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Statistical variations in impact resistance of polypropylene fibre-reinforced concrete

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Abstract

The impact resistance of polypropylene fibre-reinforced concrete (FRC) was investigated using the repeated drop-weight impact test recommended by ACI Committee 544. The results were analysed based on a statistical approach. The variation in results was examined within the same batch and between different batches. Statistical parameters were compared with reported variations in impact resistance of concrete composites reinforced with other types of fibres such as carbon and steel fibres. Statistical analysis indicated that the results obtained from this test had large variations and it is necessary to increase the number of replications to at least 40 specimens per concrete mix to assure an error below 10%. It is concluded that this test with its current procedures and recommendations should not be considered as a reliable impact test. This study has highlighted the need for modifying this test in such a way as to increase its accuracy and reduce the large variation in results.

Keywords: Fibres; Polypropylene; Statistical variation; Impact resistance

1. Introduction

The utilisation of fibre-reinforced concrete (FRC) in construction is rapidly expanding due to the potential economic and technical benefits. Most fibres which are added to concrete are man-

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made, and can be classified into two main categories: metallic (such as steel) or synthetic (such as polypropylene). Although steel fibres are dominant in the field of FRC, polypropylene fibres have proved to have a high efficiency in many practical applications [1–5].

Many deficiencies of plain concrete may be overcome by using polypropylene fibre reinforcement. Polypropylene fibres are capable of improving the ductility of concrete by enhancing properties such as its flexural toughness and impact resistance [6,7]. Polypropylene FRC has impact resistance that compares favourably with that observed in concretes made with many other commercially available fibres at higher dosage rates [8].

Several impact tests have been used to demonstrate the relative brittleness and impact resistance of concrete and similar construction materials [9–12]. However, none of these tests has been declared to be a standard test, at least in part due to the lack of statistical data on the variation of the results. In this regard, ACI Committee 544 [13] has proposed a drop-weight impact test to evaluate the impact resistance of fibre concrete. The test is widely used since it is simple and economical. However, the results obtained from this test are often noticeably scattered [14]. The variation in the impact resistance as determined from this test is reported in the literature for some types of FRC but not for polypropylene fibre-reinforced concrete (PPFRC). Clearly, the type of fibres could have a great effect on the variation of the results due to differences in the geometry and physical properties of the fibres. The main objective of this paper is to investigate the statistical variation in the impact resistance of PPFRC using the ACI Committee 544 drop-weight impact test and to compare it with the variations reported for other types of FRC. The objective was achieved by testing 40 specimens (2 batches $\times$ 20 specimens) of PPFRC under impact loading according to the ACI Committee 544 drop-weight impact test. The results were subjected to comprehensive statistical analysis. Compressive strength tests were also conducted on cubes as a means of quality control.

2. Materials, mix proportions and sample preparation

2.1. Materials

Ordinary Portland cement (OPC), conforming to BS 12: 1996, was used in this study. The chemical composition of the cement, as given by the supplier, is represented in Table 1.

Table 1
Chemical composition of the cement

Oxide	Content %
CaO	63.28
SiO_2	20.77
Al_2O_3	4.93
Fe_2O_3	3.06
MgO	2.42
Na_2O	0.28
K_2O	0.7
LOI.	0.81

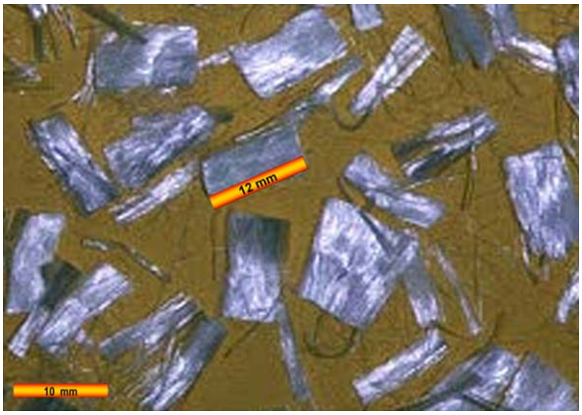

Fig. 1. Polypropylene fibre used in this study.

Table 2
Physical properties and dimensions of PPF

Physical properties	
Specific gravity	0.91
Melting point	160–170 °C
Ignition point	590 °C
Tensile modulus	4.1 GPa
Tensile strength	560 MPa
Dimensions	
Length	12 mm
Nominal diameter	18 μm

The coarse aggregate was quartzite natural gravel of 10 mm nominal maximum size. It had a specific gravity of 2.63 and bulk density of 1588 kg/m^3. The fine aggregate was quartzite sand with a specific gravity and water absorption of 2.66 and 0.17%, respectively. Sieve analysis of this sand showed that it has grading which complies with zone M of BS 882, 1992. A superplasticiser based on naphthalene sulphonate polymer, which has a powerful dispersing effect on the cement particles, was used as a water-reducing admixture. Virgin polypropylene fibre (Fig. 1) was used. Table 2 presents the dimensions and physical properties of this fibre.

