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Strength Modeling of Mechanical Strength of Polyolefin Fiber Reinforced Cementitious Composites

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Abstract: RCC consumes large quantities of natural resources like gravel stone and steel, and there is a need to investigate on an innovative material that utilizes limited quantities of natural resources but should have good mechanical strength. This study deals with the experimental investigation of strength evaluation of cementitious composites reinforced with polyolefin fibers from 0% to 2.5% (with interval of 0.5%), namely Polyolefin Fiber Reinforced Cementitious Composites (PL-FRCC) and developing statistical regression models for compressive strength, splitting-tensile strength, flexural strength and impact strength of PL-FRCC. Paired t-tests (for each PL fiber percentage 0 to 2.5%) bring out that there is significant difference in compressive and splitting-tensile strength when curing periods (3, 7, 28 days) are varied. Also, a strong relationship exists between the compressive and flexural strength of PL-FRCC. The proposed mathematical models developed in this study will be helpful to ascertain the mechanical strength of FRCC, especially, when the fiber reinforcing index is varied.

Keywords: Cement-based composites, impact energy, mechanical properties, paired-t tests, regression analysis, sustainability

I. Introduction

A. Sustainable Building Materials

Building industry is widely expanding worldwide and the unprecedented growth in construction activities leads to depletion of natural resources. The world concrete industry uses non-renewable minerals such as limestone (for manufacturing cement), gravel stone (quarried from rocky/ hilly sites, used as coarse aggregate), natural sand (from river beds, used as fine aggregate) leading to large amount of carbon emissions [1]. Concrete production employs about 10 million (in short scale billion) tons of rock and sand, and 1 billion ton of water annually [2]. Thus the cement industry faces a number of challenges such as managing the increasing demand in supply, reduce use of scarce raw materials, and address the growing environmental concerns linked to climatic change and an ailing world [3]. This shows that the built environment has a significant impact on the sustainability agenda as it accounts for nearly 40% of limited natural resources consumed [4-5]. In order to minimize the environmental impact and human health risks, the sustainability criterion of reduction in use of natural resources should be practiced or new eco-friendly and sustainable building materials should be explored as replacement for conventional concrete [2, 6].

Fiber Reinforced Cementitious Composites (FRCC) brings out new opportunities as sustainable materials [7-8] and alternatives for conventional materials, as huge amount of material reduction is possible with FRCC, as thin elements are fabricated (ranging from 10-25 mm thickness) using cement as binder, sand as filler and fiber material as structural constituent (substituting steel bars).

B. Fiber Reinforcement in Cementitious Composites

Twentieth century interests in non-metallic synthetic fibers as a component of construction materials was first reported in 1965 in USA; synthetic microfilament fibers were used in blast resistant structures for the US Army Corps of Engineers, R & D Section [9]. Wang and Li (2003) [10] have used Poly-Vinyl Alcohol (PVA) fibers of moderate volume fraction (typically 2%) in lightweight engineered cementitious composites; and PVA fibers have been used as reinforcement in cementitious composites as they are hydrophilic, synthetic and organic prefabricated materials that provide higher bond strength than glass or Polypropylene (PP) fibers [11]. Cavdar (2012) [12] used polypropylene (PP), carbon (CF), glass (GF) and polyvinyl alcohol (PVA) fibers in five different ratios 0%, 0.5%, 1%, 1.5% and 2% by volume and determine the flexural strength and ductility properties of cementitious composites (mortar) under high temperature. Some authors (like Ahmed et al., 2007) [13] have used 2.5% fibers but it is advisable to restrict the fiber volume to 2% to avoid workability problems during preparation of fibrous mortar, and some adjustments in matrix design is needed [14, 15]. PVA fibers have replaced asbestos fibers in cement boards and are widely used in engineered cementitious composites (ECC) such as road and deck slab outlays, tunnel lining, and secondary slabs, and other applications using shotcreting methods [16].

