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A Statistical Study to Investigate the Efficiency of Steel and Polypropylene Fiber in Enhancing the Durability Properties of Concrete Composites

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Abstract

Concrete deterioration is associated with factors like surface abrasion and transport of water through capillary action in the concrete matrix. These factors may catalyse other forms of deformation such as cracking and corrosion of reinforcing steel. This paper presents an experimental evaluation to compare the effectiveness of steel and polypropylene fiber in enhancing the mechanical and durability properties, in terms of impact, sorptivity, and abrasion. In the present study, abrasion resistance is strongly related to flexural strength as high correlation coefficient existed as compared to that of compressive strength and split tensile strength. Sorptivity test results demonstrated a substantial decrease in capillary porosity when PPF is used in concrete. The average initial sorptivity versus fiber volume fraction represents a linear relationship with high R^2 value. Positive correlations were also detected between abrasion and initial sorptivity of ordinary Portland cement concrete composite with polypropylene fiber.

Keywords: Fiber; Impact Energy; Ductility Index; Abrasion; Sorptivity.

1. Introduction

Construction is an important part of the development plan of growing countries like India. Maintenance and life enhancement of structures are very important to meet the large demand for infrastructure development. As a construction material Concrete plays an important role around the universe. Plain concrete has a very low cracking resistance, limited ductility and has low tensile strength. The micro cracks present at the interface of mortar–aggregate are responsible for the inherent weakness of plain concrete. Because of the poor tensile strength, cracks distribute with the application of load, leading to brittle fracture of concrete. Microcracks are formed in concrete during the curing stage. One such development to counter such weakness has been two-phase complex materials, i.e. fiber reinforced concrete (FRC), in which cement-based matrix, is reinforced with the orderly or arbitrary distribution of fibers [1–5]. The fibers help to distribute the loads at the internal micro-cracks, thus producing materials with increased tensile strength, ductility, toughness and improved durability properties [6–10]. There is a wide range of fibers available to improve toughness and different properties of hardened concrete. High modulus fibers improve both the flexural strength as well as the impact resistance of concrete, whereas low modulus fibers improve only the impact resistance of concrete. The examples of Fibers whose moduli are lower are cellulose, polypropylene, nylon, etc. glass, asbestos; steel etc comes under Fibers with higher moduli [11–13].

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According to Yazici, Inan and Tabak [14], the addition of steel or synthetic fibers in concrete mix improves upon the tensile, flexural, fatigue and wear strength, deformation resistivity, load-bearing capacity after cracking and toughness properties of the resulting product. Some researchers such as Bentur and Mindness [15], Tchrakian, O'Dwyer and West [16] and Kazemi and Lubell [17] report a significant improving effect on the peak strength and post-peak ductility in compression, flexure and direct shear as the fiber volume fraction increases. Various research papers have looked at how the introduction and dosage of fibers in a concrete mix affect the compressive strength of the hardened concrete. Richardson [18] suggested that a higher dosage of polypropylene fibers would lower the compressive strength. O.Kayali et al. 2003 [19] reported on the effect of polypropylene and steel fibers on high strength lightweight aggregate concrete. He concluded that indirect tensile strength increase by 90% with the addition of polypropylene fibers at 0.56% by volume of the concrete. A 20 % increase in the modulus of rupture was also reported. An experimental study on the relative effectiveness of different types of steel fiber in concrete has been reported by Bayasi and Soroushian in 1991 [20]. Through their study, they concluded that crimped fiber produced higher slump as compared to other steel fiber types further hooked fibers were helpful in enhancing the flexural and compressive behavior of concrete as compared to straight and crimped fibers.

Concrete deterioration is associated with factors like surface abrasion and transport of water through capillary action. These factors can be a catalyst for other forms of deterioration such as cracking and corrosion of reinforcing steel. In concrete science, durability improvement is one of the important issues that must be taken care of by researchers. The durability in terms of impact, abrasion and sorptivity can be improved by incorporation of fibers in the concrete. Furthermore, research on durability properties of fiber-reinforced concrete, such as abrasion resistance and sorptivity, has been very limited and the results of the existing studies have been contradictory [21–23]. The response of concrete subjected to impact loading is of the main interest of several military and civil applications. Several authors used to modify Charpy impact test [24] to study impact behavior of concrete in bending. In the recent year assessment of impact-bending property of concrete through drop hammer test based on the principle of weight falling down on the sample from specified falling weight has been reported [25–29].

Further, abrasion of concrete occurs due to scraping, rubbing, skidding or sliding of objects on its surface. The abrasion resistance of concrete is influenced by a number of factors, for example, compressive strength, flexural strength, aggregate type, aggregate properties, surfacing finish, types of hardeners, and curing. Abrasion, as defined by ASTM, is the physical wear due to hard particles or protuberances forced against and moving along a solid interface [30]. Therefore Abrasion resistance is defined as the ability of the surface to resist being worn away by rubbing or friction. In general, the concrete’s hardness, which is related to its strength, determines how strong it will be to resist abrasion [14]. Liu et al. 2005 [31] outlined the chronological process of abrading concrete with water-borne sand. However, from detailed literature review, it became apparent that only a handful of researchers [32–36]. The authors concluded that inclusion of fiber into concrete matrix results in a greater abrasion resistance. However, the correlation between abrasion depth and a strength parameter, namely compressive strength, split tensile strength and flexural strength has been rarely reported.

Sorptivity is an easily measured material property which characterizes the tendency of a porous material to absorb and transmit water by capillarity. It is a measure of the capillary forces exerted by the pore structure causing fluids to be drawn into the body of the material. It determines the rate of inflow or the depth of water penetrated by allowing the dry concrete to absorb water uni-directionally under a negligible applied pressure. Some of the earlier work on the measurement of sorptivity of mortar and concrete was carried out by Ho and Lewis, 1984 [37] and Hall, 2012 [38]. A review on the recent researches on the measurement of sorptivity indicates contradictory outcomes [39, 40].

The current research work was carried out to compare the effectiveness of steel and polypropylene fiber in enhancing the mechanical and durability properties, in terms of impact, sorptivity and abrasion.

2. Materials

Ordinary Portland cement grade 43 confirming to IS 8112–1989 [41] with specific gravity 3.15 and fineness 3.5 was used in the present investigation. The initial and final setting time was 48 and 220 min respectively. Coarse aggregate used was crushed stone with size 20 and 10 mm availed locally. The aggregates crushing value and the aggregate impact value measured was 24% and 29% respectively. The specific gravity and water absorption found through laboratory test were 2.7 and 0.755 respectively. After grading, the aggregate was dried under laboratory conditions. Fine aggregate with a 2.6 fineness modulus was natural sand with a Zone 3 grading. The particle size distribution curve of fine aggregate is shown in Figure 1. The specific gravity and water absorption of the fine aggregate were 2.66 and 1.35%, respectively.

Figure 1. Particle Size Distribution of Fine Aggregate

Two types of fibers with different elastic modulus were used in the present work. The high modulus fiber used was crimped Steel Fiber (SF) with aspect ratio 50 and length 30 mm. The density and modulus of elasticity the steel fiber was 7900 kg/m^3 and 200 GPa respectively. While the low modulus fiber, Polypropylene Fibers (PPF), was fine hair like fibers having length 12 mm, and an equivalent diameter 32 µm. The density of the polypropylene fiber was 0.91 g/cm^3. The samples of both the fibers are shown in Figure 2.

Figure 2a. Crimped Steel Fiber

Figure 2b. Polypropylene Fibers

Figure 2. Fiber Samples

2.1. Mix Proportions

All mixes had the same basic mixture proportions. The cement content was 427 kg/m^3, fine aggregate 540 kg/m^3, and coarse aggregate 1277 kg/m^3. The water-cementitious materials ratio was kept constant at 0.43. The mixes are designed to give a compressive strength of 50 MPa at 28 days. The 50 MPa concrete matrix was reinforced at variable fiber addition rates to produce mono-fibre composites as described in Table 1.

