Int. J. of GEOMATE, Sept., 2014, Vol. 7, No. 1 (Sl. No. 13), pp.993-1002
Geotech., Const. Mat. & Env., ISSN:2186-2982(P), 2186-2990(O), Japan

EXPERIMENTAL AND PREDICTIVE MECHANICAL STRENGTH OF FIBER REINFORCED CEMENTITIOUS MATRIX

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ABSTRACT: Fiber Reinforced Cementitious Matrix (FRCM) are sustainable building materials as it uses lesser quantities of natural resources as raw materials for production, when compared to conventional concrete. This study is an attempt to explore the possibility of using crimped mild steel (MS) fibers (12.5 mm length) as reinforcement in cementitious matrix, with sand-cement and water-cement ratio in line with the ACI Codes. From the experimental results, it was found that when the percentage of MS fibers is increased in cement-based mortar from 0.5% to 2.5% of volume of specimens (with 0.5% interval), there is a corresponding increase in the cylinder compressive strength and splitting-tensile strength at 7 and 28 days, and flexural strength at 28 days. There was an increase in compressive strength of 74%, splitting-tensile strength of 38% and flexural strength of 35% at 28 days, when MS fibers of 2.5% was used, when compared to control mortar specimens (with no fibers). Also, the predictive strength models were developed from the experimental data using statistical regression analysis. It was observed that the experimental results of FRCM highly correlate with the predicted values, with minimum prediction error.

Keywords: ANOVA, Fibers, Mechanical Properties, Mild Steel, Statistical Models

1. INTRODUCTION

1.1 Sustainability in Construction

Concrete production and sustainability are highly related to each other. Concrete is widely used as a construction material in building foundations, cast-in-situ roofs and floors, and precast structural elements and employs large amount of natural and non-renewable resources like mineral and water as its raw material [1]. Around half of the world's Ordinary Portland Cement (OPC) is used to make around 11 billion metric tonnes of concrete annually and the rest is used in mortars, screeds, stucco, coatings, soil stabilization and other applications; and it was predicted that the total annual demand of cement in the world will exceed 2.4 billion tons in 2020 [2]-[3]. Also, the rock which is quarried mostly for use as coarse aggregates (gravel) in concrete not only exhausts the natural resources but also creates health hazards and atmospheric pollution. In the present context, the key sustainability challenges for the future include design and production of concrete which uses less clinker and a material that releases lower CO_2 into the atmosphere [4].

Fiber Reinforced Cementitious Matrix (FRCM) is a sustainable product produced with cement, river sand, and water, with total elimination of coarse aggregate (such as gravel/ crushed rock); and the discontinuous fibers (<2% of volume of specimens) which is used as reinforcement (in place of steel bars) enhances the material performance [5].

The compressive strength is necessary for almost all structural designs, and tensile strength for specific structural designs such as airfield runways and pavement slabs [6]-[7]. Fibers create an interlock or a strong mechanical bond with the cementitious matrix, and due to the stress transfer between the fibers and the matrix, the mechanical strength (compressive strength, tensile and flexural strength) of cementitious matrix is substantially increased. The dispersion of fibers in the brittle matrix offer not only convenience and practical means of achieving improvement in many of the engineering properties of the materials such as tensile and flexural strength but also provide advantages in terms of fabrication of products and components [8].

FRCM is being increasingly used as alternatives for conventional materials for roofing and wall paneling systems primarily because of their high specific strength (strength-to-weight ratio), specific stiffness or modulus (stiffness-to-weight ratio) and tailorable properties (meeting needs of specific applications with considerable ease) [9]-[13].

The fibers normally used in FRCM are metallic (mild steel - MS), synthetic (polymeric), ceramic (glass) and natural (organic) type [14]. Even though the use of MS fibers may increase the environmental impact of the plain cementitious matrix due to energy consumption and CO_2 emissions related to the production and shipping of the fibers, its use can extend the maintenance-free life of the structures and thus reduce the overall environmental impact of the construction [15] Also, MS fiber material has good bonding and higher Young's modulus, when compared to other fiber types, and therefore, several authors, Xu and Shi [6], Gencel *et al.* [16] and Dawood and Ramli [17] have recommended MS fibers for use as reinforcement in cementitious matrix but its overall applicability in cement matrix and workability-related issues are to be investigated.

The objective of this study is to investigate the mechanical strength (compressive and splitting-tensile strength) of cementitious composites at 7 and 28 days and prismatic flexural strength at 28 days, with varying MS fiber percentages.

