Quality Control of Concrete through Accelerated Curing

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Abstract – *The importance of quality control of concrete in civil engineering structures, especially in structures which demands a huge and continuous casting of concrete in a short period of time, becomes an essential issue to be emphasized now a days in the construction industry. The conventional retrospective quality control method is to take samples from the mix which is going to be cast in the desired structure and make inferences based on the 28th day compressive strength result. The problem associated with this method is the length of time required before the result are known, leading to be late to take remedial action as the earliest as the concrete is in its green state. To avoid the problem, correlations has been established by different researchers and different codes (such as* IS 9013, BS 1881and CAN/CSA-A23.2) *to predict the 28th day strength of concrete from early test (usually 1 day) depending on different parameters. However, every correlation is sensitive to changes in mix proportions. This paper investigated the reliabilities of one single correlation when changes made in the mix proportion for the selected W/C ratios of 0.60, 0.50 and 0.35 and the obtained correlation is also compared with that proposed in IS 9013 of warm water curing method. The result showed that single correlation is not a reliable prediction tool when changes made in proportions. Whereas, comparison with IS 9013 is found statistically similar.*

Key Words: **accelerated curing, curing regimes, control mix, modified mix, correlation and linear regression**

1. INTRODUCTION

Concrete is the most commonly used versatile construction material in the world. Following the development of infrastructure, civil engineering structures which demands a huge and continuous casting of concrete using Ready Mixed Concrete (RMC) are becoming prevalent now a days [1]. The importance of quality control is, not only to comply with specification requirements, but also for economic reason. Thus frequent monitoring and control becomes an important aspect over the field. The standard procedure in quality control of concrete over the industry is taking samples from the mix which is going to be cast on the desired structure and doing the conventional 28th day compressive strength. The major problem regarding this method is, the length of time required before the result are known, by which time considerable quantity of additional concrete may have been placed in the structure. Consequently, it results to be late to take remedial action [2]. Therefore early age estimation of the strength becomes crucial.

The reaction of cement with water (hydration) is an exothermic reaction which enables the formation of hydrated product and consequently allows development of strength to the concrete [1]. The curing procedure is being control of the temperature and moisture movement from and into the concrete. To an extent, an increased curing temperature will result in an increased rate of strength gain and enabling of an early strength gain by elevating the curing temperatures is called accelerated curing. Predicting the 28th strength from early strength using this temperature and strength development concept becomes an important aspect to take immediate action either on the ingredient and mix proportioning stage or on the early removal of defective green concrete. In favor of this, correlations has been established by different researchers so far to predict the 28th day strength of concrete from early test (usually 1 day) depending on different parameters. And some countries such as India, Britain and Canada has also established general empirical equations with respect to curing regimes for prediction of 28th day strength from early age accelerated curing strength in their codes [3]. Correlation is reaffirmed or adjusted on the basis of continuous monitoring of the relationship between early age and later age test results by ensuring that every early age specimen is matched by an identical specimen made at the same time under the same conditions from the same sample of concrete and cured under standard conditions until the time it is tested, normally 28 days [4].

1.1. Problem Statement

As the behavior of concrete in response to the application of heat is dependent upon the mineralogical composition of the cement type including any additions, any developed empirical equation is a function of different parameters (such as cement type and curing regime). I.e. Every correlation equation is unique to a single reference concrete. One single correlation to be used universally for prediction is not certain. The accuracy level of the equation established in the codes, to serve as a universal prediction tool is not guaranteed.

The reliability of one specific single correlation, which is established for specific mix in certain production, against variations in quantity of ingredients within the prescribed tolerance limit in RMC is not studied. As this variations in quantity of ingredients leads to change in the quality (strength) of the concrete, Initial/single correlation along the process may not be reliable even when minor changes to the mix proportion occurred. Moreover, there should be a mechanism to detect the reliability of the established single correlation along the production process and frequent update and reestablishing of new correlation becomes necessary.

