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Impact Response and Strength Reliability of Green High Performance Fibre Reinforced Concrete Subjected to Freeze-thaw Cycles in NaCl Solution

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A drop-weight impact test was conducted to evaluate the impact resistance of Green High Performance Plain Concrete (GHPPC) and Green High Performance Fibre Reinforced Concrete (GHPFRC) subjected to freeze-thaw cycles in water containing 3.0 % NaCl solution. The green high performance concrete mixtures were prepared using 10 % of micro silica as cement replacement, 30 % of copper slag as fine aggregate replacement and hooked end steel fibres were incorporated at 1.0 % volume fraction. All the specimens were frozen and thawed for 25 cycles, following which the impact strength of the frozen and thawed specimens was determined. Due to the variations in impact test results, a reliability analysis was carried out using two parameter Weibull distribution and its Weibull parameters were determined using two methods viz., Energy pattern factor method (EFM) and Method of Moments (MOM). Furthermore, impact strength in terms of reliability was reported using the average value of Weibull parameters obtained from these two methods. The results revealed that impact resistance of GHPPC and GHPFRC specimens subjected to 25 cycles of freeze and thaw in water containing 3% NaCl solution was significantly reduced.

Keywords: green concrete, fibre, impact strength, Weibull parameter, reliability.

1. INTRODUCTION

Enhancing the impact resistances of the civil and/or military infrastructure has attracted the attention of researchers to a greater extent [1, 2]. Concrete is a brittle material (low ductility) and due to its low crack prevention capacity, depleted tensile strength; exhibits severe damage [3] when subjected to impact loading [4]. The low ductility of concrete has been overcome by using the techniques of addition of various types of fibres [5, 6], especially steel fibres into the concrete mixtures [7, 8]. Furthermore, adding fibres reduces the possibility of spalling and scabbing failures thereby improving its tensile strength [9], deformability [10], the crack and pore-bridging capacities of the concrete [11].

In cold regions, concrete structures are susceptible to freeze and thaw cycling due to significant seasonal variations of temperature and humidity, which can reduce its durability leading to cracks and structural deterioration [12]. This deterioration triggered by freeze-thawing can be of two different forms: internal destruction such as growth of internal cracks and disintegration; surface cracking [13] such as removal of small pieces of mortar within the surface region.

Usage of deicer salt to melt of prevent the ice formation has been identified to cause severe scaling damage on the surface of fibrous and non-fibrous concrete. The efficiency of concrete incorporating fibres in structural members is generally based on the mechanical properties of concrete [14]. Nevertheless, the resistance of concrete under frost has not yet been explored widely. Some of the earlier researches on the Fibre Reinforced Concrete (FRC) exposed to frost displayed dissimilar results owing to differences in constituting materials of concrete, several types of incorporating fibres and various test methods involved. However, the concrete incorporating short fibres of length 3 mm exhibited comparatively less damage. Also, the study carried out by Sun et al. [15] and Mu et al. [16] revealed that steel fibres of length 20 mm provided a greater resistance against the internal destruction of concrete under frost and this was assessed based on the differences in dynamic modulus of elasticity. A similar trend was noticed by Niu et al. [17] while using steel fibres of length 30 mm. Zhang et al., [18] investigated the flexural impact response of steel FRC exposed to 0, 100, 150, 200 freeze–thaw cycles in 3.0 % NaCl solution. The effect of freeze–thaw cycles on the final impact strength of steel FRC was significantly less. Also, for the freeze – thaw cycles not greater than 200, the variations in initial impact strength was smaller.

The effect on FRC due to low velocity impact has been focused in various experimental, numerical and analytical investigations [19 – 21] and some important results are obtained; though the FRC's long-term behaviour under freeze-thaw cycles was considered to be of major importance [22]. However, in practice, the combined effect of mechanical stress, physical and chemical attack leads to

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the deterioration of FRC. In general, the results obtained from distinct tests will be uncertain in nature and hence it becomes vital to study the properties of FRC subjected to the joint action of two or more deterioration mechanisms [23]. However, the scattered results of drop weight impact test owing to nonhomogeneous condition of the concrete visual identification of the first crack and failure; the applied load was a single point of impact which might befall either a hard particles of coarse aggregate or on a soft area of mortar; height of the drop hammer is difficult to control exactly due to the handmade process; the free falling of the drop hammer can be influenced by the initial hand triggered work, so the experimental result can be controlled by the man-made factors [24, 25]. Therefore, a statistical analysis is the best technique to analyse the variation in drop weight test. Thus, the impact responses of FRC subjected to 25 freeze – thaw cycles in 3.0 % NaCl solution were investigated experimentally and statistically in this paper.