Fibers work as primary reinforcement in thin products in which the conventional reinforcing steel bars is either difficult to use or cannot be used; and in these applications, the uniformly dispersed fibers act to increase both the strength and toughness of the

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cementitious composites [17-19]. FRCC are extremely useful in providing fins, facades, sunscreens and claddings and creating other aesthetically appealing shapes in buildings [2]. FRCC is stronger, more ductile and durable than any other conventionally used building materials, and they are increasingly used in structural applications such as roofing slab and floorings [20], roofing tiles and building enclosures (wall panels) [21-22], pavements, and also in repair and rehabilitation of structures. In components such as slabs and pavements, fibers are added to control cracking induced by humidity or temperature variations and in these applications they work as secondary reinforcement [17]. The selection of appropriate fiber type for a certain project may sometimes be confusing [15] as the performance of FRCC depends on several factors like fiber properties (e.g. fiber strength), fiber volume content and matrix properties (e.g. matrix strength). Therefore, thorough investigative studies are required to understand the mechanical strength of cement composites for various kinds of fiber reinforcements used [23] since the type and quantity of fibers are key parameters influencing the performance of FRCC [24]. Some test methods like low velocity impact tests will help to evaluate the mechanical strength of the composite material because the impact strength determines the total energy required to break a standard test specimen of a specified size under specified impact conditions (ACI 544). Also, the mechanical bonding between the fiber and cementitious matrix is reflected by the energy absorbed by the specimens after impact loading [25-27].

C. Mechanical Strength

Previous experimental studies have shown that fibers used in cement-based composites improve the mechanical properties such as compressive and flexural strength [19, 25, 28-29]; and many laboratory research works have demonstrated that fibers lead to performance enhancement, especially the impact strength and toughness [17, 30]. The factors that influence the physical and mechanical properties of FRCC include type and characteristics of reinforced fibers, type of cement, cementitious matrix and the way of mixing, placing or casting and curing of the specimens respectively [31-32]. The compressive strength of concrete and cement-based composites increases with curing time [33] but the increase in strength seems insignificant after 60 days [34]. As the hydration period is increased, the compressive strength increases accordingly, hence curing age is generally defined in quantifying the strength of cementitious composites. The strength of FRCC should therefore be evaluated for a given degree or period of hydration.

D. Research Significance

The recent technological development of a wide variety of fibers has been creating new opportunities for the improvement of FRCC [35]. Many types of new fibers from different origin at variable strength and dimensions have recently been commercialized in the construction market [15], viz., fiber materials made of steel, glass and synthetic materials (made of acrylic, polyvinyl alcohol, polyolefin, polyethylene and polypropylene) [24, 36-38]. Polyolefin fiber is a kind of chemical synthetic fiber, which can equably disperse in concrete and has high corrosion resistance to acid, alkali and salt, so it has been incrementally applied in engineering [39]. Polyolefin chemical fibers demonstrate good performance in flexural fatigue strength, ductility toughness, and impact resistance [40-41]. Synthetic fibers have also been suggested as an alternative reinforcement material to steel fibers [42] in cementitious composites as it is non-corrosive, non-magnetic and do not result in hazardous protrusions [39].

Most of the experimental studies that are investigated on the effect of fiber types have been conducted a decade ago; therefore, the types of fibers investigated in earlier research works are quite different from that of high performance fibers currently available in the market [24] like the Barchip-54 (Olefin-based) fibers.

Most researchers have conducted experimental investigation on cementitious composites using wide variety of fibers but presented the results without any analytical or mathematical models. Also, very little studies have brought out the statistical relationship between compressive strength and fiber-reinforcing index, and flexural strength and fiber-reinforcing index [43], and also the relationship between compressive and flexural strength [44] in FRCC. Since introduced in the ACI [45], the fiber factor is a simple way to evaluate the effect of fiber content and length on a matrix's mechanical properties after the fibers have been introduced into the matrix; and fiber factor has a significant relationship with mechanical properties of cementitious materials [31].