1.2 Predictive Empirical Models

Statistical regression analysis is a powerful tool to predict the mechanical properties or strength, considering the fiber volume fraction [18]. Statistical model is used to predict the effect of changes in the variables to the system, but should be as close as possible to the real system and incorporate most of its salient features [19]. Multiple Regression Analysis will help in establishing a mathematical relationship between two or more independent variables and a dependent variable by fitting a linear equation to observed data; and every value of the independent variable is associated with a value of the dependent variable [20].

Statistically predicted models have the ability that once derived or formulated, using the experimental data, they can be employed to estimate the values more accurately and easier than any other modeling techniques, and are compatible with statistical packages like SPSS [21]. Several researchers, Maruthachalam [19] and Ramadoss and Nagamani [22]-[23] have used simple linear models and developed statistical empirical expressions/ models for the prediction of strength of high performance fiber reinforced concrete (HPFRC); and the influence of fiber content in terms of fiber reinforcing index on the flexural and splitting tensile strengths of HPFRC have been determined. 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 [24]. Recently, Dawood and Ramli [17] and Chakraborthy *et al.* [25] have studied the relationship between fiber factor and compressive and flexural strength of cement mortar, and have reported that the effect of fiber reinforcement (in terms of fiber content) on the mechanical properties of cement composites is best evaluated through the measurement of these properties as a function of fiber factor.

Ismail [26] has conducted an experimental investigation to study the mechanical properties of fiber-reinforced cement composites by using short natural (roselle) fibers in volume fraction of 0-4% and developed statistical relationship between the mechanical strength (compressive, tensile and flexural strength) and fiber reinforcing volume (Vf). Also, Maruthachalam *et al.* [19] and Sahmaran *et al.* [27] used statistical tools to test the properties of fiber reinforced high performance concrete (FRHPC), and developed regression models using Analysis of Variance which adequately fit the experimental data with $p<0.05$.

Deshpande *et al.* [20] have brought out that the compressive strength of concrete can be derived through appropriate statistical regression analysis. While Ramadoss and Nagamani [28] have established the relationship of both flexural and splitting tensile strength at 28 days with fiber reinforcing index (RI) (at a given fiber content) in fiber reinforced concrete, the present authors have found out through thorough review of literature that there are limited studies on the prediction of mechanical strength (compressive, splitting-tensile and flexural strength) of fiber reinforced cementitious matrix (FRCM). Therefore, an attempt has been made by the present authors to conduct statistical analysis on the results obtained from laboratory tests to determine the influence of MS fibers in cementitious composites at different fiber percentages, and develop predictive models for compressive strength, splitting-tensile strength and prismatic strength of MS-FRCM.

2. MATERIALS & METHODS

2.1 Materials

The crimped Mild Steel (MS) fibers of 12.5 mm length and 0.45 mm diameter supplied by Stewols India (P) Ltd., Nagpur, India have been used in this study (see Table 1), which conform to ASTM A 820 90 standards [29].

Table 1. Steel Fiber Properties

S.No	Properties	Dimensions
1	Size (mm)	0.45
2	Length (mm)	12.5
3	Shape	Crimped
4	UTS (N/mm2)	1159

The materials employed in the casting of FRCM are cement (binder), river sand (fine aggregate), and mild steel fibers (reinforcing material). Ordinary Portland Cement (OPC-53 Grade) conforming to IS 12269 [30] with specific gravity of 3.37 and locally available natural river sand with fineness modulus of 2.91 and specific gravity of 2.64 conforming to Zone II of IS 383 [31] have been used in this study. Sand passing through 2.36 mm size sieve (Fig.1) was used for preparing the cement mortar (Mohammed and Assi, 2011) [32].

Fig. 1 Sand passing through 2.36 mm sieve

2.2 Methods

2.2.1 Casting of Specimens

The cylinder compressive strength (CS), and splitting-tensile strength (TS) of plain and fibrous mortar (using MS fibers) at 7 and 28 days were determined using cylinders of 100 mm (diameter) X 200 mm (height) [15], [33]. The flexural strength (FS) test was performed using 40 mm X 40 mm X 160 mm prismatic samples [34] at 28 days, in line with the specifications given in ASTM C348 [35].

In line with the research works of Mahmood and Majeed [36], Ibrahim [37], Sakthivel *et al.* [38], Sakthivel and Jagannathan [39]-[42] and Shaheen *et al.*, 2013 [43] and on conducting several trials by the present authors, it was decided to use sand-cement (s/c) ratio (by weight) of 2:1, and water-cement (w/c) ratio of 0.43 (by weight) for casting the specimens in this study.

