IJST, Transactions of Civil Engineering, Vol. 39, No. C2+, pp 449-468
Printed in The Islamic Republic of Iran, 2015

EXPERIMENTAL AND STATISTICAL INVESTIGATION ON MECHANICAL PROPERTIES AND IMPACT RESISTANCE OF SYNTHETIC FIBER REINFORCED CONCRETE*

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Abstract– In the current study an experimental/statistical approach addressing key mechanical properties (compressive, tensile and flexural strength) and impact resistance of such new fibers with inclusion of different volume of polyphenylene Sulfide (PPS) fibers has been carried out on 288 specimens. Results from this study revealed that compressive, tensile and flexural strength exhibit a good fit with normal distribution with a coefficient of variation less than 10%. However, impact resistance results were dispersed with no considerable conformity to normal distribution with a coefficient of variation around 40~50%. Additionally, higher percentage of fibers led to higher level of data scatter which may be attributed to the considerable effect of the presence of more fiber-concrete interfaces. Tests also proved a direct correlation between percentage of fibers versus mean and coefficient of variation values. Moreover, based on acquired results a General Linear Model (GLM) was developed for impact resistance of PPS fibers considering fiber content. Required replications of tests considering fiber content and required accuracy were also proposed.

Keywords– Fiber reinforced concrete, PPS fibers, statistical, impact resistance, mechanical properties

1. INTRODUCTION

In recent years, high-strength concrete has been widely used in the world. The term "high strength concrete" refers to concretes with compressive strength of more than 42MPa [1]. In the construction industry, HSC has been beneficially adopted for reinforced pre-casted and pre-stressed products, structures, columns and shear walls of high-rise buildings, etc. High strength concrete and plain concrete are brittle materials [2-3]. Adding fibers is one method which makes concrete less brittle and resistant to cracking [4-5]. Fiber incorporation in concrete enhances many of the engineering properties of these materials such as fracture toughness, flexural strength, and resistance to fatigue, impact, thermal shock and spalling [6-12]. Numerous extensive experiments were carried out by many researchers around the world on the use of fibers in concrete [13-15]. Meanwhile, there have been a few studies on the impact resistance and mechanical properties of fiber-reinforced concrete particularly in statistics sense [16-19]. Little research has been undertaken on the mechanical and impact behavior of HPFRCC materials [20]. Different types of fibers including steel, glass, plastic, etc can be used in concrete. Polyphenylene Sulfide (PPS) is an engineering plastic which is a high-performance thermoplastic and an organic polymer, consisting of aromatic rings linked with sulfides. Synthetic fibers and textiles derived from this polymer are known to resist chemical and thermal attacks. PPS polymer is formed by reaction of sodium sulfide

*Received by the editors May 4, 2013; Accepted June 15, 2015.
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with p-dichlorobenzene. There are relatively few studies about the effects of the fibers on variation values of compressive, splitting tensile and flexural strengths of concrete specimens. Also, there are a few studies on statistical parameters on the impact resistance and energy absorption of it. Several impact tests have been used to demonstrate the relative brittleness and impact resistance of concrete and similar construction materials [21–24]. However, none of these tests has been declared as standard test, due to the lack of statistical data on the variation of the results. ACI Committee 544 [25] has proposed a drop-weight impact test to evaluate the impact resistance of concrete. This test is widely used because of its simplicity and economic advantages, but its results are often noticeably scattered. Most of the data obtained from these experiments have a coefficient of variation more than 25%. The variation of the impact resistance determined from this test is reported in the literature for steel and PP fiber reinforced concrete but not for PPS fiber.

2. RESEARCH SIGNIFICANCE

Relevant literature in the research area for PPS fibers reveal that there is still lack of combined experimental/statistical studies based on large number of implemented experimental tests considering key properties of these high potential materials to further study and verify their applicability in construction. Consequently, test plan was developed by the authors to further study FRC (with PPS fiber) in this research paper. Two hundred and eighty-eight specimens in total, which is significantly larger than the tests in similar studies, to provide a reliable and accurate baseline for statistical analyses, were cast, prepared and tested to achieve this goal.

3. APPLICATIONS OF PPS FIBERS

The applications of fibers in concrete industries depend on the designer and builder in taking advantage of the static and dynamic characteristics of this new material. The main areas of PFRC applications are:

a) Runway, Aircraft Parking, and Pavements

For the same wheel load FRC slabs could be about one half the thickness of plain concrete slab. FRC pavements are now in service in severe and mild environments.

b) Tunnel Lining and Slope Stabilization

PPS fiber reinforced shotcrete (PFRS) is being used to line underground openings and rock slope stabilization. It eliminates the need for mesh reinforcement and scaffolding.

c) Blast Resistant Structures

When plain concrete slabs are reinforced conventionally, tests showed [26] that there is no reduction of fragment velocities or number of fragments under blast and shock waves. Similarly, reinforced slabs of fibrous concrete, however, showed 20 percent reduction in velocities, and over 80 percent in fragmentations.

d) Thin Shell, Walls, Pipes, and Manholes

Fibrous concrete permits the use of thinner flat and curved structural elements. PPS fibrous shotcrete can be used in the construction of hemispherical domes using the inflated membrane process

e) Dams and Hydraulic Structure

FRC is being used for the construction and repair of dams and other hydraulic structures to provide resistance to cavitation and severe errosion caused by the impact of large waterboron debris.

f) Other Applications

These include machine tool frames, lighting poles, water and oil tanks and concrete repairs.

4. EXPERIMENTAL STUDY AND PROCEDURES

Three volume fraction of PPS fiber equal to 0%, 0.25% and 0.5% were considered in this study. Considering the three different fiber contents, total specimens in this study would be categorized as: 60 specimens (100×100×100 mm) for compressive strength (20 specimens per group), 60 specimens (100×200mm) for tensile strength (20 specimens per group), 60 specimens (320×80×60 mm) for flexural strength (20 specimens per group) and 108 specimens (150×64 mm) for impact resistance (36 specimens per group). The proposed drop-weight test according to ACI Committee 544 which is commonly used for impact strength of FRC, due to its practicality, have been used for impact resistance test of PFRC (PPS fiber reinforced concrete) specimens in the current study. Most of the data obtained from such tests have a coefficient of variation of more than 25%. The variation in impact resistance as determined from this test has been reported for FRC [17–23], but not for PFRC. It must be noted that all three groups of concrete specimens were cast with identical water-cement ratio of 0.44 with three different fiber contents of 0, 0.25, and 0.5% by weight, which are designated as A-0(Ref), A-0.25(0.25%PPS) and A-0.5(0.5%PPS), respectively. Numeric value represents the percentage of fibers used in the corresponding group of specimens. For example, A-0.5 represents the group of specimens with 0.5 % fibers. Compressive strength tests were performed on twenty 100×100×100 mm cubic specimens per group according to ASTM C39. Tensile strength tests were conducted on twenty 100×200 mm cylindrical specimens per group according to ASTM C496. Flexural strength tests were conducted on twenty 60×80×320mm beam specimens per group according to ASTM C78. Although compressive, tensile and flexural strength test procedures are almost fixed, a brief explanation on drop test procedure under taken in this research seems to be of better clarification. Drop-weight tests were conducted following the ACI 544 Committee’s recommendations. For each concrete mix, ten 150×300 mm cylindrical specimens were made, and then each was sliced with a diamond-blade concrete saw into four 64 mm cylindrical discs. During impact tests, a cylindrical disc was set on a base plate within four positioning lugs, and impacted by repeated blows. Blows were applied through a 4.45 kg hammer falling continually from a 457 mm height onto a steel ball with the diameter of 63.5mm, that was centered at the top surface of the disc. The number of blows required to cause the first visible crack and then failure were recorded. With the aid of a magnifier equipped with built-in flashlight, after each blow, the number of blows to initiate the first visible crack on the top surface was defined as the first-crack strength, while the number of blows to generate failure of the disc was identified as the failure strength. All tests were performed after curing the specimens for 28 days.