2.2. Mixing and samples preparation

The mix proportions are given in Table 3. A conventional rotary drum concrete mixer was used. The coarse aggregate, cement and sand were first mixed in the dry state for 1 min before adding about half of the mixing water. After 2 min of mixing, the remaining mixing water and

Table 3
Mix proportions

Constituent	Content per m^3 of concrete
Cement	410 kg
Coarse aggregate	1000 kg
Fine aggregate	800 kg
Water	185 l
Superplasticiser	4.1 l
Polypropylene fibre	3 kg

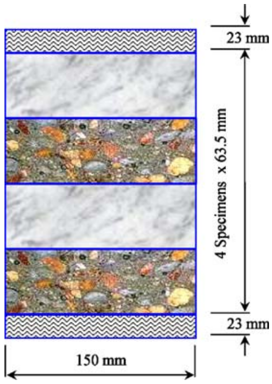

Fig. 2. Concrete disc specimens for impact test obtained from concrete cylinders.

superplasticiser were added. Mixing was continued for another 3 min before adding the polypropylene fibres. The fibres were added slowly to the running mixer to avoid clumping. Mixing was continued for a further 5 min to achieve uniform distribution of the fibres. Workability of the fresh concrete was assessed using the slump test according to BS 1881: Part 102, 1983. The slump values were 80 and 105 mm for the first and second batches, respectively.

Five standard cylinders with a diameter of 150 mm and a height of 300 mm were cast from each batch to prepare specimens for the impact test. Ten cubes (100 mm) were prepared from each batch according to BS 1881: Part 108: 1983 for the compressive strength test.

After casting, the concrete specimens were compacted using a vibrating table. The specimens were covered with wet hessian and polyethylene sheets overnight. They were then de-moulded after 24 h and cured in a fog room with curing conditions conforming to BS 1881: Part 111: 1983 ($20 \pm 2\,^{\circ}C$ and $97 \pm 3\%$) for 7 days, after which the cylinders were cut using a diamond saw to get four discs for the impact test from each cylinder, as shown in Fig. 2. All specimens and cubes were then transferred to an environmental chamber maintained at $38 \pm 2\,^{\circ}C$ and $45 \pm 5\%$ relative humidity, until testing at the age of 28 days.

3. Test procedures

3.1. Impact test

The impact test was performed in accordance with the impact testing procedures recommended by ACI Committee 544. The test was carried out by dropping a hammer weighing 44.7 N (10 lb) from a height of 457 mm (18 inch) repeatedly on a 64 mm diameter ($2\frac{1}{2}$ inch) hardened steel ball, which is placed on the top of the centre of the cylindrical specimen (disc) as shown in Fig. 3.

The test continued until failure. For each specimen, two values were identified corresponding to initial and ultimate failure. The former value measures the number of blows required to initiate a visible crack, whereas the latter measures the number of blows required to initiate and propagate cracks until ultimate failure. According to the ACI committee, the ultimate failure occurs when sufficient impact energy has been supplied to spread the cracks enough so that the test specimen touches the steel lugs. However, in this study, if the specimen separated completely into halves before touching the lugs, then this was declared the point of ultimate failure.