For casting the control specimens, the cement and sand were first measured on weight basis and mixed together in a dry state. Then the required quantity of water is added to the dry cement mortar in several parts, and thoroughly mixed. For test specimens, steel fibers (in varying MS fiber percentages - 0.5%, 1%, 1.5%, 2% and 2.5% of volume of specimens) were weighed (Fig. 2) and evenly spread to the dry mortar (Fig. 3) and then the fibers were mixed with cement mortar in a dry manner (Fig. 4). The measured quantity of water was poured into the dry mortar in parts and thoroughly mixed for 1-2 minutes or until the required homogeneity is achieved (Fig. 5). The w/c ratio of 0.43 was followed without any deviation, and no extra quantity of water was used or any admixture added for improving the workability.

The control and test specimens cast were removed from the moulds after 24 hours and necessary identification marks have been given. Then the initial curing was done by wrapping the specimens in wet gunny sacks. Subsequently the specimens were shifted to the curing tank and kept immersed in water for the required curing period of 7 or 28 days. Before testing, the specimens were removed from the water tank and wiped dry.

Fig. 2. Weighing the Mild Steel Fibers

Fig. 3. Spreading MS fibers to Dry Mortar

Fig. 4. Mixing MS fibers to Dry Mortar

Fig. 5. Adding water to the mix (in parts)

2.3 Statistical Analysis

2.3.1 Regression Analysis

Regression analysis has been performed to establish relationship between the mechanical strength (compressive strength, splitting-tensile strength and flexural strength) and variables like fiber reinforcing index and curing period. The coefficient of determination (R^2) is the proportion of the total variation in Y explained by the regression of Y on X; and R^2 ranges from 0 (when the estimated regression model explains none of the variation in Y) to 1 (when all points lie on the regression line), and the values closer to one suggest a more accurate model [44]. The statistical models are developed from the experimental data, and in turn can be used to predict the future experimental values in advance. In order to have a reasonable agreement with the adjusted R^2, a satisfactory adjustment of the quadratic model according to the experimental data is required [45].

2.3.2 Fiber Reinforcing Index

From Table 1, the length of steel fiber used is 12.5 mm, and fiber diameter of 0.45 mm (aspect ratio=28). In order to calculate the fiber reinforcing index (RI) (Equation 1), the formula suggested by several authors, Dawood and Ramli [17], Ramadoss and Nagamani [22]-[23], Li *et al.* [24]; Chakraborthy *et al.* [25] have been consolidated and given in "Eq. (1)"

$$RI = w_f * (l/d) \tag{1}$$

where weight fraction (w_f) =(density of fiber / density of fibrous mortar) * V_f

V_f is the volume fraction of fibers in percentage; and aspect ratio (l/d) = length of fiber/ diameter of fiber

For MS fibers used in test specimens, the fiber reinforcing index (RI) has been calculated as 0.47, 0.94, 1.41, 1.88 and 2.35 (corresponding to 0.5%, 1%, 1.5%, 2% and 2.5% of volume of specimens respectively) using equation (1). For control specimens cast with plain cement mortar (without fibers), RI=0. The average density of FRCM (using MS fibers) was determined from this experimental study as 2346 kg/m^3 and used to calculate the weight fraction (w_f) in Eq. (1).

2.3.3 Strength Improvement Ratio

In order to determine the efficiency of steel fibers on the compressive strength of FRCM (test specimens), when compared to plain cement matrix (control specimens), the strength improvement ratio between the fibrous and plain cement mortar specimens is calculated from "Eq. (2)" of Yu et al. (2014) [4] as given below:

$$S = (Si - So / So) \tag{2}$$

where S is the Strength Improvement Ratio; Si is the strength of FRCM (in N/mm^2), i represents varying fiber %, by volume (in terms of Reinforcing Index, RI); and So is the strength of plain cement mortar without fibers (in N/mm^2).

2.3.4 One-Sample and Paired t-tests

T-tests are performed to identify the non-significant variables. One-sample t-test is conducted to determine whether there is significant difference in the set of samples (when RI is varied) at the same testing period (7 or 28 days). The student's t-test for paired samples is conducted to check whether there is an improvement or reduction in strength of FRCM or if the means have remained the same. For testing this, two sets of samples are paired, i.e., samples cast at the same time but tested at two different periods, i.e., at 7 and 28 days. It is hypothesized in this study that cementitious composites with 7 and 28 days will achieve varying strength for each RI variable of 0, 0.47, 0.94, 1.41. 1.88 and 2.35 (corresponding to MS fiber percentages of 0%, 0.5%, 1%, 1.5%, 2% and 2.5% respectively). Accordingly, the test results of one sample and paired t-tests are brought out in Section 3.

