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Assessment of statistical variations in experimental impact resistance and mechanical properties of silica fume concrete

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Abstract. Silica fume as a new supplementary cement has several effects on initial mechanical characteristics and long term improvements. In this paper, the impact resistance and mechanical properties of concrete mixed with silica fume are statistically investigated by selecting 288 specimens in three mix designs. Zero, 7% and 14% of Portland cement by weight were replaced by silica fume in silica-fume mixtures. Twenty $100 \times 100 \times 100$ mm cubic specimens, twenty 100×200 mm cylindrical specimens, twenty $60 \times 80 \times 320$ mm specimens and thirty-six 150×64-mm discs were cast from each batch to prepare specimens for different test purposes. Cubic and cylindrical specimens were used to determine compressive strength, and prismatic specimens were tested to obtain tensile rupturing. Also, cylindrical cutting specimens were subjected to a drop-weight test, following ACI committee 544, to determine the impact strength of mixed concrete. Experimental data on the mechanical properties of the different mixes indicated that silica fume improves mechanical properties and impact resistance, while statistical analysis undertaken based on these experimental tests showed a reduction in the coefficient of variation values. In other words, adding silica fume improves the statistical dispersion of data.

1. Introduction

In recent years, high-strength concrete has been widely used throughout the world. The term "high strength concrete" refers to concrete with the compressive strength of more than 42 MPa [1-2]. In the construction industry, HSC has been beneficially adopted for pre-casted and pre-stressed products, reinforced and pre-stressed structures, columns and shear walls of high-rise buildings, etc. Using Silica Fume (SF) for production of high strength concrete is very common. Due to its extreme fineness and high silica content, silica fume is a highly effective pozzolanic material. Silica fume is used in concrete to improve its mechanical properties [2-8]. It has been found that silica fume reduces permeability, porosity and bleeding by influencing rheological properties [9-11]. Numerous extensive experiments have been carried out by many researchers around the world on using silica fume in concrete [12-18]. Meanwhile, there have been few studies on the impact resistance and mechanical properties of concrete containing silica, particularly in a statistics sense [19]. There are relatively few studies about the effects of silica fume on the variation values of the compressive, splitting tensile, and flexural strength of concrete specimens. Also, there are few studies on statistical parameters of impact resistance

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and energy absorption. Several impact tests have been used to demonstrate the relative brittleness and impact resistance of concrete and similar construction materials [20-23]. However, none of these tests has been declared to be a standard test, mostly due to the lack of statistical data on the variation of the results. ACI Committee 544 [24] proposed a drop-weight impact test to evaluate the impact resistance of concrete. This test is widely used because of its simplicity and economy. However, the results of this test are often noticeably scattered. Most data obtained from these experiments has a coefficient of variation of more than 25%, and the variation in the impact resistance as determined from this test is reported in the literature for fiber reinforced concrete but not for concrete containing silica fume.

2. Research significance

Some statistical evaluations are necessary in order to obtain accurate results regarding the effect of adding silica, on the absorbed energy and impact resistance of concrete. Also, due to the lack of statistical data, there is not a clear relationship between the amount of silica used in concrete and energy absorption. Furthermore, there is not enough information available to calculate the mean, standard deviation and coefficient of variation. The results obtained from several tests are often noticeably scattered, because concrete itself is a heterogeneous material. It seems a necessity to study the effects of silica fume on mentioned parameters; therefore several experimental tests are conducted in this paper to find the statistical parametric relationship between the amount of silica fume and concrete strength characteristics.

3. Experimental program

In the present study, three series of concrete specimens with the same water-cement ratio of 0.44 were prepared and labeled as A1 (or first group), A2 (or second group), and A3 (or third group), respectively. In the series of A2 & A3, silica fume is used as cement replacement material at 7 & 14% of cement weight, and A1 is used as the reference specimen without silica fume. Compressive strength tests were performed at an age of 28 days on $100 \times 100 \times 100$ mm cubic specimens, according to ASTM C39, and the flexural strength test was conducted on $60 \times 80 \times 320$ mm specimens, according to ASTM C78. The tensile strength test was also performed on 100×200 mm cylindrical specimens, according to ASTM C 496. A drop-weight test was conducted using ACI 544 committee recommendations [12]. Each cast of a 150×300-mm cylindrical specimen was sawed into four 64 mm cylindrical disks for the drop-weight test. In the test, a cylindrical disc was set on a base plate within four positioning lugs, and impacted by repeated blows. The blows were introduced through a 4.45 kg hammer falling continually from a 457 mm height onto a steel ball with a diameter of 63.5 mm, which stood at the center of the top surface of the disc. The number of blows required to cause the first visible crack and then failure were recorded. During the blows impacted onto the disc, the number of blows to the first visible crack on the top surface was defined as the first-crack strength, while the number of the blows to generate the 3-lug-touching action of the disc was identified as the failure strength.

Portland cement (ASTM Type II) and silica fume, a by-product of the Ferrosilice factory, were used in this research work. The cement and silica fume properties are given in Table 1. Coarse aggregate with a maximum particle size of 9.5 mm and fine aggregate with a 3.3 fineness modulus were used in this experiment. The specific gravity and water absorption of the coarse and fine aggregates were 2.73 and 0.51%, and 2.64 and 1.87%, respectively. A high range water reducer agent with the commercial name of Mape110 was used to adjust the workability of the concrete mixtures. Mix proportions of the concrete mixtures are provided in Table 2.

