International Journal of Applied Science and Engineering
2015. 13, 2: 171-185

Predicting Compressive Strength of Concrete

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Abstract: This paper deals with development of regression models for prediction of compressive strength of concrete. The compressive strength of concrete is predicted using four variables, namely, water-binder ratio, fine aggregate-binder ratio, coarse aggregate-binder ratio and binder content. Linear regression models have been developed for variations in fly ash replacements (0 and 15 percent), Zones of aggregates (A, B and C) and curing ages (28, 56 and 91 days). An effort has also been made to modify the linear models using a two step approach. First step is to develop quadratic models (termed as full models) by identifying the suitable combinations of the four variables described above. The second step is to select the best minimal subset of the predictors in full models using Mallow's C_p statistic. The proposed quadratic regression models yielded coefficient of determination $R^2 \geq 0.99$ in almost every case except for concrete with Zones A and B of aggregates without fly ash for 91 days curing period and for concrete with Zone C of aggregates without fly ash for 56 days curing period.

Keywords: Concrete; compressive strength; regression models

1. Introduction

Concrete is a strong building material composed of sand, gravel, cement and water. Additional admixtures are also added sometimes to enhance certain properties of fresh or hardened concrete. In the construction industry, among the various properties of the concrete determination of compressive strength has received a large amount of attention because concrete is primarily meant to withstand compressive stresses. The compressive strength of concrete is controlled by proportioning of cement, coarse and fine aggregates, water and various admixtures. Prediction of concrete compressive strength has been an active area of research and a considerable number of studies have been carried out in this direction. Many attempts have been made to develop a suitable mathematical model which is capable of predicting compressive strength of concrete at various ages with acceptable accuracy.

Multiple regression models have been used by researchers to improve accuracy of predictions of concrete compressive strength. Nipatsat and Tangtermsirikul [1] developed equations for estimating compressive strength of concrete containing fly ash with curing ages from 3 days up to 1 year. Kazberuk and Lelusz [2] proposed regression models to predict compressive strength of concrete with fly ash replacement percentages up to 30%. Namyong et al. [3] proposed the regression equations for predicting compressive strength of in-situ concrete. They have selected

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Received 1 May 2014
Revised 23 March 2015
Accepted 29 April 2015

principal factors that influence compressive strength of concrete using correlation analysis. The regression equations are proposed for 7 days and 28 days compressive strength taking water-cement ratio, cement content and cement-aggregate ratio as independent variables. Pande and Gupta [4] studied the significance of proportions of ingredients on compressive strength development of concrete. They showed that the two ratios, namely, water-binder ratio and binder component-inert component ratio are most significant. Chakraverty et al.[5] introduced three parameter third order regression models with ternary systems of fly ash, cement and sand by using simplex lattice design for building bricks. Abd et al. [6] developed mathematical regression models for Portland cement compressive strength for curing ages 7 and 28 days. Also, they proposed the models for compressive strength prediction of all types of concrete, especially, foam concrete for curing ages of 28 days and 365 days and concluded that proposed model yielded good correlation coefficients for both sets of data in predicting compressive strength of foam concrete. Mathematical models have also been developed by Abd and Zain [7] for prediction of compressive strength of high performance concrete for curing ages of 3, 7, 14, 28 and 91 days using statistical analysis of the concrete data obtained from the experimental work .Their models gave 99.90% correlation for strength prediction of concrete for each curing age. Abdullahi et al. [8] performed statistical modeling for slump, air-dry density and compressive strength of light weight concrete. They concluded that polynomial model is the best fit model for response prediction. Qadiet al. [9] developed statistical models to study influence of key mixture parameters, *i.e.*, cement, water-powder ratio, fly ash and super plasticizer on modulus of elasticity and compressive strength for curing ages of 3, 7 and 28 days. They concluded that full quadratic models in all the responses showed higher correlation coefficient. Chen [10] developed a multiple linear regression prediction model of concrete compressive strength based on physical properties of electric arc furnace oxidizing slag. Multiple regression analysis and artificial neural networks have been used by Ramugade [11] to estimate 3, 7, 28 days compressive strength of concrete cubes. Wu et al. [12] started from an elementary linear model to predict concrete compressive strength and then modified it by adding additional interaction terms based on correlation analysis and finally, the model was fine tuned to obtain a parsimonious regression model for compressive strength prediction of concrete.

The aim of the present study is to predict compressive strength of the concrete for a given sample, as accurately as possible. For this purpose, multiple regression analysis is used to develop linear regression models for predicting compressive strength of concrete using four variables, namely, water-binder ratio, fine aggregate-binder ratio, coarse aggregate-binder ratio and binder content. Regression models have been developed for fly ash replacements (0 and 15 percent), Zones of aggregates (A, B and C) and curing ages (28, 56 and 91 days). An effort has also been made to modify the linear models using a two step approach. First step is to develop quadratic models (termed as full models) by identifying suitable combinations of these four variables. The second step is to select the best minimal subset of the predictors in full models. It is worth mentioning here that coefficient of determination (R^2) increases with the addition of each new explanatory variable in the model. Thus, R^2 which is a measure of "Goodness of Fit", favours more complex models. However, model selection should be on the basis of a complexity adjusted goodness of fit criterion which rewards goodness of fit and penalizes complexity.

Mallow's C_p statistic has been used as a criterion for selecting among many alternative subset regressions in the present study. This statistic is an estimate of the standardized total mean square error of estimation for the given data set. It measures the performance of variables in terms of the standardized total mean square error of prediction for the observed data points irrespective of the unknown true model. It takes into account both the bias and the variance. So, it helps in identifying the model with least number of predictors and high goodness of fit.