3. RESULTS & DISCUSSION

3.1 Experimental Observations

Proper sand-cement (s/c) and water-cement (w/c) ratios are crucial for increasing the strength of FRCM. Flow behavior of the cement mortar prepared in a fresh manner (indicating its workability) is evaluated through flow table and slump test methods [25]. Based on several trials that were conducted by the present authors, constant s/c ratio of 2:1 and w/c ratio of 0.43 were fixed with varying MS fibers (0.5%-2.5%). Good workability was obtained for fibrous mortar using MS fibers from 0.5% to 2% and medium level of workability for 2.5%. The river sand passing through 2.36 mm sieve would have helped in the particle-size packing density and minimization of any localized non-homogeneity [46].

When the present authors tried to increase the MS fiber percentage to 3% on trial basis, there were difficulties in mixing and casting, showing clumping of fibers in the cement mortar, and the resultant stiff mix showed poor workability. Therefore, the steel fibers in cementitious matrix have been restricted to 2.5% in this study.

After demoulding of the specimens, a good outer mortar finish of the specimens was observed without any small pores or honeycombing or cavities, demonstrating proper compaction of the plain and fibrous cement mortar matrix.

3.2 Test Results

3.2.1 Cylinder Compressive Strength

The Cylinder Compressive Strength (CS) of control (plain cement mortar) specimens and test (MS-FRCM) specimens are tested at 7th and 28th day, after required curing, and the results are given in Table 2 and Fig. 6. At least three samples of each mix were tested each at the age of 7 and 28 days. It is seen that the CS of control specimens (at 28 days) is 16.98 N/mm^2 at 7 days and 24.20 N/mm^2 at 28 days, showing an increase in strength of about 42% between these two periods.

From Table 2 and Fig. 6, it is noticed that for the test specimens, when RI is increased from 0.47 to 2.35 (for MS fiber % of 0.5 to 2.5 respectively), the CS has increased to 50%, i.e., from 20.38 N/mm^2 to 30.57 N/mm^2 at 7 days, and from 28.02 N/mm^2 to 42.04 N/mm^2 at 28 days.

Table 2. Compressive Strength of MS-FRCM

RI	CP	Set No	CS (E)	CS (P)	PE	CS(I)
			N/mm^2	N/mm^2	%	%
0.00	7	Set 1	16.98	16.14	-5.20	--
0.47	7		20.38	19.17	-6.31	20.02
0.94	7		22.50	22.20	-1.35	32.51
1.41	7		25.05	25.23	+0.72	47.53
1.88	7		26.79	28.26	+5.49	57.77
2.35	7		30.57	31.29	+2.36	80.04
0.00	28	Set 2	24.20	25.13	+3.84	--
0.47	28		28.02	28.16	+0.50	15.78
0.94	28		29.30	31.19	+6.45	21.07
1.41	28		35.67	34.22	-4.24	47.40
1.88	28		36.94	37.25	+0.84	52.64
2.35	28		42.04	40.28	-4.37	73.72

Note: MS-FRCM - Mild Steel Fiber Reinforced Cementitious Matrix; RI - Reinforcing Index; CP - Curing Period; CS (E) - Experimental Cylinder Compressive Strength; CS (P) - Predicted Cylinder Compressive Strength; PE-Predicted Error; CS (I) % - Cylinder Compressive Strength Improvement (in %)

3.2.1.1 One Sample t-test for Comp. Strength

In order to determine whether there is statistically significant difference in CS of MS-FRCM (at 7 and 28 days) when RI is varied as 0, 0.47, 0.94, 1.41, 1.88 and 2.35 (corresponding to steel fiber percentage of 0%, 0.5%, 1%, 1.5%, 2% and 2.5%), one sample test is conducted for Set 1 and Set 2 using CS (E) data (see Table 2) and the results are shown in Table 3. It is seen from Table 3 that t-value of 12.049 ($p<0.001$) (for Set No.1) for CS-7 days and 12.080 ($p<0.001$) (for Set No.2) for CS-28 days shows that there is significant difference in CS values when RI is varied (0, 0.47, 0.94, 1.41, 1.88 and 2.35) in Set 1 and Set 2, meaning that the strength is different when RI is varied at both curing periods, 7 and 28 days.

Table 3. One-sample test for Compressive Strength (CS)

Set No./ Curing Period	df	t-value
Set 1 - CS (E) -7 days	5	12.049*
Set 2 - CS (E) -28 days	5	12.080*

Note: CS (E) - Experimental Cylinder Compressive Strength (at 7 and 28 days); *Significant at $p<0.001$

3.2.1.2 Paired t-test for Compressive Strength

Also, the paired t-test is conducted between CS- 7 and 28 days. From Table 4, t-value of 11.029 ($p<0.001$) shows that there is a significant difference in values between 7 and 28 days for all RI values of 0, 0.47, 0.94, 1.41, 1.88 and 2.35, showing an increase in compressive strength.