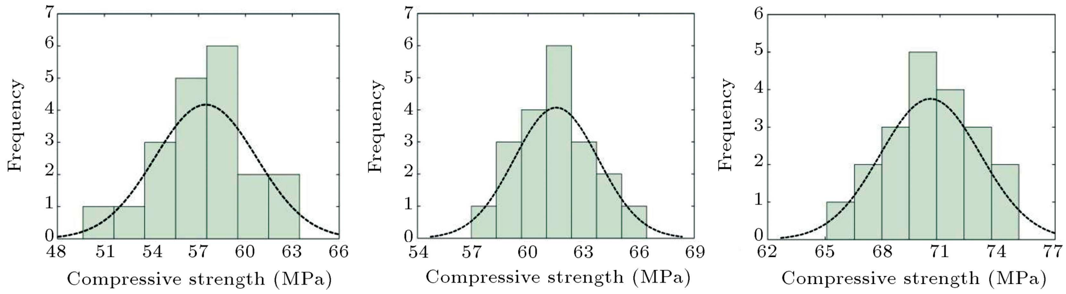
Each type of freshly mixed concrete was cast into cubic (100 mm), cylindrical (100×200 mm specimens), prismatic and cylindrical cutting specimens for compressive, splitting tensile, flexural and impact tests, respectively. All specimens were stored at 23°C and 100% relative humidity for about 24 h, and then cured in saturated water for 28 days.

Table 1. Properties of cement and silica fume.

Composition	Cement	Silica fume
SiO_2	21.1	85-95
Al_2O_3	4.37	0.5-1.7
Fe_2O_3	3.88	0.4-2
MgO	1.56	0.1-0.9
K_2O	0.52	0.15-1.02
Na_2O	0.39	0.15-0.2
CaO	63.33	-
C_3S	51	-
C_2S	22.7	-
C_3A	5.1	-
C_4AF	11.9	-
	Physical properties	
Specific gravity	3.11	2.21
Specific surface (cm^2/gr)	3000	14000

Table 2. Mix proportions of the concrete mixtures (each cubic meter concrete).

Mix no.	Label	$\left(\frac{\text{Water}}{\text{Cement+S.F}}\right)$	Water $\left(\frac{\text{kg}}{\text{m}^3}\right)$	Cement $\left(\frac{\text{kg}}{\text{m}^3}\right)$	Silica fume $\left(\frac{\text{kg}}{\text{m}^3}\right)$	Fine agg. $\left(\frac{\text{kg}}{\text{m}^3}\right)$	Coarse agg. $\left(\frac{\text{kg}}{\text{m}^3}\right)$	SP $\left(\frac{\text{kg}}{\text{m}^3}\right)$
1	A1 (0%SF)	0.44	165	375	0	980	980	3.9
2	A2 (7%SF)	0.44	165	348.75	26.25	980	980	3.9
3	A3 (14%SF)	0.44	165	322.5	52.5	980	980	3.9



(a) First group (b) Second group (c) Third group

Figure 1. Distribution of compressive strength test result.

4. Results and discussion

4.1. Compressive strength

The compressive strength tests were carried out using a digital automatic testing machine of 2000 kN capacity, according to ASTM C 39. Compressive strength test results are given in Table 3. The obtained results show that the addition of silica fume to specimens improved compressive strength. Figure 1 presents the histogram of 60 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 compressive strength results. From an increase in mean compressive strength of up to 22%, 15% can be observed in A3 (introduction of 14% silica fume into the mixtures), as compared to A1 and A2, respectively. Also an increase up to 7% in A2 as compared to A1 was observed. The third group's coefficients of variation were 3% and 35% less than the first and second group coefficients of variation, respectively.

The third group's coefficient of variation is 3% and 35% less than the same parameter in the first and second groups, respectively. It is clear that addition of silica fume to concrete specimens decreases the standard deviation and coefficient of variation values of the compressive strength. A decrease in standard deviation and the coefficient of variation within batches indicated good quality control over the production of the concrete specimens. A figure of 4-6 MPa is considered acceptable [25]. The values of the coefficient of variation show further evidence of good quality control. The coefficient of variation is much lower than the limit of 15% suggested

Table 3. Compressive strength test results

Specimen no.	Compressive strength (MPa) A1	A2	A3
1	58.12	62.15	73.22
2	53.1	61.1	73.39
3	57.44	60.43	71.98
4	55.76	63.21	75.11
5	61.15	64.28	70.15
6	58.52	64.49	72.05
7	54.32	60.81	69.94
8	58.59	62.15	66.56
9	60.95	63.21	73.7
10	55.78	61.54	70.06
11	54.86	58.76	69.77
12	55.18	60.82	72.18
13	62.13	56.92	67.97
14	63.47	60.85	66.85
15	58.32	58.55	70.01
16	59.06	61.15	71.16
17	49.62	58.86	72.54
18	57.41	66.42	65.1
19	58.76	61.23	68.92
20	57	63.55	69.29
Mean (MPa)	**57.47**	**61.15**	**70.49**
SD[a] (MPa)	**3.24**	**2.31**	**2.60**
CoV[b] (%)	**5.64**	**3.78**	**3.69**

[a]SD: Standard Deviation; [b]CoV: Coefficient of Variation.

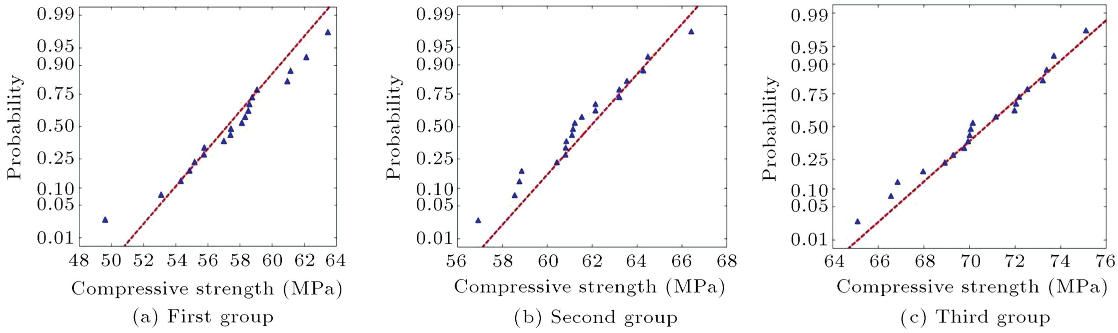


Figure 2. Normal probability plot for all groups.

Figure 3. Cylinder specimens for splitting test.

by Swamy and Stavrides [26]. However, Day [25] suggested that a coefficient of variation between 5% and 10% generally represents reasonable quality control. Figure 2 represents the normal probability plot obtained from the compressive strength test results.