5. MATERIALS AND SPECIMENS PREPARATION

In this experimental study Portland cement (ASTM Type II) was used. Fibers used in this study were PPS fibers (See Fig. 1.). Coarse aggregate with maximum particle size of 9.5 mm and fine aggregate with 3.3 fineness modulus were used. In Table 1 mechanical properties of PPS fibers are given. A high range water reducer agent with the commercial name of Mape110 was used to adjust the workability of the concrete mixtures. For batching, cement was mixed with aggregates for one minute. Then water and water reducer agent were added to the mixture and thoroughly mixed. The mixture proportions for three different mixes are provided in Table 2. Then mixed concrete was cast into cubic form (100×100×100mm), cylindrical form (100×200mm), cylindrical form (150×300mm), and prismatic form (320×80×60mm) for compressive, tensile, impact and flexural tests, respectively. All specimens were stored at 23^{0C} and 100%

relative humidity for the first 24 hours. After demolding, specimens were cured in 23^{0C} water for 28 days. Specimens were tested after 28 days from batching.

Fig. 1. PPS fiber

Table 1. Mechanical properties of PPS fibers

Length(mm)	Thickness(mm)	Density $\frac{kg}{m^3}$	Modulus of Elasticity MPa	Water Absorption(%)	Shape
50-54	0.07	0.9	3500	0.02	Straight

Table 2. Proportions of concrete mixtures per cubic meter concrete

Mix No.	Group	$\frac{W}{C}$	Water $\frac{kg}{m^3}$	Cement $\frac{kg}{m^3}$	PPS fiber $\frac{kg}{m^3}$	Fine agg. $\frac{kg}{m^3}$	Coarse agg. $\frac{kg}{m^3}$	SP (Kg/m^3)
1	A-0(0%PPS)	0.44	165	375	0	980	980	3.9
2	A-0.25(0.25%PPS)	0.44	165	348	26	980	980	3.9
3	A-0.5(0.5%PPS)	0.44	165	322	53	980	980	3.9

6. RESULTS AND DISCUSSION

a) Compressive strength

The compressive strength tests were carried out according to ASTM C39, using a digital standard automatic testing machine of 2000 kN capacity. Cube specimens are shown in Fig. 2. Compressive strength test results are given in Table 3. Results indicate that the addition of fibers to specimens improved compressive strength and it increases with increasing PPS fiber percentage. Figure 3 presents the histogram of the results obtained from 60 compressive strength test specimens. This figure shows that the results for all three concrete series are almost normally distributed and fit well with the superimposed normal distribution curve. A-0.5 specimen group has the highest mean compressive strength value among all the specimen groups, while exhibiting the highest standard deviation at the same time. Standard deviation of this group is 85 % and 28 % more than A-0 and A-0.25 groups, respectively. As it is observed, by increasing fiber percentage in concrete specimens, dispersion of compressive strength data is increased accordingly. Also, the standard deviation and coefficient of variation are increasing. The standard deviation and coefficient of variation increase as well. In compressive strength requirement of concrete, standard deviation of about 4–6 MPa is considered acceptable [27]. The values of the coefficient of variation show further evidence of good quality control of concrete specimens. The coefficient of variation is lower than a limit of 15% suggested by Swamy and Stavrides [28]. Moreover, Day [27] suggested that a coefficient of variation between 5% and 10% generally represents reasonable quality control, as the acquired results here fit in that range of variation. Figure 4 represents the normal probability plot obtained from the compressive strength tests results. According to this figure, experimental data are around the normal probability distribution line and only a few data points are on the normal distribution line. The stress - strain behaviour of three groups under compression is shown in Fig. 5.

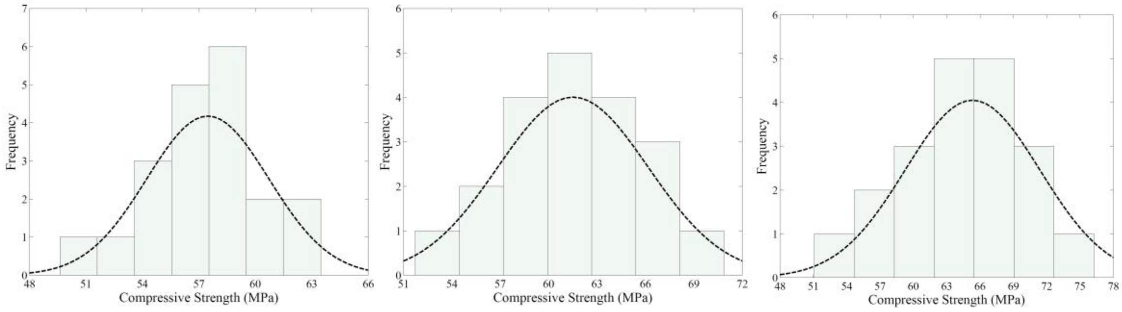
Three 150×300 mm cylindrical specimens were fabricated from each mix design (totally 9 specimens). Using compressive strength testing equipment which is capable of measuring the stress-strain curve of concrete, stress-strain curves were plotted according to ASTM C89. In Fig. 5 the obtained stress-strain curve and the way of experiment have been presented. As it is observed in the stress-strain curve, for three mix designs, increasing the fiber percentage, ultimate strain of concrete will increase. In Table 4 values of the ultimate strain and the strain corresponding to the ultimate compressive stress have been presented.

