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Statistical variations in impact resistance of steel fiber-reinforced concrete subjected to drop weight test

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Abstract

The variation in impact resistance of steel fiber-reinforced concrete and plain concrete as determined from a drop weight test is reported. The observed coefficients of variation are about 57 and 46% for first-crack resistance and the ultimate resistance in the case of fiber concrete and the corresponding values for plain concrete are 54 and 51%, respectively. The goodness-of-fit test indicated poor fitness of the impact-resistance test results produced in this study to normal distribution at 95% level of confidence for both fiber-reinforced and plain concrete. However, the percentage increase in the number of blows from first crack to failure for both fiber-reinforced concrete and as well as plain concrete fit to normal distribution as indicated by the goodness-of-fit test. The coefficient of variation in percentage increase in the number of blows beyond first crack for fiber-reinforced concrete and plain concrete is 51.9 and 43.1%, respectively. Minimum number of tests required to reliably measure the properties of the material can be suggested based on the observed levels of variation. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Composite; Concrete; Fiber reinforcement; Impact test

Steel fiber-reinforced concrete (SFRC) is a composite material made of hydraulic cements, fine and coarse aggregate, and a dispersion of discontinuous, small steel fibers. It may also contain pozzolans and admixtures commonly used with conventional concrete [1]. The addition of steel fibers significantly improves many of the engineering properties of mortar and concrete, notably impact strength and toughness. Some examples of structural and nonstructural uses of SFRC are hydraulic structures, airport and highway paving and overlays, industrial floors, refractory concrete, bridge decks, shotcrete linings and coverings, and thin-shell structures [2,3]. In addition to static loads, many concrete structures are subjected to short duration dynamic loads. These loads originate from sources such as impact from missiles and projectiles, wind gusts, earthquakes, and machine dynamics. Many investigators have shown that addition of fibers greatly improves the energy absorption and cracking resistance of concrete. This energy absorption of SFRC is termed as toughness under impact.

1. Test methods

Impact resistance of SFRC can be measured using a number of different test methods [4]. Drop weight test is the simplest test for evaluating impact resistance. The test method cannot be used to determine basic properties of composites. Rather, the method is designed to obtain the relative performance of plain concrete and SFRC containing different types and volume fractions of fibers. The impact test equipment and procedure have been published in the ACI committee-544 report [5]. Standard equipment used for testing compaction of soil has been used [4,5]. The number of blows to first visible crack as well as to failure are recorded. Because of the nature of the impact test, especially because of the variability and nonhomogeneous condition of concrete, data from the impact test can be noticeably scattered, as reported by Schrader [5].

2. Statistical study

The impact strength of fiber reinforced composites is strongly influenced by the fabrication process, sampling, and testing. Geometry of the fiber in relation to the mould size will cause preferred orientation of the fibers near the surface of the mould, which is different from that in the

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Table 1
Chemical composition of the cement in percentage

SiO_2	CaO	Fe_2O_3	MgO	Al_2O_3	K_2O	Na_2O	Free lime
21.7	64.7	4.2	1.8	5.2	0.3	0.8	1.3

body of the composite. The concentrations and orientations within the mass of the composite depend on many factors such as the method of placing, flow characteristics of the green concrete, and the type and degree of compaction. Thus, there are a number of factors that tend to increase the statistical variations in the properties of fiber-reinforced cement composites when compared to those of the corresponding plain cementitious materials. The design of fiber-reinforced concrete elements should be based on statistical considerations of their properties.

2.1. Background

The factors contributing to the variation in the compressive strength of plain concrete and the number of test results required for determining the standard deviation of concrete strength are available in the literature [6–8]. Swamy and Stavrides [9] have reported a comparative statistical study on the compressive and flexural strengths of plain concrete and SFRC. However, no results are available on the impact resistance of SFRC. Soroushian et al. [10] have reported statistical variations in the mechanical properties of carbon fiber-reinforced cement composites. The flexural toughness and impact-resistance test data deviated from normal distribution at 95% level of confidence. The observed coefficient of variation in impact resistance is as high as 54.6% for carbon fiber concrete and no comparison with plain concrete is made.

The variations in mechanical properties should be considered in deciding the minimum number of tests required for measuring material properties or when selecting the required levels of material properties based on the levels of specified design.