2. Experimental dataset

Data for the present work has been taken from the experiments conducted by Kumar [13]. He has considered seven parameters, namely, water-binder material ratio, binder content, water content, percentage replacement of cement by fly ash, workability, aggregate zones and curing ages in his experiments. The binder content is cement content for concrete without fly ash and this is a combination of cement content and fly ash for concrete with fly ash.

The experiments were performed in controlled laboratory conditions. Variation in the values of parameters is given in Table 1. One can note from Table 1 that coarse aggregates are divided into three zones. The principle characteristics of these zones are given in Table 2. The physical properties of fine aggregates used in this study are given in Table 3 and that of coarse aggregates: CA-I, CA-II and CA-III are given in Tables 4. A set of 15 cubes for each of mixes so proportioned were cast and tested after 28, 56 and 91 days of curing. Thus, an extensive data bank for analyzing compressive strength of concrete has been generated and the same has been used in the present work.

Table 1. Variation in parameters

Water-binder material ratio	0.42-0.55
Binder content	350-475@25 kg/m^3
Water content	180-230@10 kg/m^3
Percentage replacement of cement by fly ash	0 and 15%
Workability	Medium and High
Aggregate zones	A, B, C
Curing ages	28,56,91 days

Table 2. Principal characteristics zones of coarse aggregates

Zone	Percentage passing 20 mm sieve and retained on 10 mm sieve (CA –I)	Percentage passing 10 mm sieve and retained on 4.75 mm sieve (CA –II)	Percentage passing 4.75 mm sieve and retained on 2.36 mm sieve (CA –III)	Fineness Modulus
A	67	33	-	6.67
B	50	50	-	6.50
C	-	50	50	6.50

Table 3. Physical properties of fine aggregates

S. No.	Property	Observed values
1.	Unit mass (compact)	1,680 kg/m^3
2.	Unit mass (loose)	1,590 kg/m^3
3.	Specific gravity (oven-dry basis)	2.54
4.	Percentage voids (compact)	33.7 percent
5.	Percentage voids (loose)	37.4 percent
6.	Percentage absorption	0.5 percent
7.	Fineness modulus	2.09

Table 4. Physical properties of coarse aggregates

S. No.	Property	Observed values		
		CA – I	CA - II	CA - III
1.	Unit mass (compact)	1,580 kg/m^3	1,480 kg/m^3	2,150 kg/m^3
2.	Unit mass (loose)	1,380 kg/m^3	1,350 kg/m^3	1,980 kg/m^3
3.	Specific gravity			
	(a) Saturated surface dry	2.61	2.63	2.58
	(b) Oven-dry	2.68	2.68	2.60
4.	Percentage voids (compact)	41.2 percent	43.7 percent	17.3 percent
5.	Percentage voids (loose)	48.6 percent	48.7 percent	23.85 percent
6.	Percentage absorption	1.8 percent	1.18 percent	1.20 percent

3. Mallow's C_p statistic

Mallow's C_p statistic given by Mallows [14] is:

$$C_p = \frac{SSE_p}{\hat{\sigma}^2_{full}} - (n - 2p) \tag{1}$$

where p is defined as number of parameters in the model, $\hat{\sigma}^2_{full}$ is the estimate of mean square error σ^2 when all the available variables are used, SSEp is the residual sum of squares for a particular subset model with (p – 1) predictors.

The regression analysis is conducted for each subset of the predictors in the selected full model and those subsets are selected for which C_p is nearly equal to p or less than p. If, however, there are two subsets of different sizes for which C_p=p or less than p, then the smaller of the two subsets is selected.

4. Experimentation, results and discussion

The multiple linear regression models for compressive strength prediction of concrete with fly ash replacements (0 and 15 percent), Zones of aggregates (A, B and C) and curing ages (28, 56 and 91 days) have been developed using four predictor variables, namely, water-binder ratio(x_1), fine aggregate-binder ratio(x_2), coarse aggregate-binder ratio(x_3) and binder content (x_4). The linear models thus developed with their respective coefficient of determination $R^2$and mean square error (MSE) are summarized in Tables 5-7.

Table 5. Regression coefficients of multiple linear regression models predicting compressive strength of concrete with zone A of aggregates

Predictors	Regression coefficients					
	Without replacement of cement by fly ash			With 15% replacement of cement by fly ash		
	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)
x_1	-199.1076	-281.9690	-114.9539	-89.2182	-222.3524	-82.6893
x_2	13.2500	26.1404	1.8239	-7.7283	10.0046	-5.3534
x_3	-1.1978	1.6752	-1.7213	-2.7444	3.5655	-2.4693
x_4	0.0043	-0.0018	0.0202	0.0453	0.0110	0.0153
Constant	124.6751	147.4826	101.9913	77.5148	122.0548	95.7174
R^2	0.97113	0.95399	0.97074	0.98783	0.93033	0.97450
MSE	1.37900	2.15240	1.13307	0.25561	1.28781	0.31488

Table 6. Regression coefficients of multiple linear regression models predicting compressive strength of concrete with zone B of aggregates

