STATISTICAL SCRUTINY OF VARIATIONS IN IMPACT STRENGTH OF GREEN HIGH PERFORMANCE FIBRE REINFORCED CONCRETE SUBJECTED TO DROP WEIGHT TEST

G. MURALI[1] *, K. KARTHIKEYAN[2] , M.K. HARIDHARAN[3]
[1]*School of Civil Engineering, Sastra Deemed University, Thanjavur, India*
[2]*SMBS, VIT Deemed University, Chennai, Tamil Nadu, India.*
[3]*Department of Civil Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India*

In this paper, the impact strength of four concrete mixtures namely green high performance plain concrete (GHPPC), green high performance and steel fibre reinforced concrete (GHPSFRC) subjected to drop weight test was statistically investigated. The steel was incorporated each at a dosage of 0.5%. The pre-determined green concrete mixtures were prepared with 2% of nano silica as cement replacement and 30% of copper slag as fine aggregate replacement. From each type, 40 specimens were tested using the drop weight test in accordance with procedure proposed by ACI Committee 544 and their impact strength was determined. Results showed that the distribution of impact strength of GHPPC and GHPSFRC were approximately normal. The minimum number of tests necessary for attaining the impact failure strength of, GHPPC and GHPSFRC specimens were found to be 57 and 41 respectively at 95% level of confidence with an error below 10%.

Keywords: *Statistical analysis, First crack strength, Failure strength, Fibres, Steel*

1. Introduction

The concrete industry stands in third position among the world-wide industrial sector in largest CO_2 emission [1]. It is well recognized that for every year the world currently produces nearly 3.6 billion metric tonnes of portland cement [2, 3], accounts for approximately 7% of the global anthropogenic CO_2 emissions [4, 5]. By the year 2030, the volume of portland cement production is predicted to increase beyond 5 billion metric tonnes [6, 7]. The present rate of release of this CO_2 emission into the atmosphere poses a serious threat to future life and growth on the planet. The evolution of green high performance concrete (GHPC) consisting of recycled materials and industrial by-product waste materials such as silica fume, fly ash and ground granulated blast furnace slag, etc decreased the consumption of raw materials, reduced environmental load [8-10] along with enhancement of mechanical properties and durability of concrete [11-16].

Several studies [17-20] have reported the material and structural behaviors of GHPC under a static loading condition. Unfortunately, current understanding of the structural behavior of green high performance fibre reinforced concrete under impact loading is insufficient [1, 21], compared to that under static loading conditions [21, 22]. Several researchers have widely used the ACI committee 544 [23] drop weight test method to evaluate the impact resistance of fibre reinforced concrete [24-28] However, large variations occurred in the experimental results of the ACI impact test as reported in the previous studies [29-33]. The source of these large variations in results may be imputed to the following reasons [29, 30]: (1) The assessment of the first crack that appears in the test is by visual identification and it may occur in any direction. (2) The impact strength of concrete depends upon on that single point of impact that may occur either on a hard particle of coarse aggregate, or on a soft area of mortar. (3) Concrete is a heterogeneous material. The change in mix design may result in change of its impact strength, including the type and shape of aggregate, shape of the fibre, distribution of fibres, etc. (4) As the drop weight test is a handmade process, it is difficult to control exactly the height of fall. (5) The subjectivity of initial hand actuated work on the free fall of the drop weight, makes the experimental result to be influenced by the man-made factors. (6) Lack of standards for test specimens preparation lets the cut or smooth mould-faced surfaces to be tested, that accounts for the source of variability. (7) Absence of standards for accepted or rejected failure mode. In the regard of features of the experimental results of impact test, statistical analysis technique is ought to be the best option for elucidating the test result. Thus, the response of concrete under impact load needs to be statistically investigated, and an appropriate analytical model needs to be developed for practical applications.