Table 4. Paired t-test for Compressive Strength, CS (E)

Pairing Variables	No. of pairs	t-value
Pairing of 7 and 28 days - CS (E) Results	6 (RI=0, 0.47, 0.94, 1.41, 1.88 & 2.35)	11.029*

Note: CS (E) - Cylinder Compressive Strength (at 7 and 28 days); *Significant at $P<0.001$

3.2.1.3 Compressive Strength Improvement

The Compressive Strength Improvement Ratio (CS-IR) is calculated between test and control specimens using Eq.2 in Section 2.3.3 and shown in percentage as CS (I) % (see Table 2). When RI is increased from 0.47 to 2.35, the CS (I) % increases from about 20% to 80% respectively at 7 days and 16% to 74% respectively at 28 days.

3.2.1.4 Modeling of Compressive Strength

The statistical analysis for CS (Model 1), based on experimental values, CS (E), is done using RI and Curing Period (CP) as independent variables and CS as dependent variable, and Model 1 for Predicted Compressive Strength, CS (P) is given in Table 5. The CS (P) at 7 and 28 days, for varying RI are calculated using the regression model (in Table 5) and shown in Table 2. It is observed that the prediction error is between -6.31 and +6.45%, which is within tolerable limits of 15% deviation. The results indicate that RI had significant effects on CS at 99% confidence level, and the model shows significance level of $p<0.001$. F value is significant at $p<0.001$. R^2 of 0.975 (97.5%) shows that there is strong statistical association between RI and CP with CS. R, co-efficient of correlation (square-root of adjusted R square) of 0.997 shows high correlation (99.7%) between RI, CP and CS.

Table 5. Predictive Model for Compressive Strength

Model No.	Predicted Model for Compressive Strength	Statistical Values
1	CS (P) =13.144+ 6.446 RI + 0.428 CP	R=0.997
		R^2=0.975
		F=172.167**

MS-FRCM - Mild Steel Fiber Reinforced Cementitious Matrix; CS (P) - Predicted Cylinder Compressive Strength; RI - Reinforcing Index; CP - Curing Period; **Sig. at $p<0.001$

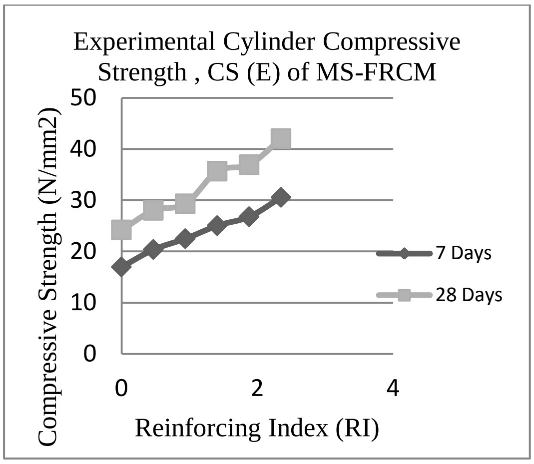

Fig. 6 Experimental Compressive Strength, CS (E)

3.2.2 Splitting-tensile Strength (TS)

The experimental splitting tensile strength (TS-E) of control specimens at 7 and 28 days are 2.86 N/mm^2 and 4.6 N/mm^2 respectively as shown in Table 6 and Fig. 7, with strength increase of 61%.

From Table 6 and Fig. 7, for test specimens with RI ranging between 0.47 and 2.35, the split-tensile strength has increased 60% (i.e., from 3.18 N/mm^2 to 5.09 N/mm^2) for 7 days, and 36% (i.e., from 4.67 N/mm^2 to 6.37 N/mm^2) for 28 days. From Table 6, the predicted values for RI=0 to 2.35 range between 3.0 N/mm^2 and 5.06 N/mm^2 for 7 days and 4.28 N/mm^2 and 6.34 N/mm^2 with a small prediction error ranging from -7.48 and +7.23% is observed between the experimental and predicted values, which is within tolerable limits.

Table 6. Experimental and Predicted Splitting Tensile Strength (TS) of MS-FRCM

RI	CP	Set No.	TS (E) N/mm^2	TS (P) N/mm^2	PE %	TS(I) %
0.00	7	Set 3	2.86	3.00	+4.90	--
0.47	7		3.18	3.41	+7.23	11.19
0.94	7		3.82	3.82	0.00	33.57
1.41	7		4.45	4.24	-4.95	55.59
1.88	7		4.78	4.65	-2.80	67.13
2.35	7		5.09	5.06	-0.59	77.97
0.00	28	Set 4	4.60	4.28	-7.48	--
0.47	28		4.67	4.69	+0.43	1.52
0.94	28		5.10	5.10	0.00	10.87
1.41	28		5.41	5.52	+2.03	17.60
1.88	28		5.73	5.93	+3.49	24.56
2.35	28		6.37	6.34	-0.47	38.48