Predictors	Regression coefficients					
	Without replacement of cement by fly ash			With 15% replacement of cement by fly ash		
	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)
x_1	-176.2127	-129.3865	-299.5893	-131.9172	-325.7427	-76.9575
x_2	8.8879	3.8913	27.6956	-2.5693	27.8105	-8.0358
x_3	2.2364	1.8828	8.0558	-3.0681	6.1818	-2.6060
x_4	0.0298	0.0315	0.0224	0.0247	-0.0056	0.0152
Constant	100.7980	90.5065	130.9611	101.6288	150.2411	97.0259
R^2	0.99349	0.96190	0.96685	0.97344	0.94814	0.98767
MSE	0.25758	1.15394	1.11693	0.81873	1.27240	0.24338

Table 7. Regression coefficients of multiple linear regression models predicting compressive strength of concrete with zone C of aggregates

Predictors	Regression coefficients					
	Without replacement of cement by fly ash			With 15% replacement of cement by fly ash		
	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)
x_1	-174.2669	-158.5451	-255.1084	246.5444	-832.8792	199.9641
x_2	7.3344	8.9288	23.9295	-77.6751	135.8383	-66.9980
x_3	1.8340	2.4043	3.3035	-3.3346	8.5119	-1.4040
x_4	0.0168	0.0209	0.0083	0.0144	0.0385	0.0168
Constant	109.6235	102.5263	136.7151	16.3413	240.6253	31.6960
R^2	0.98710	0.96643	0.98818	0.97455	0.96649	0.97819
MSE	0.43048	0.80308	0.33732	0.80622	1.35898	0.59829

It can be seen from Table 5 that for concrete with zone A of aggregates, best prediction is for the situation when 28 days compressive strength of concrete with fly ash is predicted and the model gives the value of R^2=0.988 and MSE 0.506. Table 6 reveals that among the linear models for predicting compressive strength of concrete with zone B of aggregates, best prediction is for 28 days strength for concrete without fly ash with R^2=0.993 and MSE 0.508. The linear models for compressive strength prediction of concrete with zone C of aggregates given in Table 7, unveil that best prediction is for the case when 91 days compressive strength is predicted for concrete without fly ash and the model gives value of R^2=0.988 and MSE 0.581. Also, it is observed from Tables 5-7 that predictions are better for 28 and 91 days compressive strength in comparison to 56 days strength for concrete with any zone of aggregates with or without fly ash.

The experimentation has also been carried out to identify the quadratic terms that should be added to linear models in order to improve the prediction of the compressive strength of concrete.

This is worth mentioning here that interaction terms x_1x_4, x_2x_4 and x_3x_4 have not been considered in the development of full model since these terms will represent values of water, fine aggregate and coarse aggregate contents and the aim of the present investigation is to develop regression models while taking their ratios with binder content into account. The term x_4^2 has also not been considered in the full model as inclusion of this term makes the coefficient matrix of normal equations an almost singular matrix. Also, the study of correlations among the predictor variables reveals that for concrete with zone C of aggregates without replacement of cement by fly ash, the correlation between x_2^2 and x_1x_2 is 1.000, the correlation between x_1^2 and x_2^2 is 0.999 and the correlation between x_1^2 and x_1x_2 is also 0.999.This is the case of extreme multicollinearity. Therefore, here x_2^2 and x_1x_2 have not been considered as predictors in developing regression models for concrete with zone C of aggregates without replacement of cement by fly ash.

It has been found with the help of experimentation that models developed using $x_1, x_2, x_3, x_4, x_1^2, x_2^2$ and x_3^2 as predictors for compressive strength prediction of concrete with fly ash and all zones of aggregates give the value of coefficient of determination R^2 greater than or equal to 0.998 in each case. Hence, these seven variables are taken as predictors for developing full model to predict compressive strength of concrete with zones A, B and C of aggregates with 15% replacement of cement by fly ash and curing ages 28, 56 and 91 days.

As such, full model for prediction of compressive strength of concrete with zones A and B of aggregates without replacement of cement by fly ash is:

$$compressive\ strength = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 x_4 + \alpha_5 x_1^2 + \alpha_6 x_2^2 + \alpha_7 x_3^2 + \alpha_8 x_1 x_2 + \alpha_9 x_1 x_3 + \alpha_{10} x_2 x_3 \quad (2)$$

where α_i, $i = 0, 1, 2, \dots, 10$ are the regression coefficients.

Full model for prediction of compressive strength of concrete with zone C of aggregates without replacement of cement by fly ash is:

$$compressive\ strength = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_1^2 + \beta_6 x_3^2 + \beta_7 x_1 x_3 + \beta_8 x_2 x_3 \quad (3)$$

where β_i, $i = 0, 1, 2, \dots, 8$ are the regression coefficients.

Full model for prediction of compressive strength of concrete with zone A, B and C of aggregates with 15% replacement of cement by fly ash is:

$$compressive\ strength = \gamma_0 + \gamma_1 x_1 + \gamma_2 x_2 + \gamma_3 x_3 + \gamma_4 x_4 + \gamma_5 x_1^2 + \gamma_6 x_2^2 + \gamma_7 x_3^2 \quad (4)$$

where γ_i, $i = 0, 1, 2, \dots, 7$ are the regression coefficients.

Now, as given above there are 10 predictors in full model for prediction of compressive strength of concrete with zone A of aggregates without replacement of cement by fly ash for 28 days curing period, *i.e.*, six additional predictors are added to the linear model. So, there are $2^6 - 1 = 63$ possible subsets of predictors to be considered. Regression analysis is conducted for each of these subsets. Among the subsets of a particular size $(p - 1)$ (say),one is selected with least value of residual sum of squares SSE_p as that will give the minimum value of C_p statistic corresponding to subset size $(p - 1)$. Table 8 summarizes the selected subsets of each size with their respective residual sum of squares SSE_p, mean residual sum of squares MSE_p, coefficient of determination R^2 and C_p statistic. From this table, it can be seen that for full model $C_p = p = 11$ (for full model, C_p is always equal to p) and there is only one subset of size 9 with predictors $x_1, x_2, x_3, x_4, x_1^2, x_2^2, x_3^2, x_1 x_2$ and $x_1 x_3$ for which C_p = 9.856 which is slightly less than $p = 10$.