In this study, the variations in experimental impact test results of GHPPC and GHPSFRC were

* Autor corespondent/*Corresponding author*,
E-mail: murali_220984@yahoo.co.in

statistically investigated. For this purpose, two mixtures (GHPPC and GHPSFRC) were fabricated and tested using a drop-weight impact test machine. The main goals achieved in this study include:

1. Normality test was performed for the first crack and failure strength using the distribution plot, normal probability plot and its accuracy was verified with Kolmogorov-Smirnov test.
2. The regression technique, linear relationships between the first crack and failure strengths were proposed.
3. Validation of the performance of each model.
4. The minimum number of tests to be carried out to reliably measure the impact strength has been suggested.

2. Experimental program

2.1. Cement

The ordinary portland cement of 53 grade conforming to IS 12269-1987 [34] was used, with a specific gravity of 3.15. The chemical properties of cement are listed in Table 1.

2.2. Fine and coarse aggregates

The natural siliceous river sand conforming to zone II grading of IS 383-1970 [35] was used as fine aggregate. The fine aggregate is characterized with a bulk density of 1781 kg/m^3 and specific gravity of 2.64. The coarse aggregate used was crushed granite gravel with a nominal size of 12.5 mm and a specific gravity of 2.71.

2.3. Fibres

Two different fibres were used in this study each at a dosage of 0.5%. The hooked end steel fibres were 50 mm in length and 1.0 mm in diameter with an aspect ratio of 50 and had a tensile strength of 1050 MPa.

2.4. Superplasticizer

Sulphonated naphthalene polymer based superplasticizer (SP) conplast 430 conforming to IS 9103-1999 [36] with a specific gravity of 1.20 at 30°C was used to obtain a nominal target slump value of 70 ± 5 mm.

2.5. Nano silica

The colloidal nano silica solution was used in this study as partial substitution for cement. The particle size varied from 5 to 40 nm, pH value was 9.5 at 20°C, active nano SiO_2 content was 41% and the specific gravity was 1.3.

2.6. Copper slag

In this study, copper slag conforming to zone II was used with a fineness modulus of 3.39, bulk density of 2180 kg/m^3 and specific gravity of 3.91. Table 1, presents the chemical composition of copper slag.

2.7. Mix proportions

The M60 grade of concrete was adopted as per ACI-2008 [37] method of mix proportioning. Four concrete mixtures namely GHPPC and GHPSFRC were prepared by incorporating steel fibres, each at a dosage of 0.5%. The pre-determined green concrete mixtures were prepared with nano silica as 2% of cement replacement and copper slag as 30% of fine aggregate replacement. Based on the optimized particle-packing model, the developed GHPC mixtures are shown in Table 2.

2.8. Mixing procedure and specimen moulding

In the beginning, the fine aggregate, coarse aggregate, copper slag and cement were mixed in the dry state for 2 minute, following which half of the water that is premixed with colloidal nanosilica and superplatizer was added to the mixture and it was mixed for 2 minutes. The remaining water was then added to the mixture, after which mixing was done for 1minute and mix was kept at rest for 1 minute to allow the superplasticizer to react for achieving better workability. Finally, fibres were added in the proportions of 0.5% to the mixture that was mixed for 2 minutes for preventing loss of slump and attaining the homogeneous mix. Each mixture of freshly mixed concrete was then cast into cylindrical discs 150 mm Φ x 64 mm and was used for the impact test.

Table 1

Chemical characteristics of cement and copper slag

Constituents	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	Na_2O (%)	LOI (%)	IR (%)	SO_3 (%)	K_2O (%)
Cement	63.85	21.53	5.39	4.24	1.01	0.11	0.68	0.53	1.02	-
Copper slag	0.15	25.81	0.22	68.30	-	0.60	6.57	14.82	0.12	0.27

Table 2

Recipes of developed green high performance concrete

Mix No	W/B	Water (Kg/m^3)	Cement (Kg/m^3)	Fine Agg. (Kg/m^3)	Coarse Agg. (Kg/m^3)	CS (Kg/m^3)	NS (Kg/m^3)	Fibre dosage (%)	Weight (Kg/m^3)	Fibre Type	Sp (%)	Slump (cm)
1	0.32	171.21	525.56	484.05	1113.84	121.01	16.26	0	0	-	0.5	6.5
2	0.32	171.21	525.56	484.05	1113.84	121.01	16.26	0.5	39	SF	1.4	7.5