Fig. 2. Concrete specimens for compressive strength test

Table 3. Compressive strength test results

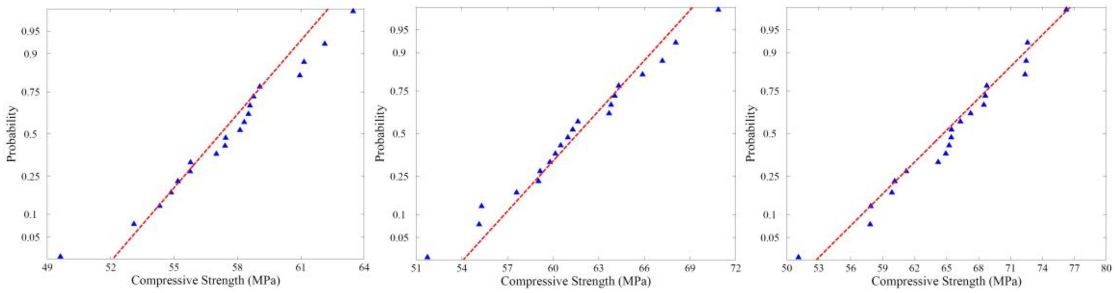
Specimen No.	Compressive Strength (MPa)		
	A-0	A-0.25	A-0.5
1	58.12	59.04	57.83
2	53.1	55.14	68.50
3	57.44	61.29	76.24
4	55.76	60.50	65.24
5	61.15	64.05	57.88
6	58.52	70.86	67.26
7	54.32	67.18	51.10
8	58.59	60.97	68.64
9	60.95	57.60	65.46
10	55.78	61.63	65.44
11	54.86	68.06	64.93
12	55.18	63.68	66.30
13	62.13	64.31	64.21
14	63.47	59.79	61.22
15	58.32	51.74	72.47
16	59.06	65.88	68.78
17	49.62	59.15	60.13
18	57.41	60.15	72.60
19	58.76	55.30	72.37
20	57	63.81	59.87
Mean(MPa)	**57.47**	**61.51**	**65.32**
SD(MPa)	**3.24**	**4.7**	**6**

CoV(%)	5.64	7.58	9.29



a)A-0 (Ref.) b) A-0.25 (0.25% PPS) c) A-0.5 (0.5% PPS)

Fig. 3. Distribution of compressive strength test results



a)A-0 (Ref.) b) A-0.25 (0.25% PPS) c) A-0.5 (0.5% PPS)

Fig. 4. Normal probability for compressive strength specimens

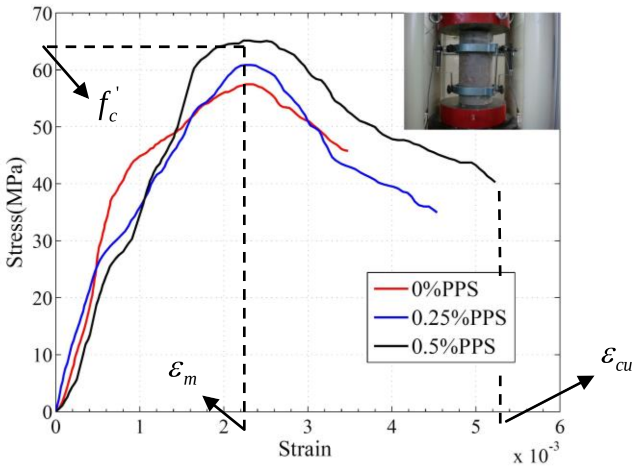


Fig. 5. Stress-strain curve and test setup for three groups

Table 4. Stress-strain curve test results

	A-0 (Ref.)	A-0.25 (0.25% PPS)	A-0.5 (0.5% PPS)
$f_c^{'}$ (MPa)	57.46	60.85	65.14
ε_m	0.002301	0.002324	0.002347
ε_{cu}	0.003479	0.004538	0.005232

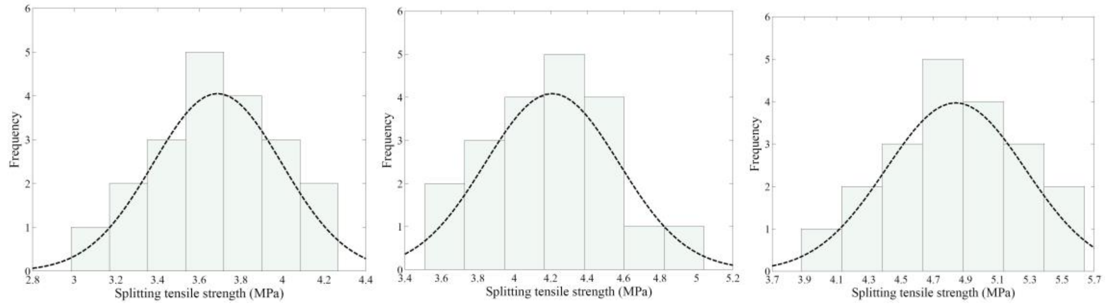
b) Splitting test

Tensile strength tests were performed on 100×200mm cylindrical specimens according to ASTM C 496. Figure 6 shows cylindrical specimens for splitting test and failure mode of specimens. Histogram of tensile strength of all groups is shown in Fig. 7. As it can be seen in this figure, results are almost normally distributed and fit well with the normal distribution curve. Results of splitting tensile strength tests for three groups are presented in Table 5. Table 5 shows that inclusion of fibers in specimens improves the mean value of tensile strength. Mean tensile strength values were 3.69, 4.21 and 4.84MPa in A-0, A-0.25 and A-0.5 groups, respectively. Therefore a maximum increase of 31%, 15% in the mean tensile strength can be observed in A-0.5 compared to A-0 and A-0.25, respectively. Range of variation (the difference between maximum and minimum values) of 1.76 MPa in A-0.5 and 1.28 MPa in A-0 were observed in results. The standard deviation values for A-0 to A-0.5 groups were 0.31, 0.36 and 0.43 MPa, respectively. So, the increase of PPS fibers in mixtures increased the standard deviation. The A-0.5 has the highest values of standard deviation that were 39% and 19% more than A-0, A-0.25, respectively. The coefficient of variation, also known as normalized measure of dispersion of probability distributions, was 8.38, 8.71 and 8.95% in A-0, A-0.25 and A-0.5 groups, respectively. The coefficient of variation (meaningful index of variability) of 8.95% belongs to specimen A-0.5 that are 7% and 3% greater than A-0, A-0.25, respectively. Normal probability plots for all groups are shown in Fig. 8. According to this figure, few data points are in full agreement with normal distribution lines and most data are around the normal probability distribution line.

Fig. 6. Cylinder specimens for splitting test and Failure mode of specimens

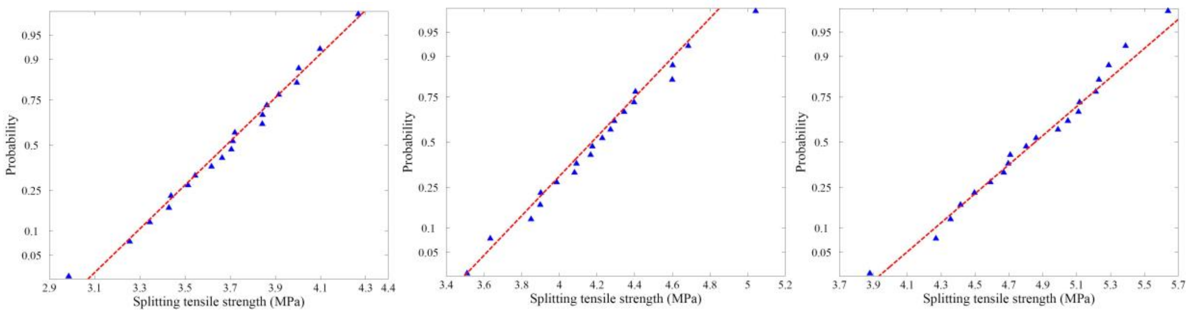
Table 5. Splitting tensile strength for three groups