For all other subsets C_p is greater than p. So, the latter subset with lesser value of p is selected to develop the regression model for prediction of compressive strength of concrete with zone A of aggregates without replacement of cement by fly ash for 28 days curing period. This process is repeated for selecting best subset of predictors for development of regression models for compressive strength prediction of concrete in other cases as well. The final quadratic regression models with their respective coefficient of determination R^2 and *MSE* have been summarized in Tables 9-11.

Table 8. Summary of the selected subsets of predictors for concrete with zone A of aggregates without replacement of cement by fly ash and 28 days curing period

Subset of predictors	P	SSE_p	MSE_p	R^2	c_p
$x_1, x_2, x_3, x_4, x_1^2, x_2^2, x_{3,}^2$ x_1x_2, x_1x_3, x_2x_3	11	2.5793	0.3685	0.996	11
$x_1, x_2, x_3, x_4, x_1^2, x_2^2, x_{3,}^2$ x_1x_2, x_1x_3	10	2.8948	0.3619	0.995	9.86
$x_1, x_2, x_3, x_4, x_1^2, x_{3,}^2$ x_1x_2, x_1x_3	9	4.8374	0.5375	0.992	13.13
$x_1, x_2, x_3, x_4, x_1^2, x_3^2, x_2x_3$	8	6.1984	0.6198	0.990	14.82
$x_1, x_2, x_3, x_4, x_1^2, x_1x_2$	7	11.2310	1.0210	0.982	26.48
$x_1, x_2, x_3, x_4, x_1x_3$	6	13.1738	1.0978	0.979	29.75

Table 9. Regression coefficients of selected quadratic regression models predicting compressive strength of concrete with zone A of aggregates

Predictors	Regression coefficients					
	Without replacement of cement by fly ash			With 15% replacement of cement by fly ash		
	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)
x_1	17887.6956	12779.6914	-39.3138	-107.9192	33954.2046	-3075.0744
x_2	-2703.8280	-939.4225	2.9853	-78.3137	-2718.5216	144.0929
x_3	-549.9670	-706.2202	19.2633	-2.0758	-1026.7863	1.8502
x_4	0.0444	0.0316	0.0301	0.0440	0.0350	0.0176
x_1^2	-46325.6889	-27767.1268	-	-	-38186.7844	3308.7281
x_2^2	-1271.2732	-	-4.8964	32.5878	1208.1150	-63.8213
x_3^2	-206.2456	-209.0696	-4.1089	-	203.6076	-
x_1x_2	12533.9161	2013.7737	-	-	-	-
x_1x_3	3591.1998	3930.2013	-	-	-	-
x_2x_3	-	-	-	-	-	-
Constant	-1705.2790	-1395.0179	42.2659	122.5628	-4696.5309	672.5580
R^2	0.99534	0.99107	0.97851	0.99696	0.99998	0.99953
MSE	0.36185	0.60324	0.98361	0.08515	1.2667e-03	0.01151

Table 10. Regression coefficients of selected quadratic regression models predicting compressive strength of concrete with zone B of aggregates

Predictors	Regression coefficients					
	Without replacement of cement by fly ash			With 15% replacement of cement by fly ash		
	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)
x_1	1166.5347	12347.8066	-348.5521	-7868.718	15052.5811	-9006.7171
x_2	548.7525	81.6962	-9.3414	531.1628	-1118.4896	663.8663
x_3	-300.8919	-1345.2784	-9.8313	126.0294	-460.9304	195.1550
x_4	0.0298	0.0346	0.0314	0.0142	0.0067	0.0084
x_1^2	-	-34025.6123	-	8542.3278	-17145.7760	9945.1114
x_2^2	560.7547	826.4374	-	-233.5574	504.9301	-295.4089
x_3^2	-74.0327	-208.8439	-	-24.7730	91.9924	-38.3995
x_1x_2	-4165.2911	-	-	-	-	-
x_1x_3	1481.4322	7349.7768	-	-	-	-
x_2x_3	-	-805.0685	16.0927	-	-	-
Constant	-155.6642	-1099.1816	189.8170	1375.2020	-2061.9279	1468.8519
R^2	0.99668	0.99504	0.98723	0.99839	0.99945	0.99862
MSE	0.19722	0.25738	0.46942	0.19848	0.05426	0.10897

Table 11. Regression coefficients of selected quadratic regression models predicting compressive strength of concrete with zone C of aggregates

Predictors	Regression coefficients					
	Without replacement of cement by fly ash			With 15% replacement of cement by fly ash		
	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)	28 days compressive strength(MPa)	56 days compressive strength(MPa)	91 days compressive strength(MPa)
x_1	336.9060	346.3954	-16723.4208	-948.4647	-2375.4540	-952.3322
x_2	-66.1693	-92.9208	3046.9720	1.7799	238.4031	127.4556
x_3	15.6490	31.7473	-1355.5975	1.3682	14.5906	-196.6082
x_4	0.0099	0.0175	-0.00939	0.0121	0.0355	0.0332
x_1^2	-	-	4217.8888	855.1453	1103.8597	207.2442
x_3^2	-	-8.7008	-	-	-	54.7924
x_1x_3	-	-	7240.0870	-	-	-
x_2x_3	-15.499	-	-1727.4919	-	-	-
Constant	-30.8240	-35.9847	3376.9748	285.9394	588.6353	459.7622
R^2	0.99323	0.97226	0.99712	0.99982	0.99939	0.99913
MSE	0.25432	0.74663	0.12351	7.414e-03	0.03315	0.04719

It can be seen from Table 9 that quadratic models for predicting compressive strength of concrete with zone A of aggregates give value of coefficient of determination R^2 greater than 0.99 in each case except only for 91 days compressive strength prediction of concrete without fly ash. For concrete with zone A of aggregates, predictions are better for concrete with fly ash and the best and almost perfect prediction is for 56 days strength with $R^2 = 0.99998$ and MSE 0.00127.