CS: Copper slag, NS: Nano silica, Sp: Superplasticizer, SF: Steel fibre

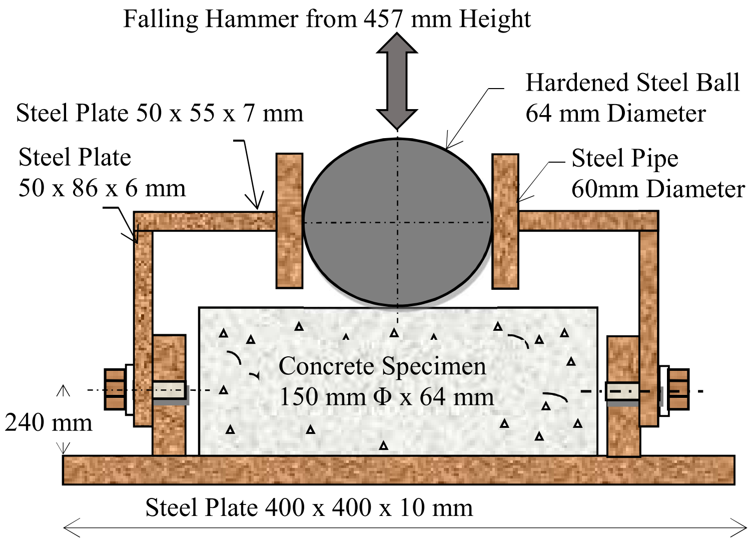

Fig.1- Drop weight impact test device used in this study.

Table 3

Impact resistance test results for GHPPC

Specimen No	First crack strength (blows)	Failure strength (blows)	INPB (blows)	Specimen No	First crack strength (blows)	Failure strength (blows)	INPB (blows)
1	68	75	7	21	268	278	10
2	155	167	12	22	309	315	6
3	51	53	2	23	128	132	4
4	95	100	5	24	168	179	11
5	77	94	17	25	202	220	18
6	213	217	4	26	177	186	9
7	58	69	11	27	233	245	12
8	174	183	9	28	337	350	13
9	68	78	10	29	108	121	13
10	144	153	9	30	73	88	15
11	144	158	14	31	248	260	12
12	303	326	23	32	163	170	7
13	204	218	14	33	147	158	11
14	82	86	4	34	138	145	7
15	115	125	10	35	264	276	12
16	224	233	9	36	178	185	7
17	115	124	9	37	132	142	10
18	348	357	9	38	96	107	11
19	88	96	8	39	257	266	9
20	151	162	11	40	189	194	5

2.9. Test procedures

A drop weight test was conducted by dropping a hammer on 150 mm diameter and 64 mm height cylindrical specimen based on the procedure suggested by ACI Committee 544. In this test, a 4.45 kg drop hammer was released repeatedly from a height of 457 mm on 64 mm steel ball that was placed on the centre of the top surface of the cylindrical specimen as shown Fig 1. For each specimen, the number of blows required to cause the first visible crack and failure was noticed.

3. Results and discussions

3.1. Statistical analysis

The first crack strength, failure strength of the GHPPC and GHPSFRC specimens are given in Tables 3, 4. In view of the results variability exhibited in Tables 3, 4, the results were evaluated statistically, as shown in Table 5. A statistical technique namely Kolmogorov–Smirnov (K–S test) was applied to the impact strength results.

3.2. Green high performance plain concrete

The impact test results for GHPPC specimens reported that the first crack and failure strength were in the range of 51-348 blows and 53-357 blows respectively as shown in Table 3. From Table 5, it can be observed that the mean, standard deviation, standard error of mean and the coefficient of variation corresponding to first crack strength are 167 blows, 80 blows, 13 blows and 48% respectively and for the failure strength these

Table 4

Impact resistance test results for GHPSFRC.