4.2. Splitting test

The tensile strength test was performed on 100 × 200 mm cylindrical specimens, according to ASTM C 496. Figure 3 shows the cylindrical specimens for the splitting test. The results of splitting tensile strength for three groups are presented in Table 4. The A3 specimen group has the highest mean tensile strength value among all the specimen groups. A maximum increase of 35% and 24% in mean tensile strength can be observed in A3 (introduction of 14% silica fume into the mixtures), as compared to A1 and A2, respectively. The first and third groups have the highest and lowest values of coefficient of variation, respectively. The coefficient of variation (meaningful index of variability) of 7.99% belongs to specimen A3, i.e. 5% and 2.7% lower than A1 and A2, respectively. In other words, adding silica fume reduces the scatter in the tensile strength results. A histogram of the tensile strength of all groups is shown in Figure 4. As seen in this figure, the results are almost normally distributed and

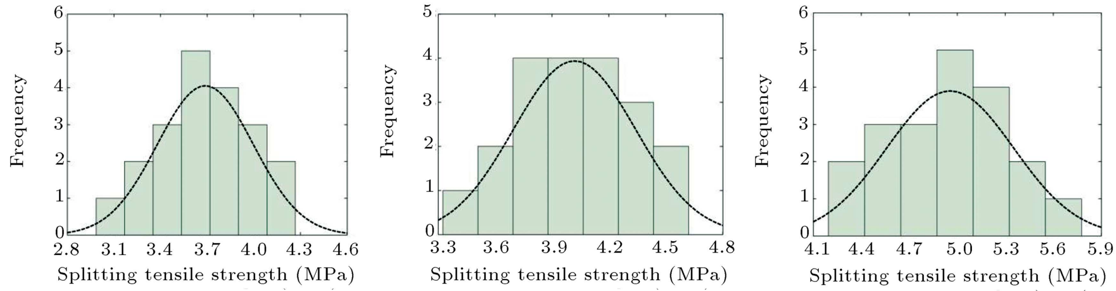
Table 4. Splitting tensile strength for three groups.

Specimen no.	**Tensile strength (MPa)**		
	A1	**A2**	**A3**
1	3.26	4.17	4.75
2	2.99	4.34	4.84
3	3.71	4.50	5.78
4	3.55	4.02	4.40
5	3.34	4.23	4.46
6	3.44	4.28	5.25
7	3.51	3.57	5.45
8	3.84	4.10	4.97
9	3.71	3.92	5.43
10	3.86	3.84	4.20
11	3.43	3.79	4.90
12	3.62	3.66	5.09
13	3.66	3.32	5.15
14	3.72	4.34	4.74
15	3.84	3.77	5.16
16	4.00	3.84	5.03
17	4.10	3.92	5.09
18	3.92	4.03	5.27
19	4.27	4.11	4.63
20	4.00	4.62	4.54
Mean (MPa)	**3.69**	**4.02**	**4.96**
SD (MPa)	**0.31**	**0.33**	**0.40**
CoV (%)	**8.38**	**8.21**	**7.99**

fit well with the normal distribution curve. A normal probability plot for all groups is shown in Figure 5. According to this figure, a few data points are in full agreement with normal distribution lines, and most data are around the normal probability distribution line.

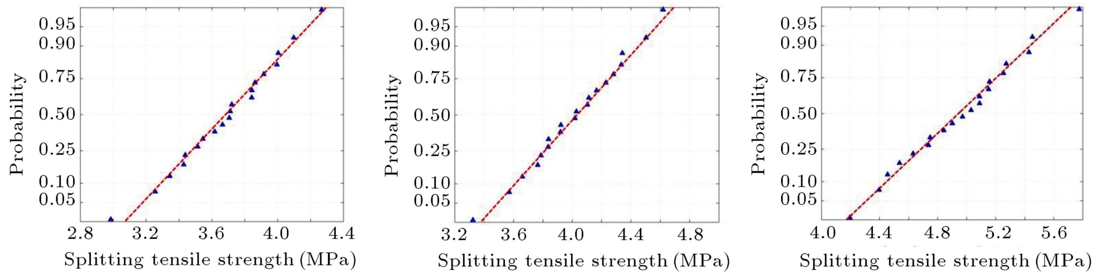
4.3. Flexural strength

The flexural strength test was performed on a 60 × 80 × 320 mm simple beam with third-point loading,



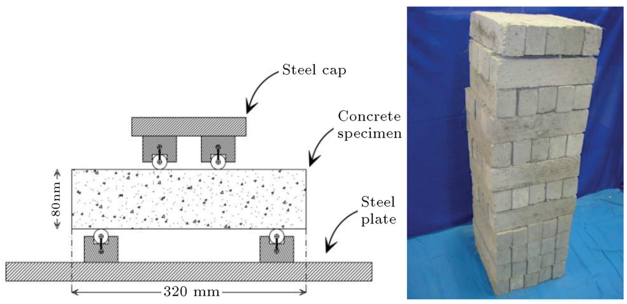
(a) First group (b) Second group (c) Third group

Figure 4. Distribution of splitting tensile strength for test results.



(a) First group (b) Second group (c) Third group

Figure 5. Normal probability plot for all groups.



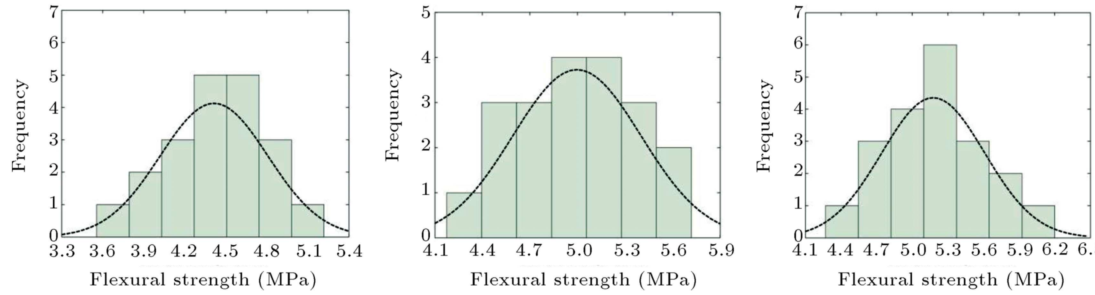
(a) Flexural test machine (b) Flexural specimens