Table 10 shows that for concrete with zone B of aggregates also, quadratic models give value of R^2 greater than 0.99 in each case except only for 91 days compressive strength prediction of concrete without fly ash and predictions are better for concrete with fly ash. The best prediction is for 56 days strength of concrete with fly ash and the model gives value of R^2=0.99945 and *MSE* 0.05426. Table 11 reveals that quadratic models for compressive strength prediction of concrete with zone C of aggregates without fly ash give value of R^2greater than 0.99 for 28 and 91 days strength prediction. It can also be seen from the table that R^2 is greater than 0.999 for quadratic models for concrete with zone C of aggregates with fly ash and best prediction is for 28 days compressive strength with R^2=0.99982 and *MSE* 0.00741.

To compare the performances of corresponding linear and quadratic models given in Tables 5-7 and Tables 9-11, the predicted compressive strength values for linear and quadratic models are plotted against the actual compressive strength values. The graphs obtained are shown in Figs. 1-6. It can be seen from Figures 1-6 that predicted values of quadratic models distribute closer along the diagonal in comparison to linear models indicating that prediction power of quadratic models is better than that of linear models. The above observation is also supported by *MSE* and R^2 values for each of the models given in Tables 5-7 and Tables 9-11. On comparing the corresponding linear and quadratic models given in Tables 5-7 and Tables 9-11, it is observed that there is a significant improvement in value of coefficient of determination R^2 and correspondingly significant decrease in the value of *MSE* on adding quadratic terms in linear model in each case. These observations show that the prediction power of the regression models is greatly improved by the proper choice of quadratic terms to be included in the quadratic model.

5. Conclusion

In this paper, 18 linear and 18 quadratic models have been developed for predicting compressive strength of concrete. The data set that has been used in the development of these models was generated in controlled laboratory conditions. The quadratic regression models have been developed using a list of selected predictors. This selection is based on the theoretical concepts behind the development of regression models. The C_p statistic has been used to select best minimal subset of predictor variables. The quadratic models obtained in this work give coefficient of determination $R^2 \geq 0.99$ in 15 cases out of total 18 cases (Figure7). The mean value of R^2 for the quadratic models increases from 0.97111 (with standard error 0.00376) for linear models to 0.99432 (with standard error 0.00183) for quadratic models. The best prediction with a coefficient of determination R^2=0.99998 and *MSE* 0.00127 has been obtained for the case when 56 days strength of concrete with zone A of aggregates with fly ash is predicted.

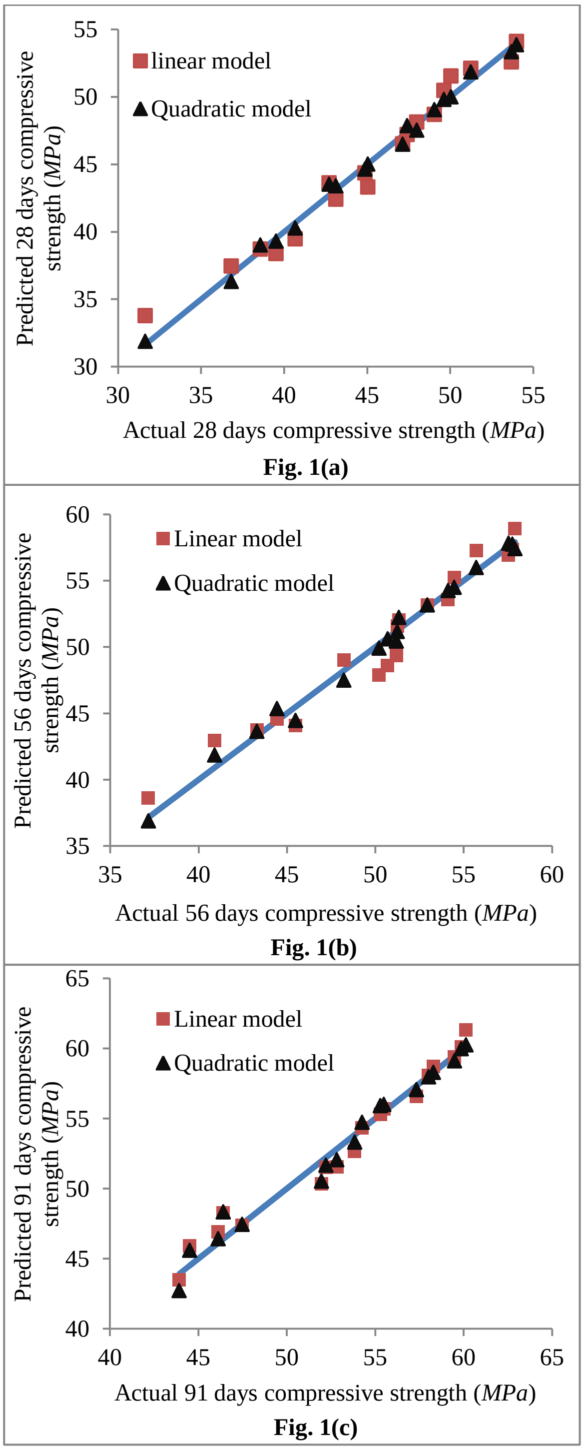

Figure 1. Comparison of performance of linear andquadratic models for concrete with zone Aof aggregates without fly ash and curing age of 28, 56 and 91 days