Specimen No.	**Tensile strength (MPa)**		
	A-0	**A-0.25**	**A-0.5**
1	3.26	4.08	4.70
2	2.99	4.29	4.80
3	3.71	4.27	5.64
4	3.55	3.51	4.35
5	3.34	4.60	4.41
6	3.44	4.09	5.21
7	3.51	4.22	4.67
8	3.84	3.63	4.27
9	3.71	3.84	5.38
10	3.86	3.98	3.88
11	3.43	5.04	4.86
12	3.62	4.16	5.29
13	3.66	4.34	5.11
14	3.72	4.39	4.69
15	3.84	4.17	5.11
16	4.00	4.40	4.99
17	4.10	3.89	5.05
18	3.92	4.6	5.23
19	4.27	4.68	4.59
20	4.00	3.90	4.49
Mean(MPa)	**3.69**	**4.21**	**4.84**
SD(MPa)	**0.31**	**0.36**	**0.43**
CoV(%)	**8.38**	**8.71**	**8.95**



a)A-0 (Ref.) b) A-0.25 (0.25% PPS) c) A-0.5 (0.5% PPS)

Fig. 7. Distribution of splitting tensile strength for test results

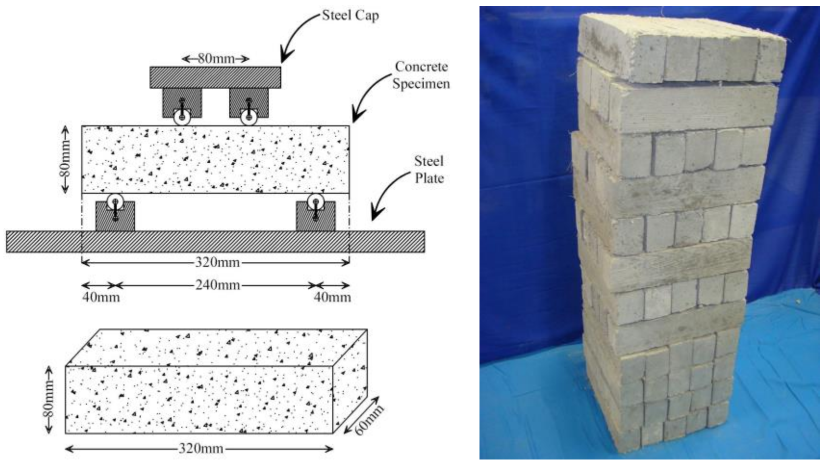


a)A-0 (Ref.) b) A-0.25 (0.25% PPS) c) A-0.5 (0.5% PPS)

Fig. 8. Normal probability plot for all groups versus splitting tensile strength

c) Flexural strength

Flexural strength test was performed on sixty 320×80×60 mm specimens following ASTM C78. Flexural test apparatus and specimens are shown in Fig. 9. Results of flexural strength test, carried out on 60 specimens in three groups, are presented in Table 6. The highest mean flexural strength values belong to A-0.5 specimens, which is 32 % and 7 % more than mean flexural strength values of A-0 and A-0.25 specimens, respectively. The standard deviation of A-0.5 group is 59% and 22% more than standard deviation values of A-0 and A-0.25 specimens, respectively. Frequency histograms of flexural strength for all three groups are shown in Fig. 10. This figure shows that flexural strengths of all three groups follow the normal distribution. Coefficient of variation of A-0.5 group is 18% and 13% more than this parameter for A-0 and A-0.25, respectively. As it is considered, with increasing the fiber percentage, coefficient of variation increases. This shows that using fibers leads to more data scattering. Also, increasing the fiber percentage makes the flexural strengths higher. Normal probability distribution curve for the flexural strength of all three groups is shown in Fig. 11.



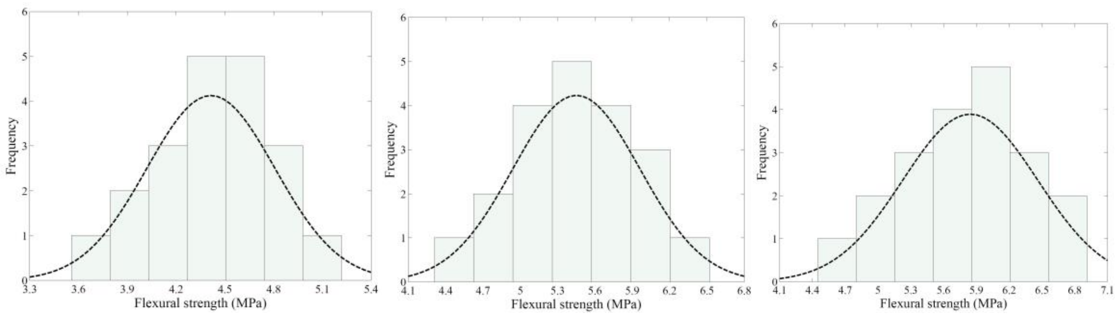
a) Flexural test machine b) Flexural specimens

Fig. 9. Third-Point loading method

The tensile and flexural strength, in terms of compressive strength were calculated, based on the mean values. As it is seen, flexural strength has higher values than the tensile strength. The relation between compressive strength and tensile strength is approximately linear (see Fig. 12.)

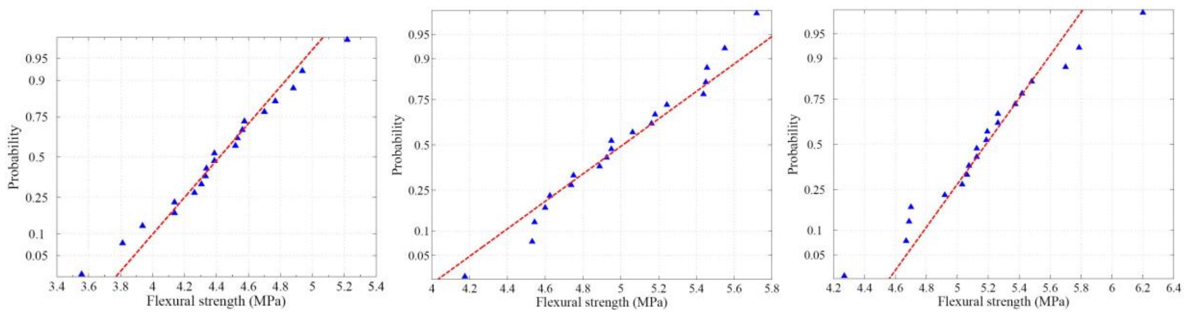
Table 6. Module of rupture for three groups

Specimen No.	**Modulus of rupture (MPa)**		
	A1(0%PPS)	**A2(0.25%PPS)**	**A3(0.5%PPS)**
1	4.14	5.43	5.49
2	4.31	5.92	6.18
3	3.56	6.52	6.38
4	4.58	5.54	6.03
5	4.56	6.01	5.34
6	4.34	5.23	5.99
7	4.39	4.31	5.08
8	4.77	4.97	5.87
9	4.88	5.79	5.80
10	4.52	5.23	6.44
11	5.22	5.36	4.45
12	3.94	5.74	5.80
13	4.70	6.00	4.95
14	4.39	5.53	6.48
15	4.94	5.63	5.34
16	4.53	4.73	6.13
17	4.14	4.81	5.71
18	4.33	5.42	6.74
19	3.81	5.12	5.71
20	4.26	5.69	6.91
Mean(MPa)	**4.41**	**5.45**	**5.84**
SD(MPa)	**0.39**	**0.51**	**0.62**
CoV(%)	**8.92**	**9.37**	**10.56**



a)A-0 (Ref.) b) A-0.25 (0.25% PPS) c) A-0.5 (0.5% PPS)