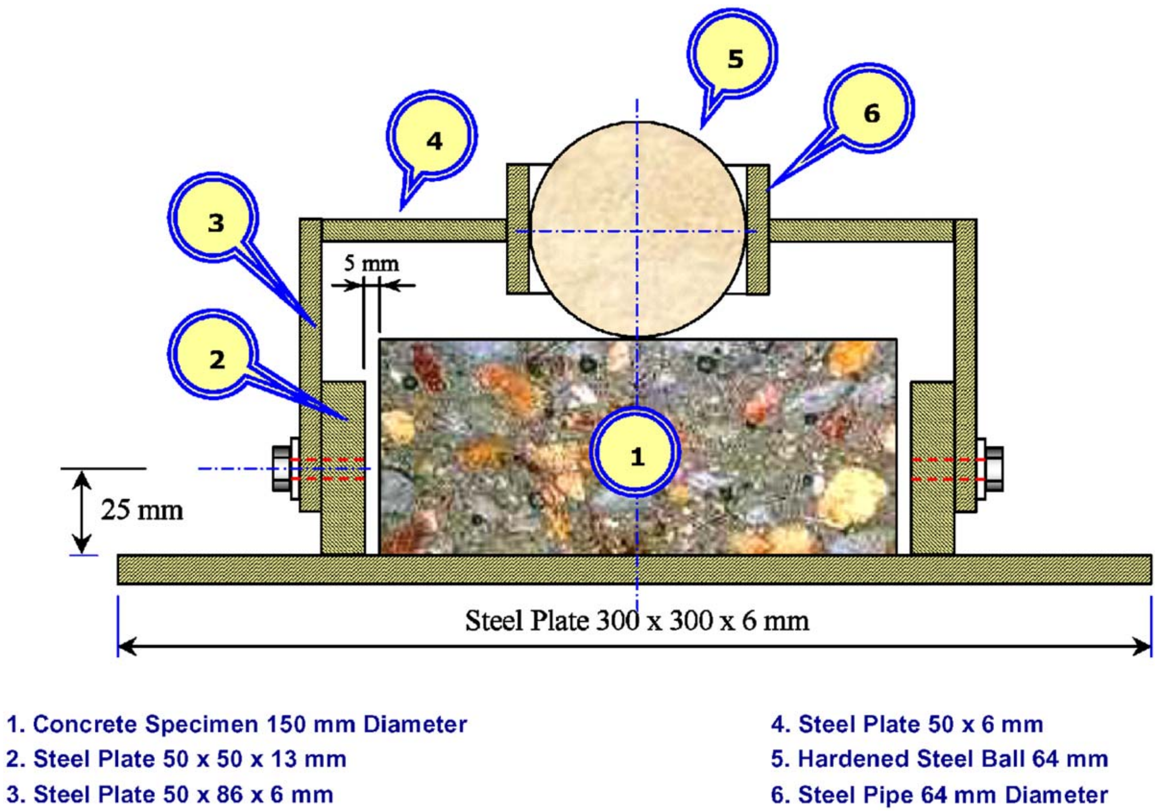

Fig. 3. Impact test apparatus with the concrete disc in place.

3.2. Compressive strength

Compressive strength of the hardened concrete cubes was determined according to BS 1881: Part 116: 1983. The tests were carried out using a digital automatic testing machine of a 3000 kN capacity.

4. Results and discussion

4.1. Compressive strength

The results of the compression tests are given in Table 4. Compressive strength was determined at the age of 28 days, as a means of quality control.

Fig. 4 presents the histogram of the 20 results obtained from the compressive strength tests. The figure shows that the results are almost normally distributed and fit well with the superimposed normal distribution curve of the same mean and standard deviation as the compressive strength results.

The average 28-day compressive strength was 41.3 MPa and the standard deviation was 4.17 MPa. The coefficient of variation was 10.09%. The mean compressive strengths within batches were 38.6 and 44.1 MPa with standard deviations of 2.80 and 3.46 MPa, The corresponding coefficients of variation within batches were 7.26% and 7.85%.

The overall standard deviation and the standard deviations within batches indicated good quality control over the production of the concrete specimens. A figure of 4–6 MPa is considered acceptable in the UK [15]. The values of the coefficient of variation show further evidence of good

Table 4
Compressive strength test results

No.	Batch 1	Batch 2	Overall
1	34.3	38.8	—
2	35.9	40.8	—
3	36.4	41.3	—
4	37.1	41.9	—
5	37.9	43.2	—
6	38.9	44.9	—
7	39.7	45.9	—
8	40.2	46.4	—
9	41.8	47.7	—
10	43.4	49.9	—
Mean (MPa)	**38.6**	**44.1**	**41.3**
SD (MPa)	**2.80**	**3.46**	**4.17**
CoV (%)	**7.26**	**7.85**	**10.09**

SD = standard deviation; CoV = coefficient of variation.

