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Predicting the Mechanical Properties of Fibrous Concrete by ANN

Athira M*, Dr. Deepa Balakrishnan**, Dr. Dipak Kumar Sahoo***
**(Research scholar, Department of Civil Engineering, CUSAT, Kochi*
*** (Professor, Department of Civil Engineering, CUSAT, Kochi*
****(Professor, Division of Safety & Fire Engg.,School of Engineering, CUSAT, Kochi*

ABSTRACT
This study predicts the cylinder compressive strength and flexural strength of fibrous concrete based on existing experimental results. The database used for this research comprehends steel, glass and synthetic fibers such as polypropylene and basalt fibers. The ANN models with seven input and two output data set were developed using the following algorithm; Bayesian Regularization and Levenberg Marquardt in MATLAB and linear regression equations were formulated. The performance of the networks was evaluated by RMSE, R-values and statistical values of performance factor. The results indicate that ANN has strong potential in predicting the strength properties so as to design FRC with desired mechanical properties without trial mixes and loss of time.

Keywords – Artificial Neural Network, Fiber Reinforced Concrete, Compressive Strength, Flexural Strength, Regression

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I. INTRODUCTION

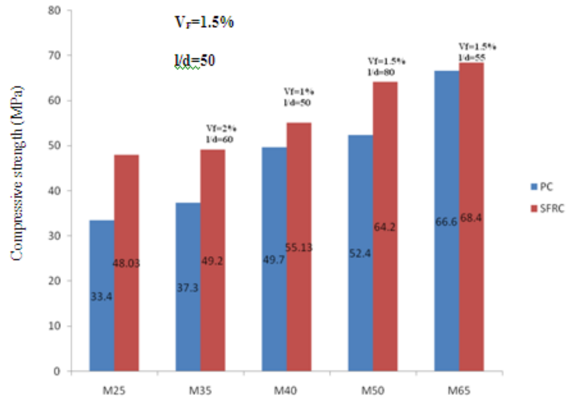
Fiber-reinforced concrete (FRC) is concrete containing fibrous material which increases its structural integrity. Concrete is weak in tension and has a brittle character. Addition of fibers to concrete makes it a homogeneous and isotropic material. When concrete cracks, the randomly oriented fibers start functioning, arrest crack formation and propagation, and thus improve strength and ductility. FRC is now treated as a performance-based material in several recent building codes and currently being specified in tunneling, bridge decks, pavements, loading docks, thin unbonded overlays, concrete pads, and concretes slabs. Fibers include steel fibers, glass fibers, synthetic fibers and natural fibers – each of which lends varying properties to the concrete. In addition, the character of fiber-reinforced concrete changes with varying concretes, fiber materials, geometries, distribution, orientation, and densities.

In recent years, analyzing the concrete properties through prediction modeling is gaining importance due to its accuracy and effectiveness in real-time application. A Neural Network is a machine learning algorithm based on the model of a human neuron and extensively used to answer many complex civil engineering concerns [1]. A neural network is a non– linear system consisting of a large number of highly interconnected processing units, nodes or artificial neurons. Each input signal is multiplied by the associated weight value (w_i) and summed at a neuron. The result is put through an activation function to generate a level of activity for the neuron. This activity is the output of the neuron. When the weight value at each link and the connection pattern are determined, the neural network is trained. This process is accomplished by learning from the training set and by applying for certain learning rule. The trained network can be used to generalize for those inputs that are not including in the training set.

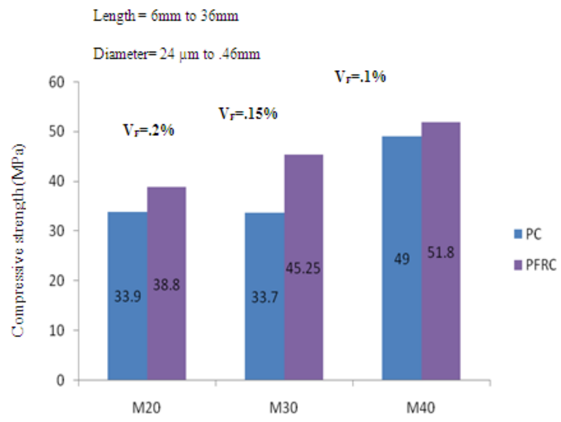
The concrete strength models developed are used to predict the properties through certain factors which are used as input parameters. There are numerous factors which govern the strength of concrete. The strength of concrete is affected partly by the relative proportion of cement and of the fine and coarse aggregates [2] but the water-cement ratio is another important factor. There is an optimum amount of water that will produce a concrete of maximum strength from a particular mix of fine and coarse aggregate and cement. [3] investigated the effect of aspect ratio and volume fraction of fibers on the mechanical properties of concrete and another significant influence is caused by the matrix and fiber tensile strengths. Therefore, the inputs chosen for compressive and flexural strength models were cement, coarse aggregate, fine aggregate, w/c ratio, fiber aspect ratio, volume fraction and its tensile strength. The models comprise single output which is a strength parameter. Therefore the optimization of strength properties of FRC can be utilized in sustainable building practices.