Using the experimental data, it will be interesting to establish the statistical relationship between the dependent variable (such as compressive, splitting-tensile, flexural and impact strength) and independent variables (volume fraction of reinforcing fibers, curing period) [46]. Therefore, this study makes an attempt to study the relationship between the mechanical strength of FRCC and polyolefin fiber volume fractions [22, 36, 38]. The regression model proposed in the present study will be helpful to predict the strength of FRCC, and accordingly vary the input parameters or the matrix design. In order to arrive at the best set of predictors of a particular dependent variable [14, 47], the objective of the present study is to develop linear regression equations using SPSS [48] to evaluate the effect of fiber percentage and/or curing days on the mechanical strength of FRCC.

II. Experimental Investigation

A. Materials

Ordinary Portland Cement (OPC-53 Grade) was used (with a specific gravity of 3.14) in this study conform to IS 12269-1987 (Reaffirmed 2008) [49], IS 4031 (Part 3 to 6) 1988 (Reaffirmed 2009) [50] and (IS 4031 (Part 2)) 1999 (Reaffirmed 2008) [51]. Natural river sand (with specific gravity 2.74) free from clay matter, silt and organic impurities, and passing through 2.36 mm sieve size has been used as fine aggregate in PL-FRCC [52-55], and the material conforms to ACI 549 [56] and FMC [57]. The river sand tested in the standard laboratory conform to IS 2386 (part I to VIII) 1963 (Reaffirmed 2007) [58] and IS 383-1970 (Re affirmed 2007) [59]. The Polyolefin (Barchip-54) fibers, manufactured by Elasto Plastic Concrete (EPC, Australia) were used as reinforcement in cementitious matrix, and the properties, as given by the manufacturer, are shown in Table I.

TABLE I
PROPERTIES OF POLYOLEFIN FIBERS

S. No.	Appearance	
	Properties	**Measurement**
1	Base Material	Modified Olefin
2	Length of Fiber (mm)	54 mm
3	Tensile Strength (N/mm^2)	640
4	Density (gm/cm^3)	0.92
5	Young's Modulus (kN/mm^2)	10

B. Materials

The specimens were cast with Ordinary Portland Cement (OPC-53 Grade) and natural river sand, potable water, and Polyolefin (PL) fibers. In order to achieve a normal strength with good workability, the dry cement mortar is prepared using sand-cement ratio (by weight) of 2:1 [26-27, 52-53, 60-61] and water-cement ratio of 0.43 [26-27, 52], in line with the specifications of ACI 549, FMC and Naaman, 2000 [56-57, 62], after several trials by the present authors using polyolefin fibers (0.5% to 2.5% of volume of specimens, with 0.5% interval).

The PL fibers were evenly spread by hand and mixed with cement mortar in order to obtain a homogenous dry mixture to avoid balling of fibers at one place. Now the requisite amount of potable water is added to the fibrous mortar and mixed well with mason's trowel. The moulds were lightly oiled before casting the specimens in order to prevent mortar sticking to the sides of the mould. Using the fibrous mortar prepared, the PL-FRCC slabs of 250 mm X 250 mm X 25 mm (thickness) were cast in wooden moulds. Along with these test specimens, reference specimens were cast using steel moulds of cube size of 100 mm X 100 mm X 100 mm (to determine the compressive strength at 3, 7 and 28 days, 3 samples each), cylinders of 100 X 200 mm (height) (to find out the splitting-tensile strength) and prismatic beam specimens of 40 X 40 X 160 mm (to determine the flexural strength at 28 days, 3 samples each). After 24 hours of demoulding of the specimens, they were cured with gunny sacks, and then transferred to the curing tank.