Figure 6. Third-point loading method.

following ASTM C78. To determine the flexural strength, a diagrammatic view of suitable apparatus for the flexure test of concrete by the third-point loading method is shown in Figure 6. The results of the flexural strength test, carried out on three different mixtures (three groups), are presented in Table 5. The highest mean flexural strength values of 5.18 MPa belong to A3 specimens, which contain 14% silica fume, so they were increased by 18% and 4% compared to A1 and A2, respectively. The range of variation of 3.56 to 5.22 MPa in A1, 4.18 to 5.72 MPa in A2, and 4.27 to 6.2 MPa in A3 are observed in the results. The A2 group has the highest standard deviation values. The frequency histogram and fitted normal curve of the modulus of rupture of all groups are shown in Figure 7. The coefficient of variation of the third group is 8.37%, and the coefficient of variation of the third group is 6.1% and 2.5% less

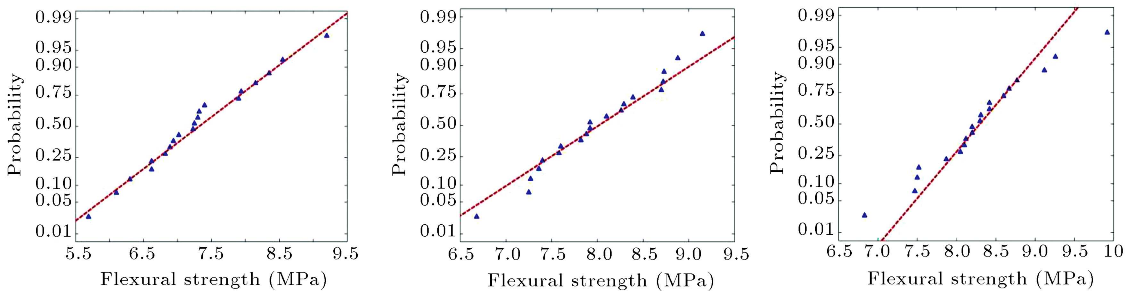
Table 5. Module of rupture for three groups.

Specimen no.	**Modulus of rupture (MPa)**		
	A1	**A2**	**A3**
1	4.14	5.55	4.70
2	4.31	5.46	5.19
3	3.56	5.72	4.67
4	4.58	5.16	5.26
5	4.56	4.74	5.13
6	4.34	5.45	4.69
7	4.39	5.06	5.08
8	4.77	4.54	4.27
9	4.88	5.18	5.70
10	4.52	4.60	5.06
11	5.22	4.75	5.13
12	3.94	4.95	5.26
13	4.70	4.95	5.19
14	4.39	4.53	6.20
15	4.94	4.89	4.92
16	4.53	5.24	5.79
17	4.14	5.44	5.38
18	4.33	4.93	5.48
19	3.81	4.63	5.03
20	4.26	4.18	5.42
Mean (MPa)	**4.41**	**4.98**	**5.18**
SD (MPa)	**0.39**	**0.43**	**0.41**
CoV (%)	**8.92**	**8.58**	**8.37**



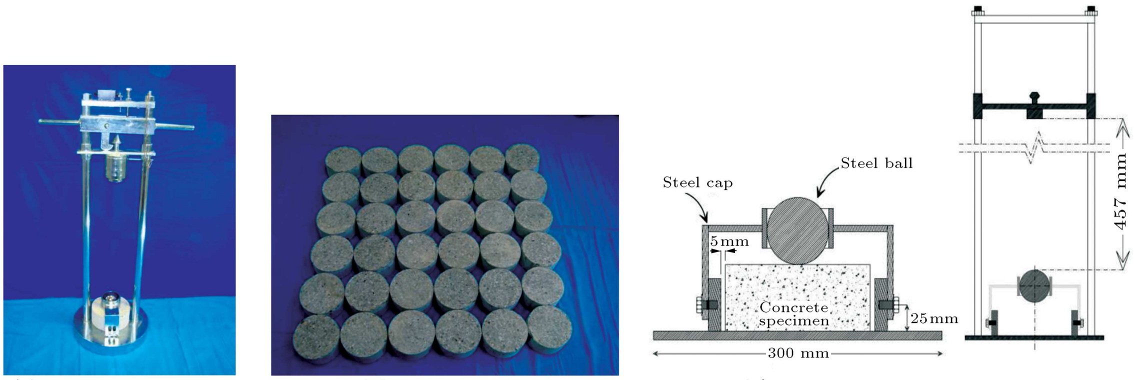
(a) First group (b) Second group (c) Third group

Figure 7. Frequency histogram and fitted normal curve of the flexural strength of all groups.



(a) First group (b) Second group (c) Third group

Figure 8. Normal probability plot for the flexural strength of all groups.



(a) Impact apparatus (b) Disc specimen (c) Dimensions of apparatus and steel cap

Figure 9. Falling hammer test.

than the same parameter for the first and second groups, respectively. As seen in Table 5, decreasing the coefficient of variation caused by increasing the amount of silica particles shows the positive effects of silica fume in decreasing data scattering. The normal probability distribution curve for the flexural strength of all groups is shown in Figure 8. The figure shows that a big proportion of data is distributed around the normal probability distribution line.

4.4. Impact resistance

Drop-weight test results on 108 disc specimens in three mix designs are given in Tables 6 to 8. The impact test apparatus, 36 disc specimens before test, and details of the impact apparatus include a steel test mold, a falling hammer and a steel cap, which have been shown in Figure 9.

First-crack strength. According to Tables 6 to 8, the first crack strength in the A3 group is greater than in the other groups. Mean values for the strength of the first-crack of the A3 group was approximately 1.74 and 1.22 times greater than A1 and A2 groups, respectively. The standard deviations were 5, 6.8 and 7.3, and the corresponding coefficients of variation were 29.9%, 28% and 24.8% in A1 to A3 groups, respectively. The frequency histogram and fitted normal curve of the first-crack strength distribution for all groups are shown in Figure 10. As shown in this figure, the first-crack strength of all group discs hardly follows a normal distribution. It is judged how approximately the first-

Table 6. Impact resistance test results and predicted failure strength for A1 group.