1.1 Experimental database

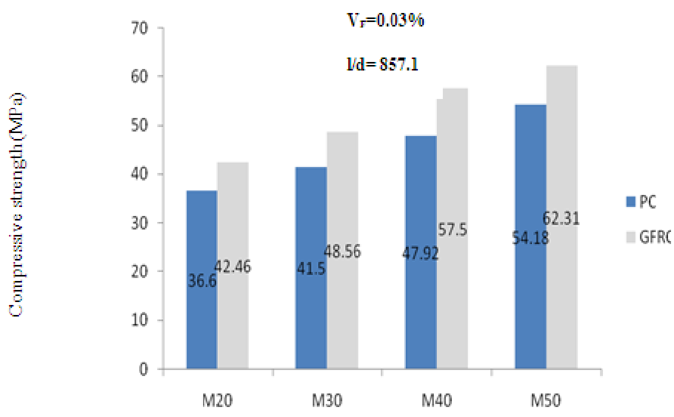
It summarizes the work that has been conducted to date by other researchers on fibrous concrete. The performance of different types of fibers is characterized by three parameters such as aspect ratio, tensile strength of fibers and bond between fibers and matrix. A large database containing 305 compressive strength tests of fibrous concrete was gathered. The cube compressive strength found in literatures was converted to cylinder compressive strength according to BS 1881: Part 120: 1983. The database of experiments regarding FRC collected from literatures for cylinder compressive strength modeling is given in **Table 1.** The fiber bridging effect across the micro cracks results in increased compressive strength. The optimum fiber content to impart maximum gain in compressive strength for various grades of concrete is shown in **Fig. 1**.



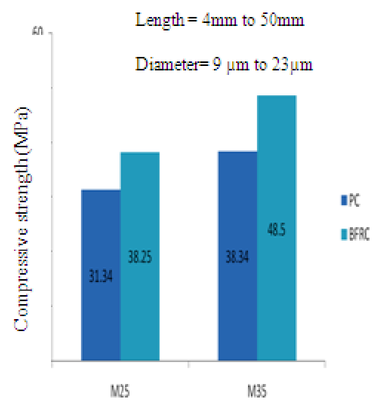
(a)Steel fiber



(b) Polypropylene fiber



(c) Glass fiber



(d) Basalt fiber

Figure1. Compressive strength values for various grades of concrete with different fibers

Figure1. Compressive strength values for various grades of concrete with different fibers

Table 1. Summary of experimental values from literatures for compressive strength modeling