2.2. Test Program and Procedures

2.2.1. Strength Test

A Digital Compression Testing Machine of 2000 kN capacity was used for measuring compressive strength of test specimens. Compressive strength was measured at 7, 14, and 28 days on 150 mm cubes in accordance with Indian Standard IS: 516-1959 [42]. Three cubes were tested for each age and average values were obtained. Splitting Tensile Strength was measured at 28 days on, Cylinders 150 mm diameter by 300 mm long in accordance with Indian Standard IS 5816,-1976 [43]. Three cylinders were tested for each age and average values were obtained. The horizontal tensile stress is expressed as:

$$\text{Horizontal Tensile Stress} = \frac{2P}{\pi DL} \tag{1}$$

Where

P = compressive load on cylinder L = Length of cylinder D = Diameter of cylinder

IS: 516 specifies that the rate of increase of stress on cement concrete specimen should be approximately 1.4 kN/ cm^2/min. (140 kgf/cm^2/min.). Accordingly approximately rate of loading for 150 cm Cube 315 kN/min (5.0 kN/sec).

For the flexural strength test, thirty-six beams were cast in moulds of 50 × 10 ×10 cm dimensions. The test specimens were kept in water for 28 days prior to testing. The flexural strength of concrete beam samples was conducted using centre point loading as per ASTM standards in accordance with practices mentioned in ASTM C-293-02[44]. ASTM C-293-02 specifies that the load shall be applied at a constant rate to the breaking point. Apply the load so that the extreme fiber stress increases at a rate betweeen 0.9 and 1.2 N/mm^2/min). The modulus of rupture as per ASTM C-293 is:

$$R = \frac{3PL}{2bd^2} \tag{2}$$

Where

R = modulus of rupture in MPa L = length of span in mm

b = width of prism in mm P = maximum load applied in N

d = depth of prism

2.2.2. Impact Resistance Test

The impact resistance of the specimens was obtained in accordance with the methodology given by ACI 544.2R-89 [45]. The impact test was conducted on 150 mm (diameter) X70 mm (depth) concrete cylindrical discs. Four numbers of cylindrical disc specimens were tested to get a normal number of blows required to bring about first visual crack and ultimate failure. The number of blows resulting in the initiation of first visual crack (N_1) and a number of blows required for ultimate rupture (N_2) of fiber strengthened concrete. Cao, 2013 [46] defined a new term ductility index (I) which is the ratio of impact energy absorbed by fiber concrete from crack to fracture (N_2-N_1) to the impact energy absorbed by the first visual crack (N_1) of the fiber concrete, which directly reflects the toughness of the fiber-reinforced concrete test specimens after cracking.

$$\text{Ductility index } (I) = \frac{(N_2 - N_1)}{N_1} \tag{3}$$

$$\text{Impact energy (E)} = N_2 \times (m.g.h) \tag{4}$$

Where

m = mass of hammer λ = ductility index

h = height of drop N_1= First visual crack

g = gravitation acceleration N_2= ultimate crack

2.2.3. Abrasion Resistance Test

Abrasion resistance test was implemented on a cube of size 70.6 mm in accordance with IS 1237- 2012[47] after 28 days of curing. A digital weighing machine was used to measure the precise weight of the specimen. Immediately after oven drying for 24 hours, the thickness of the samples was taken at four corners and one at the centre with a micrometre. The specimens were settled in the holding gadget of the abrasion machine, and a load of 300 N was applied. The grinding machine was then put inmotion at a speed of 30 rpm, and the grating powder, Corundum crystalline Al_2O_3, was consistently sprayed to abrade the specimen. The disk was revolved for four periods, while each period was comparable to 22 cycles. The decrease in volume due to wear was computed in cm^3 per 50 cm^2. The specimens were again weighed to find out the weight loss at the point when the test for abrasion was over. The specimen thickness was measured again at five different points. The degree of abrasion was settled from the refinement in estimations of thickness measured beforehand, then after the abrasion test. The average thickness loss or depth of wear was determined to utilize the accompanying equation.

$$T = \frac{W_1 - W_2}{W_1 \times A} V_1 \tag{5}$$

Where

T = average thickness loss in mm

A = the surface area in mm^2

W_1= the initial specimen weight in gram

V_1 = the initial volume in mm^3

W_2= the mass after abrasion in gram

Four specimens were made of each mixture, and values documented in this paper are the mean of the four specimens tested.

2.2.4. Sorptivity Test

For determining sorptivity, the standard test specimens of 100 mm diameter disc of thickness 50 mm were cast. These specimens were conditioned and tested as per ASTM C1585-13 [48] after 28 days of curing. The test specimens were coated with an epoxy emulsion on their sides to prevent any water movement through the sides during the test, only unidirectional uptake of water from the bottom was permitted. The concrete core specimen is then put in a container and exposed to a liquid on one plane (Figure 3). The level of fluid in the pan is kept steady to keep away from errors because of pressure gradients. At customary interims, the mass of the concrete core specimen is weighed and the measure of liquid ingested is standardized by the cross-sectional range of the uncovered surface. Sorptivity calculations were done in accordance with ASTM C1585-13. The cumulative absorbed volume of water per unit area of inflow surface (I) was related to the square root of the elapsed time ($t^{0.5}$) with the following equation.

$$I=s*t^{0.5} \tag{6}$$

Where s is sorptivity

$$I = \frac{M_t}{a \times d}... \tag{7}$$

Where

I = the absorption

a = the exposed area of the specimen, in mm^2

mt = the change in specimen mass in grams, at the time t

d = the density of the water in g/mm^3

Figure 3. Sorptivity Test. Samples Immersed In Water

3. Results and Discussion

Experimental results summarized in Table 1, represent the effect of Polypropylene Fiber Reinforced Concrete (PFRC) and Steel Fibers Reinforced Concrete (SFRC) on fresh and hardened properties of concrete.

3.1. Slump Test Results

Slump test was conducted to study the workability of the SFRC and PFRC. The results of the slump tests are presented in Table 1. The slump values of the steel fiber and polypropylene fiber based concrete show a decreasing trend in the same water to cement ratio. The rate of decrease in slump value of crimped steel fiber was approximately twice as compared to polypropylene fiber of the same percentage. Figure 4 represents the percentage decrease in a slumpat the different percentage addition of fiber in the concrete matrix. Poor workability leads to a higher content of air in the cavities and pores of the capillaries which have an important impact on the mechanical properties and the durability properties of FRCs [49].

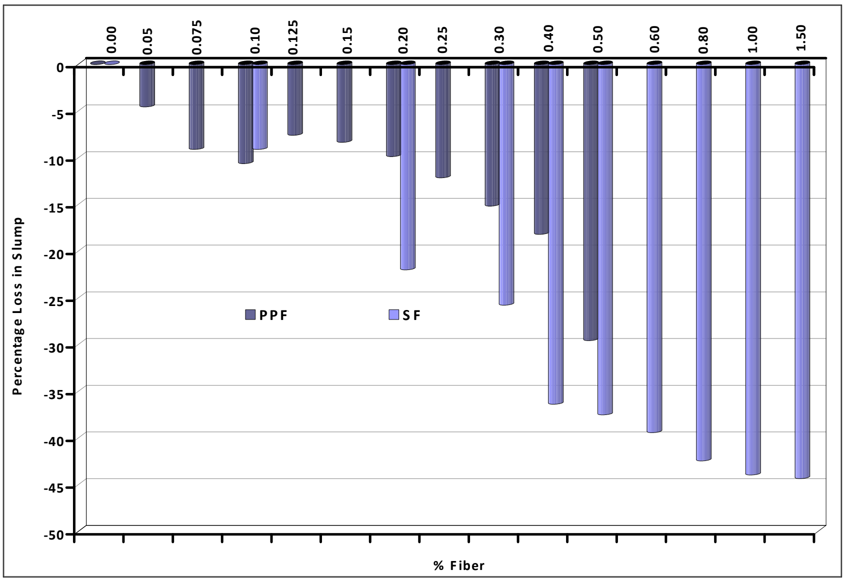

Figure 4. Percentage Change in Slump

3.2. Compressive Strength Test

Cube specimen prepared for compressive strength was tested in the laboratory and different crushing strength with different fiber percentage was found which are shown in Table 1. The loading chart on the reference mix over time for compressive strength test is shown in Figure 5.