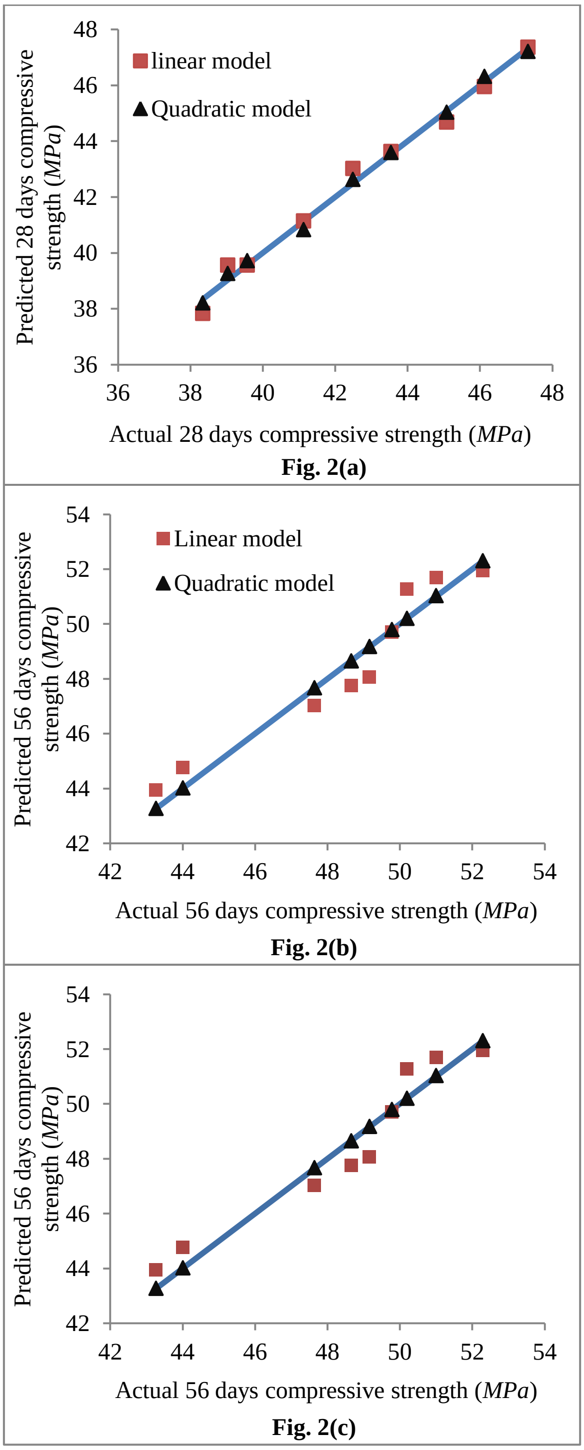

Figure 2. Comparison of performance of linear andquadratic models for concrete with zone Aof aggregates with fly ash and curing ageof 28, 56 and 91 days