Specimen No	First crack strength (blows)	Failure strength (blows)	INPB (blows)	Specimen No	First crack strength (blows)	Failure strength (blows)	INPB (blows)
1	80	99	19	21	304	354	50
2	129	155	26	22	367	401	34
3	194	235	41	23	255	298	43
4	162	180	18	24	207	261	54
5	95	112	17	25	324	385	61
6	276	305	29	26	138	148	10
7	178	201	23	27	88	121	33
8	237	263	26	28	186	208	22
9	108	150	42	29	380	407	27
10	340	375	35	30	168	195	27
11	204	229	25	31	402	435	33
12	248	284	36	32	157	185	28
13	301	345	44	33	297	327	30
14	114	156	42	34	108	143	35
15	100	143	43	35	164	189	25
16	192	222	30	36	145	167	22
17	226	265	39	37	358	391	33
18	157	198	41	38	146	182	36
19	220	275	55	39	102	146	44
20	127	154	27	40	284	309	25

Table 5

Statistical analysis for impact strength of specimens.

Mixture	First crack and failure strength	Min	Max	Mean (blows)	SD (blows)	COV (%)	SEM (blows)	95% Confidence interval (blows)		p-Value of K–S test
								Upper bound	Lower bound	
GHPC	First crack	51	348	167	80	48	13	193	142	0.200
	Failure	53	357	177	81	46	13	203	151	0.200
GHPSFRC	First crack	80	402	207	91	44	14	236	178	0.198
	Failure	99	435	240	94	39	15	270	210	0.061

SD: Standard deviation, COV: Coefficient of variation, SEM: Standard error of mean,

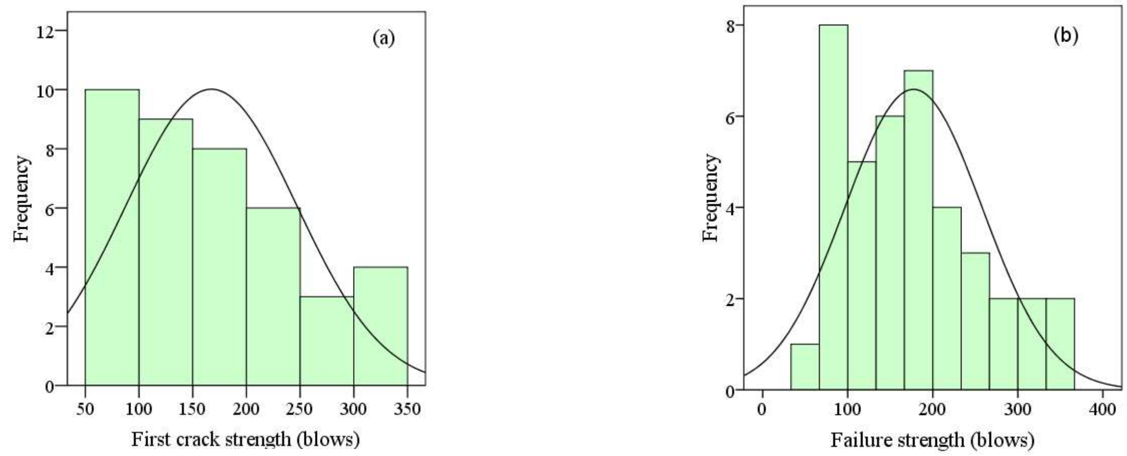

Fig. 2 - Distribution plots for GHPPC: (a) first crack strength and (b) failure strength

statistical parameters were 177 blows, 81 blows, 13 blows and 46% respectively. It is clear that the higher values of mean in GHPPC specimens as compared to HPPC resulted in lower values of coefficient of variation. The 95% confidence interval on the mean for the first crack and failure strength were 142-193 blows and 151-203 blows respectively, which suggests that there is a 95% probability that the correct estimated mean is within the interval range of 142-193 blows for first crack strength and 151-203 blows for failure strength. In Figure 2, the fitted normal curve approximately had a normal distribution for the first crack and failure strength. The normal probability plot (Fig 3), indicates that the data point are very close to straight line that shows almost a linear pattern. The distribution of first crack and failure strength of GHPPC was approximately normal and the