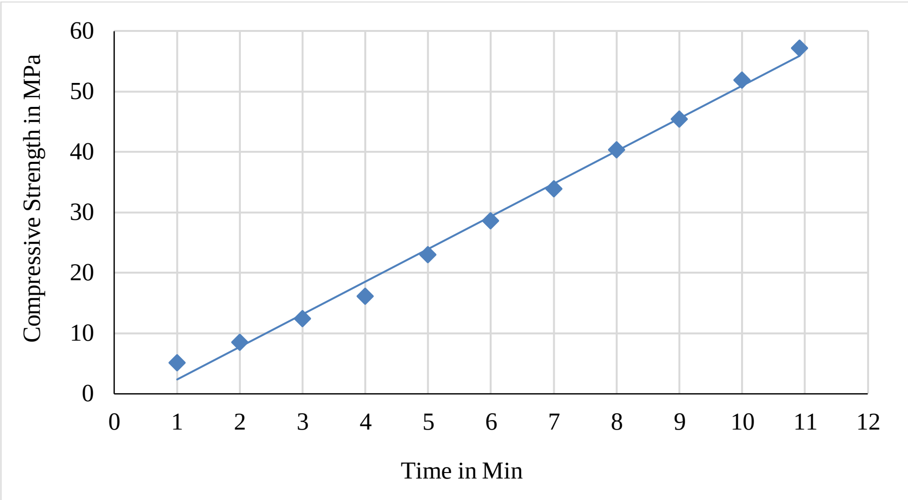

Figure 5. Loading Chart on the Reference Mix over Time for Compressive Strength Test

The effect of crimped steel fibre and polypropylene fiber on compressive strength of concrete at 28 days has been graphically represented in Figure 6. Both 14 days as well as 28 days compressive strength of concrete mixes modified by crimped steel fiber and polypropylene fiber, are less than that of plain concrete. On addition of 0.1%, 0.2%, 0.3% polypropylene fibre in concrete, decrease in percentage of the compressive strength value is 4.88%, 5.06%, 5.76% respectively at 28 days, with respect to plain concrete, however on addition of 0.1%, 0.2%, 0.3% crimped steel fiber in concrete, decrease in percentage of the compressive strength value is 3.90%, 4.20%, 4.81% respectively, with respect to plain concrete. Further, the percentage decrease in average compressive strength of PFRC with respect to SFRC is approximately 3%. Higher compressive strength in SFRC with respect to PFRC is attributed to the higher modulus of elasticity of SF as compared to PPF. From figure it can also be inferred that at a higher volume fraction of both the fiber the rate of decrement was more significant as compared to reference mix. This may be due to difficulty in the dispersion of fibers in the concrete mixes at high volume fraction which may have led to incomplete consolidation. The effect of fiber on the compressive strength of concrete has been discussed in many literatures [50– 51]. The exploratory outcomes demonstrated polypropylene fiber either red uced or improved the compressive strength of concrete, but the end product is pretty much nothing. However, the results of compressive strength, discussed here are in line with the findings of earlier researchers namely [52–55]. Very recently increase in compressive strength with increase in fiber content in the concrete mix has been reported [56–58].

Table1. Slump and Strength Test Results

% Fiber		Slump (mm)	% Change in Slump	Compressive Strength (MPa)		% Change in Compressive Strength at 28 Days	Flexural Strength MPa	% Change in Flexural Strength	Split Tensile Strength MPa 28 Day	% Change in Split Tensile Strength
				14 Day	28Day					
% Steel by Volume of Concrete	0.00	132.00	0.00	49.52	57.12	0.00	5.48	0.00	3.18	0.00
	0.10	120.00	-9.09	46.13	54.89	-3.90	5.96	8.76	3.57	12.26
	0.20	103.00	-21.97	46.83	54.72	-4.20	6.54	19.34	3.68	15.72
	0.30	98.00	-25.76	45.89	54.37	-4.81	6.61	20.62	3.75	17.92
	0.40	84.00	-36.36	46.82	54.55	-4.50	6.75	23.18	3.81	19.81
	0.50	82.50	-37.50	44.78	54.16	-5.18	6.97	27.19	3.87	21.70
	0.60	80.00	-39.39	44.36	53.11	-7.02	7.02	28.10	3.89	22.33
	0.80	76.00	-42.42	44.00	52.96	-7.28	7.16	30.66	3.91	22.96
	1.00	74.00	-43.94	43.88	53.00	-7.21	7.24	32.12	3.97	24.84
	1.50	73.50	-44.32	43.56	52.73	-7.69	7.42	35.40	4.11	29.25
% PPF by Volume of Concrete	0.05	126.00	-4.55	45.54	54.59	-4.43	5.68	3.65	3.29	3.46
	0.075	120.00	-9.09	40.32	54.37	-4.81	5.78	5.47	3.45	8.49
	0.1	118.00	-10.61	40.28	54.33	-4.88	5.85	6.11	3.48	9.43
	0.125	122.00	-7.58	42.47	54.24	-5.04	5.89	7.48	3.51	10.38
	0.15	121.00	-8.33	41.29	54.19	-5.13	5.92	8.03	3.52	10.69
	0.2	119.00	-9.85	43.12	54.23	-5.06	6.00	9.49	3.53	11.01
	0.25	116.00	-12.12	43.48	54.36	-4.83	6.14	12.04	3.59	12.89
	0.3	112.00	-15.15	44.21	53.83	-5.76	6.27	14.42	3.66	15.09
	0.4	108.00	-18.18	44.36	53.78	-5.85	6.43	17.34	3.74	17.61
	0.5	93.00	-29.55	44.44	53.69	-6.00	6.48	18.25	3.86	21.38