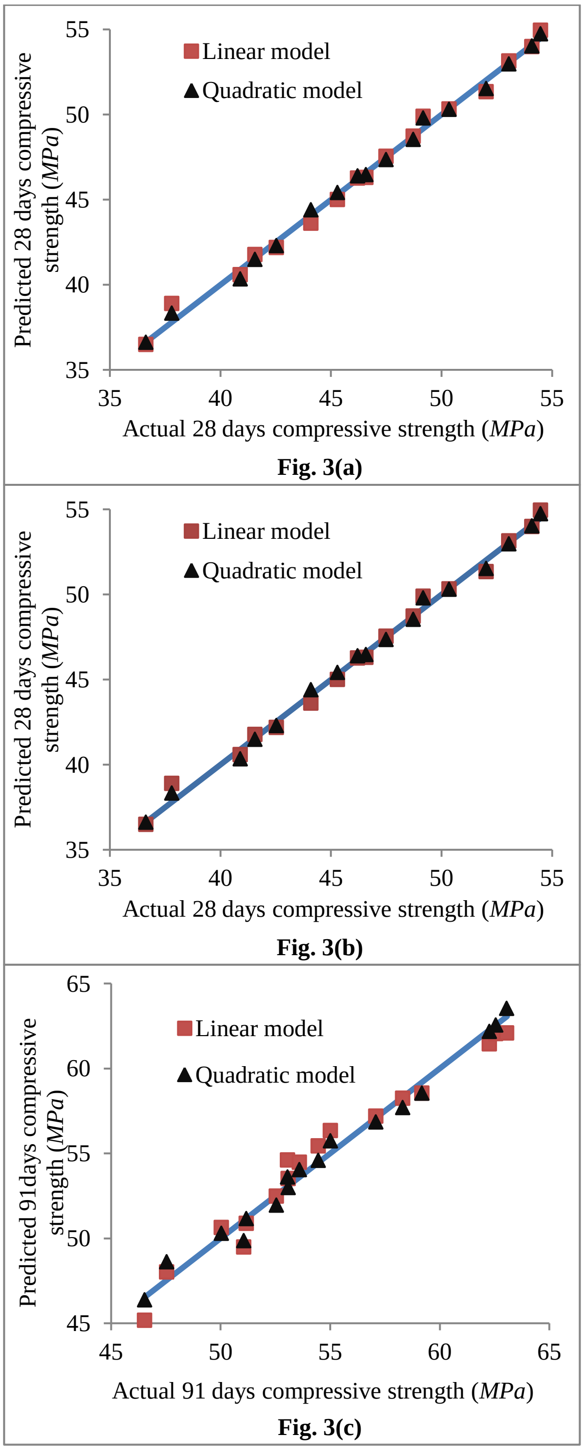

Figure 3. Comparison of performance of linear andquadratic models for concrete with zone B of aggregates without fly ash and curingage of 28, 56 and 91 days

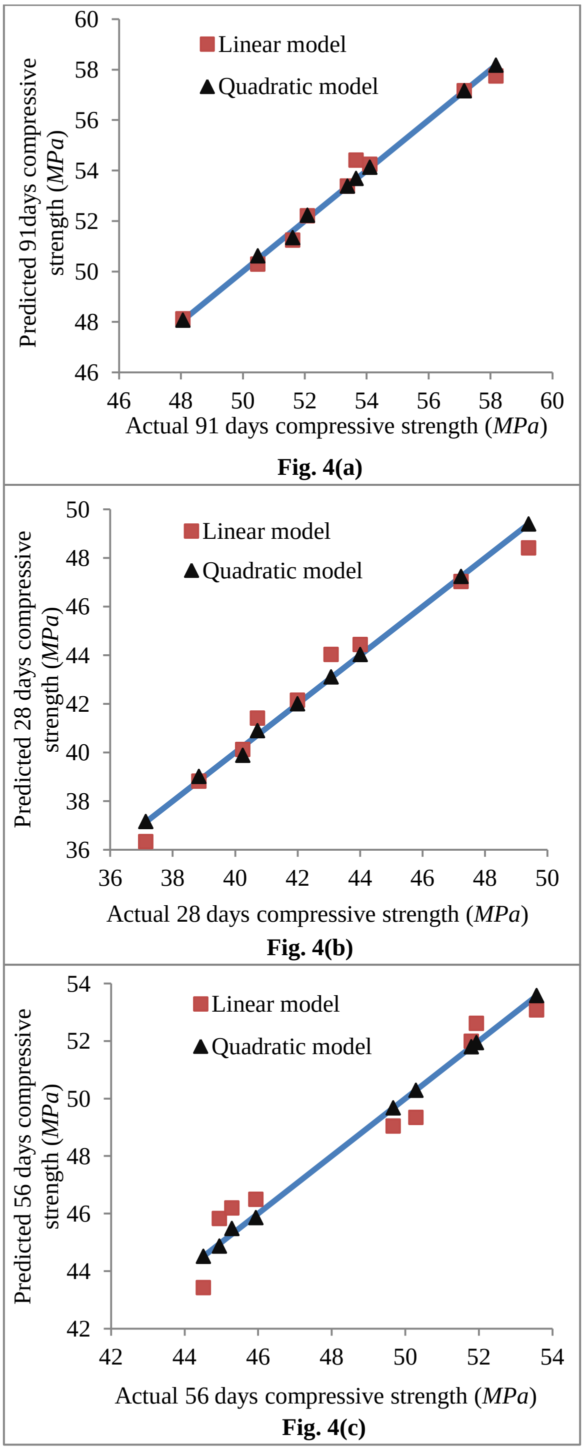

Figure 4. Comparison of performance of linearand quadratic models for concretewith zone B of aggregates with flyash and curing age of 28, 56 and 91 days