2. EXPERIMENTAL PROGRAM

2.1. Materials

Ordinary portland cement 53 grade conforming to IS 12269-1987 [26], natural river sand conforming to zone II grading of IS: 383:1970 [27] with a specific gravity of 2.66, copper slag conforming to zone II, the chemical composition of copper slag and micro silica are presented in Table 1. Crushed granite coarse aggregate of specific gravity 2.72 with maximum size of 12 mm, hooked end steel fibres of length 30 mm and diameter 0.6 mm with an aspect ratio of 40. High commercial super plasticizer complast SP430 DIS Sulphonated napthalene formaldehyde, were used in this study.

2.2. Details of mixtures

In this research, two concrete mixes (plain concrete (PC) and FRC) were designed with water/cement ratio (W/C) of 0.34. The cement content of 410 kg/m^3 was replaced by 10 % of micro silica and fine aggregate was replaced by 30 % of copper slag. In addition, the concrete incorporated with hooked end steel fibres with 1.0 % volume fraction. Based on the optimized particle packing model, the developed green high performance concrete mixtures are listed in Table 2.

2.3. Mixing procedure and specimens

Initially, the cement with micro silica and fine aggregate with copper slag were mixed for 1 minute, and half of the mixing water and superplastizer were added to the mix and then it was mixed again for 2 minutes. Following the remaining water was added to the mix along with coarse aggregate and mixed for 5 minutes. Finally, fibres were added at 1.0 % to the mixture and the mixing was done for 5 minutes. From the mix, cylindrical discs of size 100 diameter and 50 mm height were prepared for the freeze and thaw test followed by impact tests after 28 days curing.

2.4. Freeze and thaw test

In this paper, PC and FRC specimens were subjected to 25 cycles of freezing and thawing in water containing 3 % NaCl solution in accordance with procedure suggested by ASTM C666 [28]. In single cycle, alternatively the temperature of the specimens was lowered from 4 ± 2 ºC to – 18 ± 2 ºC and again raised to 4 ± 2 ºC within 2.0 – 4.0 hours. For this test, tap water with 3 % NaCl solution (by weight) was used.

2.5. Impact test

The drop weight test was carried out by dropping a weight repeatedly on 100 mm diameter and 50 mm height cylindrical specimen based on modification recommended by ACI Committee 544 [29] as shown in Fig. 1. In this modified impact test, a 4.45 kg weight was dropped repeatedly from a 457 mm height on the top surface of the cylindrical specimens. For each specimen, the number of blows required to cause the failure was noted as failure strength.

Table 1. Chemical composition of micro silica and copper slag

Materials	SiO_2 %	CaO %	Al_2O_3 %	Fe_2O_3 %	CuO %	Na_2O %	TiO_2 %	K_2O %	Mn_2O_3 %	SO_3 %	Cl %	Other %
Copper Slag	25.84	0.15	0.22	68.59	1.2	0.58	0.41	0.28	0.22	0.11	0.018	-
Micro Silica	96	0.2	0.6	1.2	-	-	-	-	-	-	-	2

Table 2. Recipes of developed green high performance concrete

Mix No.	Series	W/C	W, kg/m^3	Cement, kg/m^3	Fine agg., kg/m^3	Coarse agg., kg/m^3	Micro silica, %	Copper slag, %	Volume fraction, V_f	Freeze and thaw, cycle	Sp, %
1	GHPPC	0.34	140	410	801	1130	10	30	-	-	0.6
2	GHPPC-FT	0.34	140	410	801	1130	10	30	-	25	0.6
3	GHPFRC	0.34	140	410	801	1130	10	30	1.0	-	1.0
4	GHPFRC-FT	0.34	140	410	801	1130	10	30	1.0	25	1.0