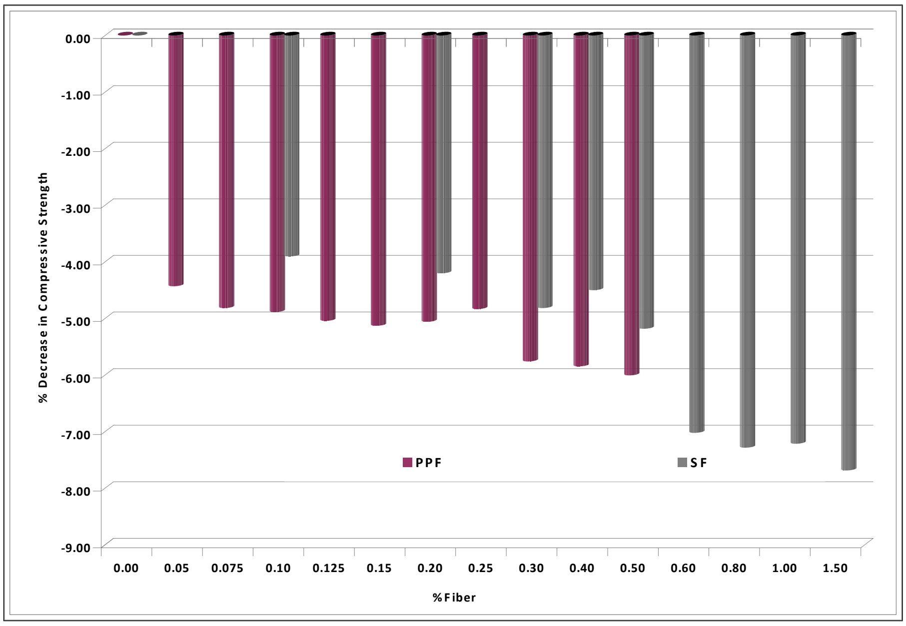

Figure 6. Percentage Change in Compressive Strength

3.3. Flexural Strength Test

The flexural strength test of concrete beam samples was conducted using centre point load as per ASTM standards in accordance with practices mentioned in ASTM C293-02. The result of flexural strength test is substantiated in Table1. The result shows that flexural strength of fiber reinforced concrete composites increases with the increase in steel fiber and polypropylene fiber content. Flexural strength range for SFRC was in between 5.5 and 7.5 MPa, and for PFRC it ranged between 5.5 and 6.5 MPa. From Figure 7 it can be inferred that at 0.1%, 0.2%, 0.3% addition of steel fiber in the concrete mix, the percentage increase in flexural strength observed 8.76%, 19.34%, 20.62% respectively as compared to plain concrete. The same enhancement in flexural strength due to fiber reinforcement has been reported earlier [59]. Further, for 0.1%, 0.2%, 0.3% addition of polypropylene fibre in concrete mix, the percentage increase in flexural strength was 6.11%, 9.49%, 14.42% respectively as compared to plain concrete. Average percentage increase in the flexure strength of crimped steel fiber based concrete with respect to polypropylene fiber based concrete is approximately 11%. The consequences of the present investigation plainly demonstrate that the presence of steel and PP fibers influences the flexural strength of concrete in an unexpected way. Since PP fibers are short and have the lower tensile strength and elastic modulus contrasted with those of steel fibers, they bridged only on micro-cracks and did not have a major effect on the flexural strength. On the other hand, owing to their higher tensile strength and modulus of elasticity, steel fibers had a remarkable influence on the flexural strength of concrete. Moreover due to sufficient bridging action of steel fibers prevented the cracks to further expand during the test.

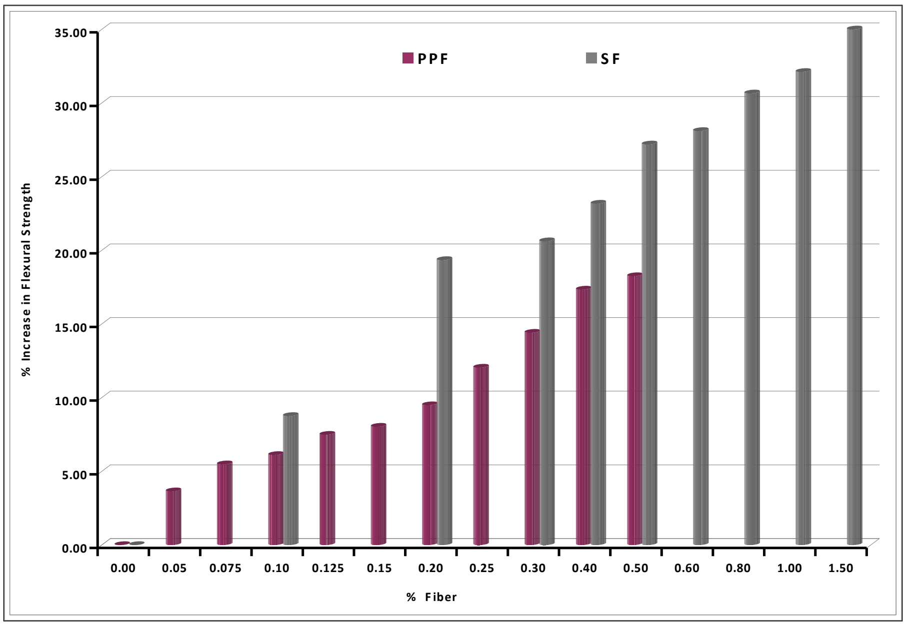

Figure 7. Percentage Changes in Flexural Strength Test Result

3.4. Split Tensile Strength Test

The splitting-tensile strength of concrete is an important mechanical property that greatly affects the size and extent of tension related failure behaviour, such as flexural cracking in beams. The test results of splitting tensile strength are substantiated in Table 1. Direct tensile strength calculated by split tensile strength does not give fair idea due to mixed stress field and fiber alignment. However, its failure mode contributes to the analysis of the ductility of the concerned material. It was observed during the experimentation that the specimen does not split out from each other, unlike the plain concrete. Substantial damage zone was formed because of smaller scale micro cracks encompassing a splitting plane. Stress transfer mechanism due to fiber bridging action is accountable for such heightened ductile failure pattern. From Figure 8 it can be inferred that the effect of SF was more significant than that of PPF in the improvement of splitting tensile strength of the cement concrete composites. The enhancement in the splitting tensile strength of steel fiber reinforced concrete was due to the higher modulus of elasticity of steel fiber in comparison to polypropylene fiber which further result in their higher efficiency in bridging macro-cracks and consequently increasing the splitting strength. The same has been reported by Song P. S and Hwang S (2003) [60]. The higher the number of fibers bridging the splitting cracks, the higher would be the splitting tensile strength [28].

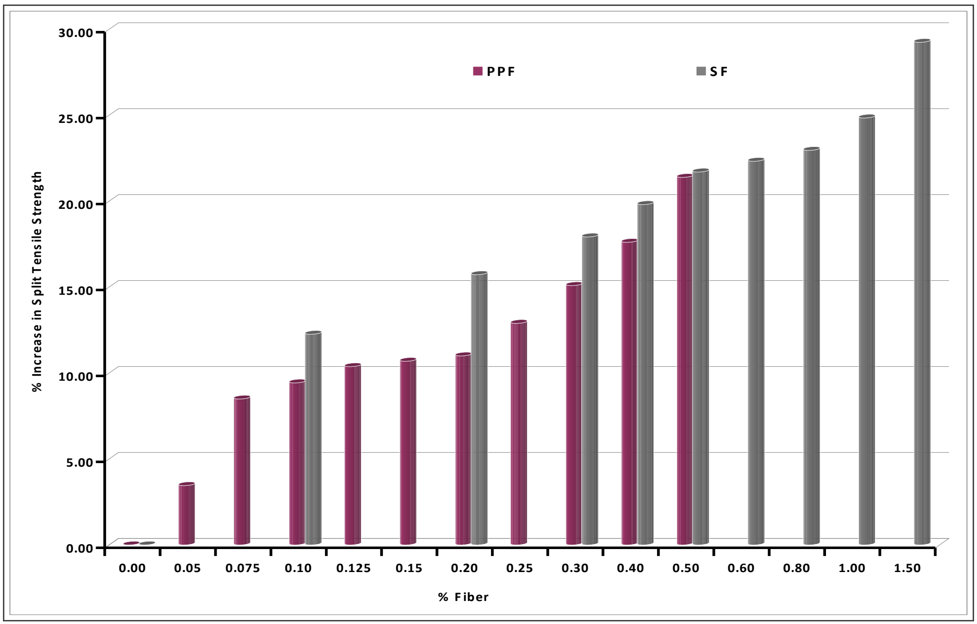

Figure 8. Percentage Changes in Split Tensile Strength

3.5. Impact Resistance Test

Table 2 presents the impact resistance test results of SFRC. A frequency histogram and fitted normal curve for first and ultimate crack strength of FRC discs are shown in Figure 9. A frequency histogram displays data that have been summarized into intervals. The horizontal axis is divided into equal intervals which display the no. of blows to failure, and a vertical bar is drawn at each interval to represent its frequency (the number of values that fall within the interval). The statistical analysis for first and ultimate crack strength of both the FRCs are presented in Table 3. Figure 9 suggested that the first crack strength of both concrete mixes hardly follows a normal distribution because the plot fits poorly into the straight line. This is ascertained from the P value of the probability plot presented in Table 3. However the P value of the first crack strength and second crack strength of steel fiber reinforced concrete is neighbouring zero. Hence, indicating that inclusion of steel fiber has a significant impact on the ductility of the concrete matrix when compared to polypropylene fiber.