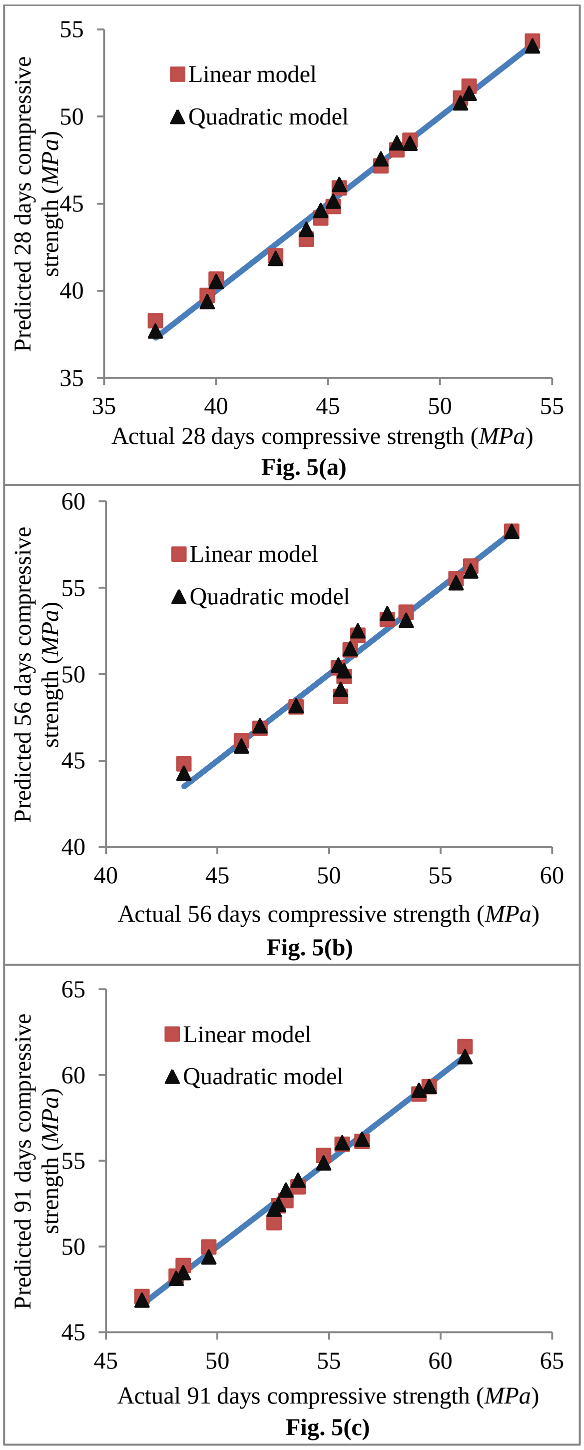

Figure 5. Comparison of performance of linearand quadratic models for concrete withzone C of aggregates without fly ash and curing age of 28, 56 and 91 days

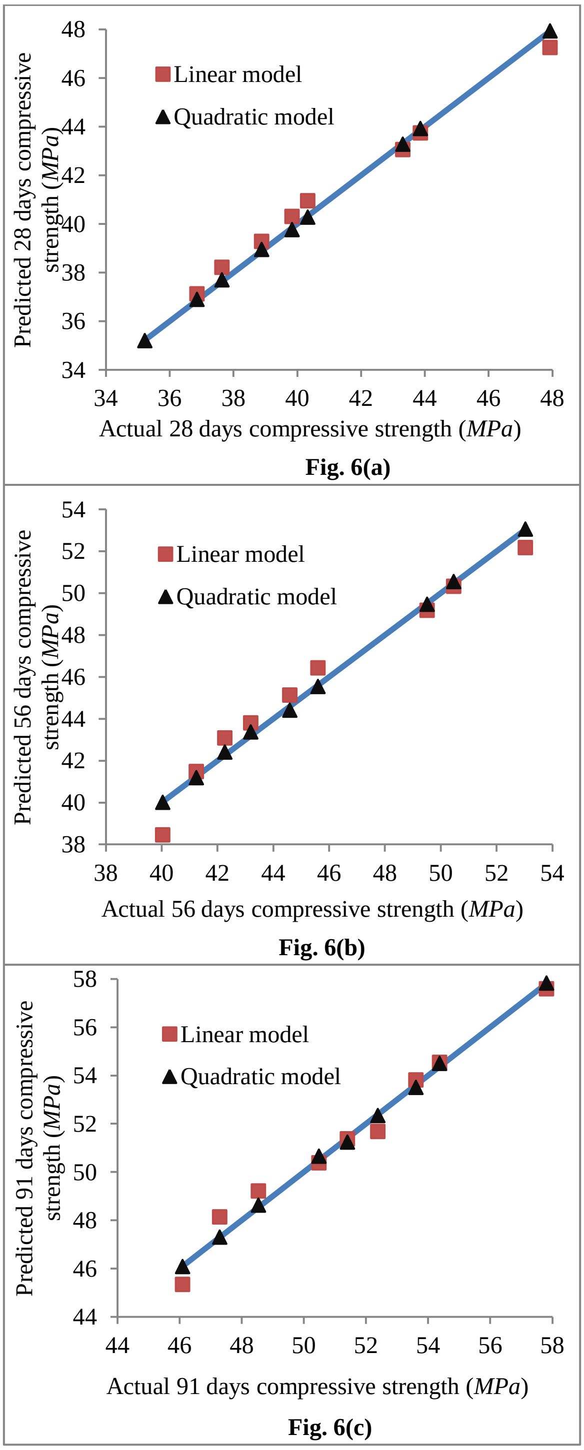

Figure 6. Comparison of performance of linearand quadratic models for concrete with zone C of aggregates with fly ash and curing age of 28, 56 and 91 days

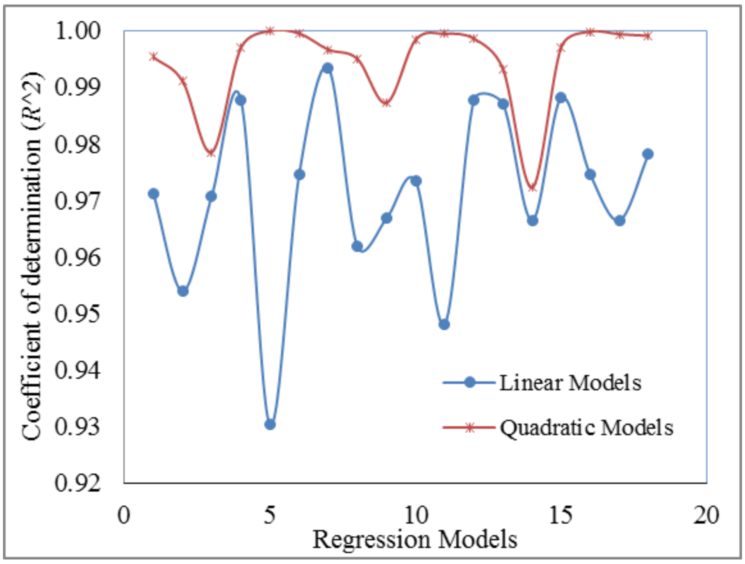

Figure 7. Coefficient of determination R^2 for linear and quadratic models

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