C. Impact Test

After the required curing period of 28 days, the impact test was conducted on PL-FRCC slabs of size 250 X 250 X 25 mm (thickness) as per the procedure of Sakthivel and Jagannathan (2012); Sakthivel et al., (2012) [26-27]. The slabs were placed on a metal platform in a simply supported position and a steel ball (weighing 9.81 N) was repeatedly made to fall freely on to the slab from a height of 600 mm through a pulley and rope arrangement. The number of blows received during first crack and at ultimate failure of the specimen were noted down and the total energy absorbed by the slab is calculated (in Joules) based on the procedure of Sakthivel and Jagannathan (2012) and Sakthivel et al. (2012) [26-27].

III. RESULTS AND DISCUSSION

A. Mechanical Strength

From Table II, it is seen that the compressive strength of control specimens at 3,7 and 28 days is 12.67 N/mm^2, 20 N/mm^2 and 33 N/mm^2 respectively. For reference specimens, the compressive strength varies between 18 N/mm^2 and 28 N/mm^2 for 3 days, 23 N/mm^2 and 35 N/mm^2 for 7 days, and 33.5 N/mm^2 and 50 N/mm^2 for 28 days, when the PL fiber is varied between 0.5 and 2.5%. Similarly, the split-tensile strength of control specimens at 3,7 and 28 days is 2.70 N/mm^2, 4 N/mm^2 and 4.6 N/mm^2 respectively. For PL-FRCC test specimens, the split-tensile strength varies between 3.02 N/mm^2 and 5.10 N/mm^2 for 3 days, 4.45 N/mm^2 and 6.21 N/mm^2 for 7 days, and 4.87 N/mm^2 and 7.01 N/mm^2 for 28 days, when the PL fiber is varied between 0.5 and 2.5%. Also, the prismatic flexural strength at 28 days is 5.80 N/mm^2 for control specimens, and varies between 6.08 N/mm^2 and 8.6 N/mm^2 for PL-0.5% to 2.5%.

TABLE II
EXPERIMENTAL TEST RESULTS OF PL-FRCC

S. No.	Dependent Variables			Independent Variables				
	FP	RI	CP	CS	TS	FS	IIEA	UIEA
	%		Days	N/mm^2			Joules	
1	0.0	0.00	3	12.67	2.70	--	-	-
2	0.5	0.09	3	18.00	3.02	--	-	-
3	1.0	0.18	3	20.50	4.14	--	-	-
4	1.5	0.27	3	24.00	4.35	--	-	-
5	2.0	0.36	3	26.00	4.78	--	-	-
6	2.5	0.45	3	28.00	5.10	--	-	-
7	0.0	0.00	7	20.00	4.00	--	-	-
8	0.5	0.09	7	23.00	4.45	--	-	-
9	1.0	0.18	7	25.00	5.10	--	-	-
10	1.5	0.27	7	28.00	5.31	--	-	-
11	2.0	0.36	7	32.00	5.41	--	-	-
12	2.5	0.45	7	35.00	6.21	--	-	-
13	0.0	0.00	28	33.00	4.60	5.80	5.89	11.77
14	0.5	0.09	28	33.50	4.87	6.08	11.77	41.20
15	1.0	0.18	28	40.33	5.41	6.83	17.66	70.63
16	1.5	0.27	28	45.00	5.64	7.88	23.54	100.06
17	2.0	0.36	28	48.00	6.05	8.26	35.32	153.04
18	2.5	0.45	28	50.00	7.01	8.60	52.97	264.87

FP- Fiber Percentage; RI-Reinforcing Index; CP - Curing Period (Days); CS-Cube Compressive Strength; TS-Splitting Tensile Strength; FS-Prismatic Mortar Flexural Strength; IIEA-Initial Impact Energy Absorption; UIEA-Ultimate Impact Energy Absorption

In order to find out whether the increase is significant between the various curing periods, paired t-tests were conducted in this study and presented in Table III. From the results of the paired t-tests (see Table III), it is seen there is significant difference (at $p<0.01$) in the compressive strength between 3 and 7 days (Pair No.1), and 7 and 28 days (Pair No.2) for compressive strength (CS), and split-tensile strength (TS) between 3 and 7 days (Pair No.3), and 7 and 28 days (Pair No.4) for all fiber percentages (0%, 0.5%, 1%, 1.5%, 2% and 2.5%). The R-values of 0.971, 0.965 (Pairs 1, 2 respectively for CS) and 0.969 and 0.978 (Pairs 3, 4 respectively for TS) demonstrate that there is a high level of correlation of CS/ TS between 3 and 7 days, and also 7 and 28 days at each fiber-percentage.