Table 2. Impact Resistant Test Results

Types of Fiber	% fiber by volume of concrete	Initial-crack N_1	Relative increase	Ultimate crack N_2	Relative increase	Impact energy N-m	Ductility index l $(N_2-N_1)/N_1$	Relative increase
PPF	0	9	0%	12	0%	599.34	0.33	0%
	0.05	10	11%	14	17%	699.23	0.40	21%
	0.075	11	22%	16	33%	799.11	0.46	39%
	0.1	14	56%	22	83%	1098.78	0.57	73%
	0.125	15	67%	24	100%	1198.67	0.60	82%
	0.15	16	78%	28	133%	1398.45	0.75	127%

	0.2	19	111%	34	183%	1698.12	0.79	139%
	0.25	23	156%	37	208%	1847.95	0.61	84%
	0.3	25	178%	42	250%	2097.68	0.68	106%
	0.4	33	267%	47	292%	2347.40	0.42	29%
	0.5	37	311%	53	342%	2647.07	0.43	31%
	0.1	16	78%	25	108%	1248.62	0.56	70%
	0.2	21	133%	37	208%	1847.95	0.76	131%
	0.3	27	200%	47	292%	2347.40	0.74	124%
	0.4	38	322%	52	333%	2597.12	0.37	12%
SF	0.5	41	356%	67	458%	3346.29	0.63	92%
	6	44	389%	74	517%	3695.91	0.68	107%
	8	49	444%	77	542%	3845.74	0.57	73%
	1	52	478%	81	575%	4045.52	0.56	69%
	1.5	54	500%	87	625%	4345.19	0.61	85%

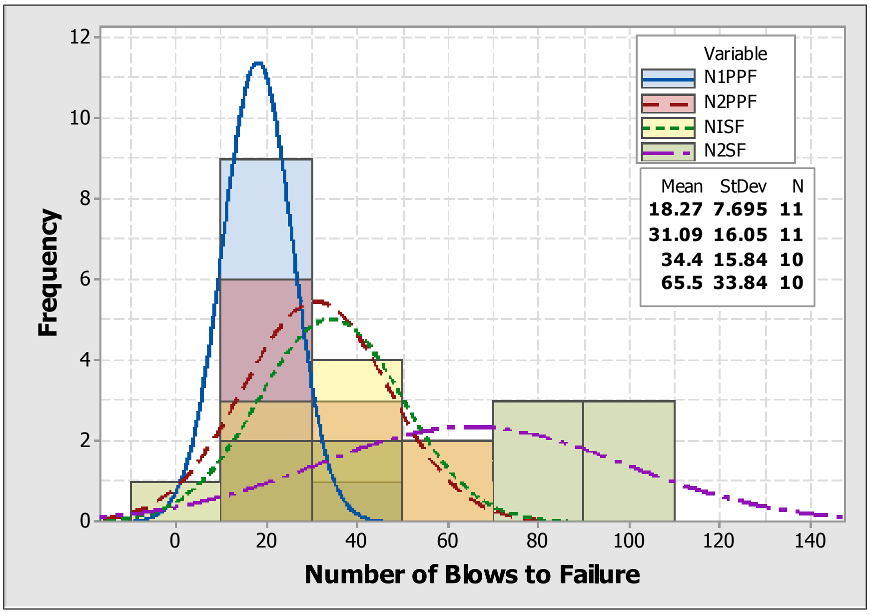

Figure 9. Frequency Histogram and Fitted Normal Curve for First and Ultimate Crack Strength of FRC Discs

Table 3. Statistical Analysis for First and Ultimate Crack Strength of FRCs

Parameters	First crack strength (N_1)		Ultimate crack strength (N_2)	
	PPF	SF	PPF	SF
Mean	18.27	34.4	31.09	65.5
Standard deviation	7.695	15.84	16.05	33.84
P Value	0.571	0.48	0.588	0.409
Anderson Darling (AD)	0.280	0.316	0.274	0.344

$(N_2-N_1)/N_1$ value presented in Table 2 indicates the ability to absorb kinetic energy. This factor increase means adding fiber, delay the onset of failure. Hence, it can be inferred that in general impact resistance increases with the incorporation of fibers in concrete. Effect of steel fiber showed significant improvement in impact resistance of concrete as compared to polypropylene fiber.

Several regressions were performed to establish a correlation between ductility index and strength parameters. Figure 10 and 11 show the regression for ductility index with flexural strength and split tensile strength respectively. A negative correlation existed between ductility index and compressive strength indicating that compressive strength increases ductility decreases. However, a positive correlation existed with split tensile strength and flexural strength indicating split and flexural strength parameters increases ductility increases. Moreover, ductility was strongly related to flexural strength as higher correlation coefficient existed as compared to the R^2 value of split tensile strength.