Fig. 10. Frequency histogram and fitted normal curve of the flexural strength of all groups



a)A-0 (Ref.) b) A-0.25 (0.25% PPS) c) A-0.5 (0.5% PPS)

Fig. 11. Normal probability plot versus the flexural strength of all groups

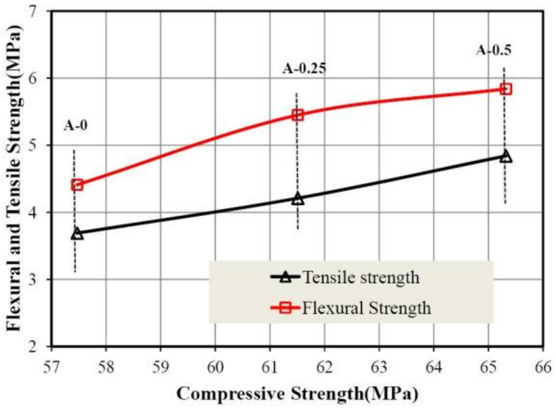
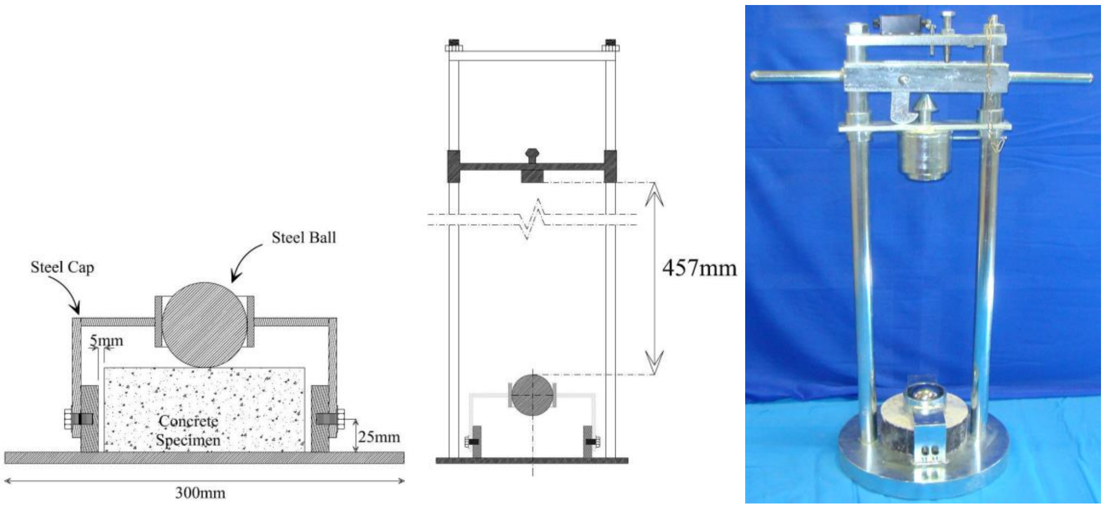


Fig. 12. Relation between compressive strength with tensile and flexural strength

d) Impact resistance

Drop-weight test results of 108 disc specimens including, 36 specimens per group, are given in Tables 7 to 9. Each table represents results for one group only of three mixes. The impact test apparatus and disc specimens are shown in Fig. 13a before test. Details of impact apparatus includes a steel test mold, a falling hammer and a steel cap which are presented in Fig. 13b.

a) Disc specimen



b) Dimensions of apparatus and steel cap

Fig. 13. Falling hammer test

Table. 7. Impact resistance test results and predicted failure strength for A-0 (Ref.) group

Specimen No.	Impact resistance test results					Predicted failure strength		
	FC	UC	PINPB (blows)	Impact energy (kN mm)		UC_p	0.95% Prediction interval on number of blows for failure strength	
				En-FC	En-UC		Lower prediction bound	Upper prediction bound
1	11	16	45.5	223.6	325.3	13	10	16
2	12	13	8.3	244	264.3	14	11	17
3	25	28	12	508.3	569.2	29	26	32
4	15	16	6.7	305	325.3	17	14	20
5	18	20	11.1	365.9	406.6	21	18	24
6	7	8	14.3	142.3	162.6	8	5	11
7	9	10	11.1	183	203.3	10	7	14
8	17	22	29.4	345.6	447.3	20	17	23
9	22	24	9.1	447.3	487.9	26	22	29
10	15	16	6.7	305	325.3	17	14	20
11	16	20	25	325.3	406.6	18	15	22
12	21	25	19	426.9	508.3	24	21	27
13	15	16	6.7	305	325.3	17	14	20
14	14	17	21.4	284.6	345.6	16	13	19
15	19	22	15.8	386.3	447.3	22	19	25
16	16	18	12.5	325.3	365.9	19	16	22
17	20	23	15	406.6	467.6	23	20	26
18	17	19	11.8	345.6	386.3	20	17	23
19	13	17	30.8	264.3	345.6	15	12	18
20	19	24	26.3	386.3	487.9	22	19	25
21	10	11	10	203.3	223.6	11	8	15
22	26	31	19.2	528.6	630.2	30	27	33
23	28	32	14.3	569.2	650.6	33	29	36
24	12	13	8.3	244	264.3	14	11	17
25	15	16	6.7	305	325.3	17	14	20
26	14	16	14.3	284.6	325.3	16	13	19
27	16	18	12.5	325.3	365.9	18	16	22
28	25	32	28	508.3	650.6	29	26	32
29	13	17	30.8	264.3	345.6	15	12	18
30	12	13	8.3	244	264.3	14	11	17
31	19	25	31.6	386.3	508.3	22	19	25
32	25	27	8	508.3	548.9	29	26	32
33	15	17	13.3	305	345.6	17	14	20
34	18	19	5.6	365.9	386.3	21	18	24
35	16	18	12.5	325.3	365.9	19	16	22
36	23	27	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(MPa)	**5**	**6.1**	**9.3**	**102.6**	**123.1**	**6**	**5.9**	**5.9**
CoV(%)	**29.9**	**30.9**	**57.8**	**29.9**	**30.9**	**30.6**	**35.6**	**26**

FC: Number of blows for First-crack strength.
UC: Number of blows for failure strength.
SD= standard deviation;
En-FC: Energy of first-crack strength
En-UC: Energy of failure strength
UC_p= failure strength predicting
PINPB: Percentage increase in number of post-first-crack blows in A-0 (Ref.) series.
CoV= coefficient of variation