Note: MS-FRCM - Mild Steel Fiber Reinforced Cementitious Matrix; RI - Reinforcing Index; CP-Curing Period; TS (E)-Experimental Splitting-tensile Strength; TS (P)-Predicted Splitting-tensile Strength; PE-Predicted Error; TS (I) (%)-Splitting-Tensile Strength Improvement (in percentage)

3.2.2.1 One Sample t-test for Tensile Strength

One sample t-test was also conducted on the data (from Table 6) in Set 3 and Set 4, and the statistical significant difference in TS (E) with varying fiber RI (0, 0.47, 0.94, 1.41, 1.88 and 2.35) has been studied and presented in Table 7. From the results (in Table 7) of one sample t-test for TS (E) - 7 days in Set 3 and TS (E) - 28 days in Set 4, t-value of 11.039 ($p<0.001$) and 19.236 ($p<0.001$) for 7 and 28 days (respectively) shows a significant difference in the TS (E) values for RI varying between 0 and 2.35 (with 0.47 interval). This means that the strength is different for all varying percentages of fibers added to cementitious matrix, in both curing periods.

Table 7. One-sample test for Splitting-tensile Strength

Set No./ Curing Period	df	t-value
Set 3 - TS (E) -7 days	5	11.039*
Set 4 - TS (E) -28 days	5	19.236*

Note: TS (E) - Experimental Splitting-tensile Strength (at 7 and 28 days); *Significant at $p<0.001$

3.2.2.2 Paired t-test for Compressive Strength

The results of the Paired t-test conducted between TS - 7 and 28 days are shown in Table 8. From Table 8, the t-value of 10.287 ($p<0.001$) brings out that there is a significant difference in the paired values between 7 and 28 days for RI of 0, 0.47, 0.94, 1.41, 1.88 and 2.35, demonstrating that there is an increase in splitting-tensile strength between these two periods (7 and 28 days).

Table 8. Paired t-test for Splitting-tensile Strength

Pairing Variables	No. of pairs	t-value
Pairing of 7 and 28 days - TS (E) Results	6 (RI=0, 0.47, 0.94, 1.41, 1.88 & 2.35)	10.287*

Note: TS (E) - Experimental Splitting-Tensile Strength of FRCM (at 7 and 28 days); *Significant at $P<0.001$

3.2.2.3 Split-Tensile Strength Improvement

The Tensile Strength Improvement Ratio (TS-IR %) is calculated for TS (E) between the test and control specimens using Eq. (2) in Section 2.3.3 and shown in percentage, TS (I) % in Table 6. It can be noticed that when RI is increased in cement mortar from 0.47 to 2.35 (when compared to control specimens with RI=0), the TS (I) % increases from about 11% to 78% at 7 days and 2% to 38% at 28 days.

3.2.2.4 Modeling of Splitting-Tensile Strength

From Table 9, it can be seen that while using the experimental data of TS from Table 6 and developing the regression equation for TS (Model 2), R value of 0.987 and R^2 of 0.974, with F value of 168.389 ($p<0.001$) have been obtained, showing good relationship and high level of correlation between the two independent variables (RI and CP) and the dependent variable (TS).

Based on TS (E) in Table 6, the predicted model for splitting tensile strength (TS-P) of MS-FRCM (Model 2) is presented in Table 9. The regression equation show R^2 of 0.974 (97.4%)

shows strong relationship of RI and TS, and any increase in RI will show a corresponding increase in TS. R value of 0.987 (98.7%) demonstrate a high level of correlation between the independent variables (RI and CP) and dependent variable, TS.

Table 9. Predicted Model for Splitting-tensile Strength (TS) of MS-FRCM

Model No.	Predicted Model for Tensile Strength (TS)	Statistical Values
2	TS (P) = 2.569+ 0.879 RI + 0.061 CP	R=0.987
		R^2=0.974
		F=168.389**

Note: MS-FRCM - Mild Steel-Fiber Reinforced Cementitious Matrix; TS (P) - Predicted Splitting-tensile Strength; RI - Reinforcing Index; CP-Curing Period; **Sig. at p<0.001