3. Experimental programme

3.1. Objective

In the present study, an attempt has been made to study the impact strength of SFRC as determined from the drop weight test. This work is mainly concerned with the assessment of the variations in the impact properties of steel fiber-reinforced composite. The results are analyzed based on the statistical approach. Ultrasonic pulse velocity test was conducted to study the uniformity of composite, including fiber distribution.

3.2. Materials used

53 grade ordinary portland cement having a 28-day compressive strength of 57 N/mm^2 conforming to IS: 12269-1987 [11] was used. The chemical composition of the cement is shown in Table 1. 20 mm and lower granite aggregate, river sand conforming to zone IV of IS: 383-1970 [12], and potable water for mixing and curing were employed. 0.5% volume fraction of round crimped steel fibers of 0.5-mm diameter having a breaking strength of 550 MPa was used. The average length and aspect ratio of fibers were 27.5 mm and 55, respectively. M20 concrete designed based on the guidelines of IS: 10262-1982 [13] was used. The final proportions per cubic meter of concrete for both plain and fiber-reinforced concrete consists of 397 kg cement, 562 kg fine aggregate, and 1,152 kg coarse aggregate with a water/cement ratio of

Table 2
Test results for fiber-reinforced concrete (batch I)

Sl. no.	Average thickness at center (mm)	Transit time (μs)	Pulse velocity (m/s)	Mass (g)	Blows to first crack	Blows to failure	Percentage increase in number of blows
1	64	13.9	4604	2904	196	270	37.8
2	65	14.7	4422	2914	98	140	42.8
3	63	13.5	4667	2834	72	95	31.9
4	64	13.8	4638	2798	46	80	73.9
5	62	13.9	4460	2776	46	86	86.9
6	64	14.0	4571	2880	153	181	18.3
7	62	13.3	4662	2737	144	189	31.3
8	64	13.9	4604	2800	160	210	31.3
9	61	13.3	4586	2710	39	60	53.8
10	64	14.0	4571	2932	35	70	100.0
11	63	13.9	4532	2840	81	128	58.0
12	66	14.4	4583	2990	130	153	17.7
13	62	13.5	4593	2770	84	131	55.9
14	61	13.6	4485	2760	160	222	38.8
15	67	14.4	4653	3012	34	68	100.0
Mean (x)	63.5	13.87	4575	2844	98	139	51.9
S.D. (σ)	1.73	0.40	73	92	54	64	27.3
Coefficient of variation (σ/x)%	2.72	2.91	1.60	3.2	55.1	46.0	52.6

Table 3
Test results for 30 samples (batches I and II)

	Average thickness at center (mm)	Transit time (μs)	Pulse velocity (m/s)	Mass (g)	Blows to first crack	Blows to failure	Percentage increase in number of blows
Mean (x)	63.3	13.85	4573	2837	103	142	45.9
S.D. (σ)	1.67	0.46	85	98	59	66	23.8
Coefficient of variation (σ/x) %	2.64	3.32	1.86	3.5	57.3	46.5	51.9

0.49. The average compressive strength of plain and fiber concrete at 28 days were 29.4 and 36.0 N/mm^2, respectively.

3.3. Casting and testing

Twelve SFRC cylinders measuring 150 mm × 300 mm in two batches of six each were cast in moulds and well vibrated. The workability of plain concrete mix was 0.87 compacting factor with a slump of 36 mm. The slump of fiber-reinforced concrete was 20 mm. Though the slump value is less, the fiber concrete was compacted without any difficulty, indicating the fact that the slump is not a good measure of workability for SFRC. Care was exercised to ensure the uniform distribution of fibers so that balling of fibers can be avoided. First, the aggregates were put into the mixer and mixed for few minutes and then cement was added and mixed for 2 min during which about 50% volume of water were added. Next, the fibers were fed continuously for a few minutes and then the remaining water was added slowly. The whole mixing operation took about 8 min. From each batch, five cylinders were taken and cut with the help of diamond cutter to get three samples of 150-mm diameter and 64-mm thickness from each cylinder for an impact test. A total of 30 samples were tested. The number of blows required to cause the first crack on the surface and the number of blows to cause failure (ultimate failure as per definition) were determined. Similarly, for plain concrete, 12 cylinders were cast in two batches of six each. Three discs were cut from each cylinder. A total of 32 samples, 16 from each batch, were taken for the study.