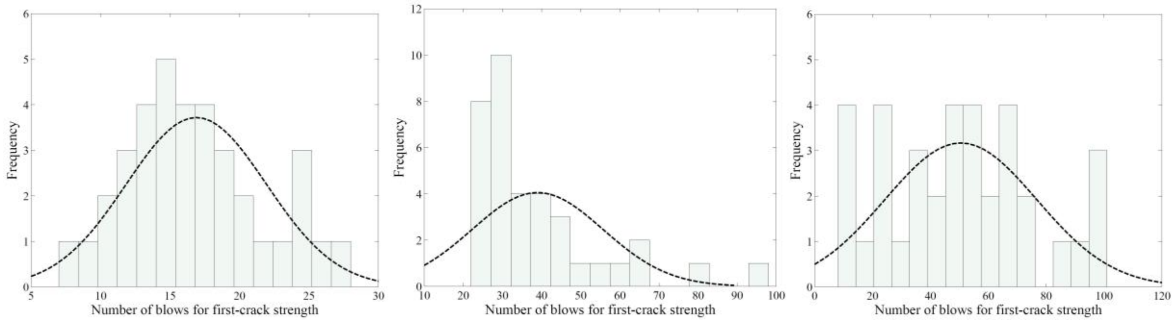
Table. 8. Impact resistance test results and predicted failure strength for A-0.25 (0.25%PPS) group

Specimen No.	**Impact resistance test results, A2(0.25%PPS) group**					**Predicted failure strength**		
	FC	UC	**PINPB (blows)**	**Impact energy (kN mm)**		**UC_p**	**0.95% Prediction interval on number of blows for failure strength**	
				En-FC	**En-UC**		**Lower prediction bound**	**Upper prediction bound**
1	27	33	22.2	549	671	33	26	40
2	60	68	13.3	1221	1383	72	62	81
3	30	34	13.3	610	692	36	30	43
4	31	40	29	631	814	38	31	44
5	33	38	15.2	671	773	40	34	46
6	44	51	15.9	895	1038	53	47	59
7	63	87	38.1	1282	1770	75	65	86
8	32	39	21.9	651	793	39	32	45
9	30	36	20	610	732	36	30	43
10	31	35	12.9	631	712	38	31	44
11	63	72	14.3	1282	1465	75	65	85
12	41	51	24.4	834	1038	49	43	55
13	46	59	28.3	936	1200	55	49	62
14	27	37	37	549	753	33	26	40
15	25	30	20	509	610	30	23	38
16	27	31	14.8	549	631	33	26	40
17	29	37	27.6	590	753	35	28	42
18	24	30	25	488	610	29	21	37
19	27	32	18.5	549	651	33	26	39
20	54	66	22.2	1099	1343	65	57	73
21	28	33	17.9	570	671	34	27	41
22	38	45	18.4	773	916	46	40	52
23	35	42	20	712	854	42	36	48
24	33	38	15.2	671	773	40	34	46
25	23	34	47.8	468	692	28	20	36
26	39	46	17.9	793	936	47	41	53
27	40	48	20	814	977	48	42	54
28	36	43	19.4	732	875	43	37	49
29	43	50	16.3	875	1017	52	46	58
30	32	38	18.8	651	773	39	32	45
31	30	35	16.7	610	712	36	30	43
32	29	31	6.9	590	631	35	28	42
33	82	94	14.6	1668	1912	98	82	113
34	98	118	20.4	1994	2401	117	96	137
35	22	29	31.8	448	590	27	19	35
36	51	61	19.6	1038	1241	61	54	68
Mean(MPa)	38.97	46.97	**21**	**793**	**956**	47	**39.78**	**54.17**
SD(MPa)	16.74	20.02	**8**	**341**	**407**	20	**17.56**	**22.18**
CoV(%)	42.97	42.63	**38.3**	**43**	**43**	42	**44.15**	**40.95**

Table. 9. Impact resistance test results and predicted failure strength for A-0.5 (0.5%PPS) group

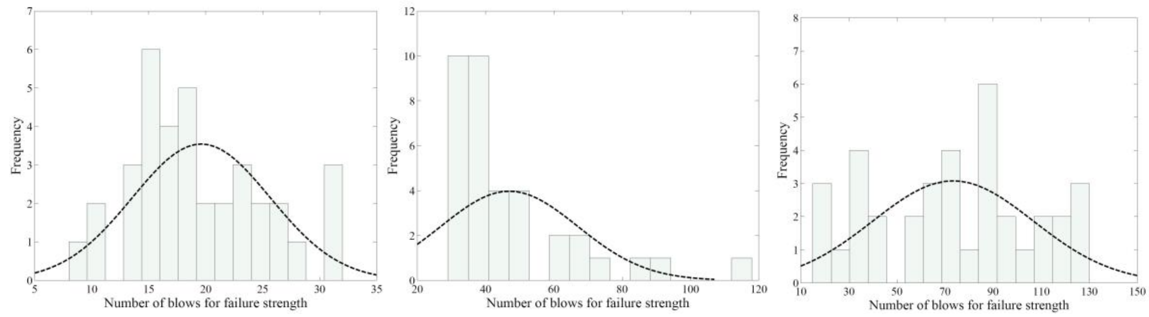
Specimen No.	Impact resistance test results, A3(0.5%PPS) group					Predicted failure strength		
	FC	UC	PINPB (blows)	Impact energy (kN mm)		UC_p	0.95% Prediction interval on number of blows for failure strength	
				En-FC	En-UC		Lower prediction bound	Upper prediction bound
1	70	116	65.7	1424	2360	97	86	108
2	24	35	45.8	488	712	41	28	54
3	61	83	36.1	1241	1688	86	76	96
4	94	113	20.2	1912	2298	126	109	144
5	76	123	61.8	1546	2502	104	92	117
6	10	17	70	203	345	24	8	41
7	68	89	30.8	1383	1810	95	84	105
8	38	68	78.9	773	1383	58	48	68
9	44	59	34.1	895	1200	65	56	75
10	11	21	90.9	223	427	25	9	41
11	47	69	46.8	956	1403	69	60	78
12	23	35	52.2	467	712	40	27	53
13	24	39	62.5	488	793	41	28	54
14	38	68	78.9	773	1383	58	48	68
15	48	85	77.1	976	1729	70	61	79
16	13	24	84.6	264	488	28	12	43
17	47	72	53.2	956	1464	69	60	78
18	84	110	30.9	1708	2237	114	100	129
19	98	128	30.6	1993	2604	131	113	150
20	69	96	39.1	1403	1953	96	85	107
21	101	116	14.8	2054	2360	135	115	154
22	57	87	52.6	1159	1770	81	72	91
23	8	15	87.5	162	305	22	5	39
24	26	34	30.8	528	691	44	31	56
25	55	87	58.2	1118	1770	79	70	88
26	30	61	103.3	610	1241	48	37	60
27	74	97	31.1	1505	1973	102	90	114
28	56	70	25	1139	1424	80	71	89
29	19	35	84.2	386	712	35	21	49
30	49	65	32.6	996	1322	71	62	81
31	59	73	23.7	1200	1485	84	74	93
32	56	87	55.3	1139	1770	80	71	89
33	33	42	27.3	671	854	52	41	63
34	44	85	93.2	895	1729	65	56	75
35	97	130	34	1973	2644	130	112	148
36	67	107	59.7	1363	2176	93	83	104
Mean(MPa)	**50.49**	**73.4**	**52.8**	**1027**	**1492**	**73**	**61.64**	**85.1**
SD(MPa)	**26.25**	**33.4**	**24.1**	**534**	**678**	**32**	**31.62**	**32.5**
CoV(%)	**51.97**	**45.4**	**45.6**	**51**	**45**	**44**	**51.29**	**38.25**