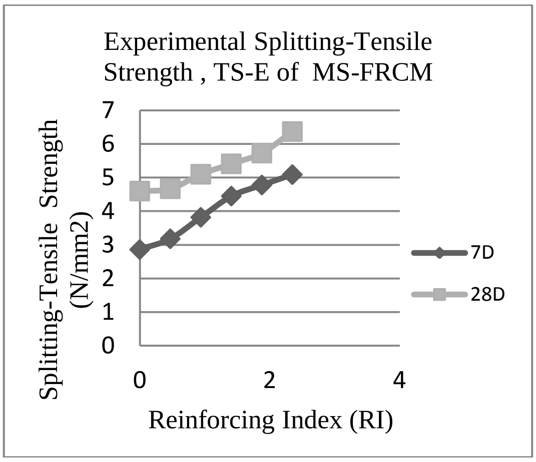

Fig. 7 Experimental Tensile Strength (TS-E)

3.2.3 Flexural Strength (FS)

The prismatic flexural strength (FS) of control specimens (RI=0) and test specimens (RI=0.47, 0.94, 1.41, 1.88 and 2.35) of MS-FRCM at 28 days is given in Table 10. From Table 10 and Fig. 8, the experimental flexural strength, FS (E) is seen to be 5.80 N/mm^2 for control specimens, and shows an increase in FS (E) of about 34% for test specimens, i.e., from 5.84 N/mm^2 and 7.84 N/mm^2, when RI is varied between 0.47 and 2.35, showing an increase in FS of about 34%.

Table 10. Experimental and Predicted Flexural Strength

RI	CP	Set No.	FS (E) N/mm^2	FS (P) N/mm^2	PE %	FS(I) %
0.00	28	Set 5	5.80	5.57	-4.13	--
0.47			5.84	6.01	+2.91	0.69
0.94			6.24	6.45	+3.36	7.59
1.41			6.95	6.89	-0.87	19.83
1.88			7.37	7.34	-0.41	27.07
2.35			7.84	7.78	-0.77	35.17

Note: MS-FRCM - Mild Steel Fiber Reinforced Cementitious Matrix; RI-Reinforcing Index, FS (E) - Experimental Flexural Strength; FS (P) - Predicted Flexural Strength; PE - Predicted Error; FS(I)(%)-Flexural Strength Improvement (in percentage)

3.2.3.1 One Sample t-test for Tensile Strength

Next, one-sample t-test for FS (Set No.5) presented in Table 11 shows t-value of 19.351 (p<0.001) with significant difference in FS values (when RI is varied from 0 to 2.35) demonstrating that the prismatic flexural strength is different when MS fiber percentage is varied in MS-FRCM.

Table 11. One-sample test for Flexural Strength (FS)

Set No./ Curing Period	df	t-value
Set 5 - FS (E) -28 days	5	19.351*

Note: FS (E) - Experimental Flexural Strength of FRCM (at 28 days); *Significant at p<0.001

3.2.3.2 Flexural Strength Improvement

From the experimental data of flexural strength (FS-E), the Flexural Strength Improvement Ratio (FS-IR)% is calculated using Eq. 2 in Section 2.3.3 between the test and control specimens and shown in Table 10. The FS (I) % has increased from 1% to 35% when RI is increased in from 0.47 to 2.35.

3.2.3.3 Modeling of Flexural Strength

The predicted model (Model No.3) for flexural strength (FS-P) of MS-FRCM in Table 12 has been developed using regression analysis from the experimental data in Table 10. The model for FS (P) with R^2 of 0.942 (94.2%) shows that a strong relationship exists between RI and FS. R value of 0.981 (98.1%) show high correlation between RI and FS. *F* value of 101.101 is significant at p<0.001. Table 10 shows that the predicted values for RI=0 is 5.57 N/mm^2 and for RI of 0.47 to 2.35, it ranges between 6.01 N/mm^2 and 7.78 N/mm^2 (respectively) at 28 days, and predicted error for FS of -4.13 and +3.36 is within reasonable limits.

Table 12. Predicted Model for Flexural Strength (FS)

Model No.	Predicted Model of Flexural Strength (FS)	Statistical Values
3	FS (P)=5.566+ 0.942 RI	R=0.981
		R^2=0.942
		F=101.101**

Note: MS-FRCM - Mild Steel Fiber Reinforced Cementitious Matrix; FS (P) - Predicted Flexural Strength; RI-Reinforcing Index, **Sig. at p<0.001

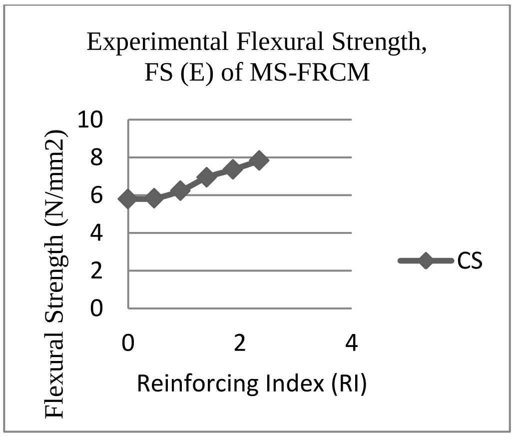

Fig. 8 Experimental Flexural Strength, FS (E)

3.3 Fitness of Predictive Models

From the experimental values given in Tables 2, 6 and 10 for compressive, splitting-tensile and prismatic flexural strength (respectively), the predictive strength of FRCM has been evaluated through statistical regression analysis. From Models 1 and 2, the equation for CS (P) and TS (P), it is seen that the contribution of MS fiber (in terms of RI) is several times more than the curing period in cementitious matrix.