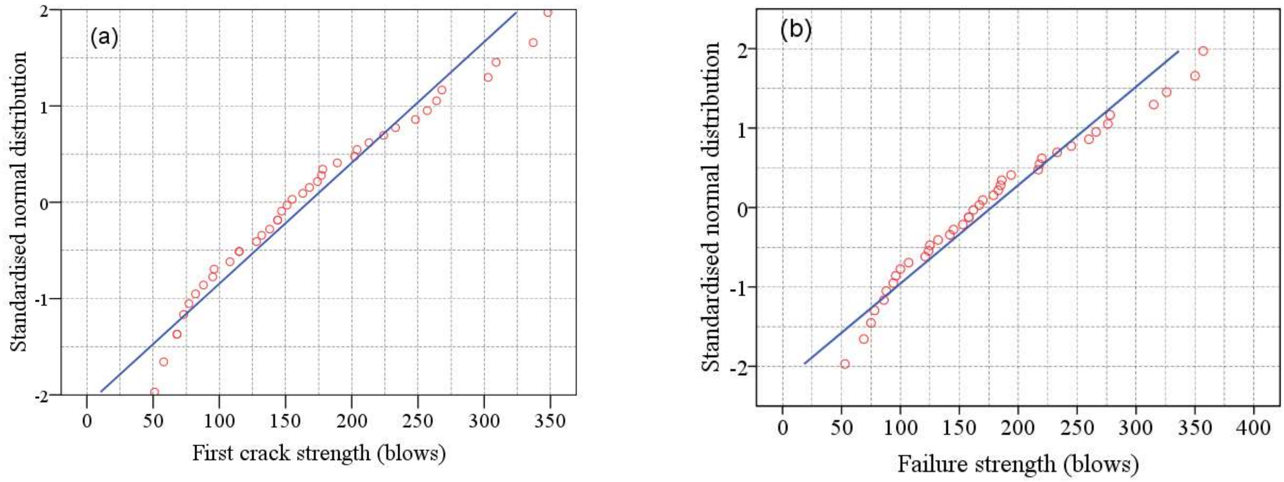

Fig. 3 - Normal probability plots for GHPPC: (a) first crack strength and (b) failure strength.

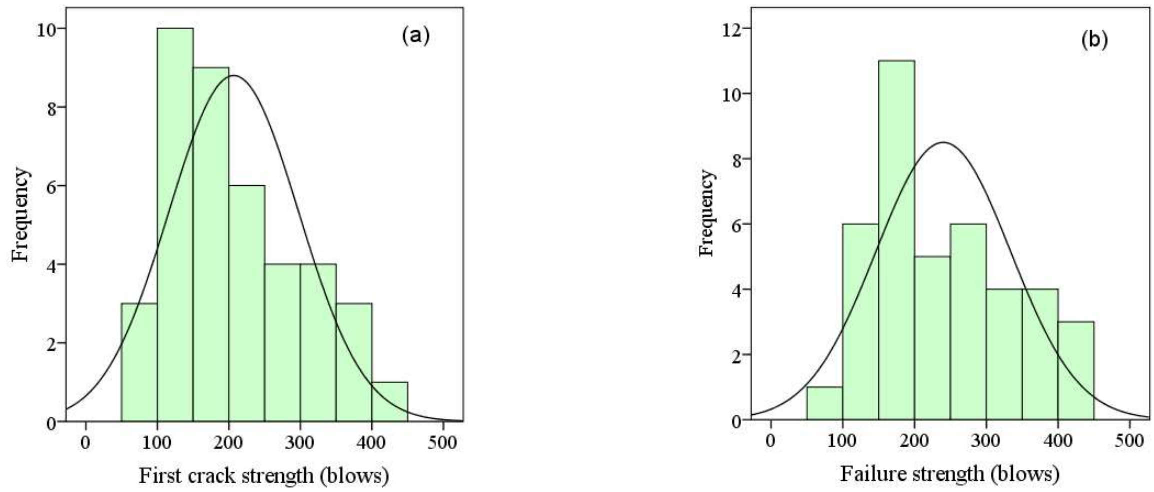

Fig. 4 - Distribution plots for GHPSFRC: (a) first crack strength and (b) failure strength.