Specimen no.	Impact resistance test results					Predicted failure strength		
	FC[a]	UR[b]	PINPB[c] (blows)	Impact energy (kN mm)		UR	0.95% prediction interval on number of blows for failure strength	
				FC	UR		Lower prediction bound	Upper prediction bound
1	11.0	16.0	45.5	223.6	325.3	13	10	16
2	12.0	13.0	8.3	244.0	264.3	14	11	17
3	25.0	28.0	12.0	508.3	569.2	29	26	32
4	15.0	16.0	6.7	305.0	325.3	17	14	20
5	18.0	20.0	11.1	365.9	406.6	21	18	24
6	7.0	8.0	14.3	142.3	162.6	8	5	11
7	9.0	10.0	11.1	183.0	203.3	10	7	14
8	17.0	22.0	29.4	345.6	447.3	20	17	23
9	22.0	24.0	9.1	447.3	487.9	26	22	29
10	15.0	16.0	6.7	305.0	325.3	17	14	20
11	16.0	20.0	25.0	325.3	406.6	18	15	22
12	21.0	25.0	19.0	426.9	508.3	24	21	27
13	15.0	16.0	6.7	305.0	325.3	17	14	20
14	14.0	17.0	21.4	284.6	345.6	16	13	19
15	19.0	22.0	15.8	386.3	447.3	22	19	25
16	16.0	18.0	12.5	325.3	365.9	19	16	22
17	20.0	23.0	15.0	406.6	467.6	23	20	26
18	17.0	19.0	11.8	345.6	386.3	20	17	23
19	13.0	17.0	30.8	264.3	345.6	15	12	18
20	19.0	24.0	26.3	386.3	487.9	22	19	25
21	10.0	11.0	10.0	203.3	223.6	11	8	15
22	26.0	31.0	19.2	528.6	630.2	30	27	33
23	28.0	32.0	14.3	569.2	650.6	33	29	36
24	12.0	13.0	8.3	244.0	264.3	14	11	17
25	15.0	16.0	6.7	305.0	325.3	17	14	20
26	14.0	16.0	14.3	284.6	325.3	16	13	19
27	16.0	18.0	12.5	325.3	365.9	18	16	22
28	25.0	32.0	28.0	508.3	650.6	29	26	32
29	13.0	17.0	30.8	264.3	345.6	15	12	18
30	12.0	13.0	8.3	244.0	264.3	14	11	17
31	19.0	25.0	31.6	386.3	508.3	22	19	25
32	25.0	27.0	8.0	508.3	548.9	29	26	32
33	15.0	17.0	13.3	305.0	345.6	17	14	20
34	18.0	19.0	5.6	365.9	386.3	21	18	24
35	16.0	18.0	12.5	325.3	365.9	19	16	22
36	23.0	27.0	17.4	467.6	548.9	27	24	30
Mean (MPa)	**16.9**	**19.6**	**16.1**	**343.4**	**398.7**	**19.5**	**16.5**	**22.6**
SD[d] (MPa)	**5.0**	**6.1**	**9.3**	**102.6**	**123.1**	**6.0**	**5.9**	**5.9**
CoV[e] (%)	**29.9**	**30.9**	**57.8**	**29.9**	**30.9**	**30.6**	**35.6**	**26.0**

[a]FC: Number of blows for first-crack strength;

[b]UR: Number of blows for failure strength;

[c]PINPB: Percentage increase in number of post-first-crack blows in A1 series;

[d]SD: Standard Deviation;

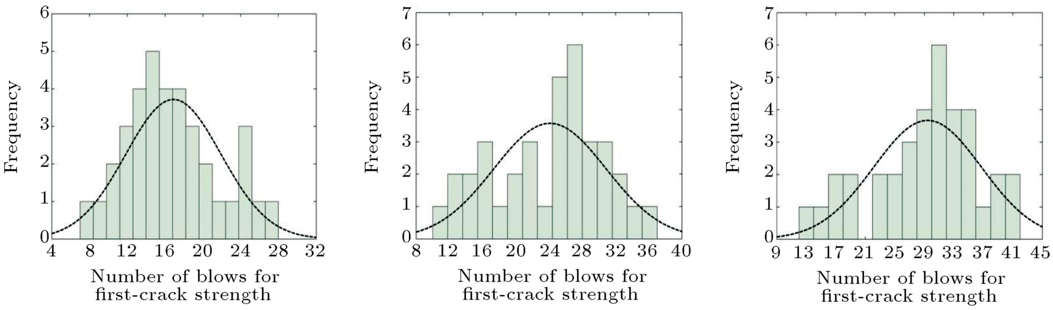
[e]CoV= Coefficient of Variation.

Table 7. Impact resistance test results and predicted failure strength for A2 group.