Fig. 1. Impact test device

3. RESULTS AND DISCUSSION

3.1. Impact strength

The impact strength results of sixteen specimens from each mix are presented in Table 3. Adding 1 % volume fraction of steel fibre to the green high performance fibre reinforced concrete (GHPFRC) increases its impact failure strength by 193 % when compared to green high performance plain concrete (GHPPC). Table 3 shows the comparison between impact failure energy of GHPPC and GHPFRC mixes before and after 25 freeze-thaw (FT) cycles. As observed from the Table 3, the impact failure strength gradually decreases after being exposed to freeze-thaw cycling.

Table 3. Impact strength of specimens under drop weight

S. No	Number of blows needed for failure			
	GHPPC	GHPPC-FT	GHPFRC	GHPFRC-FT
1	12	11	45	59
2	16	19	56	61
3	18	20	66	62
4	20	22	74	69
5	21	24	84	73
6	22	27	86	73
7	26	29	90	80
8	28	31	95	85
9	32	35	99	87
10	33	36	101	87
11	35	39	101	91
12	36	41	118	92
13	37	43	119	92
14	40	46	125	97
15	41	52	133	102
16	49	54	159	108
Mean	33	29	97	82
σ	12.36	10.40	29.56	14.98
σ – standard deviation				

The average number of blows required to cause failure was 33 and 97 in case of GHPPC and GHPFRC respectively, while, the average number of blows required to cause failure after its exposure to 25 freeze- thaw cycles in 3 % NaCl solution was 29 and 82 respectively. Therefore, the decrease in the impact failure strength of GHPPC and GHPFRC after 25 freeze-thaw cycles were 12 % and 15 % respectively. It was found that all the GHPPC specimens were broken into two pieces under impact load and hence experienced brittle failure. On the other hand, multiple cracks were observed in the case of GHPFRC specimens and it did not break into two pieces. Thus, it can be concluded that, by adding fibres in concrete, the failure mode was altered from a single large crack to multiple cracks, which reveals the valuable effects of fibre reinforced concrete when exposed to impact loading.

3.2. Statistical methods for determining the Weibull parameters

Several studies reported the large scatter in the drop weight test results [24, 25] and this may be attributed to the fact that drop weight test is influenced by handmade work and hence the test results would also be greatly influenced by man made errors. This leads to the necessity of employing statistical analyses for their safe utilization in design of structures. Table 3, shows that impact strength is a random variable and in order to evaluate the accurate impact strength of GHPPC and GHPFRC before and after freeze and thaw it is essential to analyse the results data, statistically. The Weibull distribution is broadly used in reliability studies; in recent years, several modifications have been developed which greatly enlarged the applications [30, 31]. Based on impact strength test results two parameter Weibull distribution can be defined as a probability density function F(N) as given:

$$F(N) = 1 - \exp[-(\tfrac{N}{\alpha})]^{\gamma}, \qquad (1)$$

where γ and α are the shape and scale parameters respectively and N is the impact strength (Number of blows causing failure). For determining the Weibull parameters two numerical methods has been used. The impact strength N_R in form of probability of survival (R) i.e, reliability.

$$N_R = \alpha(-\ln(R)^{\frac{1}{\gamma}}). \qquad (2)$$

3.2.1. Energy pattern factor method

The energy pattern factor method is related to the averaged data of impact strength and is defined by the following equations.

$$Epf = \frac{\overline{N^3}}{\overline{N}^3}; \qquad (3)$$

$$\gamma = 1 + \frac{3.69}{(Epf)^2}; \qquad (4)$$

$$\overline{N} = \alpha\Gamma(1 + 1/\gamma), \qquad (5)$$

where Epf is the energy pattern factor and the gamma function is defined by

$$\Gamma(x) = \int_0^{\infty} t^{x-1} \exp(-t)\, dt. \qquad (6)$$

3.2.2. Method of moments (MOM)

The dimensionless Weibull and scale parameters can be calculated as follows [40] and α is obtained from Eq. 5:

$$\gamma = \left(\frac{0.9874}{\frac{\sigma}{\overline{N}}}\right)^{-1.086}. \qquad (7)$$