1.2. Objectives

I. To investigate the reliability of a single correlation with minor changes in mix proportions.
II. To investigate the reliability of a single correlation equation established in IS 9013 of warm water curing method

1.3. Significance

The significance of this research to the concrete producers/suppliers and contractors are quite vital for their quality assessment/ control. It will give an insight to concrete producers about how reliable a single correlation is when changes made in the mix proportion along the production process. This tells how valid the correlation equation is to that specific production process anymore and helps to establish new correlation, in case found unsatisfactory. Frequent updating of the correlation equation accordingly in RMC is quite vital to have reliable 28th day prediction strength to take early corrective action (such as modifying the mix proportion). Therefore, the research will contribute methods to establish new correlations. Moreover, it will serve as an input for related future researches to be carried out.

2. MATERIALS AND CURING REGIME

The materials used are coarse aggregates (crushed aggregates 10mm and 20mm tested complying to IS 2386:1963), Fine aggregates (clean and uncrushed natural river sand complying to IS 2386:1963), Ordinary Portland Cement (OPC) of 43 grade and specific gravity of 3.15 confirming to IS 8112: 1989, Potable water, Poly Carboxylic Ether (PCE) superplastisizer and curing regime of 55^{0}C as per IS 9013 of warm water curing method.

Table -1: Ingredient properties

Properties	Material		
	Coarse aggregate 20mm	Coarse aggregate 10mm	Fine aggregate
Specific gravity	2.85	2.70	2.65
Bulk density(loose)	1433Kg/m^3	1373Kg/m^3	1350 Kg/m^3
Bulk density (compacted)	1600Kg/m^3	1483Kg/m^3	1492 Kg/m^3
Percentage voids	43%	45%	44%
Water absorption (%)	0.32%	0.73%	

3. METHODOLOGY/PROCEDURE

Mix proportioning is performed by packing density method and three water cement ratios (0.50, 0.60 and 0.35) are selected to account for lower to higher normal strength ranges. The main objective of mix design using packing density approach is to attain maximum packing of aggregates and decreasing the void content which is occupied by a paste, The lesser the void content between aggregates, the less paste requirement to fill the voids and thereby reduction in cement consumption. First packing of 10 mm and 20mm (M_{12}) and then packing of M_{12} with fine aggregate were performed to arrive at maximum packing density of overall aggregates (M_3). Then the minimum void content is calculated. Different level of excess paste content was considered for trial mix and 2% were chosen to proceed. Finally, mix proportion is calculated for each W/C accordingly using conservation of mass and volume principle.

Table-2: Mix proportion for the control mix

Ingredients (Kg/m^3)	Water to cement ratio		
	0.60	0.50	0.35
Water	217.63	203.54	174.50
Cement	362.72	407.09	498.57
Fine aggregate	728.98	728.98	728.98
10mm aggregate	437.39	437.39	437.39
20mm aggregate	656.08	656.08	656.08

After fixing the mix proportions for the reference concrete, the modified mix is prepared by only making minimum changes for each W/C ratio in the mix proportions up to the tolerance limit specified in the codes for RMC [5].

Table -3: percentage modification made to the control mix

Reference /control mix	Changing item	Variation as per IS 4925 of tolerance limit	Designation
Single/ particular W/C	Cement (C)	ΔC by +1%	M1
		ΔC by -1%	M2
		ΔC & ΔW by +1%	M3
	Water (W)	ΔW by +1%	M4
		ΔW by -1%	M5
		ΔC & ΔW by -1%	M6
	Sand (S)	ΔS by +2%	M7
		ΔS by -2%	M8