TABLE III
PAIRED T-TESTS FOR COMPRESSIVE STRENGTH OF PL-FRCC

Pair No.	Pairing Variables	ANOVA Results			
		df	R	t	df
1	CS - 3 & 7 Days	5	0.971	10.163*	5
2	CS - 7 & 28 Days	5	0.965	15.065*	5
3	TS - 3 & 7 Days	5	0.969	9.203*	5
4	TS - 7 & 28 Days	5	0.978	6.504*	5

CS-Compressive Strength; TS-Splitting-tensile Strength; *Significance at $p<0.001$

From Table II, it can also be found that the initial impact energy absorption (IIEA) for control specimens is 5.89 J and ultimate impact energy absorption (UIEA) is 11.77 J. When PL fibers were added from 0.5 to 2.5%, the IIEA values range between 11.77 J and 52.97 J, showing an increase of 2 to 9 times (respectively) as that of control specimens (with value of 5.856 J). Similarly, for UIEA, the values range between 41.20 J and 264.87 J demonstrating that there is a strength improvement of 2.5 times to 22.5 times (respectively) as that of control specimens (with value of 11.77 J).

B. Regression Models

In this study, the regression analysis was performed to determine the statistically significant (p-level<0.05) independent parameters and their percentage contributions on the dependent parameters. The fiber reinforcing index (RI) has been calculated using the properties of polyolefin fibers (see Table I) as well as the average density values of PL-FRCC of 2280 kg/m^3 obtained from the present experimental study. For calculating the RI, the formula specified by Li *et al*., 2006 (p.498) [31] and Ramadoss and Nagamani (2008, p.312) [43] have been used here.

Regression analysis was conducted between the independent variables (Reinforcing Index, RI / Curing Period, CP) and the five dependent responses, CS, TS, FS, IIEA and UIEA were constructed. Based on ANOVA results, the prediction models 1, 2, 3, 4 and 5 (respectively) were formulated and presented in Table IV.

Models 1 and 2 demonstrate the joint effect of the independent variables (RI and CP) on each of the dependent variables, CS and TS respectively. Also, the effect of the independent variable, RI, on each of the dependent variables, FS, IIEA and UIEA are evaluated in Models 3, 4 and 5. In Models 1, 2, 3, 4 and 5, the correlation co-efficient R show values of 0.988, 0.920, 0.983, 0.968 and 0.953 corresponding to Model 1 (CS), Model 2 for (TS), Model 3 (FS), Model 4 (IIEA), and Model 5 (UIEA), respectively, all significant at p<0.001. The *F* values (overall model) of the regression equation for CS, TS, FS, IIEA, and UIEA are found to be 301.880 (p<0.01), 41.538 (p<0.01), 115.841 (p<0.01), 60.093 (p<0.01) and 40.014 (p<0.01) respectively. The co-efficient of determination (R2) values of 0.976, 0.847, 0.967, 0.938 and 0.909 (all at p<0.001) can be accepted as the significant models [14]. For Models 1 and 2 representing CS and TS respectively, the R^2 of 0.976 and 0.847 suggest that both the independent variables, CP and RI jointly predict the CS and TS of PL-FRCC and explains 97.6 and 84.7 per cent of the variations in CS and TS respectively. This should be due to the combined effect of effective hydration in cementitious matrix and the mechanical properties of polyolefin fiber (such as the strength and the ability of the fiber to mechanically bond well with cementitious matrix) [34]. In Models 3, 4 and 5, R^2 values explain variability of 96.7%, 93.7% and 90.8% of FS, IIEA and UIEA respectively.