Type of fiber	References	No of samples	Cement(kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	w/c	Aspect ratio	Volume fraction (%)	Tensile strength of fiber (N/mm^2)	Cylinder Compressive strength (N/mm^2)
Steel fiber	[4]	10	479	1133.31	521	0.40	80	0.50-4.50	1050	33.87-36.26
	[5]	6	410	866	915	0.45	35-50	0.50-1	1050-1100	31-49
	[6]	10	375	1044.10	696	0.44	60	0.50-2	1200	29.84-38.10
	[7]	6	385	884	877	0.46	80	0.50-1	1050	33.04-48.17
	[8]	17	400	1027.20	713.80	0.45	80	0.19-.64	1050-1100	23.78-35.98
	[9]	4	453	1242	624	0.40	80	0.60	1100	21.68-25.28
	[10]	5	338	760	1049.20	0.68	80	0.5-1.25	1050	25.52-28.08
	[11]	6	325	965	891	0.55	80-85	0.33-1	1050-2000	47.90-50.90
	[12]	2	351	994.70	914.80	0.50	50	0.26-.45	1100	27.47-27.54
	[13]	8	322	752.30	1055.90	0.59	60-80	0.19-.76	1200-1250	23.20-38.40
	[14]	10	373	975	800	0.35 -.49	54-60	0.51	1100-1200	32.68-54.09
	[15]	18	375	982	805	0.29-.49	54-60	0.49-.74	1100-1200	30.56-55.68
	[16]	7	440	366	1225	0.50	33-41	0.50-1.50	1050	37.28-43.84
	[17]	2	311-366	1156-1170	623-665	.56-0.66	62.50	1	1700	29.96-41.15
	[18]	16	400-450	1110-1140	590-610	.35-0.48	55	0.50-1.50	1100	29.28-59.40
	[19]	8	450	1036	682	0.39	55-80	.50	1050-1100	58.50-67.90
	[20]	8	435.45	1073.34	656.60	0.50	50-62.50	0.50	1100	21.35-34.77
	[21]	9	403.20	1276.80	693	0.45	59	0.50-3	1200-3500	18.05-22.77
	[22]	16	337-410	1011-1176	680-715	0.45-.55	50	0.50-1.50	1100	22.96-60.67
	[23]	34	550	1051-1053	682-716	0.25-.35	65-80	0.50-1.50	1250	37.09-93
	[24]	6	400	1216	572	0.43	60-67	1-3	1200-1250	37.06-45.04
	[25]	10	347.50-451.80	1078.20-1181.50	660.80-664.50	0.40-0.50	50	1-2	1100	53-78
Polypropylene fiber	[26]	5	350	910	455	0.40	26-55	0.10-.30	445-480	39.20-41.44
	[27]	5	475	840	302	0.35	240-480	0.15-.35	326	17.76-21.04
	[28]	14	350	875-896	497	0.42	80	0.50-3	450	22.40-31.60
	[29]	5	395	1152	597	0.50	600	0.50-2	600	32.40-36.20
	[30]	5	465	1218.57	661.08	0.40	80	0.50-2	600	31.36-36.74
Basalt fiber	[31]	4	380	1215	720	0.45	1500	0.50-1	3200	30.60-38.80
	[32]	5	375	1207	692	0.45	976	0.50-2	1735	29.84-30.72
	[33]	4	427	1179	648	0.45	50	0.25-.35	2800	25.07-30.74
	[34]	4	427	1179	648	0.45	50	0.20-.30	2800	25.07-30.67
	[35]	10	407.62	1146.92	570.97	0.50	2117.60-2941.20	0.15-.46	2800	20.90-39.50
Glass fiber	[36]	8	318-450	1118-1170	590-732	0.40-.55	857.10	0.03	2500	29.28-49.85
	[37]	6	410	1170	604	0.40	857.10	0.33-1.66	2500	35.90-39.10
	[38]	4	363.63	1210.90	607.20	0.60	100	.01-.03	2500	15.83-22.64
	[21]	4	350	1110	873	0.40	857	0.33-1	1700	22.50-32.80
Carbon fiber	[39]	4	360.42	1148	691.94	0.48	45.45	0.75-1.25	4900	22.50-36

A review of literatures on FRC indicates that addition of fibers increases the flexural strength of plain concrete by taking into account the type and content of fibers. A dataset containing 300 flexural strength test results were collected. The database required for flexural strength model construction is given in **Table 2**.

Table 2. Summary of experimental values from literatures for Flexural strength modeling