The models (1, 2 and 3) developed for CS, TS and FS in Tables 5, 9 and 12 (in Section 3.2.1, 3.2.2 and 3.2.3) respectively show a measure of true goodness of fit, demonstrating reliable confidence in the estimation of the response coefficients (R^2) and high R^2 values (close to 1). The prediction error also is very less, which implies that the prediction model matches with the experimental results and the predicted error is within acceptable limits. All the three models have high coefficient of correlation (R^2) of more than 0.9. Thus, these models (1, 2 and 3) can be reliably used to predict the mechanical strength of FRCM.

Also, from the linear equations that have been derived and shown in Models 1, 2 and 3 (for compressive strength, splitting-tensile and prismatic flexural strength in Tables 5, 9 and 12 respectively), any intermediate strength values for a particular fiber reinforcing index (RI) can be predicted from the regression equations. For example, if the strength of FRCM (s/c ratio=2:1 and w/c ratio=0.43) with MS fiber of 1.75% (with Reinforcing Index, RI=1.645) and Curing Period (CP) of 28 days, then from equations Model 1, 2 and 3, the cylinder compressive strength=35.73 N/mm^2, splitting-tensile strength=5.72 N/mm^2 and prismatic flexural strength=7.12 N/mm^2. These predicted values can be verified through experimental work and predicted error determined.

4. CONCLUSION

An experimental investigation was conducted on Mild Steel Fiber Reinforced Cementitious Composites (MS-FRCM). The results show that there is a significant improvement in the mechanical strength of MS-FRCM when the MS fiber is increased from 0.5% to 2.5% of volume of specimens (represented in terms of reinforcing index, reinforcing index, RI=0.47 to 2.35 respectively), when compared to the control specimens (plain cement mortar cast without fibers). The compressive strength improvement of MS-FRCM (using MS fibers 0.5% and 2.5%) is between 20% and 80% (respectively) at 7 days, and 16% and 74% (respectively) at 28 days, with reference to control specimens.

Also, there has been a significant increase in splitting-tensile strength to the extent of 78% at 7 days and 38% at 28 days, when MS fiber of 2.5% (of volume of specimens) is used in FRCM, compared to control specimens. Also, at MS fibers of 2.5%, the flexural strength has increased upto 35%, when compared to plain cement mortar mix. Also, the hypothesis that cementitious composites with MS fibers will achieve varying strength for different reinforcing index (RI of 0, 0.47, 0.94, 1.41, 1.88 and 2.35 with MS fiber percentage of 0%, 0.5%, 1%, 1.5%, 2% and 2.5%) at 7 and 28 days is true, with increase in compressive, splitting-tensile and flexural strength as RI and curing period increases.

From the results, a high level of correlation is observed between the predicted and experimental results. The statistically predicted models developed from experimental data in this study are found to be reliable with less prediction error. Thus, this study concludes that these statistical models will be useful to predict the mechanical strength of matrix, before actual implementation of FRCM in construction. Future research can be done on flexural study of thin cementitious composite slab/ plate elements using fibers.

5. ACKNOWLEDGEMENTS

The present authors, P.B. Sakthivel, Ph.D. Research Scholar in Civil Engineering (Part-time External), Pondicherry Engineering College, (P.E.C.), Puducherry and Associate Professor of Civil Engineering, Agni College of Technology, Chennai; Dr. A. Ravichandran, Principal, Christ College of Engineering & Technology, Puducherry; Dr. N. Alagumurthi, Professor of Mechanical Engineering, P.E.C. thank Dr. D. Govindarajalu, Professor of Civil Engineering and Principal, Pondicherry Engineering College for providing facilities for this research work. The authors also thank Mr. S.K. Doongaji, Director, Stewols India (P) Ltd., Nagpur, India for sponsoring the MS fibers for this research work.

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Int. J. of GEOMATE, Sept., 2014, Vol. 7, No. 1 (Sl. No. 13), pp.993-1002.
MS No. 131219 received on Dec. 19, 2013 and reviewed under GEOMATE publication policies.

Pertinent discussion including authors' closure, if any, will be published in the Sept. 2015 if the discussion is received by March 2015.
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