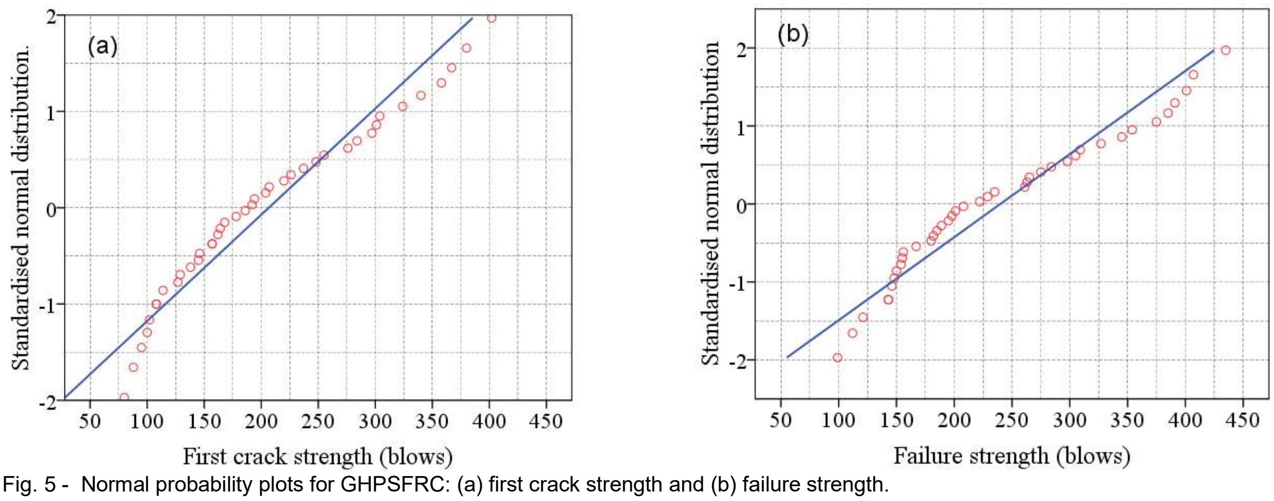

Fig. 5 - Normal probability plots for GHPSFRC: (a) first crack strength and (b) failure strength.

corresponding p-values from K-S test were 0.2 and 0.2 respectively, which was much higher than the confidence level α=0.05.

3.3. Green high performance steel fibre reinforced concrete

Table 4, presents the impact strength at first crack and failure of the GHPSFRC specimens. The first-crack strength of GHPSFRC ranged from 80 to 402 blows and their failure strength ranged from 99 to 435 blows. The statistical properties such as mean, standard deviation, standard error of mean and the coefficient of variation for the first-crack strengths of GHPSFRC specimens were 207 blows, 91 blows 14 blows and 44% respectively and for failure strength these statistical parameters were 240 blows, 94 blows, 15 blows and 39% respectively. The mean at 95% confidence interval