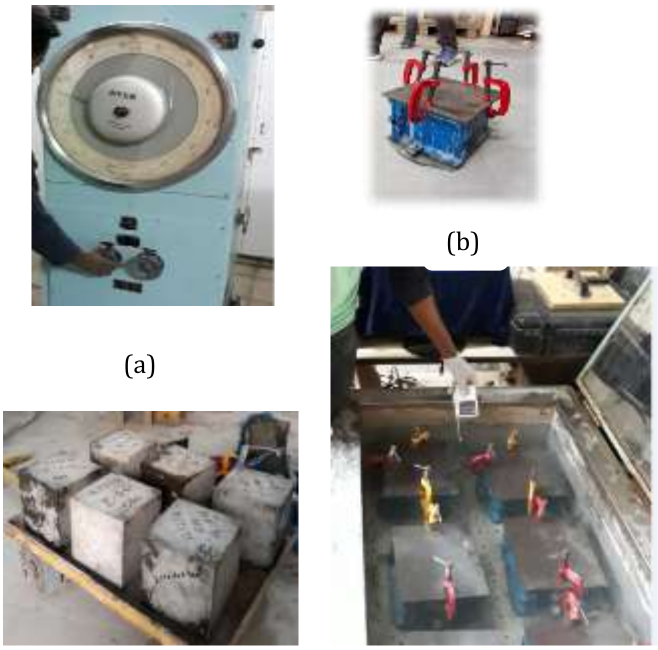
4. EXPERIMENTAL PROCEDURE

150mm steel molds are used in all the tests. For accelerated curing, special heavy duty steel cubes with top plate are used. To prevent adhesion of water during curing Teflon sheet (which is found resistant to melt) in between the edges of molds and beneath the steel cover plate are used. Then special steel clappers are used to tight the plate with the molds. Slump value of 125±25 mm were attained in all the mixes and 0.26% by mass of cement PCE has been used for W/C of 0.35 mix. A total of 102 specimens has been casted. For the control mix, 18 specimens for each W/C (9 normal and 9 accelerated specimens), total of 3*18 = 54 and for the modified mix, 16 specimens for each W/C (8 normal and 8 accelerated specimens), and total of 3*16 = 48 were casted.

One batch of fresh mix were casted in three stages. I.e. six cubes (3 for accelerated and 3 for normal) per one stage and remixing again for the next stage, which gives a total of 18 cubes per one W/C. In all accelerated curing tests, specimens are immersed into the hot water curing tank exactly 1 hour after casting, cured for 20 hour with a temperature range of 55±1^{0}C, cooled for 1 hour with water at temperature of 27±1^{0}C and tested for compressive strength and normally moist cured specimens are tested as per their 28 day timing.

4.1. Standards/Codes Followed and Machines Used For The Experiment

All accelerated specimen curing done as per IS 9013:1978 of warm water curing method [6], all normally moist specimen curing's as per IS 516, 1959 [7], all specimens compressive strength tests as per IS 516, 1959 [7] and Hydraulic Compressive Testing Machine of capacity 250 ton is used for all specimens.



(a) (b) (c) (d)

Fig - 1: Hydraulic CTM (a), Mold for accelerated curing (b), Spec mmersed into warm wa accelerated curing (c) and accelerated cubes rea compressive strength test (d).

5. RESULT AND ANALYSIS

All the compressive strength results of both 28th day normally moist cured and 20hr accelerated cured data's with respect to their W/C are presented below in the table for the two groups of mixes.

Table - 4: Compressive strength results for the control mix

	No	Water to cement ratio					
		0.60		0.50		0.35	
		20hr	28 day	20hr	28 day	20hr	28 day
Compressive strength (MPa)	1	10.02	24.84	15.25	25.06	29.80	37.92
	2	10.72	25.06	15.25	25.28	30.45	40.32
	3	10.89	26.80	15.25	28.85	31.00	41.84
	4	12.86	27.90	15.47	29.42	32.69	42.93
	5	13.07	29.20	15.91	31.16	32.91	44.24
	6	13.29	29.42	16.13	33.34	32.91	44.67
	7	13.95	29.85	16.34	37.05	33.12	45.76
	8	14.60	31.82	16.56	39.22	33.34	47.97
	9	15.04	35.96	17.22	39.44	33.34	50.12
Average		12.71	28.98	15.93	32.09	32.17	43.97
% [(f_a/f_{28}) *100]		43.86%		49.64%		73.16%	