Type of fiber	References	No of samples	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	w/c	Aspect ratio	Volume fraction (%)	Tensile strength of fiber (N/mm^2)	Flexural strength (N/mm^2)
Steel fiber	[40]	17	395	1134	669	0.45	50-100	0.50-1.50	1162-1178	5.26-8.37
	[41]	10	410	833-1040	780-902	0.56	66.70	0.50-2	1100	16.70-19.90
	[42]	4	200	797.40	1002.60	0.45	43.40	1.50-4	1200	5.51-7.35
	[18]	8	400	1110-1130	590-610	0.35-.48	55	0.50-1.50	1345	5.20-10
	[24]	67	338-465.06	1121.86-1140	610-722.41	0.35-0.55	50-67	0.50-3	1050-1720	5.39-10
	[43]	12	382-422	1144-1284	621-638	0.35-0.40	80	0.75-1.50	1050	3.05-7.72
	[44]	4	360	1108	738	0.50	60	0.50-2	1195.50	5.40-9.05
	[45]I	6	338	760	1049.20	0.68	80	0.50-1.25	1050	6.40-7.90
	[16]	7	440	366	1193-1225	0.50	33-41	0.50-1.50	1050	3.80-6
	[6]	6	375	1044.10	696	0.44	60	0.50-2	1200	3.73-4.51
	[23]	34	550	1051-1053	682-716	0.25-0.35	65-80	0.50-1.50	1250	4.36-13.66
	[4]	11	479	1133.31	521	0.40	80	0.50-4.50	1050	6.01-7.01
	[21]	5	403.20	1276.80	693	0.45	59	0.50-3	1200	3.73
	[25]	10	347.50-451.80	1078.20-1181.50	660.80-664.50	0.40-0.50	50	1-2	1100	3-11.80
Polypropelene fiber	[26]	5	350	910	455	0.40	26-55	0.10-.30	445-480	8.70-10.20
	[30]	5	465	1218.57	661.08	0.40	80	0.50-2	450	7.05-8.55
	[46]	3	200	797.40	1002.60	0.45	51.30	1.50-2.50	450	4.67-5.76
	[47]	9	425	1037	561	0.44	66.70-150	0.50-1.50	400	3.51-5.26
	[48]	18	226-410	1230-1356	615-678	0.50	352	0.10-.50	400	2-7
Basalt fiber	[34]	4	427	1179	648	0.45	50	0.20-.30	2800	5.25-7.66
	[49]	12	410	902	833	0.50	555	0.50-2	2800	4.56-7.26
	[50]	5	410	1141.56	701.68	0.42	444	0.25-.75	2800	3.69-10.22
	[35]	11	407.62	1146.92	570.97	0.50	2117.60	0.15-2	280 0	4.01-9.22
	[51]	7	217	1416	694	0.50	345	0.10-.50	2000	1.71-2.08
Glass fiber	[52]	6	338-465	1121.86-1132.42	628.54-722.41	0.40-0.55	857.10	0.03	1700	14.33-21.57
	[53]	8	382-395	1136-1144	638-633.9	0.40	857	0.03-.10	1700	5.33-7.97

	[54]	6	377.50	1178.20	567.28	0.50	857	1-5	1700	2.9-4
	[21]	4	403.20	1276.80	693	0.45	59	0.50-3	3500	2.45-2.94
Carbon fiber	[39]	4	360.42	1148	691.94	0.48	45.45	0.75-1.25	4900	6.50-13.50

The **Figure 2** below compares the optimum values of flexural strengths for each grade of concrete