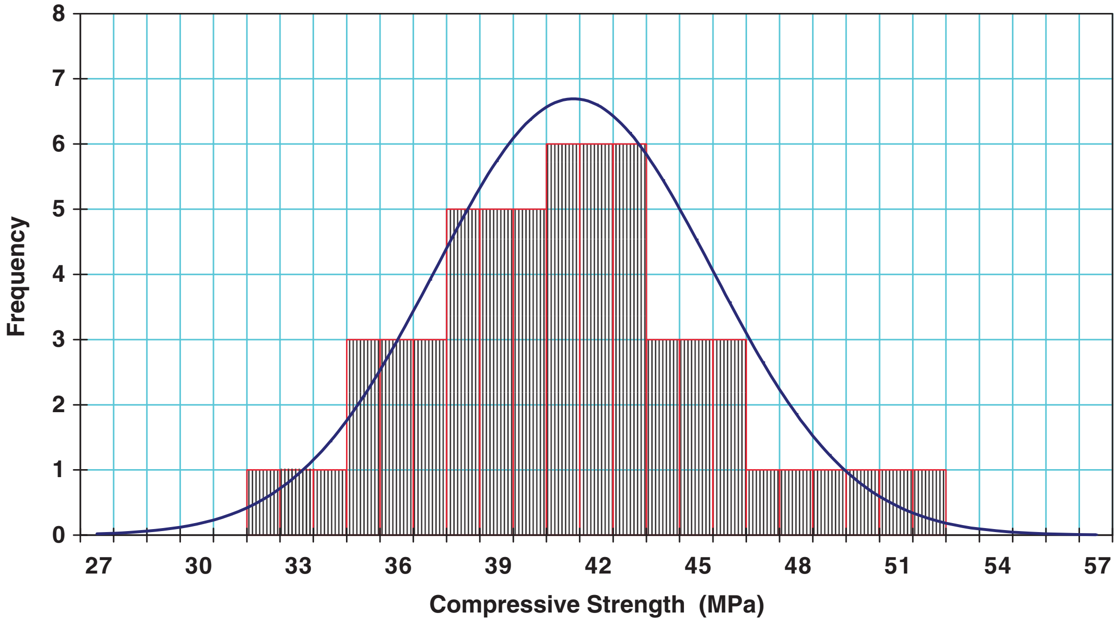

Fig. 4. Distribution of compressive strength test results.

quality control. The overall coefficient of variation (10.09%) is much lower than a limit of 15% suggested by Swamy and Stavrides [16] for good quality control, even though the within batches coefficients of variation are slightly higher than the 5% limit suggested by them. However, Day [15] suggested that a coefficient of variation between 5% and 10% generally represents a reasonable quality control.

4.2. Impact resistance

The first-crack (FC) and the ultimate impact resistance (UR) values obtained from the impact test are given in Table 5 for both batches. The statistical parameters are also presented in Table 5 for all results (40 samples) and within batches (20 samples each). The overall average of the ultimate impact resistance was 80 blows with a standard deviation of 40.4, which makes a coefficient of variation of more than 50%. The mean ultimate impact resistance for the first batch was 84 blows, which is slightly higher than the overall mean. The standard deviation of the same batch was 43.9 and the corresponding coefficient of variation was 52.1%. The counterpart values for the second batch were slightly less than the overall values, with a mean, standard deviation and coefficient of variation of 76 blows, 37.3 blows and 48.7%, respectively.

The standard deviation values obtained in this study are very high. However, a wide range of standard deviation is reported in the literature. Higher values of 59 and 66 blows were obtained by Nataraja et al. [17] for steel FRC, whereas Soroushian et al. [18] reported a

Table 5
Results from impact test (blows)

Sample	Batch 1		Batch 2		Overall	
	FC	UR	FC	UR	FC	UR
1	43	73	109	129	—	—
2	17	30	66	81	—	—
3	34	65	14	25	—	—
4	11	18	15	28	—	—
5	77	121	118	134	—	—
6	65	95	24	43	—	—
7	97	135	55	79	—	—
8	28	40	90	141	—	—
9	99	127	56	73	—	—
10	54	100	58	89	—	—
11	26	38	33	52	—	—
12	108	141	70	85	—	—
13	53	89	76	103	—	—
14	79	121	12	20	—	—
15	46	60	76	98	—	—
16	12	27	68	101	—	—
17	148	173	43	74	—	—
18	32	41	9	16	—	—
19	81	104	47	63	—	—
20	67	89	64	95	—	—
Mean (blow)	59	84	55	76	57	80
SD (blow)	36.2	43.9	31.2	37.3	33.4	40.4
CoV (%)	61.4	52.1	56.6	48.7	58.6	50.2

SD = standard Deviation; CoV = coefficient of variation.

lower value of 18 blows for carbon fibre-reinforced composites. However, unlike compressive strength, it is not realistic to use the standard deviation to judge or compare the impact resistance results, and it is more appropriate to use the coefficient of variation. The coefficient of variation is considered a more meaningful index of variability because it accounts for the mean as well as the standard deviation. Day [15] stated that several ACI committees including 212 (mixture proportioning), 214 (evaluation of test results) and 363 (high strength concrete) have adopted the coefficient of variation as a measure of variability rather than the standard deviation.

The coefficient of variation of 50.2% obtained for PPFRC in this study is of the same order of magnitude as those reported for other fibre-reinforced composites. Values of 54.6% and 57.3% were reported by Soroushian et al. [18] for carbon FRC and Nataraja et al. [17] for steel FRC, respectively. However, Shin Hwang et al. [19] reported coefficient of variations between 32% and 36% for concrete with and without polypropylene fibres. The relatively lower values of coefficients of variations compared to those obtained in this study can be attributed to their higher values of means. They reported means of 188 and 207 blows compared to 57 and 80 blows obtained in this study, for first and ultimate impact resistance, respectively.