Specimen no.	Impact resistance test results					Predicted failure strength		
	FC	UR	PINPB (blows)	Impact energy (kN mm)		UR	0.95% prediction interval on number of blows for failure strength	
				FC	UR		Lower prediction bound	Upper prediction bound
1	29	33	13.8	589.6	670.9	33	31	36
2	27	32	18.5	548.9	650.6	31	29	34
3	21	25	19.0	426.9	508.3	25	23	27
4	30	36	20.0	609.9	731.9	35	32	37
5	17	21	23.5	345.6	426.9	21	18	23
6	26	30	15.4	528.6	609.9	30	28	33
7	28	34	21.4	569.2	691.2	32	30	35
8	25	28	12.0	508.3	569.2	29	27	32
9	25	31	24.0	508.3	630.2	29	27	32
10	32	38	18.8	650.6	772.5	37	34	39
11	33	37	12.1	670.9	752.2	38	35	40
12	30	35	16.7	609.9	711.6	35	32	37
13	29	32	10.3	589.6	650.6	33	31	36
14	31	34	9.7	630.2	691.2	36	33	38
15	29	34	17.2	589.6	691.2	33	31	36
16	28	35	25.0	569.2	711.6	32	30	35
17	16	20	25.0	325.3	406.6	20	17	22
18	37	42	13.5	752.2	853.9	42	40	45
19	23	27	17.4	467.6	548.9	27	25	29
20	20	24	20.0	406.6	487.9	24	21	26
21	14	16	14.3	284.6	325.3	18	15	20
22	25	29	16.0	508.3	589.6	19	27	32
23	22	25	13.6	447.3	508.3	26	24	28
24	10	14	40.0	203.3	284.6	13	11	16
25	17	22	29.4	345.6	447.3	21	18	23
26	26	31	19.2	528.6	630.2	30	28	33
27	35	38	8.6	711.6	772.5	40	37	42
28	21	23	9.5	426.9	467.6	25	22	27
29	13	17	30.8	264.3	345.6	17	14	19
30	28	32	14.3	569.2	650.6	32	30	35
31	27	31	14.8	548.9	630.2	31	29	34
32	13	15	15.4	264.3	305.0	17	14	19
33	15	19	26.7	305.0	386.3	19	16	21
34	20	22	10.0	406.6	447.3	24	21	26
35	28	34	21.4	569.2	691.2	32	30	35
36	18	22	22.2	365.9	447.3	22	19	24
Mean (MPa)	**24.1**	**28.3**	**18.3**	**490.2**	**574.9**	**28.0**	**25.8**	**30.7**
SD (MPa)	**6.8**	**7.3**	**6.8**	**137.3**	**148.9**	**7.2**	**7.2**	**7.2**
CoV (%)	**28.0**	**25.9**	**36.9**	**28.0**	**25.9**	**25.8**	**28.0**	**23.6**

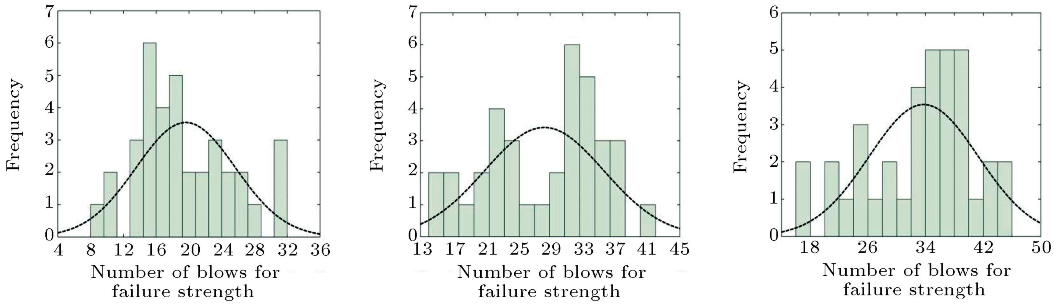
Table 8. Impact resistance test results and predicted failure strength for A3 group.

Specimen no.	Impact resistance test results					Predicted failure strength		
	FC	UR	PINPB (blows)	Impact energy (kN mm)		UR	0.95% prediction interval on number of blows for failure strength	
				FC	UR		Lower prediction bound	Upper prediction bound
1	28	39	39.3	569.2	792.9	32	29	35
2	12	16	33.3	244.0	325.3	17	12	19
3	27	32	18.5	548.9	650.6	31	28	34
4	15	18	20.0	305.0	365.9	19	16	22
5	31	36	16.1	630.2	731.9	35	32	38
6	31	36	16.1	630.2	731.9	35	32	38
7	33	37	12.1	670.9	752.2	37	34	40
8	26	29	11.5	528.6	589.6	30	27	33
9	35	39	11.4	711.6	792.9	39	36	42
10	42	46	9.5	853.9	935.2	46	43	49
11	35	39	11.4	711.6	792.9	39	36	42
12	39	44	12.8	792.9	894.5	43	40	46
13	31	35	12.9	630.2	711.6	35	32	38
14	30	34	13.3	609.9	691.2	34	31	37
15	31	35	12.9	630.2	711.6	35	32	38
16	30	34	13.3	609.9	691.2	34	31	37
17	41	45	9.8	833.5	914.9	45	42	48
18	38	42	10.5	772.5	853.9	42	39	45
19	32	36	12.5	650.6	731.9	36	33	39
20	24	26	8.3	487.9	528.6	28	25	31
21	19	23	21.1	386.3	467.6	24	20	26
22	34	38	11.8	691.2	772.5	38	35	41
23	30	34	13.3	609.9	691.2	34	31	37
24	17	22	29.4	345.6	447.3	21	18	24
25	18	22	22.2	365.9	447.3	22	19	25
26	33	37	12.1	670.9	752.2	37	34	40
27	20	25	25.0	406.6	508.3	24	21	27
28	23	26	13.0	467.6	528.6	27	24	30
29	33	38	15.2	670.9	772.5	37	34	40
30	35	40	14.3	711.6	813.2	39	36	42
31	35	40	14.3	711.6	813.2	39	36	42
32	32	37	15.6	650.6	752.2	36	33	39
33	25	28	12.0	508.3	569.2	29	26	32
34	27	30	11.1	548.9	609.9	31	28	34
35	39	43	10.3	792.9	874.2	43	40	46
36	29	34	17.2	589.6	691.2	33	30	36
Mean (MPa)	**29.44**	**33.75**	**15.66**	**598.60**	**686. 13**	**33.5**	**30.4**	**36.4**
SD (MPa)	**7.30**	**7.57**	**6.79**	**148.47**	**153.93**	**7.2**	**7.4**	**7.3**
CoV (%)	**24.80**	**22.43**	**43.42**	**24.80**	**22.43**	**21.5**	**24.2**	**20.0**



(a) First group (b) Second group (c) Third group

Figure 10. Frequency histogram and fitted normal curve of the first-crack strength distribution for all groups.



(a) First group (b) Second group (c) Third group

Figure 11. Frequency histogram and fitted normal curve of the failure strength distribution for all groups.

crack strength of the A1 group discs follows a normal distribution.