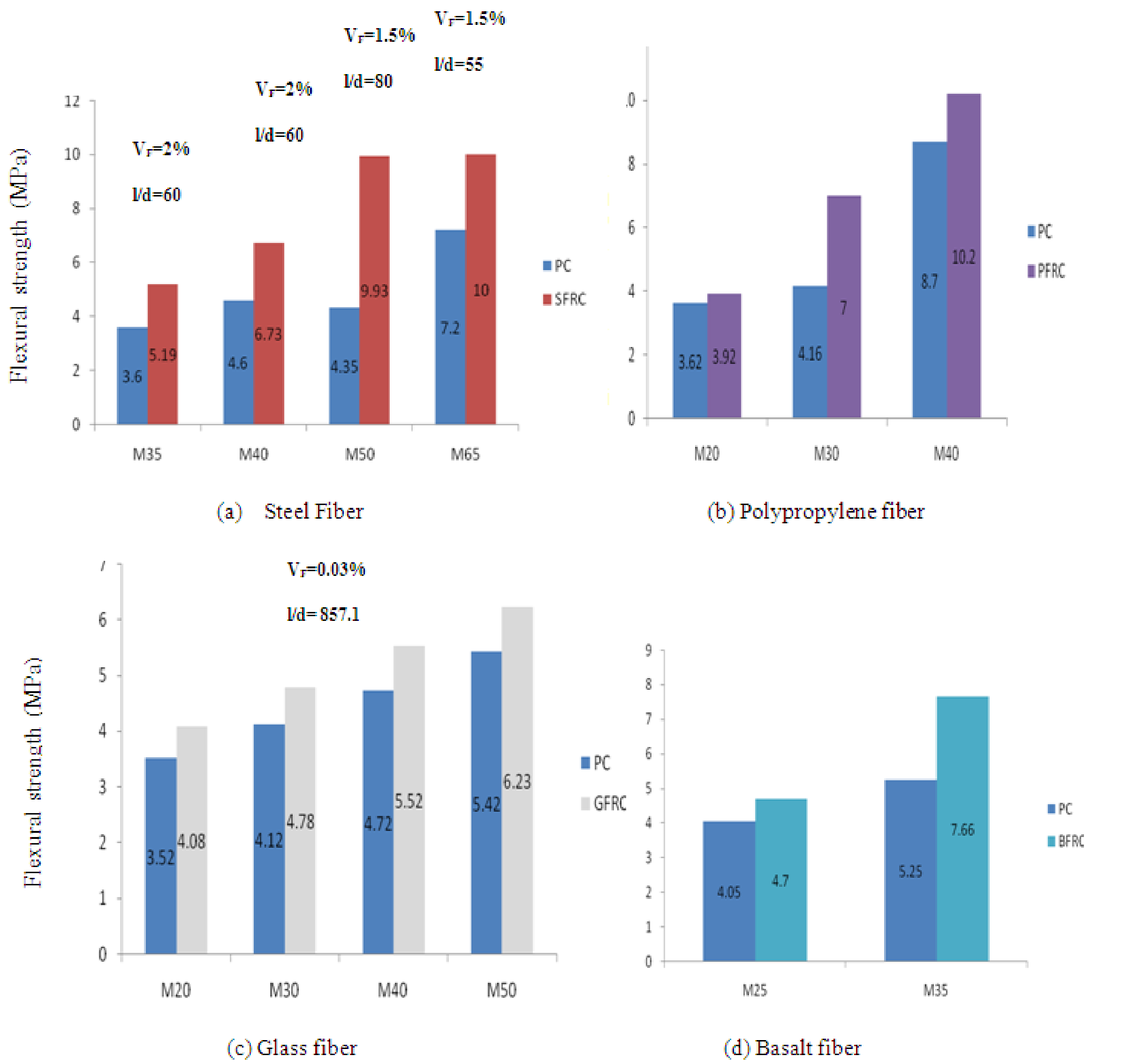


Figure 2. Flexural strength values for various grades of concrete with different fiber

1.2 ANN model description

The computer program "MATLAB Neural Network Toolbox" was employed for the neural network models. The advantage of using this program is that many types of networks are included in the program and many training algorithms can be used for specific network model. In order to find the relationship between input parameters and output parameters, a Feed forward back propagation type neural network was used. Models were developed to predict compressive strength and flexural strength. The input parameters chosen for compressive and flexural models were cement, coarse aggregate, fine aggregate, w/c ratio, fiber aspect ratio, volume fraction and fiber tensile strength. Neural network properties are shown in **Table 3**. The data division was random. 80 % of data had been used for training and 10 % each for validation and testing. **Table 4** presents training properties.

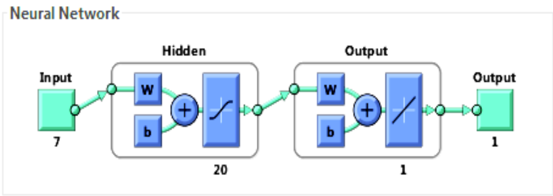
Table 3. Neural network properties

Models	Compressive Strength	Flexural Strength
Network Type	Feed Forward Back propagation algorithm	Feed Forward Back propagation algorithm
Training Function	TRAINBR (Bayesian regularization)	TRAINLM (Levenberg–Marquardt algorithm)
Adaption Learning Function	LEARNGDM	LEARNGD
Performance Function	MSE	MSE
Transfer Function	TRANSIG	TRANSIG
Number of Hidden Layers	2	2
Number of Neurons in each layer	20	50

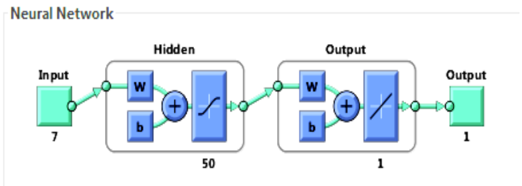
Table 4. Training properties

Show window	True
Show command line	False
Show	25
Epochs	1000
Time	Inf
Min grad	$1e^{-07}$
Max Fail	6
Mu	.001
Mu_max	10000000000

The developed ANN models for various strengths are depicted in **Fig. 3** and the regressions of the relations between target and output for each of training, testing, and all are presented in **Fig. 4**.