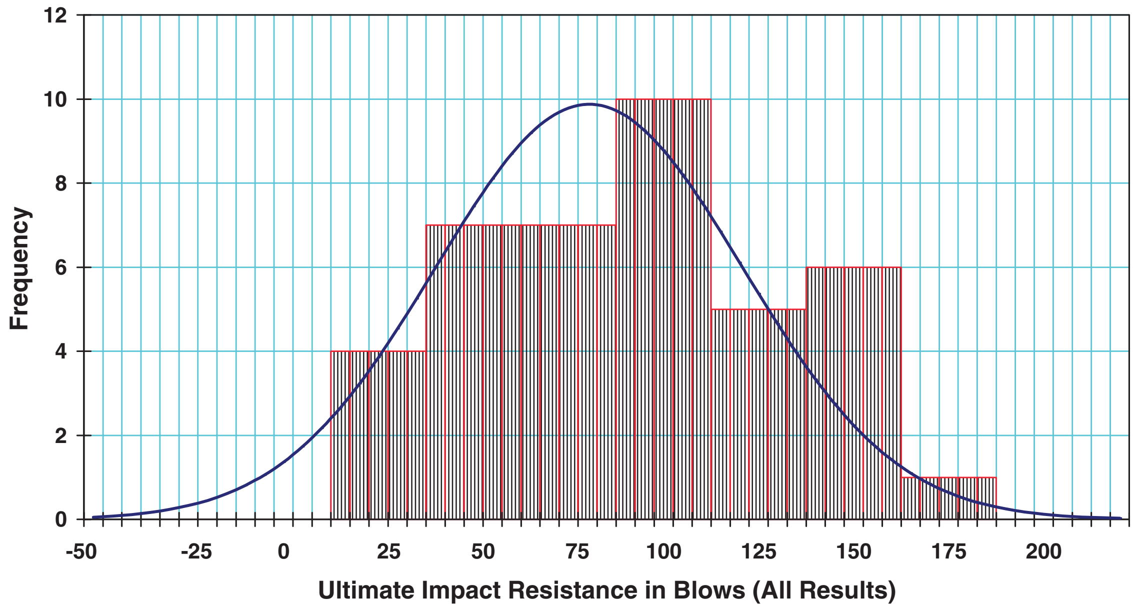

Fig. 5. Distribution of the ultimate impact resistance (all results).

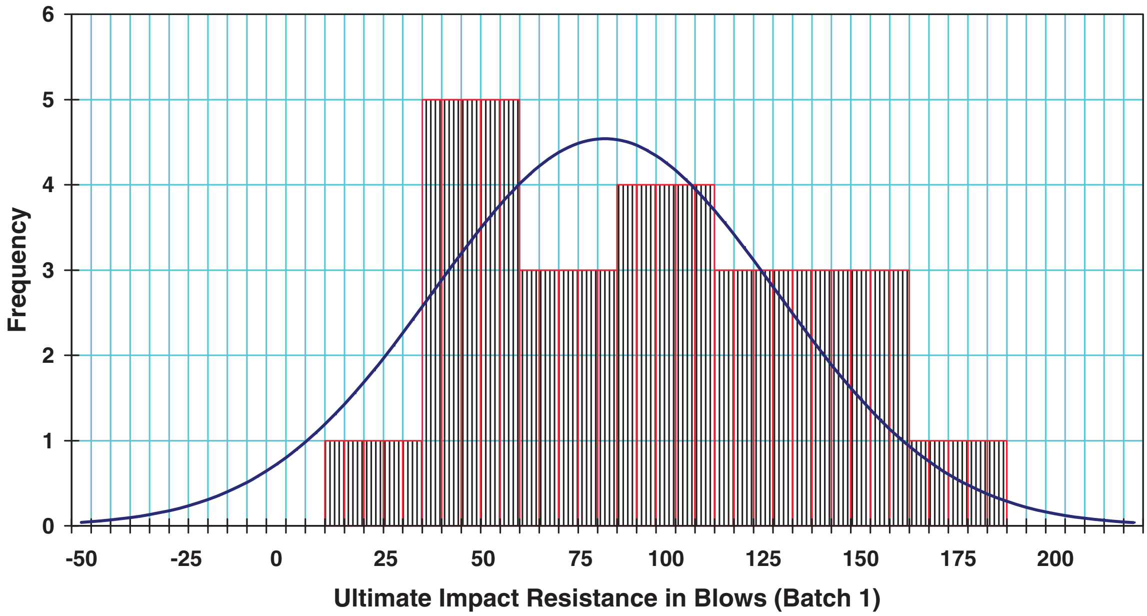

Fig. 6. Distribution of the ultimate impact resistance (batch 1).