Pulse velocity readings were taken at different points on the disc and the variation in pulse velocity was marginal, indicating the uniformity in compaction of the concrete. However, the pulse velocity presented in Tables 1–4 was measured at the center of the discs. Visual observation of the cut surface of the cylinder indicated the absence of balling and the uniform distribution of the fibers.

4. Results and discussions

4.1. SFRC

A total of 30 disc samples was considered in the case of fiber-reinforced concrete in two batches of 15 samples each. The results of batch I are presented in Table 2 and the results of batches I and II are combined and are presented in Table 3.

Table 4
Test results for plain concrete (batch I)

S1. no.	Average thickness at center (mm)	Transit time (μs)	Pulse velocity (m/s)	Mass (g)	Blows to first crack	Blows to failure	Percentage increase in number of blows
1	64	13.6	4706	2790	114	124	8.8
2	63.5	13.9	4568	2826	86	92	7.0
3	64	13.8	4638	2850	119	125	5.0
4	63	13.3	4737	2852	51	55	7.8
5	63.5	14.1	4410	2872	34	41	20.6
6	63.5	13.0	4885	2780	38	42	10.5
7	63	13.5	4667	2792	63	70	11.1
8	65.5	14.2	4613	2950	130	136	4.6
9	63	13.2	4773	2745	21	30	42.9[a]
10	62.5	13.7	4562	2800	60	62	3.3
11	65	14.5	4483	2862	43	51	18.6
12	63	13.0	4846	2690	79	83	5.1
13	63.5	13.8	4601	2864	38	44	15.8
14	64	14.0	4571	2800	90	96	6.7
15	62	13.4	4627	2814	48	56	16.7
16	63.5	13.6	4669	2818	120	130	8.3
Mean (x)	63.53	13.66	4647	2819	71	77	10.0
S.D. (σ)	0.87	0.43	124	59	35	36	5.5
Coefficient of variation (σ/x) %	1.37	3.15	2.67	2.09	49.3	46.7	55.0

[a] Not considered.

Table 5
Test results for 32 samples of plain concrete (batches I and II)

	Average thickness at center (mm)	Transit time (μs)	Pulse velocity (m/s)	Mass (g)	Blows to first crack	Blows to failure	Percentage increase in number of blows
Mean (x)	63.2	13.66	4630	2812	70	77	10.9
S.D. (σ)	0.97	0.43	116	63	36	39	4.7
Coefficient of variation (σ/x) %	1.53	3.15	2.51	2.24	53.7	50.6	43.12

4.2. Plain concrete

In this case a total of 32 samples were considered in two batches of 16 each. The results are presented in Tables 4 and 5.

4.3. Analysis of test results for fiber-reinforced concrete

From Tables 2 and 3, corresponding to first-crack strength, the sample mean for all 30 samples was 103 blows, and the standard deviation was 59 blows; the coefficient of variation was thus 57%. The standard error of mean was 11 blows. The 95% confidence interval about the mean is 81 to 125 blows, which indicates that there is a 95% probability that the correct estimate for the mean is obtained within the 81–125 blows interval. The 95% confidence interval for standard deviation is 47–79 blows.

The mean within the batches was 98 and 108 blows, and the corresponding standard deviations were 54 and 65 blows. The coefficients of variation were 55 and 60%, respectively. The Bartlett's test of hypothesis indicated that the variations in impact resistance within batches are not different from the variations between batches at 95% level of confidence. The goodness-of-fit (chi-square test) [14,15] test indicated poor fitness of the impact-resistance test results produced in this study to normal distribution at 95% level of confidence. Because of the large variations in impact-resistance test results, a larger sample size would be helpful in drawing more reliable conclusions regarding the normality of the distribution of impact test results.

Tables 2 and 3 also present the impact-resistance results for the 30 samples corresponding to failure. The sample mean for all 30 samples was 142 blows, and the standard deviation was 66 blows; the coefficient of variation was thus 46.5%. The standard error of mean was 12 blows. The 95% confidence interval about the mean is 118–166 blows. The 95% confidence interval for standard deviation is 53–89 blows.

The mean within the batches was 139 and 144 blows, and the corresponding standard deviations were 64 and 71 blows. The coefficients of variation were 46 and 49%, respectively. The goodness-of-fit test indicated poor fitness of the impact-resistance test results produced in this study to normal distribution at 95% level of confidence.