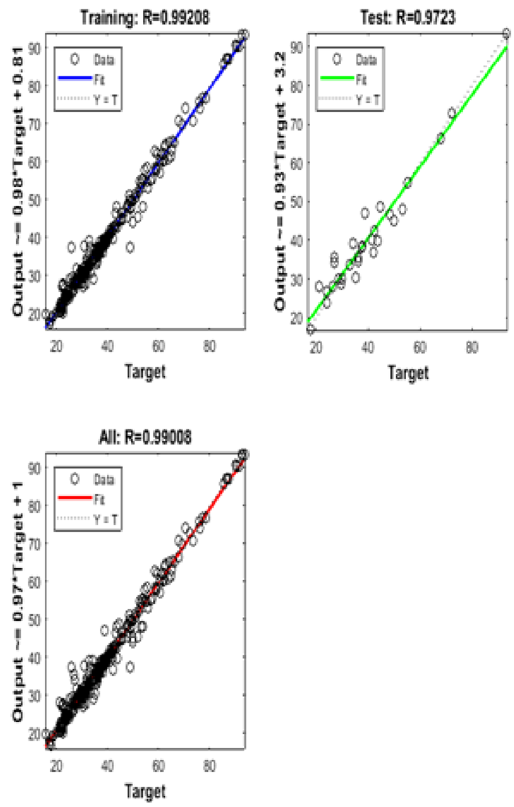


(a)

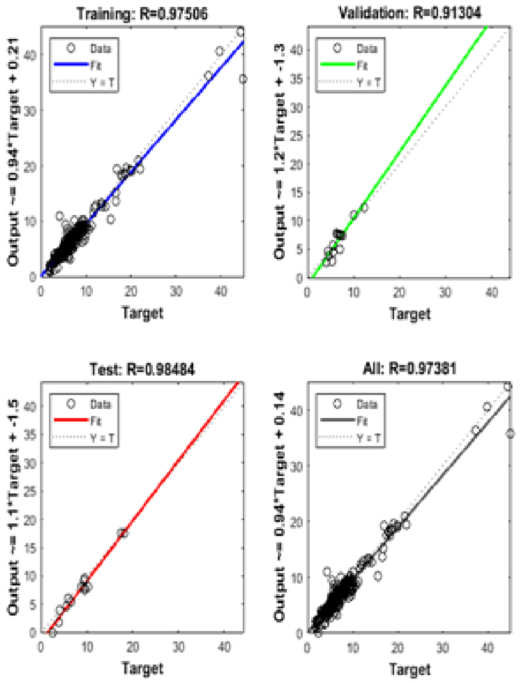


(b)

Figure 3: Architecture of ANN Models (a) compressive strength (b) flexural strength



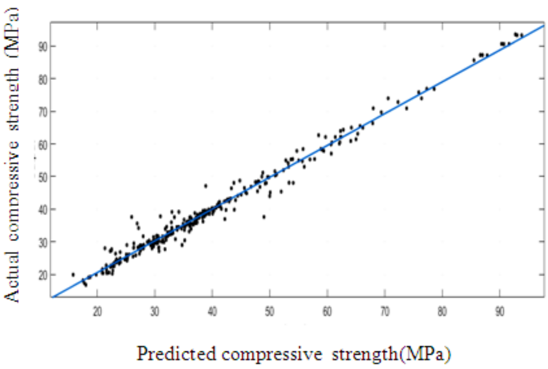
(a)



(b)

Figure 4 . Regressions (a) compressive strength (b) flexural strength

The graph below compares the actual strength properties and predicted values which are shown in **Fig. 5.**



