased against the first visible crack and final failure; which meant the energy absorption capacity in concrete with fibers increased.

The study rejects the average experimental test results of Impact failure energy of FRC. In this respect, the Weibull distribution allows researchers to describe the Impact failure energy of a plain concrete (PC) and FRC in terms of its reliability function. Hence it enables researchers to present the necessary impact strength that minimizes the number of experiments to be conducted to find the probability of failure. The Impact failure energy of the seven types of concrete samples are proven to fit well within the two-parameter Weibull distribution indicated by the goodness-of-fit technique.

5. ACKNOWLEDGEMENT

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