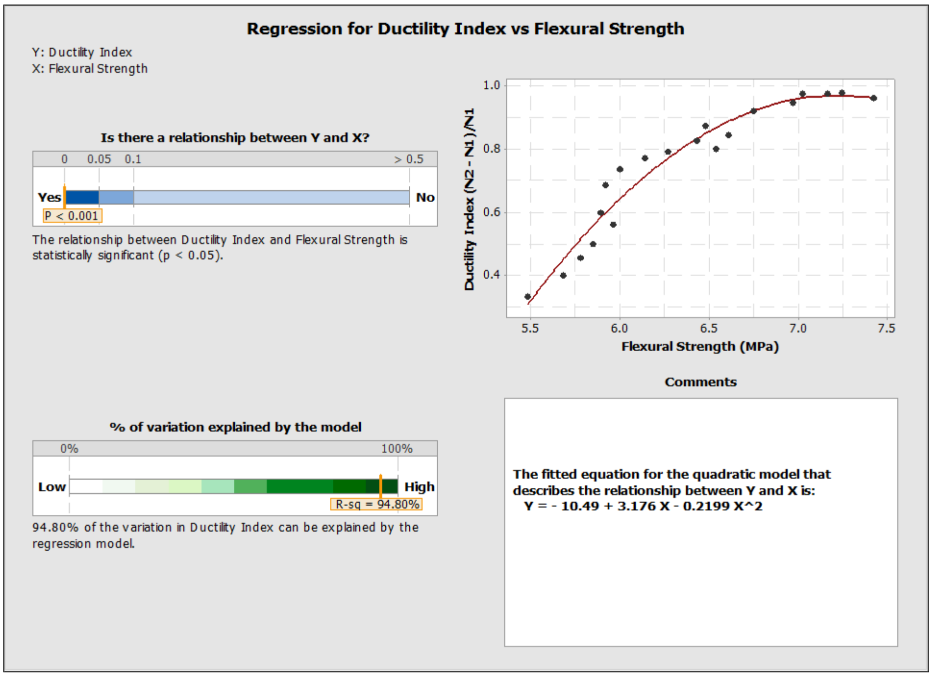

Figure 10. Regression of Ductility Index versus Flexural Strength

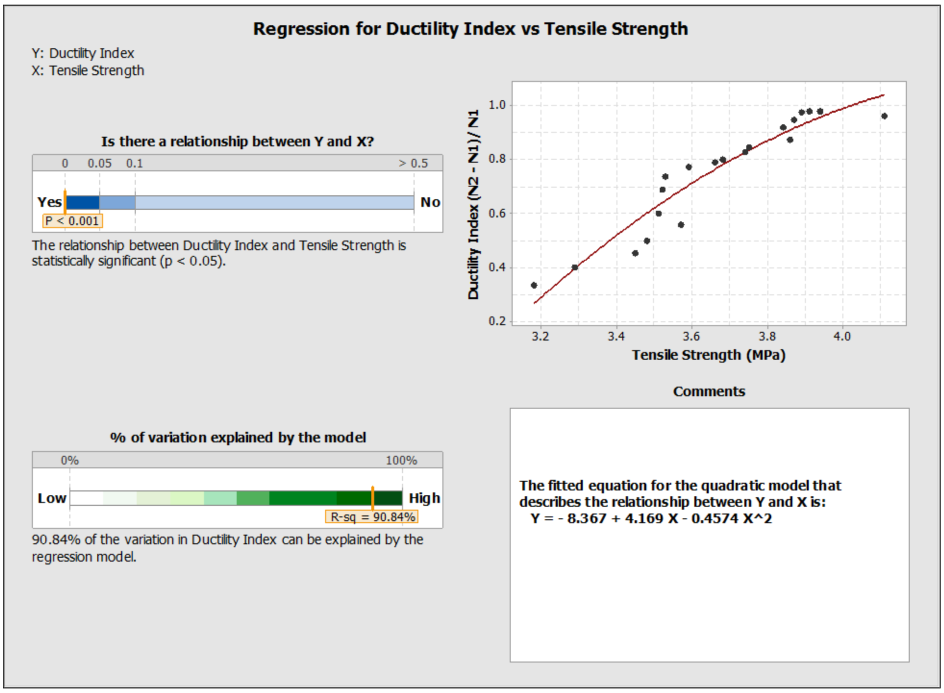

Figure 11. Regression for Ductility Index versus Tensile Strength

Visuals presented in Figure 12 and 13 show the failure pattern of the specimens with and without fibers under impact loading. The failure mode changes from brittle to ductile after incorporation of fibers. In case of the plain concrete specimen, the predominant mode of failure is a tensile failure through the aggregate, although local crushing and shearing occur in the region where the falling weight impacts the surface. As expected, all normal concrete fails suddenly and wide cracks are detected in the failure specimen with no significant gap in the first visual crack and ultimate crack. This shows the brittle nature of plain concrete. In case of fiber reinforced concrete, the failure occurs when the specimen breaks into at least three pieces. Narrow crack with debris and dust is accompanied by such failure. Chu, et al (1989) [61] reported that there is a 29 % increase in impact resistance of the small concrete beams made with the addition of polypropylene fibers. For the steel fiber reinforced concrete (SFRC), the failure was characterized by multiple cracking, excessive separation of the aggregates from the matrix, and fiberpulls out, while still retaining their integrity. G l Oyekan August 2001 [62] stated that the pattern of failure of concrete made of polypropylene fiber depends on “the aggregate strength, the matrix strength, the aggregate-matrix bond strength, the specimen and the test boundary conditions and the fiber matrix-bond strength”.

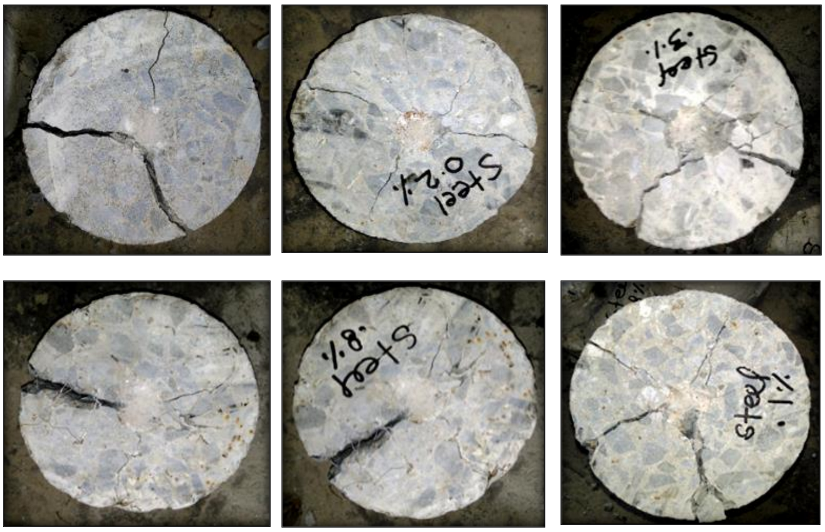

Figure 12. Failure Mode of SFRC

Figure 13. Failure Mode of PFRC

3.6. Abrasion Resistance Test

Surface abrasion of the all-concrete mixtures was measured at 28 days. Table 4 depicts the abrasion value and the depth of wear of the test specimens after abrasion. Figure 14 to 16 graphically presents the comparative analysis of abrasion test result with the strength data. The outcomes of the laboratory work showed that fiberaddition to the concrete mix enhanced the abrasion resistance of concrete. Polypropylene fiber significantly improved the abrasion resistance of concrete as compared to steel fiber as the depth of wear recorded was more in concrete mixes with steel fiber in comparison to concrete mixes with polypropylene fiber. The results obtained in the present investigation are in line with Vassou et al 2005 [35] but were in contrast to what has been reported by Atis et al. 2009 [36]. Further, for concrete mixes with polypropylene fiber higher correlation existed between abrasion value and flexural strength. However, for concrete mixes with steel fiber higher correlation existed between abrasion values and split tensile strength. This may be ascribed to the fact that during the abrasion testing as the rolling wheels removed the concrete surface, some of the steel fiber was left exposed and due to the brittle nature of aggregate surrounding each of them, the contact of the fiber with mortar was sometimes stopped and later taken out by circular motion allowing a large relative depth reading, which consequently results in higher abrasion depth reading as compared to PPF. The abrasive test tended to cut pull out the steel fibers from the cement matrix.

Table 4. Abrasion Resistance Test Results

Types of Fiber	% Fiber	Abrasion value ($cm^3/50\ cm^2$)	Depth of Wear (mm)
% PPF	0	5.13	1.026
	0.05	5.00	1.000
	0.075	4.97	0.994
	0.1	4.94	0.988
	0.125	4.93	0.986
	0.15	4.92	0.984
	0.2	4.89	0.978
	0.25	4.86	0.972
	0.3	4.83	0.966
	0.4	4.79	0.958
	0.5	4.78	0.956
% SF	0.00	5.13	1.026
	0.10	5.08	1.016
	0.20	5.05	1.010
	0.30	5.04	1.008
	0.40	5.02	1.004
	0.60	4.98	0.996
	0.80	4.97	0.994
	1.00	4.94	0.988
	1.50	4.91	0.982

According to Atis and Celik, 2002 [63] strength is the most imperative variable overseeing the abrasion resistance of concrete. The relation between abrasion and compressive strength of concrete has been discussed by C. D. Atis 2000 [64]; Atis and Celik 2002 [63]. There, C. D. Atis stated that a good relationship existed between abrasion and compressive strength of concrete". However, in this work, the sliding and scraping of abrasion material change the nature and action of abrasion to surface abrasion. It is opined here that direct tensile strength and flexural tensile strength occur on the abrading surface of the fiber reinforced concrete due to the scraping and sliding action of abrasion material. The results discussed herein, concludes the opinion. From Figure 14 it can be seen that Abrasion resistance is directly proportional to compressive strength. The observation is in contrast to what has been reported in the literature review. Further, from Figure 15 and 16 it can be inferred that Abrasion value is inversely proportioned to the split tensile and flexural strength. This is in line with the result reported in the literature review. Moreover, abrasion resistance is strongly related to flexural strength as high correlation coefficient existed as compared to the R2 value of compressive strength and split tensile strength.