Percentage increase in the number of blows from first crack to failure was also presented in Tables 2 and 3. Since the addition of fibers has a significant effect on all properties of concrete, an attempt has been made to study the percentage increase in impact resistance beyond the first crack. Generally, the samples resisting fewer numbers of blows for the first crack have a higher percentage of increase in the number of blows. The sample mean for all 30 samples was 45.9%, and the standard deviation was 23.8%; the coefficient of variation was thus 51.9%. The standard error of mean was 4.4%. The 95% confidence interval about the mean is 36.8–54.9%. The 95% confidence interval for standard deviation is 19–32%.

However, it is interesting to note that the percentage increase in the number of blows beyond first crack fits better to normal distribution even though it departs a little from the theoretical normal distribution. The goodness-of-fit test

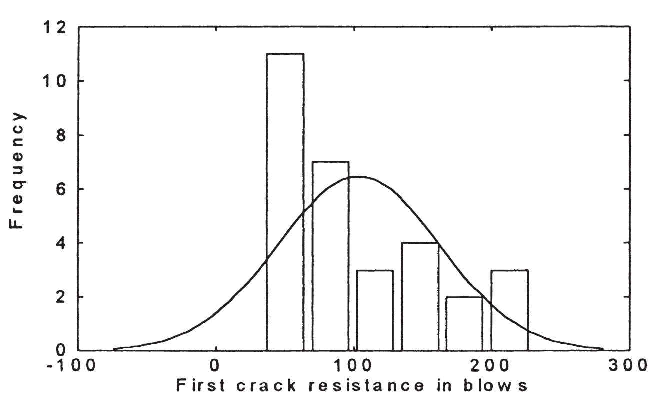

Fig. 1. Distribution of impact test results for first-crack resistance (SFRC).

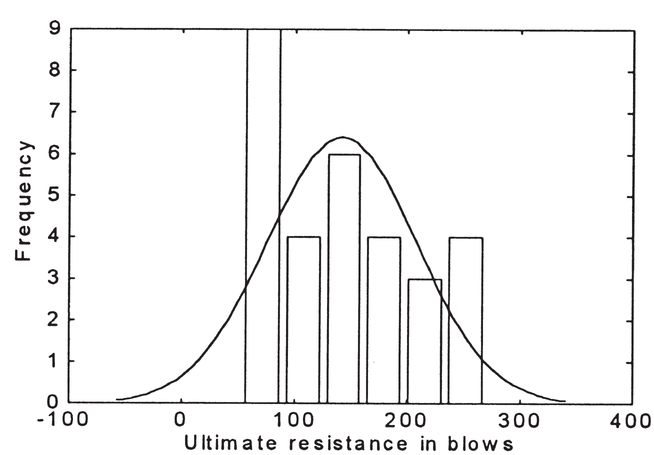

Fig. 2. Distribution of impact test results for ultimate resistance (SFRC).

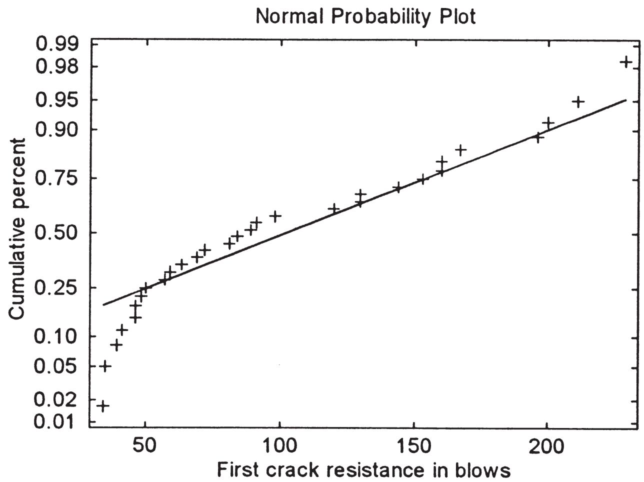

Fig. 3. Normal probability plot for first-crack resistance (SFRC).