It is interesting to notice that the values of coefficient of variation obtained in this study or reported in the literature are three to four times the recommended value for a standard test such as compressive strength. These very high values of the coefficient of variation of the impact resistance obtained from test results in different studies–despite the difference in the physical properties of the fibres— indicates clearly that the test with its current recommendations is not anywhere near the status of a standard test.

Similar conclusions can be obtained from a similar discussion of the statistical parameters obtained for the first-crack impact resistance results. However, it is interesting to note that the coefficients of variations for the overall results and within individual batches are higher than the corresponding values for the ultimate impact resistance (Table 5). This can be easily attributed to the lower values of the means.

The histogram of the 40 impact resistance results is presented in Fig. 5, with a superimposed normal distribution curve. It can be seen that the distribution of the results has departed from the normal distribution. The departure from the normal distribution was even clearer within each batch as shown in Figs. 6 and 7, giving further evidence of scatter in the impact resistance results. Again, similar charts can be obtained for the case of first-crack impact resistance as shown in Fig. 8 for all results.

Figs. 9 and 10 present the normal probability plots of the results of batch 1 and batch 2. Two straight lines, chosen subjectively, have been drawn through the plotted points. It can be seen that the results for FC and UR for both batches are not close to straight lines, indicating that the results are not normally distributed. The goodness-of-fit test for the impact resistance indicated poor fitness of the results to a normal distribution at the 95% level of confidence, confirming the conclusions drawn from Figs. 5–10.

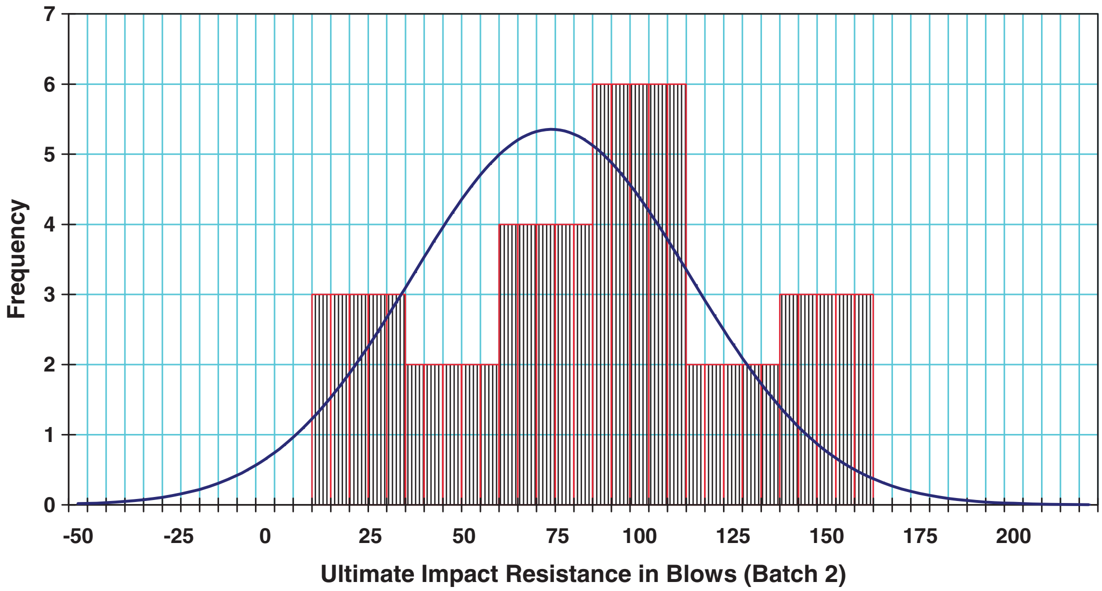

Fig. 7. Distribution of the ultimate impact resistance (batch 2).