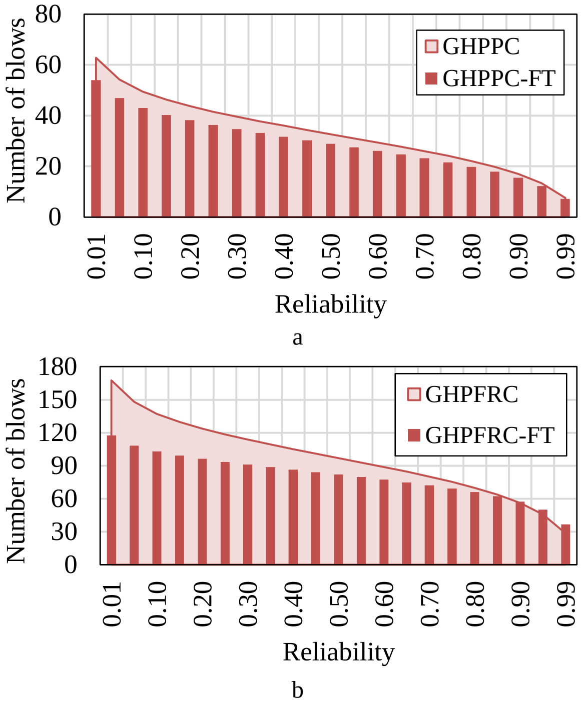

Fig. 2. Number of blows in terms of reliability: a – GHPPC and GHPPC-FT; b – GHPFRC and GHPFRC-FT

The Weibull parameter values estimated using two different statistical methods are presented in Table 4.

Table 4. Estimated Weibull parameters

Mix	Parameters	Methods		Average
		EFM	MOM	
GHPPC	γ	2.89	2.91	2.90
	α	37.11	37.11	37.11
GHPPC-FT	γ	2.99	3.06	3.03
	α	32.62	32.59	32.61
GHPFRC	γ	3.30	3.63	3.47
	α	108.07	107.59	107.83
GHPFRC-FT	γ	4.10	6.44	5.27
	α	90.91	84.87	87.89

The average value of Weibull parameter obtained from the two methods was used for reliability analysis. The number of blows required to cause failure in terms of reliability N_R is calculated by using Eq. 2 and the plot obtained for both GHPPC and GHPFRC is shown in Fig. 2. For example, at 0.90 reliability level the number of blows required cause failure of GHPPC, GHPPC-FT, GHPFRC and GHPFRC-FT specimens, in terms of reliability were 13, 12, 45 and 53 respectively. Similarly, at 0.50 reliability level the number of blows for causing failure of GHPPC, GHPPC-FT, GHPFRC and GHPFRC-FT specimens were 32, 28, 94 and 81 respectively. This method discards the assessment of average values of the experimental test results and in this respect, Weibull distribution enables the designers to safely choose the impact strength (Number of blows) values for design calculations for the desired reliability/probability of failure.

4. CONCLUSIONS

It is critical to choose the design values based on the drop weight test results owing to its lack of reliability and it might maximise the probability of failure. In this paper, a proficient, practical and enhanced method was employed to analyse the variations in drop weight test results using two different statistical methods of two parameter Weibull distribution and the impact strength was offered in terms of reliability. Experimental and statistical analysis has yielded the following conclusions;

1. The impact failure strength of GHPFRC increases by 193 % when compared to GHPPC.
2. When the concrete is exposed to 25 cycles of freeze-thaw, the impact failure strength decreases by 12 % and 15 % in case of GHPPC and GHPFRC respectively. The number of blows required to cause failure at 0.90 reliability level were 13, 12, 45 and 53 for the mixes GHPPC, GHPPC-FT, GHPFRC and GHPFRC-FT respectively.
3. These statistical methods prove to be very effective in determining the impact strength values accurately. Also, this method discards the assessment of average values of the experimental test results and in this respect Weibull distribution enables the designers to safely choose the impact strength (Number of blows) value for design calculation in terms of a reliability function.

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