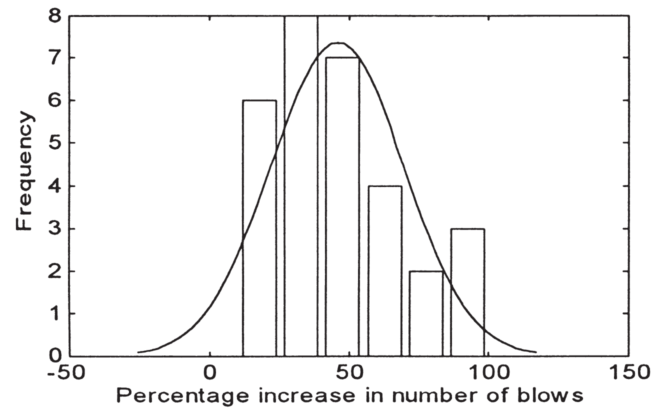

Fig. 5. Distribution of percentage increase in the number of blows beyond first crack (SFRC).

indicated good fitness of these results produced in this study to normal distribution at 95% level of confidence. The Bartlett's test of hypothesis and Cochran's test [14–16] indicated that the variances in percentage increase in the number of blows within batches are the same as the variances between batches at a 0.01 level of significance.

Figs. 1 and 2 show the scatter in the impact-resistance test results with the normal curve overlapping them. Figs. 3 and 4 present the normal probability curve, which is not close to a straight line, indicating rather poor normality of the distribution of the impact-resistance test results. Fig. 5 shows the scatter for percentage increase in the number of blows with the normal curve overlapping them and Fig. 6 presents the normal probability curve, which is close to a straight line, indicating the normality of the distribution of these results.

Variations in other results such as thickness, transit time, pulse velocity, and mass are marginal and are within acceptable limits.

4.3.1. Analysis of test results for plain concrete

Tables 4 and 5 present the impact-resistance test results for the 32 samples of plain concrete tested in this study. Corresponding to first-crack strength, the sample mean for all 32 samples was 70 blows, and the standard deviation was 36 blows; the coefficient of variation was thus 53.7%. The standard error of mean was 7 blows. The 95% confidence interval about the mean is 57–83 blows. The 95% confidence interval for standard deviation is 29–48 blows.

The mean within the batches was 71 and 69 blows, and the corresponding standard deviations were 35 and 39 blows. The coefficients of variation were 49.3 and 56.4%, respectively. The goodness-of-fit test indicated poor fitness of the impact-resistance test results produced in this study to normal distribution at 95% level of confidence. Because of the large variations in impact-resistance test results, a larger sample size would be helpful in drawing more reliable conclusions regarding the normality of the distribution of impact test results.

Tables 4 and 5 also present the impact-resistance results for the 32 samples corresponding to failure. The sample

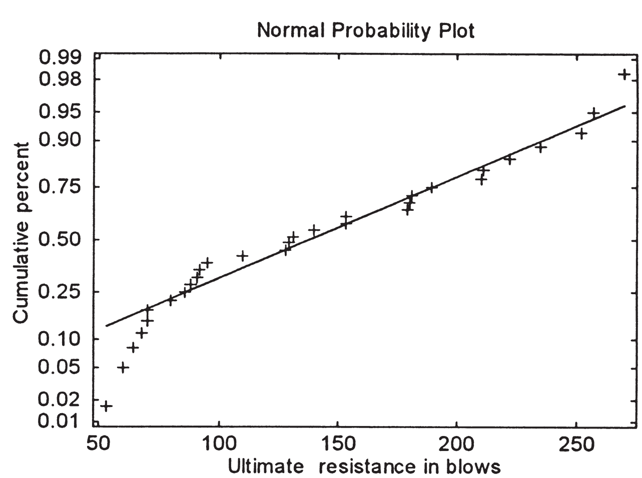

Fig. 4. Normal probability plot for ultimate failure (SFRC).

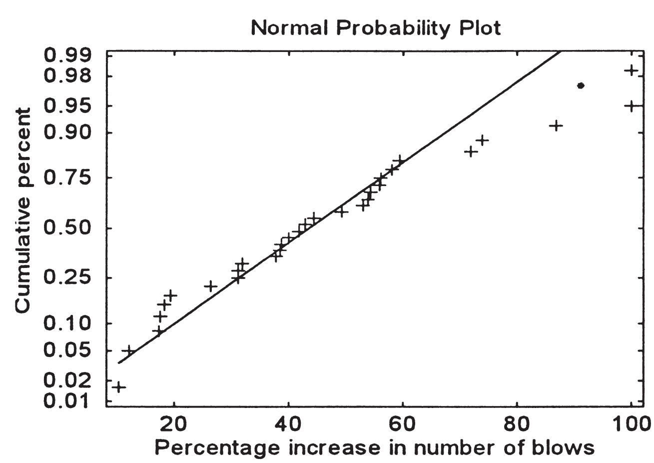

Fig. 6. Normal probability plot for percentage increase in the number of blows beyond first crack (SFRC).