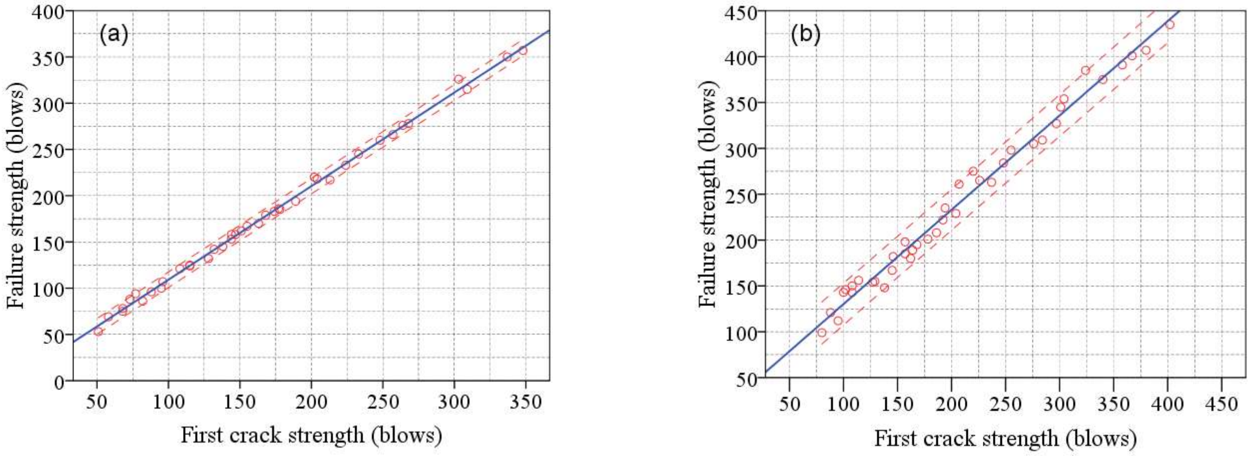

Fig. 6 - Scatter diagram of impact data with fitted regression line and 95% prediction intervals: (a) GHPPC (b) GHPSFRC.

were 178-236 blows at first crack strength and 210-270 blows at failure strength. Figure 4, discloses that the first crack and failure strength of GHPSFRC specimens barely follows the normal distribution. This support recognized from the normal probability plot in Figure 5, carrying pronounced linearity, and corresponding K-S test p-value was 0.198 for first crack strength and 0.061 for failure strength.

3.4. Failure strength predictions

The regression analysis was carried out based on impact test results. The strong linear relationship was obtained between the first crack strength and failure strength for GHPPC and GHPSFRC specimens, with the correlation coefficient (R) values hitting 0.998 and 0.992 respectively. The positive linear relationship between the first crack and failure strengths were described using the linear regression model as follows.

$$N_{(failure)} = 1.011 \times N_{(first\ crack)} + 8.005 \quad \text{for GHPPC} \qquad (1)$$

$$N_{(failure)} = 1.028 \times N_{(first\ crack)} + 27.380 \quad \text{for GHPSFRC} \qquad (2)$$

Where $N_{(failure)}$ is the failure strength predicted from the first crack strength ($N_{(first\ crack)}$) which is experimentally measured. Therefore, the equations derived from regression analysis may effectively be used to represent the relationship between the first crack and failure strengths of GHPPC and GHPSFRC specimens at 95% prediction interval along with the fitted regression model graphically, as shown in Figure 6. The obtained coefficients of determination (R^2) from the equations (1)-(2) were 0.997 and 0.986 respectively. The model that possessed the coefficient of determination value higher than 0.7 was considered as reasonable by most statisticians [38]. According to [39], the validity of appropriate model was also based on the values of correlation coefficient (R) and determination coefficient (R^2). However, the value of R and R^2 alone cannot validate the predicted model [40] and these results have to be combined with root mean squared error (RMSE), mean absolute percentage error (MAPE), mean absolute deviation (MAD) and Relative Root Mean Square Error (RRMSE) to evaluate their accuracy.

Root Mean Squared Error (RMSE) denotes the square root value of the average of the residual squares and it can be determined from equation (3). If RMSE value is nearer to zero it indicates, a good fit [41]. The obtained RMSE values from the regression models were 0.820 and 0.521 for the mixtures GHPPC, and GHPSFRC respectively.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(N_m - N_p)^2} \qquad (3)$$

The MAPE is the average of the absolute percentage error and MAD is the mean absolute deviation that is calculated as follows equations (4)-(5):

$$\mathrm{MAPE} = \left(\frac{1}{n}\sum_{i=1}^{n}\left|\frac{N_m - N_p}{N_m}\right|\right) \times 100\% \qquad (4)$$

$$\mathrm{MAD} = \frac{\sum|N_m - N_p|}{n} \qquad (5)$$

The RRMSE is obtained by dividing the RMSE to the average of loss of flexural strength obtained from E_V as given by the equation (6) [42].

$$\mathrm{RRMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(N_m - N_p)}}{\frac{1}{n}\sum_{i=1}^{n}N_m} \qquad (6)$$

Different ranges of RRMSE can be well-defined to indicate the models' accuracy as [43, 44]: Excellent for RRMSE less than 10%; good for RRMSE value range of 10% to 20%; fair for RRMSE value range of 20% to 30% and poor for RRMSE value greater than 30%.