Table- 5: Compressive strength results for the modified mix

	No	Water to cement ratio					
		0.60		0.50		0.35	
		20HR	28 day	20HR	28 day	20HR	28 day
Compressive strength (MPa)	M1	5.92	21.92	8.23	32.01	14.94	48.81
	M2	6.23	25.28	8.67	38.14	16.03	37.26
	M3	8.93	24.62	12.86	30.07	33.34	39.23
	M4	9.15	22.66	14.82	30.94	35.00	46.85
	M5	9.59	26.59	15.04	30.29	35.52	34.87
	M6	10.46	25.06	15.08	32.69	36.83	40.53
	M7	10.68	28.55	15.69	32.91	40.97	50.99
	M8	10.89	25.93	17.43	35.74	41.84	32.69
Average		8.98	25.07	13.48	32.85	31.81	41.40
%[(f_a/f_{28}) *100]		35.82%		41.03%		76.83%	

In both the cases, an increase in proportion of accelerated to normal 28 day strength along a decrease in W/C is observed, with an attained ratio of 43.86, 49.64 and 73.16% for the control mix and 35.82, 41.03 and 76.83% for the modified mix for W/C of 0.60, 0.50 and 0.36 respectively.

Considering all strength values of the three W/C's together, the SD of 20hr accelerated and 28 day normal strength mix is found to be 8.77 and 7.80 for the control mix and 11.81 and 8.00 for the modified mix respectively. Generally an increase in SD is observed from control mix to modified mix with a SD increase from 7.80 to 8.00 for the case of 28 day normal moist curing and 8.77 to 11.81 for 20 hour hot water curing.

Table –5: Range, standard deviation and variance. Red values are for the modified mix. (Numbers written top and bottom in one cell are values of control and modified mixes respectively)

W/C ratio	Range (R)		Sample standard deviation (s)		Sample variance (s^2)	
	20 hour	28 day	20 hour	28 day	20 hour	28 day
0.60	5.02 4.97	11.12 6.63	1.78 1.93	3.47 2.11	3.19 3.72	12.03 4.45
0.50	1.97 9.20	14.38 8.07	0.69 3.34	5.54 2.80	0.48 11.19	30.66 7.86
0.35	3.54 26.90	12.20 18.30	1.37 10.49	3.76 6.73	1.87 110.15	14.14 45.37

Average of all W/C	Control		Modified	
	20-hr	28- day	20-hr	28-day
Range	23.32	25.28	35.92	29.07
St.dev.(s)	8.77	7.80	11.81	8.00
Variance (s^2)	77.02	60.82	139.58	64.00

5.1. Analysis

First, all strength values of the two mix categories were plotted in a histogram to have an overall and quick overview of the data distributions. The trend line indicated an increase in strength with a decrease in W/C ratio of both mixes. Second, statistical hypothesis testing of different initial parameters followed by comparison of correlation coefficient and regression lines are performed and finally, statistical inferences are made. The data are assumed to be normally distributed in all the analysis.

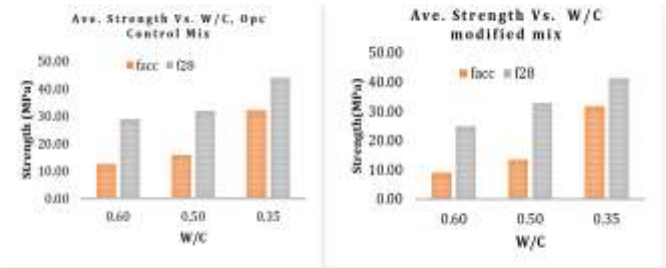


Chart -1: Average strength Vs. W/C ratio

5.1.1. Analysis of Variance And "3s"Test

To investigate the variation existed in the two groups of sample data's statistically, the two independent group variances (the actual 28 day strength of the control and modified mix) is tested using F test. The test helps to make statistical conclusions about the variations existed in the two groups based on the ratio of the two variances with a given confidence interval.

$$F = \frac{\text{Larger sample variances}}{\text{Smaller sample variance}} = \frac{(7.99)^2}{(7.79)^2} = 1.0514$$

Table - 6: Result of the F test

	Modified mix	Control mix
Mean	33.10958333	35.0162963
Variance	63.95621286	60.82577806
Observations	24	27
df	23	26
F	1.051465594	
P(F<=f) one-tail	0.447858286	
F Critical one-tail	1.956026035	