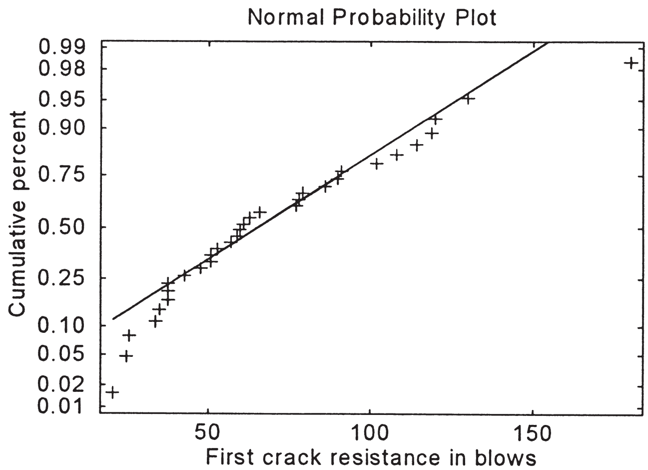

Fig. 7. Normal probability plot for first resistance (plain concrete).

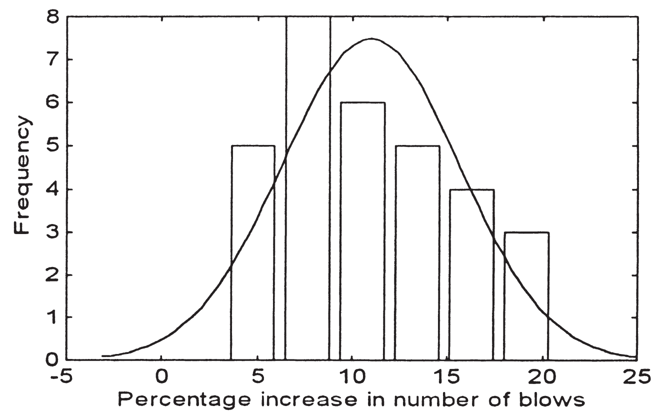

Fig. 9. Distribution of increase in the number of blows beyond first crack (plain concrete).

mean for all 32 samples was 77 blows, and the standard deviation was 39 blows; the coefficient of variation was thus 50.6%. The standard error of mean was 7 blows. The 95% confidence interval about the mean is 63–91 blows. The 95% confidence interval for standard deviation is 31–51 blows.

The mean within the batches was 77 blows for both batches, and the corresponding standard deviations were 36 and 43 blows. The coefficients of variation were 46.7 and 55.8%, respectively. The goodness-of-fit test indicated poor fitness of the impact-resistance test results produced in this study to normal distribution at 95% level of confidence. Because of the large variations in impact-resistance test results, a larger sample size would be helpful in drawing more reliable conclusions regarding the normality of the distribution of impact test results.

Figs. 7 and 8 show the normal probability curve, which is not close to a straight line, indicating poor normality of the distribution of the impact-resistance test results.

Plain concrete does not have considerable strength beyond the first crack. Once a visible crack appears on the surface, the specimen fails immediately with the addition of a few blows. However, this increase in additional blows varies from 2–24, showing an increase of about 3–20%. The corresponding mean, standard deviation, and coefficient of variation are 10.9, 4.7, and 43.1%, respectively. In this case also, the results fit to normal distribution at 95% level of confidence as indicated by the chi-square test. The normal probability curve is almost a straight line, indicating the normality of test results. However, in this analysis, 31 results are considered, eliminating one result, which is exceptionally high. The results are presented in Figs. 9 and 10. Variations in other results such as thickness, transit time, pulse velocity, and mass are marginal and are within acceptable limits.

Most of the plain concrete test results, such as compressive strength, flexural strength, etc., follow normal distribution as reported by earlier investigators [10]. However, the impact strength results do not follow normal distribution as observed in the present study.