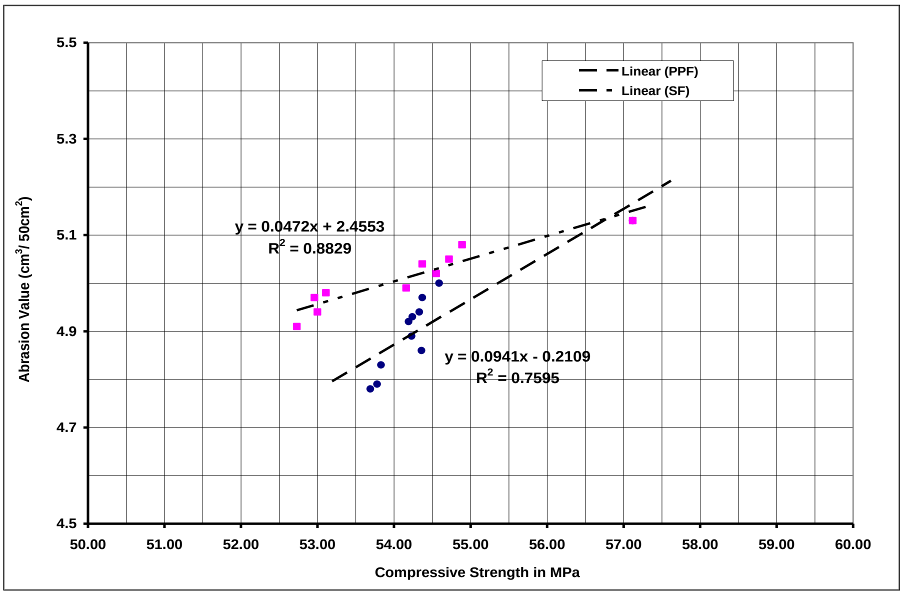

Figure 14. Abrasion Value Vs Compressive Strength

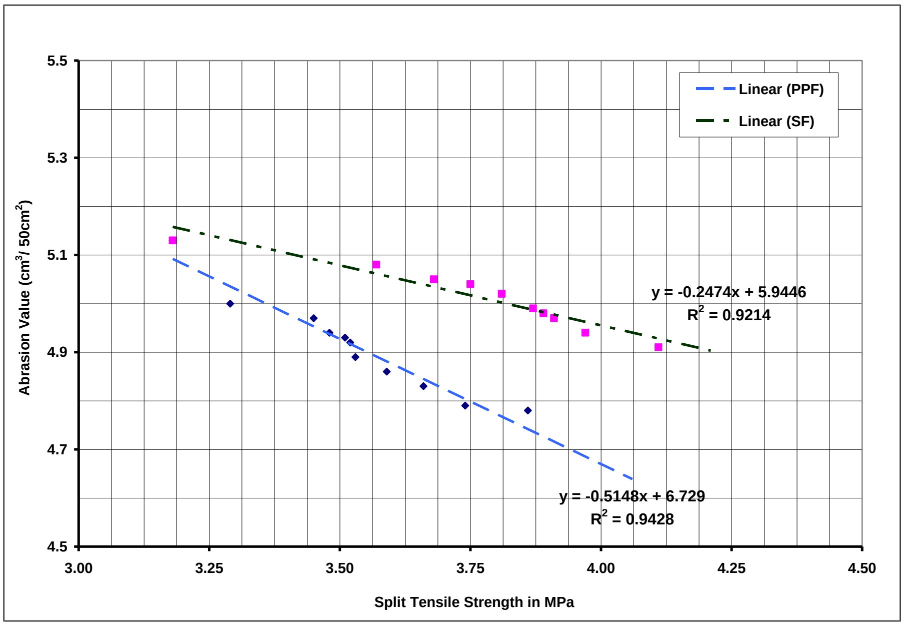

Figure 15. Abrasion Value Vs Split Tensile Strength

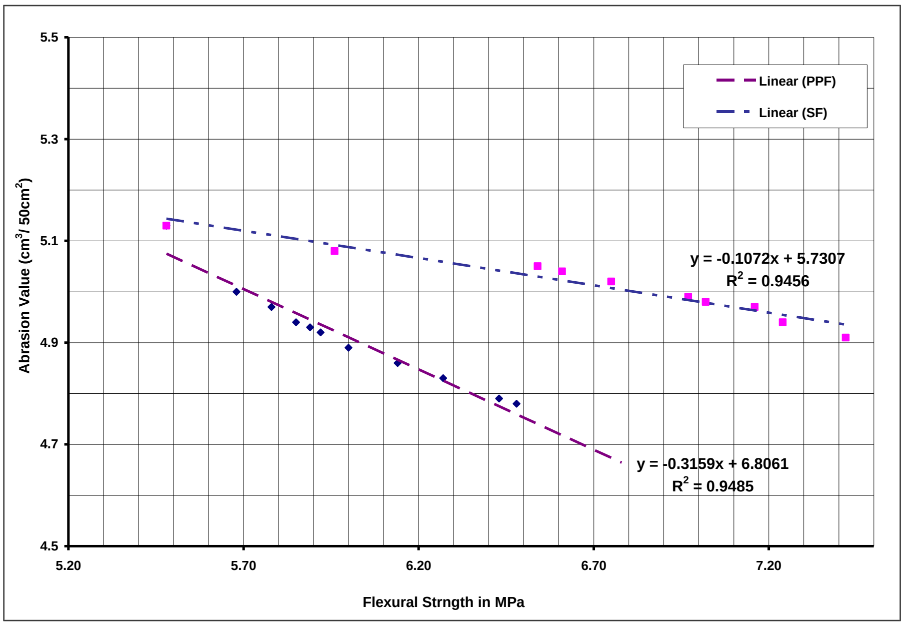

Figure 16. Abrasion Value vs. Flexural Strength

3.7. Sorptivity Test Results

The initial rate of water absorption (mm/$^{s1/2}$) is defined as the slope of the line that is the best fit to Iplotted against the Square root of time ($s^{1/2}$). This slope is obtained by using linear regression analysis. For the regression analysis, all the points measured up to 6 hrs are used, If the data between 1 min and 6 h do not follow a linear relationship (a correlation coefficient of less than 0.98) and show a systematic curvature, the initial rate of absorption cannot be determined. The sample graphs of the depth of water absorption (I, mm) versus square root of time for all specimen of FRC were plotted, from which initial sorptivity were determined by using Equations 8, respectively.

$$I = S_i\sqrt{t} + b \tag{8}$$

S_i= initial rate of absorption in mm/$\sqrt{s}$

I versus $\sqrt{t}$ graph show that for all the specimens the initial slope is practically identical further, for all samples tested, the relationship between I and $\sqrt{t}$ begins to deviate from linearity after 30 minutes. Sorptivity is an index for concrete durability and reduces with increase in fiber content. The result showed a significant reduction in capillary porosity when PPF are used in concrete. Figure 17 and 18 represents the average initial sorptivity of SFRC and PFRC respectively. Figure 18 shows that Positive correlation existed between average initial sorptivity and % variation in steel fiber indicating that when % steel increases sorptivity increases. Further, higher percentage addition of steel fiber in the concrete mixes induced a significant increase in sorptivity. This may be due to a higher amount of pores in the concrete mixes. A large number of pores in the concrete mix may have led to greater pore continuity due to coalescence of large air voids which may have led to higher concrete sorptivity. In contrast, negative correlation existed in case PFRC indicating that as PPF increases concrete sorptivity decreases.