The critical F value of 1.956 is higher than the calculated F value of 1.051. This means the variation of the two groups of variances are statistically insignificant. In other words, there is no statistically significant difference between the two sample standard deviations. Therefore further analysis is performed by pooling the variances, or by considering the two sample variations as equal in other words. "3s" is a statistical test in which nearly all, or 99.7% of the data's are the believed to fall three times the sample standard deviations from the mean in both sides (Mean±3s) of the curve. Normally moist cured actual 28 day strength of both the control and modified mix has been investigated to check for outliers.

Table - 7: 3s test of compressive strength results

Control mix (actual range 24.84 to 50.12 MPa)			Modified mix(actual range 21.92 to 51.00 MPa)		
		No of outliers			No of outliers

mean ($\bar{x}_1$)	$\bar{x}_1$ ± 3s		Mean ($\bar{x}_2$)	$\bar{x}_2$ ± 3s	
35.02	11.62 to 58.42	No	33.10	9.10 to 57.10	No

No outlier is found in both the mix categories. Therefore, all the mixes are in the 3s range of strengths.

5.1.2. Correlation and Regression Model

Correlation between 20hr strength (f_a) and normally moist cured 28 day strength (f_{28}) is made for both mixes. 27 and 24 compressive strength data points are collected from the three W/C's for the control and modified mix respectively. The scattered data points are plotted and linear regression line has been fitted in both the mixes. 20 hour strength (f_a) values on X axis (independent variable) versus 28 day strength (f_{28}) on Y axis (dependent variable) is plotted. The shaded area below in the graph is an area with a confidence interval of 95% or α = 0.05

(1) (2)

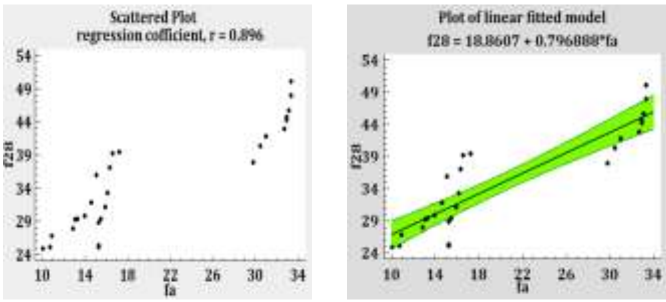


Chart 2: scattered (1) and fitted (2) models for the control mix

(3) (4)

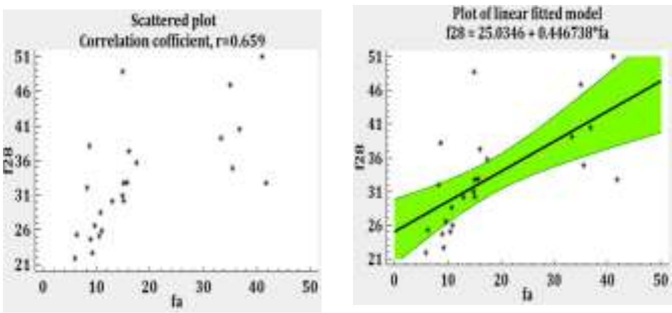


Chart 3: scattered (3) and fitted (4) models for the modified mix

5.1.3. Comparison of Correlation Coefficients

Correlation coefficient tells the extent in which values are associated. The higher the degree of association between the values, the higher value of the correlation coefficient is [8]. One statistical method of comparing the two regression lines is through hypothesis testing of correlation coefficients. Thus, the correlation coefficient of the control mix and modified mix are tested using α = 0.05. Sample size and correction coefficients are 27 and 0.896 for the control mix and 24 and 0.659 for the modified mix respectively. The null hypothesis (H_o) is formulated that the two correlation coefficients are similar (r1 = r2) whereas the alternative hypothesis (Ha) argues that two correlation coefficients are statistically different (r1 ≠ r2). The computed Z statistic and P-value is found out 2.210 and 0.027 respectively. Since the P-value for the test is less than 0.05, the null hypothesis is rejected at the 95.0% confidence level. Therefore the result of the test revealed the existence of statistically significant difference between the two group correlation coefficients.