Where N_m and N_p are the measured and predicted failure strength respectively and 'n' is the number of specimens tested in drop-weight test. The validation of RMSE, MAPE, MAD, RRMSE and R^2 for the predicted model is presented in Table 6. It can be seen that the GHPPC and GHPSFRC specimens shows relatively lower values of RMSE, MAD, MAPE and RRMSE which is close to zero and

Table 6

Regression analysis results for different mixtures

Accuracy measures	GHPPC	GHPSFRC
RMSE	0.820	0.521
MAPE	0.130	0.082
MAD	0.002	0.001
RRMSE	0.002	0.001
R^2	0.997	0.986

Table 7

Number of sample as a function of percent error in average

Error (e %)	Number of samples to be tested at 95% level of confidence		Number of samples to be tested at 90% level of confidence	
	GHPPC	GHPSFRC	GHPPC	GHPSFRC
10	57	41	35	25
15	25	18	15	11
20	14	10	9	6
25	9	7	6	4
30	6	5	4	3
35	5	3	3	2
40	4	3	2	2
45	3	2	2	1
50	2	2	1	1

highest values of R^2 nearer to 1 which indicates a good fit. In other words, the failure strength prediction from the proposed model for the GHPPC and GHPSFRC specimens achieved higher accuracy.

3.5. Minimum number of replications

The coefficient of variation for GHPPC and GHPSFRC specimens is presented in Table 7 which can also be used for other important practical applications. Swamy and Stavridis [45] displayed that coefficient of variation value can be used to determine the minimum number of tests 'n' as given in equation (7).

$$n=\frac{t^2v^2}{e^2} \quad (7)$$

Where 'n' is nothing but the compulsory number of tests to be carried out in order to guarantee the measured average value, in terms of percentage error, below a specified limit 'e' at a particular level of confidence. The 'v' is coefficient of variation and 't' is the specified level of confidence which is also dependent on the degree of freedom (related to number of tests). For large sample sizes with 95 and 90% levels of confidence, the *'t'* approaches 1.645 and 1.282 respectively [46, 47]. Considering the 95% and 90% levels of confidence, the number of samples needed to hold the error under various limits between 10% and 50% is shown in Table 7. If the error is to be kept under 10%, the minimum number of tests to be carried out for attaining the impact failure strength of GHPPC and GHPSFRC specimens should be 57 and 41 respectively at 95% level of confidence and 35 and 25 respectively at 90% level of confidence. In other words, if two samples are used for GHPPC and GHPSFRC at 95% levels of confidence, then the error in the measured value is about 50%.as shown in Table 7.

4. Conclusions

This article presents the assessment of statistical variations in impact strength of green high performance fibre reinforced concrete. From the results obtained the following conclusions are drawn:

1. The impact strength of GHPSFRC was superior over the GHPPC. The impact strength at first crack of GHPSFRC is 207 blows with a coefficient of variation of 44%, in comparison to 167 blows and 48% for GHPPC. The failure strength of GHPSFRC is 240 blows with a coefficient of variation of 39%, in comparison to 177 blows and 46% for GHPPC.

2. The impact strength results distribution at first crack and failure strengths of GHPPC and GHPSFRC were approximately normally distributed.

3. The validity of the proposed model for GHPPC and GHPSFRC specimens had lower values of RMSE, MAD, MAPE and RRMSE close to zero and highest values of R^2 nearer to 1 which indicates a good fit and higher accuracy.

4. In order to adopt this test as a standard method for evaluating the impact failure strength of GHPPC and GHPSFRC at 95% level of confidence with an error below 10%, the minimum number of tests to be carried out was found to be 57 and 41 respectively.

5. The results obtained from this procedure have large variations thereby reducing its accuracy. Hence, a better technique for testing the concrete against impact should be formulated.
6. The development of green concrete has reduced the environmental impact of CO_2 emissions from concrete production, along with a significant increase in its impact strength.

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