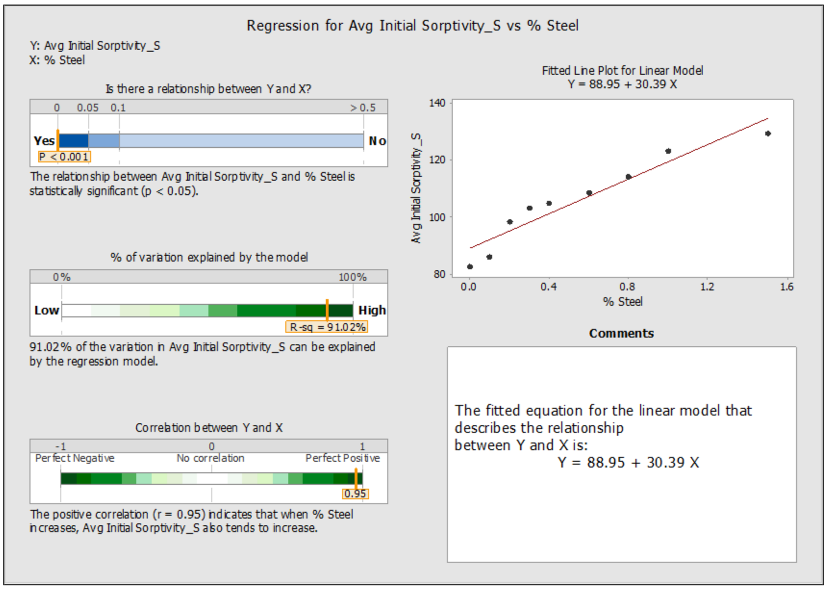

Figure 17. Average Initial Sorptivity of SFRC

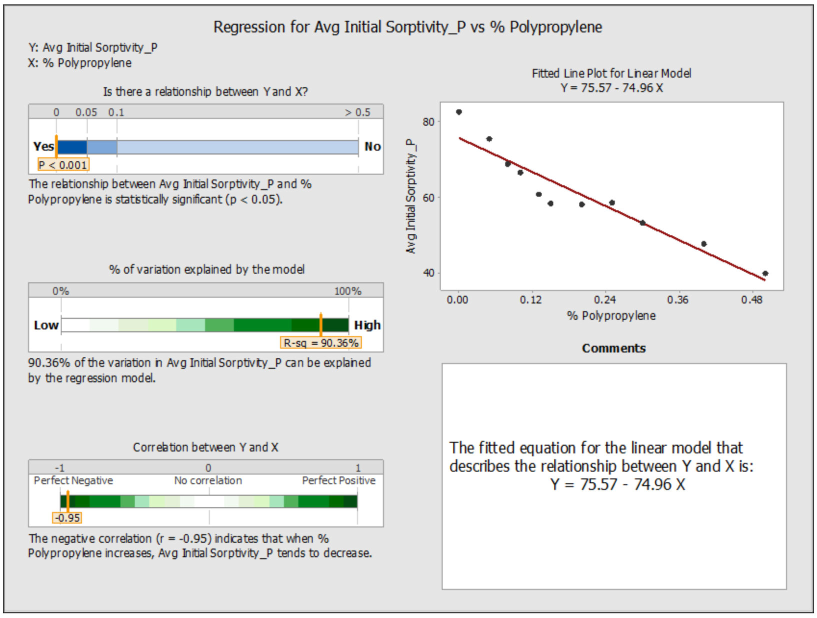

Figure 18. Average Initial Sorptivity of PFRC

4. Relationship between Sorptivity and Abrasion Resistance

In the present work, a correlation between average initial Sorptivity and Abrasion Value has been developed through linear regression. Figure 19 shows the regression for initial sorptivity versus Abrasion values. The fitted equation for the quadratic model that describes the relationship between Sorptivity and Abrasion Value.

$$\text{Sorptivity} = 4.093 + 0.02178 * \text{Abrasion Value} - 0.000118 * (\text{Abrasion Value})^2 \quad (9)$$

This equation can be used to predict Abrasion value to a value of Initial Sorptivity, or find the settings for Initial Sorptivity that correspond to a desired value or range of values for Abrasion value. Further, Figure 20 presents the prediction report for the regression analysis at 95% confidence interval. The quadratic model can explain 87.10% variation in sorptivity of fiber reinforced concrete. A positive correlation between sorptivity and abrasion indicates that when abrasion increases sorptivity increases.

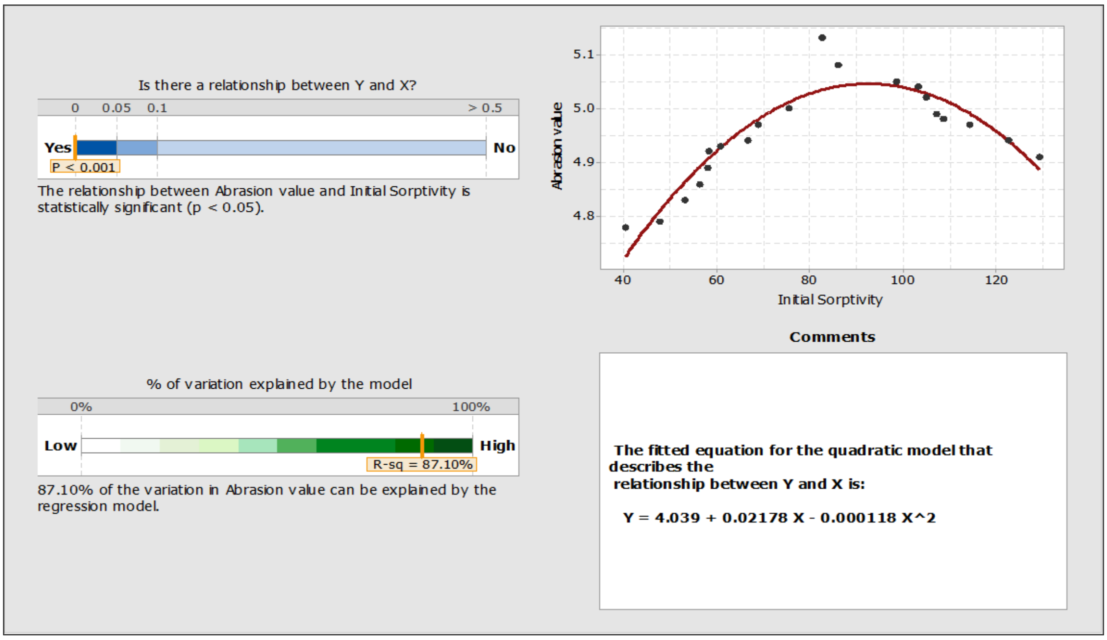

Figure 19. Regression for Abrasion value vs. Initial Sorptivity (Summary Report)

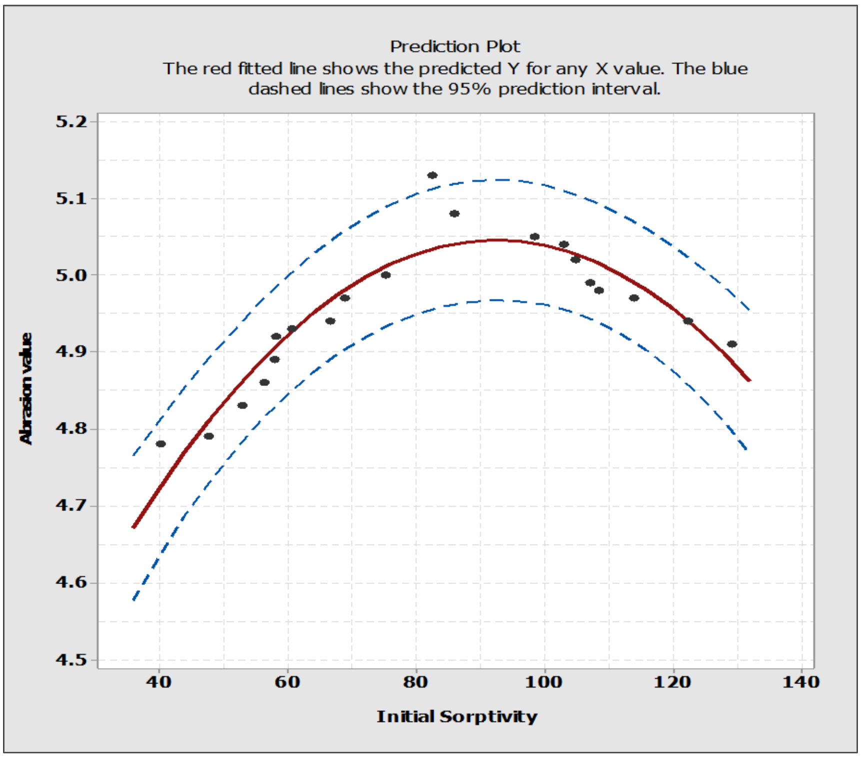

Figure 20. Prediction Plot for Abrasion value vs Initial Sorptivity

5. Conclusion

Studies were performed to determine the effectiveness of high and low modulus fiber on the abrasion resistance, impact resistance and the sorptivity of concrete. Through careful analysis of the test results, the following conclusions can be drawn:

- The results indicate that the two fiber reinforced concrete hardly followed the normal distribution on the first crack strength and the ultimate crack strength. The SFRC showed larger scatter in the percentage increase in the no. of post first crack blows when compared to those of the PFRC. Effect of steel fiber showed significant improvement in impact resistance of concrete as compared to polypropylene fiber. A negative correlation existed between ductility index and compressive strength indicating that compressive strength increases ductility decreases.
- In general, the inclusion of fibers produced an improvement in the abrasion resistance of concrete. The results of

abrasion test indicate that PPF significantly improved the surface abrasion of concrete when compared to crimped steel fiber. A strong relationship existed between surface abrasion and flexural strength than between abrasion to compressive strength.

- Sorptivity test result showed a significant reduction in capillary porosity when PPF is used in concrete. The average initial sorptivity versus fiber volume fraction represents a linear relationship with high R2 value. The result concludes that the decrease in sorptivity of polypropylene fiber based concrete is favourable to the durability of the reinforced cement concrete structure.

A positive correlation between sorptivity and abrasion indicates that when abrasion increases sorptivity increases. The quadratic model developed in the present work can be used to predict Abrasion value to a value of Initial Sorptivity or find the settings for Initial Sorptivity that correspond to a desired value or range of values for Abrasion value.

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