Failure strength. Figure 11 contains the histogram of the failure strength for all groups, with the fitted normal curve superimposed, suggesting that the failure strength distribution was hardly described using normal distribution. According to Tables 6 to 8, mean values for the failure strength of the A3 group, which contain 14% silica fume, was approximately 1.7 and 1.18 times greater than A1 and A2 groups, respectively. These results reveal that adding silica fume can increase the failure strength, which demonstrates the beneficial effects of reinforced silica concrete subject to impact loading. The true failure strength of A1 varies between 8 and 32 blows. For A2 disc groups, it varies between 14 and 42 blows and, in the case of A3 groups, it varies between 16 and 46 blows. The A1 group results showed a more scattered distribution than the other two groups. The maximum coefficient of variation of the third group is 27% and 13% less than the first and second group coefficients of variation, respectively. As shown, adding silica fume reduces the scatter in the results. The A3 specimen group has the highest standard deviation value among all specimen groups. Figure 12 demonstrates a comparison of the failure pattern in disc specimens.

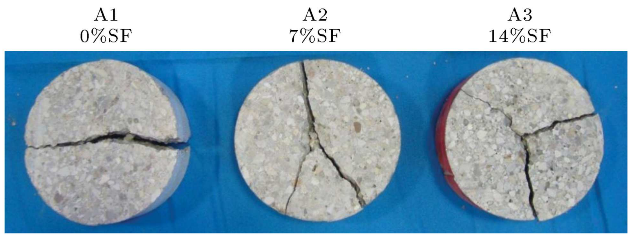


Figure 12. Failure mode of disc specimens for all groups.

Sources of large variations in impact resistance test. The source of large variations in results obtained from the ACI impact test may be attributed to the following reasons: a) The subjectivity of the test due to the visual identification of the first crack, which may occur in any direction; b) The impact resistance of concrete caused by a single-point impact, which might happen to be on a hard particle of coarse aggregates or on a soft area of mortar; c) The absence of criteria for preparing test specimens allows trawled, cut or smooth mold-faced surfaces to be tested, adding another source of variability; d) No criteria are stated for accepted or rejected failure mode [27].

Failure strength predictions. The correlation coefficient, also known as R, varies from 0.0 to 1.0, and is calculated using Eq. (1). Positive values of the correlation coefficient (the closer the coefficient is to 1), indicate a stronger degree of linear relationship between the variables. The correlation coefficient, R, takes a value of 0.971, 0.993 and 0.995 in A1 to A3 groups, respectively. The A3 specimen group has the highest correlation coefficient values:

$$R = \frac{\sum_{i=1}^{n}[(N_1)_i - \bar{N}_1][(N_2)_i - \bar{N}_2]}{\sqrt{\sum_{i=1}^{n}[(N_1)_i - \bar{N}_1]^2}\sqrt{\sum_{i=1}^{n}[(N_2)_i - \bar{N}_2]^2}}, \quad (1)$$

where N_2 is the failure strength, N_1 is the corresponding first-crack strength and n is the number of discs ($n = 36$) which have been drop-weight tested. Also, N_1 and N_2 are the mean values of the number of blows to cause the first visible crack and ultimate failure of the disc. The failure strengths behave almost linearly with the corresponding first-crack strengths. The objective of fitting the best straight line by the least square method is to minimize the sum of squares of error. The proposed linear relationship for the number of blows leading to frailer strength is shown in Eq. (2):

$$\hat{N}_2 = \alpha + \beta N_1, \quad (2)$$

where N_1 is the corresponding first-crack strength obtained from the experiment, $\hat{N}_2$ are the blows of failure strength obtained from those predicted, and α and β coefficients are derived from Eqs. (3) and (4), respectively:

$$\beta = \frac{[\sum_{i=1}^{n}(N_1)_i(N_2)_i] - n\bar{N}_1\bar{N}_2}{[\sum_{i=1}^{n}[(N_1)_i]^2] - n(\bar{N}_1)^2}, \quad (3)$$

$$\alpha = \bar{N}_2 - \beta\bar{N}_1. \quad (4)$$

Using linear regression, Eqs. (5) to (7) are obtained:

$$\hat{N}_2 = -0.37 + 1.1815N_1 \quad \text{for A1 group}, \quad (5)$$

$$\hat{N}_2 = 2.915 + 1.0533N_1 \quad \text{for A2 group}, \quad (6)$$

$$\hat{N}_2 = 5.239 + 0.9715N_1 \quad \text{for A3 group}. \quad (7)$$

Figure 13 illustrates linear regression on a data set. Based on Figure 13, the data are scattered around the line. As seen in this figure, increasing silica reduces the distance of data from the best-fitting curve. Also, using Eqs. (8) and (9), and the upper and lower bounds of Eqs. (5) to (7), a level of 95% confidence is calculated:

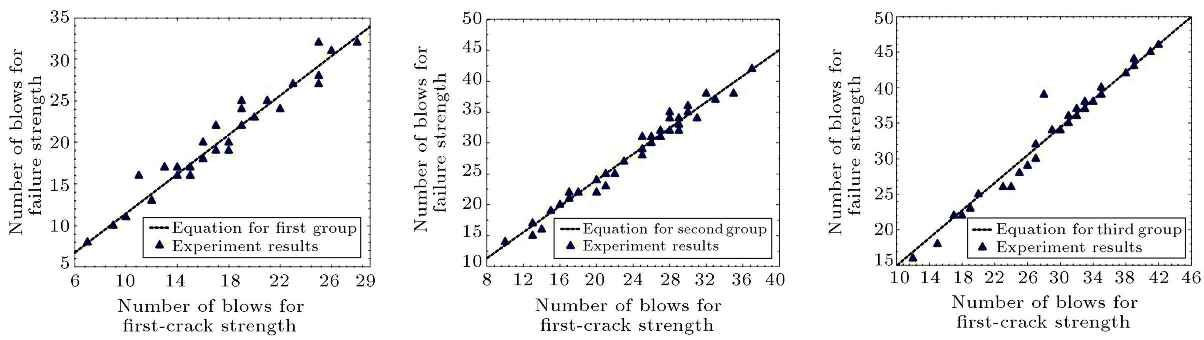
$$(\text{UPB})_j = (\hat{N}_2)_j + t\times(\text{SD})\times\sqrt{\frac{1}{n} + \frac{((N_1)_j - \bar{N}_1)^2}{\sum_{i=1}^{n}((N_1)_i - \bar{N}_1)^2}}, \quad (8)$$

$$(\text{LPB})_j = (\hat{N}_2)_j + t\times(\text{SD})\times\sqrt{\frac{1}{n} + \frac{((N_1)_j - \bar{N}_1)^2}{\sum_{i=1}^{n}((N_1)_i - \bar{N}_1)^2}}, \quad (9)$$

where t is the value of t student distribution for a level of confidence of 95% and SD is standard deviation. Lower and upper prediction bound values given in Eqs. (5), (6) and (7) are shown in Tables 6, 7 and 8.