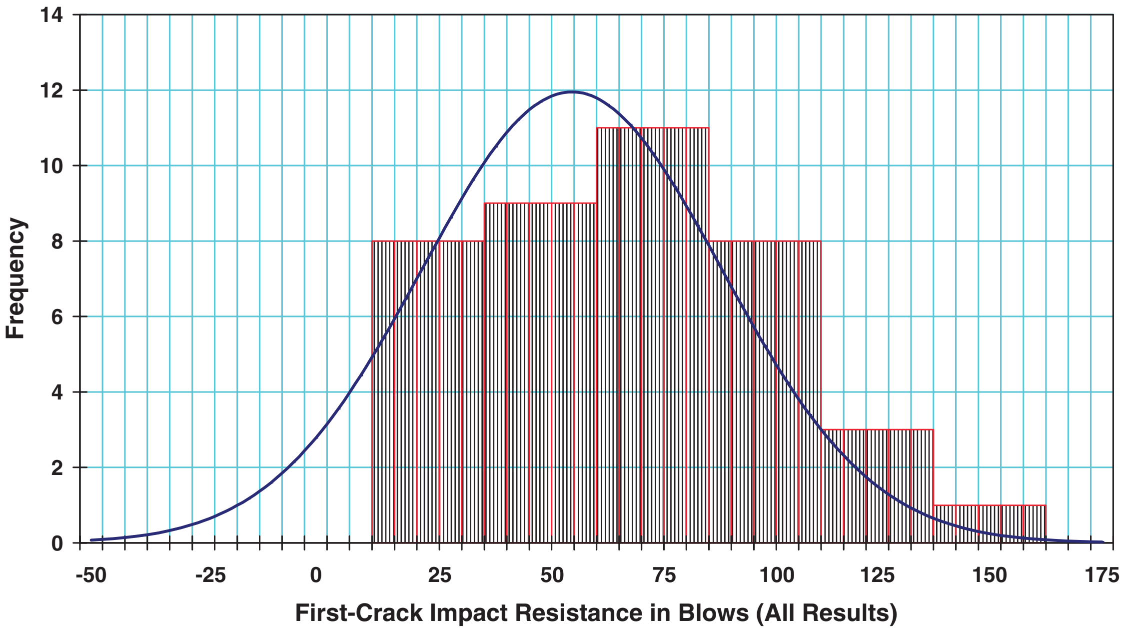

Fig. 8. Distribution of first-crack impact resistance (all results).

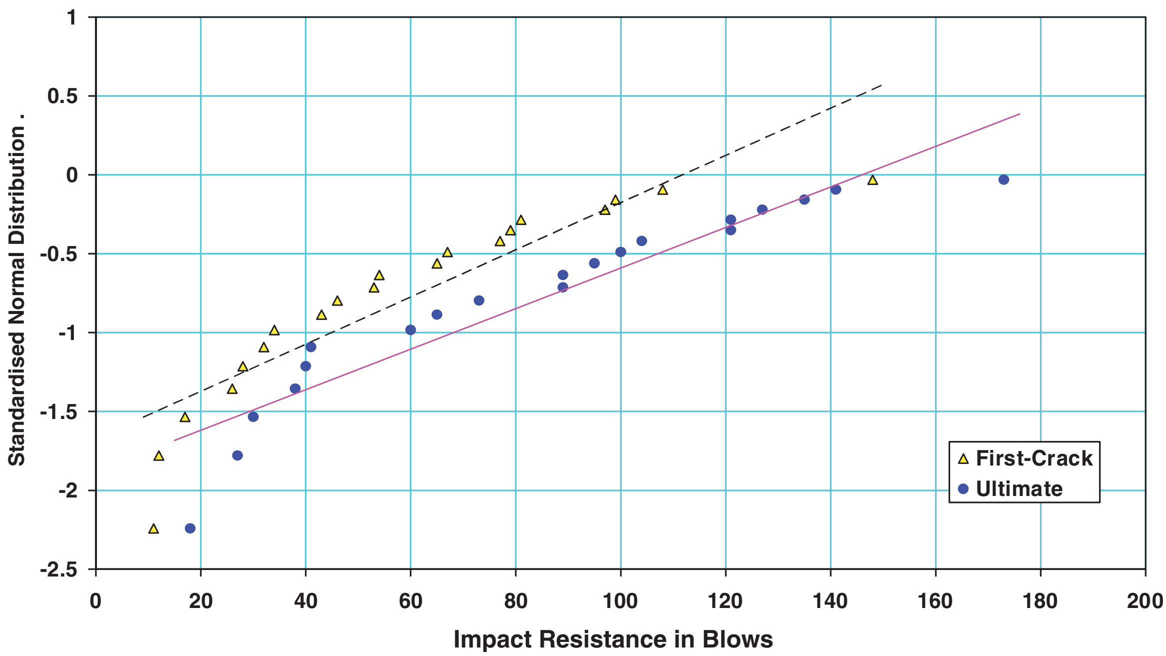

Fig. 9. Normal probability plot of batch 1 results.