4.3.2. Significance

The coefficient of variation presented in Tables 3 and 5 can be used to determine the minimum number of tests, *n*,

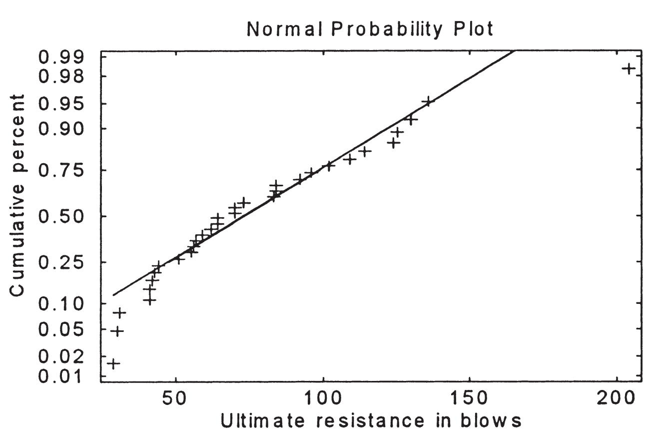

Fig. 8. Normal probability plot for ultimate failure (plain concrete).

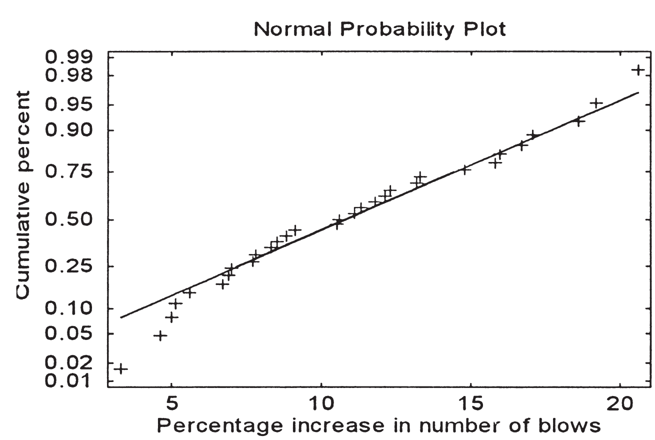

Fig. 10. Normal probability plot for increase in the number of blows beyond first crack (plain concrete).

Table 6
Number of sample as a function of percent error in average

Percent error in average	Number of samples to be tested
<5	143
<10	36
<15	16
<20	9
<25	6
<30	4
<35	3

required to assure that the percentage error in the average measured value is below a specified limit, *e*, at a certain level of confidence [9] [see Eq. (1)].

$$n = t^2 v^2 / e^2 \quad (1)$$

where *v* is the coefficient of variation and *t* is the value of student *t* distribution for the specified level of confidence. The value of *t* depends not only on the specified level of confidence but also on the degree of freedom (related to number of tests). For large sample sizes, *t* approaches 1.645 and 1.282 at 95 and 90% levels of confidence, respectively. From Eq. (1), it is clear that for SFRC impact resistance at ultimate failure, at 90% level of confidence, if the error in average measured value is to be kept below 15%, the minimum number of tests are 16 considering the coefficient of variation as 46.5%. In other words, if three samples are tested and the average is reported, then the error in average measured value is about 35%, as shown in Table 6.

5. Conclusions

Impact strength results as determined from drop weight test have large standard deviations, both for SFRC as well as plain concrete. The observed coefficients of variation are about 57 and 46% for first-crack resistance and the ultimate resistance in the case of SFRC and the corresponding values for plain concrete are 54 and 51% respectively. The goodness-of-fit (chi-square test) test indicated poor fitness of the impact-resistance test results produced in this study to normal distribution at 95% level of confidence for both fiber-reinforced and plain concrete. Because of large variations in impact-resistance test results, a larger sample size would be helpful in drawing more reliable conclusions regarding the normality of the distribution of impact test results. However, the postcrack resistance test results for both fiber-reinforced concrete as well as plain concrete fit to normal distribution as indicated by the goodness-of-fit test. The coefficient of variation in postcrack resistance for fiber-reinforced concrete and plain concrete is, respectively, 51.9 and 43.1%. Based on the observed levels of variation, suggestions can be made for the minimum number of tests to be considered to reliably measure the above properties.

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