Energy absorption and post crack strength. The impact energy per blow, applied by a 4.45 kg hammer dropped repeatedly from a 457 mm height on to a 63.5 mm steel ball, is 20.345 kN.mm (with the motion of freely falling bodies). The energy absorbed by the concrete disc for first crack and failure crack strength is shown in Tables 6 to 8. However, maximum absorbed energy for first and failure crack strength occurs in the A3 group. The mean value of energy absorbed by the A3 group for failure strength is 686.136 kN.mm, which was approximately 72% and 20% higher than the A1 and A2 groups, respectively. The percentage increase in the number of post first crack blows to failure is termed PINPB, and is also given in Tables 7, 8, and 9. Mean values of the PINPB parameter of the A2 group is 18.3%, which is 14%; 17% greater than the A1 and A3 groups, respectively. Silica increased to 7% has a positive effect on increasing PINPB; an increase of more than 7% has a negative effect on PINPB.

Minimum number of replications. The coefficient of variation of the test results, calculated above, has been presented in Tables 6 to 8. It can be used to determine the minimum number of tests, n, required for guaranteeing that the percentage error in the measured



(a) First group (b) Second group (c) Third group

Figure 13. Fitting straight lines to experimental data.

Table 9. Number of replications required to keep the error under a specific limit at 90% level of confidence.

Error (e%)	90% level of confidence					
	A1 group		A2 group		A3 group	
	FC	UR	FC	UR	FC	UR
< 10	15	17	13	11	10	8
< 15	7	8	6	5	5	4
< 20	4	4	3	3	3	2
< 25	3	3	2	2	2	1
< 30	2	2	1	1	1	1
< 35	1	1	1	1	1	1
< 40	1	1	1	1	1	1
< 50	1	1	1	1	1	1

Table 10. Number of replications required to keep the error under a specific limit at 95% level of confidence.

Error (e%)	90% level of confidence					
	A1 group		A2 group		A3 group	
	FC	UR	FC	UR	FC	UR
< 10	25	27	22	19	17	15
< 15	11	12	10	8	8	6
< 20	6	7	6	5	4	4
< 25	4	4	4	3	3	2
< 30	3	3	3	2	2	2
< 35	2	2	2	1	1	1
< 40	1	1	1	1	1	1
< 50	1	1	1	1	1	1

average value is below a specified limit, e, at a specific level of confidence, as given by Eq. (10) [26]:

$$n = \frac{[\mathrm{COV}]^2 t^2}{e^2}, \tag{10}$$

where COV is the coefficient of variation, and t is the value of the t student distribution for the specified level of confidence, 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 [28,29]. Table 9 presents the number of samples required to keep the error under various limits between 10% and 50%, at the 90% level of confidence. Table 9 shows that, if the error is retained lower than 10%, the minimum number of samples should be 15, 13 and 10 at A1, A2 and A3 groups, respectively, for the first-crack strength, at 90% levels of confidence. Also, for A1, A2 and A3 groups, at ultimate failure, at 90% levels of confidence, if the error is retained lower than 10%, the minimum numbers of samples are 17, 11 and 8, respectively. Table 10 demonstrates the number of samples required to keep the error under a specific limit, at 95% level of confidence. Moreover, Table 10 shows that if the error is retained lower than 10%, the minimum number of replications for A1 to A3 groups is 25, 22 and 17 for the first-crack strength and 27, 19 and 15, respectively. It is clear that adding silica fume to concrete decreases the number of tests required at each level of error.

5. Conclusion

In this paper, according to behavioral observations and obtained results of the statistical and experimental effects of silica fume on the impact resistance and mechanical properties of concrete, the following results were drawn:

- Adding silica fume to specimens improved the mean value of compressive strength. Mean compressive strength in the A3 group (14%SF) showed an increase of up to 22% and 15%, as compared to A1(0%SF) and A2(7%SF), respectively. The third group's coefficient of variation is 3% and 35% less than the same parameter in the first and second groups, respectively.
- The splitting test was conducted on 100 × 200 mm cylindrical specimens. The coefficient of variation of 7.99% belongs to specimen A3 (14%SF), which is 5% and 2.7% lower than A1 (0%SF) and A2 (7%SF), respectively.
- The highest mean flexural strength value of 5.18 MPa belongs to specimen A3, containing 14% silica fume, leading to 18% and 4% increase compared to A1 (0%SF) and A2 (7%SF), respectively. The coefficient of variation of 8.37% in the A3 group is 6.1% and 2.5% lower than the first and the second group coefficients of variation, respectively. Therefore, the coefficient of variation decreases with an increasing number of silica particles.
- The coefficient of variation (for failure strength) of the third group (14%SF) is 27% and 13% less than the first (0%SF) and second (7%SF) group coefficients of variation, respectively. Adding silica fume reduces the scatter in the coefficient of variation.
- Mean values for the strength of the first-crack of the A3 (14%SF) group was approximately 1.74, 1.22 times greater than A1 (0%SF) and A2 (7%SF) groups, respectively. The mean value of failure strength in the A3 group, containing 14% silica fume, was approximately 1.7 and 1.18 times greater than that of the A1 and A2 groups, respectively.
- Mean values of energy absorption of the A3 (14%SF) group was approximately 72 and 20% higher than A1 (0%SF) and A2 (7%SF) groups, respectively. Adding silica fume to concrete decreases the numbers of tests required at each level of error and improves accuracy.

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