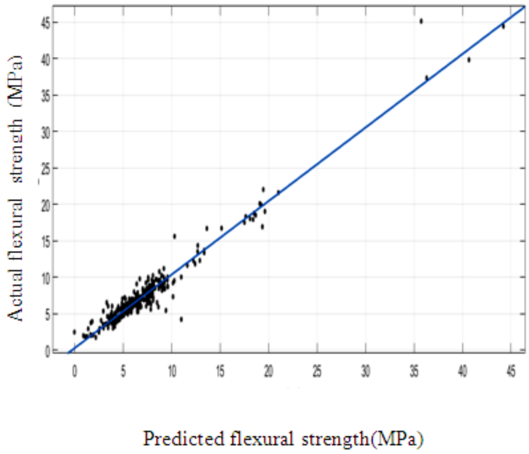


Figure 5. Graph of actual strength properties versus predicted values (a) compressive strength (b) flexural strength

The linear regression equations developed from the models for important strengths are as follows.

$$fc = 35.6115 + 0.03228c + 0.01157CA + 0.03970FA - 112.332W/C - 0.00025\frac{lf}{df} + 1.56822V \; -1.2*10^{-5} ft$$

$$fb = 6.5\ldots \quad 0.00497CA - 0.00383FA + 9.238W/C - .0016\frac{lf}{df} + 0.11223V + 0.000372ft$$

Where fc = compressive strength
f_b = flexural strength
C = cement
CA = coarse aggregate
FA= fine aggregate
W/C= water cement ratio
$\frac{lf}{df}$ = aspect ratio
V= volume fraction
f_t = fiber tensile strength

II. STATISTICAL ANALYSIS

The evaluation criteria to validate the proposed models are performance factor (PF), coefficient of variation (COV), mean absolute error (MAE), coefficient of determination (R^2) and root mean squared error (RMSE). The mean, standard deviation and coefficient of variation of the performance factors were obtained to determine the proximity of the theoretical results found with the equations to the real data found in the database. Lower values of RMSE and MAE indicate a basically good accuracy of the prediction output. If the average of the PFs is close to 1 with small standard deviation, it indicates a model that can accurately and precisely predict the experimental data. The COV was used to indicate the precision of the results obtained by using the proposed equations. The COV is defined from the following equation:

$$COV\% = \frac{\text{standard deviation}}{\text{mean}} \text{ X } 100$$

$$MAE = \sum_{i=1}^{n} \frac{|p_i - v_i|}{n}$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(p_i - v_i)^2}{n}}$$

$$R = \sqrt{\frac{\sum_{i=1}^{n}(p_i-\bar{p})(v_i-\bar{v})}{\sqrt{\sum_{i=1}^{n}(p_i-\bar{p})^2 \sum_{i=1}^{n}(v_i-\bar{v})^2}}}$$

Where *n* is the number of samples; p_i and v_i are the actual and predicted outputs, respectively. Then *p* and *v* are the mean of the actual and predicted outputs. The statistics of ratios of experimental and predicted values are shown in **Table 5.**

Table 5. Statistical values of performance factor= p_i / v_i

Models	Compressive strength	Flexural strength
Mean	1	1.07
Standard deviation	0.06	0.21
COV	0.06	0.19

The prediction models are validated through coefficient of determination (R^2), root mean squared error (RMSE) and MAE and are consolidated in **Table 6.**

Table 6. Statistical test on prediction models.

Models	Compressive strength	Flexural strength
R^2	0.9803	0.9502
Adjusted R^2	0.9802	0.9501
RMSE	2.19	1.19
MAE	1.38	0.78

III. CONCLUSION

This study investigated the feasibility of modeling a predictive analysis through earlier study data, converting the unstructured factors to possible structured parameters and using those in creating the ANN model. The compressive and flexural strength models are efficient prediction models of R^2 value closer to unity with much lesser value of COV. The models show high performance from the statistical evaluation. The fiber properties contribute to the prediction models, thus increasing the models' performance. From the literatures, it is evident that volume fractions of steel fibers are limited to 2% for better mechanical behavior of concrete. Addition of basalt up to .5% and the addition of a low volume fraction (0.1–0.3%) of polypropylene fibers is helpful to improve the microstructure and restrain the formation and growth of micro cracks in concrete. The optimum content of glass fiber of aspect ratio 857.1 is 0.03% for all grades of concrete by enhancing the compressive and flexural strengths compared to conventional concrete. In general, the satisfactory improvement in various strengths is observed with the inclusion of steel fibers in the plain concrete for each grade.

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