The sample calculation to predict the strength from the regression model is shown below.

If the Curing Period (CP) is 28 days and Reinforcing Index (RI) is 0.18, then the Predicted Compressive Strength, CS(P) from Model No.1 in Table IV is 40.34 N/mm^2. When this predicted value is compared to the experimental value for compressive strength of 40.23 N/mm^2, the predicted error is almost nil.

TABLE IV
REGRESSION MODELS FOR MECHANICAL STRENGTH OF PL-FRCC

Model No.	Dependent Variable	Regression Model	R	R^2	F
1	CS	CS(P)=12.266 + 0.766 CP + 36.794 RI+	0.988	0.976	301.880*
2	TS	TS(P)=3.129+ 0.051CP+ 5.101 RI	0.920	0.847	41.538*
3	FS	FS(P)= 5.702+ 6.961 RI	0.983	0.967	115.841*
4	IIEA	IIEA(P)= 2.269+ 100.630 RI	0.968	0.938	60.093*
5	UIEA	UIEA(P)= -9.411+ 526.026 RI	0.953	0.909	40.014*

PL-FRCC - Polyolefin Fiber Reinforced Cementitious Composites; CS(P)-Predicted Cube Compressive Strength; TS(P)-Predicted Splitting Tensile Strength; FS(P)-Predicted Flexural Strength; IIEA(P)-Predicted Initial Impact Energy Absorption; UIEA(P)-Predicted Ultimate Impact Energy Absorption; CP - Curing Period; RI=Reinforcing Index; *Significance at $p<0.001$

C. Relationship between Compressive and Flexural Strength

The statistical relationship between the compressive and flexural strength of PL-FRCC (at 28 days) has been ascertained through regression analysis, and presented as Model 5 in Table V. Also, the R^2 (co-efficient of determination), which is a measure of goodness of fit was found to be 0.989, and *F* value of 365.052 (p<0.01). The R^2 value more than 0.8 imply high level of predictive relationship between the flexural strength and the compressive strength. Also, the multiple correlation R of 0.995 (see Table V) shows high correlation between the compressive and flexural strength of PL-FRCC.

If the compressive strength (CS) is 50 N/mm^2 , then the predicted flexural strength (FS) as calculated using regression equation given for Model 6 in Table V gives a value of 8.606 N/mm^2, whereas the experimental value shows 8.60 N/mm^2, and the prediction error is almost nil.

It should be noted that in case the experimental runs are lesser in number, then the prediction error is expected to be high. If the prediction error is very high, then confirmatory experiments should be conducted by repeating the experiments and then the regression equation be reworked accordingly using the new results.

TABLE V
RELATIONSHIP BETWEEN COMPRESSIVE AND FLEXURAL STRENGTH OF PL-FRCC

Model No.	Dependent Variable	Regression Model	R	R^2	F
6	FS	FS=0.556+ 0.161 CS	0.995	0.989	365.052*

CS-Compressive Strength; FS-Flexural Strength; *Significance at p<0.001

IV. CONCLUDING REMARKS

An experimental study on Polyolefin Fiber Reinforced Cementitious Composites (PL-FRCC) was conducted and the following are the conclusions:

1. There is a significant increase in the compressive strength and split-tensile strength of PL-FRCC when curing period is increased.
2. The flexural strength of PL-FRCC increases with increase in fiber reinforcing index.
3. There exists a statistical relationship between compressive and flexural strength of PL-FRCC.
4. The ultimate impact strength of PL-FRCC increases with increase in polyolefin fibers from 0 to 2.5% (with reinforcing index from 0 to 0.45 respectively).
5. The regression models developed for the mechanical strength of PL-FRCC viz., compressive strength, splitting-tensile strength, flexural strength and impact strength adequately fit the experimental data with a p-value less than p<0.001.
6. The regression models developed in this study will certainly be helpful to the researchers and construction practitioners to ascertain the mechanical strength of fiber composites.

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