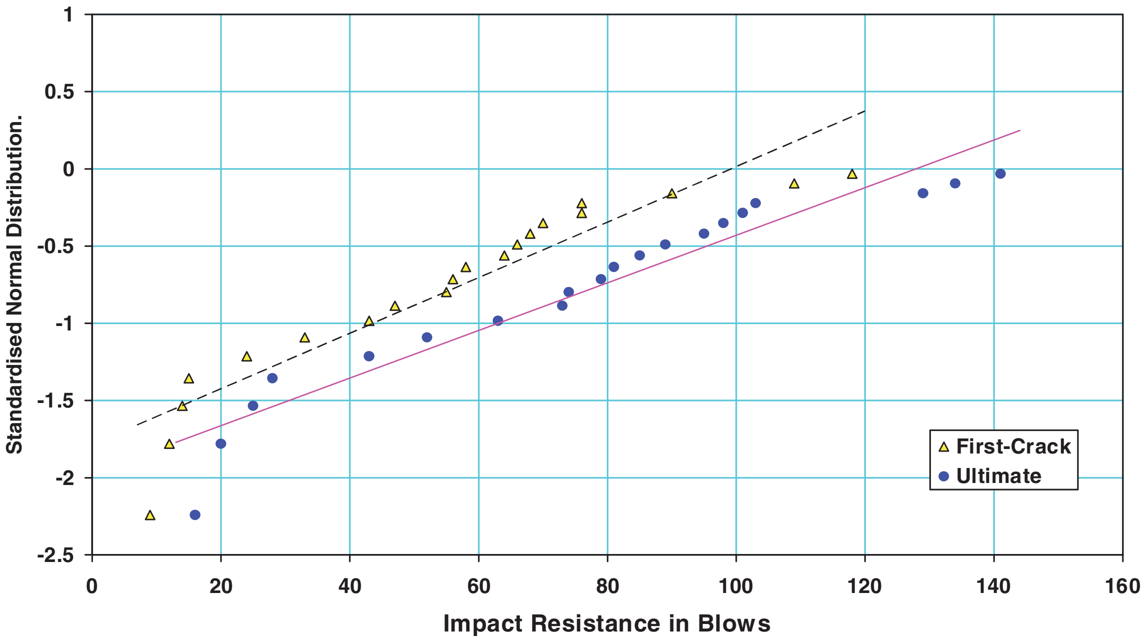

Fig. 10. Normal probability plot of batch 2 results.

4.3. Sources of large variations

The sources of large variations in results obtained from the ACI impact test may be attributed to the following reasons:

- The subjectivity of the test due to the visual identification of the first crack, which may occur in any direction.
- The impact resistance of concrete is based on a single point of impact, which might happen to be on a hard particle of coarse aggregate or on a soft area of mortar.
- The absence of criteria for preparing test specimens allows trawled, cut or smooth mould-faced surfaces to be tested, adding another source of variability.
- No criteria are stated for accepted or rejected failure mode.

4.4. Minimum number of replications

The coefficient of variation of the test results calculated above has another valuable practical application. Swamy and Stavridis [16] showed that it can be used to determine the minimum number of tests, n, required in order to guarantee that the percentage error in the measured average value is below a specified limit, e, at a specific level of confidence, as given by Eq. (1) below.

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

Table 6
Number of replications required to keep the error under a specific limit

Error (e %)	95% level of confidence		90% level of confidence	
	FC	UR	FC	UR
<10	93	68	56	41
<15	41	30	25	18
<20	23	17	14	11
<25	15	11	9	7
<30	10	8	6	5
<35	8	6	5	4
<40	6	4	4	3
<50	4	3	2	2

where v is the coefficient of variation; t is the value of t student distribution for the specified level of confidence and is dependent on the degree of freedom, which is related to the number of tests.

For a large sample size, "t" approaches 1.645 and 1.282 at 95 and 90% level of confidence, respectively [20,21]. Table 6 presents the number of samples required to keep the error under various limits between 10% and 50%, at the 95% and 90% levels of confidence.

It can be seen that for PPFRC, if the error is to be kept under 10%, the minimum number of tests should be 68 and 41 at the 95% and 90% levels of confidence even when considering the lower coefficient of variation obtained for ultimate impact resistance (50.2%). Moreover, the table shows that if three samples are used to determine the impact resistance, then the error in the measured value could be between 40% and 50% depending on the level of confidence.

5. Conclusions

For the PPFRC used in this investigation, the impact resistance results indicated a poor correlation to the normal distribution, and the following conclusions may be drawn:

1. Impact resistance of PPFRC, as determined from the ACI repeated drop-weight impact test, has a large standard deviation and coefficient of variation. The observed coefficients of variation were about four-fold the recommended value for compressive strength. The values were about 60% and 50% for first-crack and ultimate impact resistance, respectively.
2. If this test is to be considered as a standard test it is necessary to increase the number of replications to at least 40 specimens per each test or concrete mix to assure an error below 10%. This, however, is neither practical nor economical and goes entirely against the intention of this test, which is to provide an easy, simple and economical impact test.

3. It is crucial for this test to be modified in such a way that increases the accuracy and reduces the large variation of results. Alternatively, a new technique of testing concrete against impact should be developed.

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