5.1.4. Comparison of The Regression Lines

The clustered plot of the two regression lines in one graph is indicated below. The technique basically includes comparison of slope and intercepts of the two regression lines. The category A and B represents the linear regression lines of control mix and modified mix respectively.

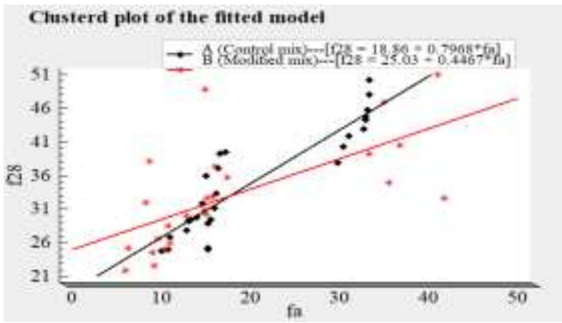


Chart - 4: Clustered plot of the fitted model

The result of comparison of the two regression lines using Stat graphics software is summarized in the table below.

Table - 8: Coefficients

Category	Intercept	Slope
A	18.8607	0.796888
B	25.0346	0.446738

Table- 9: Analysis of two linear regression lines

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
f_a	1802.3	1	1802.3	74.24	0.0000
Intercepts	4.98671	1	4.98671	0.21	0.6525
Slopes	151.209	1	151.209	6.23	0.0161
Model	1958.49	3			

Because the P-value for the slopes is less than 0.05, there is statistically significant differences among the two slopes of regression lines at the 95% confidence level. Whereas the P-value for the intercepts is greater than or equal to 0.1, there is no statistically significant differences between the intercepts of the two regression lines at the 90% or higher confidence level.

5.1.5. Comparison With IS Code

I. Actual value Vs. IS 9013 of warm water curing method

Comparison of the actual moist cured 28 day strength (control mix) with the predicted values of IS 9013 using the model (f_{28}=12.65+fa) are performed. The mean and standard deviations of both data sets are calculated. Then the mean of the two data sets are analyzed/compared using hypothesis testing. Since the population sample is less ($n < 30$), hypothesis testing using t-distribution is performed with $\alpha = 0.05$. The null hypothesis (H_0) is formulated as the two group means are equal ($x_1 = x_2$) and alternative hypothesis (Ha) says they are different ($x_1 \neq x_2$). Where x_1, n_1 and s_1, are the mean, sample sizes and standard deviation of the actual 28 day compressive strength and x_2, n_2, s_2 are the mean,

$$t = \frac{\bar{X}_1 - \bar{X}_2}{s_p \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \qquad \mathrm{df} = \frac{\left[\frac{s_1{}^2}{n_1} + \frac{s_2{}^2}{n_2}\right]^2}{\frac{(s_1{}^2/n1)^2}{n1-1} + \frac{(s_2{}^2/n2)^2}{n_2-2}}$$

sample sizes and standard deviation of the predicted 28 day compressive strength values respectively.

where

$$s_p = \sqrt{\frac{(n_1-1)\,s_{X_1}^2 + (n_2-1)\,s_{X_2}^2}{n_1+n_2-2}}.$$

And s_p is the common standard deviation of the two groups of data's. All the actual and predicted compressive strength values are summarized in **table - 10** and attached at the last page of this paper.

x1, n_1 and s_1 for the actual 28 day compressive strength are 35.02, 27 and 7.79 respectively whereas x_2, n_2 and s_2 for the predicted 28 day compressive strength are 32.92, 27 and 8.776 respectively. Similarly, the null hypothesis (Ho) says the two group means are equal and the null hypothesis (Ha) argues, not equal. The computed t statistics and P value is found out to be 0.929 and 0.357 respectively. Since the P-value for the test is greater than or equal to 0.05, the null hypothesis cannot be rejected at the 95.0% confidence level. Thus, there is no statistically significant difference between the actual and predicted 28 day mean of the two groups of data.