1. First-crack strength: The results show that the first-crack strength of all group discs hardly followed a normal distribution. It is judged how approximately the first-crack strength of A-0 (Ref.) group discs followed a normal distribution compared to other groups. Frequency histogram and fitted normal curve of the first-crack strength distribution for all groups are shown in Fig. 14. The result shows that, mean values of First-crack strength for A-0, A-0.25 and A-0.5 groups was 16.9, 38.97, 50.49, respectively. Fibers have provided three-dimensional fibrous reinforcement, which have assisted a disc in absorbing the impact energy of repeated blows. Thus fibers cause downplaying the impetus of a disc to cracks and postponing the presence of the first crack [29]. According to Tables 7 to 9, the first crack strength in A-0.5 group is greater than other groups. Mean value for strength of first-crack of A-0.5 group was approximately 199, 29% greater than A-0 and A-0.25 groups, respectively. The incorporation PPS fiber in the mixtures from 0 to %0.5, generally increased the standard deviation. The standard deviations of first-crack strength were 5, 16.74 and 26.25 and the corresponding coefficients of variation were 29.9%, 42.97% and 51.97% in A-0 to A-0.5 groups, respectively. Also, the highest standard deviations strength of first-crack belongs to A-0.5 group. As shown, with inclusion of fibers, the scatter in the results increased.The highest coefficient of variation of first-crack strength belongs to A-0.5 group that is 74% and 21% greater than those in A-0 and A-0.25 groups, respectively.



a)A-0 (Ref.) b) A-0.25 (0.25% PPS) c) A-0.5 (0.5% PPS)

Fig. 14. Frequency histogram and fitted normal curve of the first-crack strength distribution for all groups



a)A-0 (Ref.) b) A-0.25 (0.25% PPS) c) A-0.5 (0.5% PPS)

Fig. 15. Frequency histogram and fitted normal curve of the failure strengths distribution for all groups

2. Failure strength: Figure 15, the histogram of failure strengths for all groups, with fitted normal curve superimposed, suggests that the failure strength distribution was hardly described using the normal distribution. According to Tables 7 to 9, mean values of failure strengths of A-0.5, A-0.25, A-0 groups are 19.6, 46.97and 73.4, Mean values for failure strength of A-0.5 group was approximately 3.74, 1.56 times greater than A-0 and A-0.25 groups, respectively. Failure strengths will increase due to the inclusion of fiber in concrete mixture. The highest standard deviation values of 33.4 blows belongs to A-0.5 group, which is approximately 5.48, 1.67 times greater than A-0 and A-0.25 groups, respectively. The failure strength varies from 8 to 32 blows for A-0 group, from 29 to 118 blows for A-0.25 group, and from 15 to 130 blows for A-0.5 group. The coefficients of variation of failure strength were 30.9, 42.63 and 45.49% for A-0, A-0.25 and A-0.5 groups, respectively. The highest coefficient of variation of failure strength belongs to specimen A-0.5 that is 47% and 7% greater than those in A-0 and A-0.25, respectively. Results of group A0.5 show more scatter than the other two groups. The incorporation of PPS fibers in the mixtures from 0 to 0.5%, generally increases the scatter in the results. Failure modes of disc specimens for all groups are shown in Fig. 16.

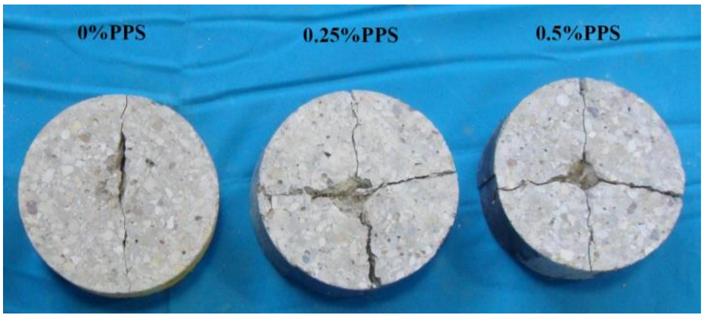


Fig. 16. Failure mode of disc specimens for all groups

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

a) The Subjectivity of the test due to visual identifications 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) Absence of criteria for preparing test specimens allows trawled, cut or smooth mold-faced surfaces to be tested, which provides another source of variability.
d) No criteria are stated for accepted or rejected failure mode [30].

4. Failure strength predictions: The correlation coefficient, also known as R, varies from -1.0 to1.0, and is calculated using Eq. (1). Positive values of correlation coefficient (the closer value to 1) indicate a stronger degree of linear relationship between the variables. The correlation coefficient, R, takes a value of 0.971, 0.944 and 0.958 in A-0, A-0.25 and A-0.5 groups, respectively. A-0 specimen group has the highest correlation coefficient values.

$$R = \frac{\sum_{i=1}^{n}\left[(N_1)_i - \overline{N}_1\right]\left[(N_2)_i - \overline{N}_2\right]}{\sqrt{\sum_{i=1}^{n}\left[(N_1)_i - \overline{N}_1\right]^2}\ \sqrt{\sum_{i=1}^{n}\left[(N_2)_i - \overline{N}_2\right]^2}} \tag{1}$$

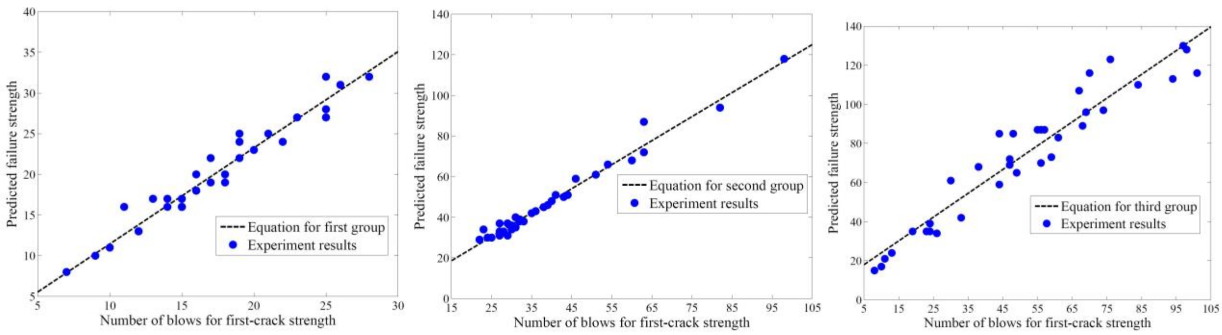
where N_2 is the failure strength, N_1 is the corresponding first-crack strength and n is the number of discs ($n = 36$) which have been drop-weight tested. Also, $\overline{N}_1, \overline{N}_2$ are the mean values of the number of blows that cause the first visible crack and ultimate failure of the disc, respectively. The failure strengths behave almost linearly with the corresponding first-crack strengths. The objective of fitting the best straight line by least square method is to minimize the sum of squares of errors.The best fit in the least-squares sense minimizes the sum of squared errors. This means that the line equation has a different sum of squares for the error in each observation. In this method, error is vertical distance between true values and calculated values. For each category of statistical observations, different lines include sum of squares of errors. The best fitting curve is the curve in which $\sum e_i^2$ includes its less amount. The proposed linear relationship for number of blows leading to failure strength is shown in Eq. (2).