II. Comparison of the predicted values

Again the two predicted 28 day strength values using both the IS 9013 regression model (f_{28}=12.65+ f_a) and the obtained regression model in this experiment (f_{28}=18.86 + 0.797f_a) is compared statistically as similar to the above procedure. Here x_1, n_1 and s_1 for the predicted 28 day compressive strength using (f_{28}=18.86 + 0.797fa) are 35.02, 27 and 7.00 respectively whereas x_2, n_2 and s_2 for the predicted 28 day compressive strength using (f_{28}=12.65 + f_a) are 32.92, 27 and 8.78 respectively. Hypothesis is formulated similar to the above. The computed t statistics and P value is found out to be 0.972 and 0.336 respectively. Since the P-value for the test is greater than or equal to 0.05, the null hypothesis cannot be rejected at the 95.0% confidence level. Thus, there is no statistically significant difference between the two predicted values.

Generally in the above both cases, the statistical hypothesis test reveals that there is no significance difference in between the IS 9013 warm water curing method linear prediction model and the linear regression model developed in this particular experiment for the control mix. Therefore, the regression model developed in the IS 9013 warm water curing method is found to be statistically reliable prediction model for this particular experiment.

6. CONCLUSIONS

- The two groups of variances are statistically insignificant and both groups of mixes are in the "3*s*" range of strengths.
- Single correlation is not reliable when minor changes made in the mix proportions.
- IS 9013 warm water curing method correlation is similar with single correlation.

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BIOGRAPHIES

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Table -10: Actual and predicted compressive strength values

W/C	All values in MPa						
	Accelerated strength (f_a)		Actual 28 day strength (f_{28})		Predicted values		
	Control (a)	Modified (b)	Control (c)	Modified (d)	$f_{28}=18.86+0.797f_a$ from (a)	$f_{28}=12.65+f_a$ from (a)	$f_{28}=25.03+0.446f_a$ from (b)
0.60	10.02	5.92	24.84	21.92	26.85	22.67	27.68
	10.72	6.23	25.06	25.28	27.40	23.37	27.82
	10.89	8.93	26.80	24.62	27.54	23.54	29.02
	12.86	9.15	27.90	22.66	29.11	25.51	29.12
	13.07	9.59	29.20	26.59	29.28	25.72	29.32
	13.29	10.46	29.42	25.06	29.45	25.94	29.71
	13.95	10.68	29.85	28.55	29.98	26.60	29.81
	14.60	10.89	31.82	25.93	30.50	27.25	29.90
	15.04		35.96		30.85	27.69	
0.50	15.25	8.23	25.06	32.01	31.01	27.90	28.71
	15.25	8.67	25.28	38.14	31.01	27.90	28.91
	15.25	12.86	28.85	30.07	31.01	27.90	30.78
	15.47	14.82	29.42	30.94	31.19	28.12	31.66
	15.91	15.04	31.16	30.29	31.54	28.56	31.75
	16.13	15.08	33.34	32.69	31.71	28.78	31.77
	16.34	15.69	37.05	32.91	31.88	28.99	32.04
	16.56	17.43	39.22	35.74	32.06	29.21	32.82
	17.22		39.44		32.58	29.87	
0.35	29.80	14.9	37.92	48.8	42.61	42.45	31.71
	30.45	16.0	40.32	37.3	43.13	43.10	32.20
	31.00	33.3	41.84	39.2	43.56	43.65	39.93
	32.69	35.0	42.93	46.9	44.91	45.34	40.67
	32.91	35.5	44.24	34.9	45.09	45.56	40.90
	32.91	36.8	44.67	40.5	45.09	45.56	41.49
	33.12	41.0	45.76	51.0	45.25	45.77	43.34
	33.34	41.8	47.97	32.7	45.43	45.99	43.73
	33.34		50.12		45.43	45.99	
Mean ($\bar{x}$)			35.02	33.11	35.02	32.92	33.12
St. deviation (s)			7.80	8.00	7.00	8.78	5.28
Range (R)			25.28	29.08	18.58	23.32	16.05