$$\hat{N}_2 = \alpha + \beta N_1 \tag{2}$$

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

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

$$\alpha = \bar{N}_2 - \beta\bar{N}_1 \tag{4}$$



a)A-0 (Ref.) b) A-0.25 (0.25% PPS) c) A-0.5 (0.5% PPS)

Fig. 17. Fitting straight lines to experimental data

The linear regression has been used in Eqs. (5-7). Figure 17 illustrates a linear regression on a data set. Using Eq. (8) and (9), with upper and lower bounds of Eqs. (7-9), a level of 95% confidence is calculated.

$$\hat{N}_2 = -0.37 + 1.1815 N_1 \qquad \text{For A-0 (Ref.)} \tag{5}$$

$$\hat{N}_2 = 0.9 + 1.1823 N_1 \qquad \text{For A-0.25} \tag{6}$$

$$\hat{N}_2 = 11.93 + 1.2164 N_1 \qquad \text{For A-0. 5} \tag{7}$$

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

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

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. (5-7) are shown in Tables 7, 8 and 9.

5. Energy absorption and post crack strength: The impact energy per blow, applied by a 4.45 kg hammer dropped repeatedly from 457 mm height on top of a 63.5 mm steel ball, is 20.345 kN.mm (with the motion of freely falling bodies). Energy absorbed by the concrete disc for first crack and failure crack strength is shown in Tables 7 to 9. According to these tables the maximum absorbed energy for first crack and failure strength occurs in A-0.5 group. Mean value of energy absorbed by A-0.5 group for failure strength was approximately 275 % and 56 % higher than A-0 and A-0.25 groups, respectively. Percentage increase in the Number of Post initial crack Blows to failure is labeled as the "PINPB" parameter. Mean values of PINPB parameter of A-0.5 group is 3.3 and 2.5 times greater than A-0 and A-0.25 groups, respectively. Adding fibers to concrete mixture causes the distance between first-crack strength and failure strength to increase by inhibiting the initial crack and delaying the ultimate failure. This may, however, be regarded as the ductility ratio. Fibers provide three-dimensional fibrous reinforcement, which assist a disc specimen in absorbing the impact energy of repeated blows, thus downplaying the impetuousness of the disc specimen against cracks.

6. Minimum number of replications: Coefficient of variations of results, calculated above, presented in Tables 7 to 9 can be used to determine minimum number of tests, N, required for guaranteeing the error percentage of measured average value to decrease a specified limit, "*e*" at a specific level of confidence, as given by Eq. (10) below [28].

$$N = \frac{[COV]^2 t^2}{e^2} \tag{10}$$

where COV is the coefficient of variation; "*t*" is the value of t student distribution for the specified level of confidence and depends on the degree of freedom, which is related to the number of tests. For a large sample size, ''*t*'' approaches were 1.645 and 1.282 at 95% and 90% level of confidence, respectively [31, 32]. Table 11 represents the minimum number of replications required to maintain the amount of error under various limits of 10% to 50%, at the 90% levels of confidence. Table 10 shows that, if the error is retained lower than10%, the minimum number of tests should be 15, 31 and 46 for A-0, A-0.25 and A-0.5 groups, respectively; for the first-crack strength, at the 90% levels of confidence. Also, for A-0, A-0.25 and A-0.5 groups at the ultimate failure, at 90% level of confidence, if the error is retained lower than10%, the minimum numbers of tests are 17, 32 and 35, respectively. Table 11 demonstrates the number of tests required to maintain the amount of error under a specific limit between 10% and 50%, at the 95% level of confidence. Moreover, Table 10 shows that if the error is retained lower than 10%, the minimum numbers of replications for A-0 to A-0.5 groups are 25, 53 and 78 for the first-crack strength, and 27, 52 and 59 for failure strength, respectively. According to Tables 10 and 11, inclusion of fiber in concrete increases the number of tests required at each level of error.

Table. 10. Number of replications required to keep the error under a specific limit at 90% level of confidence

Error (e%)	**90% level of confidence**					
	A-0 group		**A-0.25 group**		**A-0.5 group**	
	FC	**UR**	**FC**	**UR**	**FC**	**UR**
<10	15	17	31	32	46	35
<15	7	8	15	14	21	16
<20	4	4	8	8	12	9
<25	3	3	6	5	7	6
<30	2	2	4	4	5	4
<35	1	1	3	3	4	3
<40	1	1	2	2	3	2
<50	1	1	1	1	2	1

Table. 11. Number of replications required to keep the error under a specific limit at 95% level of confidence

Error (e%)	**95% level of confidence**					
	A-0 group		**A-0.25 group**		**A-0.5 group**	
	FC	**UR**	**FC**	**UR**	**FC**	**UR**
<10	25	27	53	52	78	59
<15	11	12	24	23	35	27
<20	6	7	14	13	20	15
<25	4	4	9	9	13	10
<30	3	3	6	6	9	7
<35	2	2	5	5	7	5
<40	1	1	3	3	5	4
<50	1	1	2	2	3	3

7. CONCLUSION

According to the behavior observations and obtained results of statistical and experimental effects of PPS fibers on the impact resistance and mechanical properties of concrete in this paper, the following results were drawn:

- Inclusion of up to 0.5% PPS fiber in specimens increases the coefficient of variation of compressive strength up to 65% and improves the mean of flexural strength up to 32% and also the maximum coefficient of variation increases up to 18%.
- Mean tensile strength of 0.5% PPS was increased 31% compared to other specimens, while the coefficient of variation as an index of dispersion was increased up 7%.
- The impact resistance results of A-0.5 (0.5%PPS) group have higher standard deviation, compared to the results of other specimen groups (cubic, cylindrical and prismatic).
- The first-crack and failure strengths were increased due to inclusion of fiber in concrete mixture. 0.5%PPS specimen group had the highest value of impact resistance among all the specimen groups with the mean values for failure strength up to 3.74 times greater than other groups.
- The coefficient of variation of first-crack and failure strengths of 0.5%PPS group were up to 74% and 47%, respectively, greater than those of the other groups.
- Mean values of energy absorption of A-0.5 (0.5%PPS) group for failure strength was approximately up to 275 and 56% higher than A-0 (Ref.) and A-0.25 (0.25%PPS) groups. And also inclusion of fiber in concrete increases the number of tests required at each level of error and decreases the accuracy.

8. DEFINITIONS

Arithmetic mean: The arithmetic mean is the "standard" average, often simply called the "mean".

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

Standard deviation: (represented by the symbol sigma, σ) shows how much variation or dispersion exists from the average (mean), or expected value.

$$sd = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Coefficient of variation: the coefficient of variation (CoV) is a normalized measure of dispersion of a probability distribution. It is also known as unitized risk or the variation coefficient. When only a sample of data from a population is available, the population CoV can be estimated using the ratio of the sample standard deviation S to the sample mean $\bar{x}$:

$$\bar{x} = \frac{sd}{\bar{x}}$$

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