 doi:10.20944/preprints202207.0207.v1

Correlation Monitoring of Predicted and Actual Strength in CUSUM Quality Control of Concrete

Tsegaye Arega[1], Prof. B. Bhattachrjee[2]

[1] **(Corresponding Author):** Department of Construction Engineering and Management, Dire Dawa University, Ethiopia

Email: aregatsegaye360@gmail.com

[2] **(Co-Author):** Department of Civil Engineering, IIT Delhi

Email: bishwa54@gmail.com

Abstract: Quality monitoring (QM) with CUSUM system can result in potential economy in RMC through optimal control of target strength (by avoiding overdesign) on the one hand and through reduction of producers' risk against rejection by the client on the other. To overcome the problems associated with the conventional 28-day compressive strength test, correlations are established between accelerated and the standard 28-day cube strength to predict the 28-day strength from the early age strength itself. This paper tried to demonstrate the lack of reliability of single correlation itself along the production time of RMC. The correlations vary with W/C as well as with type of cement. Hence it is demonstrated that correlation is concrete specific. Further, it is also demonstrated that correlation established with specimens having wide variation in the batching may result in poor correlation. Through CUSUM plots of mean and range for cube strength obtained by Monte-Carlo simulation demonstrate the utility of prediction through such correlation in QM and a methodology for monitoring the correlation itself.

Key Words: Accelerated Curing, Curing Regime, CUSUM, Quality Control

1. Introduction

Quality control of Concrete, especially ready mix concrete (RMC) is necessary in order to combine effectively the constituent materials in such a way so as to produce a product of consistent quality and performance [1]. Quality monitoring of RMC is required mainly because of two reasons. Firstly, to ensure the producers risk is within reasonable limits, so that the probability of rejection of concrete by the user is sufficiently low. Secondly, the mix proportions used remain optimal throughout for the grade of concrete produced, such that the additional cost due to over conservative design of the mix is minimal. Quality control of RMC can be divided into three stages. The first is forward control, which focuses on controlling ingredients and process prior to mixing. This includes testing of ingredients, calibration of weighing equipment's and maintenance of plants. The second is immediate control which is concerned with taking instant action during the production process. This includes ensuring proper weighing of ingredients, visual observation of the fresh mix, making corresponding adjustments and inspections at delivery. The third, which is the subject matter of this paper, is retrospective control. This method basically focuses on taking representative samples during casting or placing of the final concrete, testing the sample and to make inferences about the quality and acceptance of cast concrete. The conventional method to make inferences about the grade of concrete is based on the 28- day compressive strength result.

The problem associated with this method is the length of time required before the result is known, leading it to be too late to take remedial action. To avoid the problem, test is conducted on samples produced through accelerated (thermal) curing within short period of time, to represent 28-days strength. The 28-day's strength is predicted based on established correlation between accelerated strength and predicted strength, so that one does not have to wait for 28 days to take corrective actions. In the CUSUM method of quality control CUSUM is calculated on the basis of the predicted strength and corrective actions are based on the same. For such purpose, above mentioned correlation(s) has been established by different researchers and different codes such as [2], [3]and [4] to predict the 28-day strength of concrete from early test (usually 1 day) result depending on different parameters. However, single correlation may not be applicable universally as a prediction tool for every RMC plant and all concrete because, a correlation is function of different parameters from which it has been established, such as the accelerated curing regime, cement type and mix proportions. Thus, establishing initial single correlation for the specified production is quite vital. Second, the reliability of single initial correlation itself as a prediction tool along the production process of RMC has to be monitored regularly.

Reviewing the work of different researchers, quality monitoring of RMC using CUSUM and different techniques has been discussed as follows. Gohel and Sarkar [5] made a comparative study between CUSUM and EWMA regarding ease of application and detection reliability. Sarkar and Bhattacharjee [6] developed a framework about design and application of multivariate CUSUM for quality monitoring of RMC. Dutta and Sarkar [7] endeavored to incorporate risks associated with RMC production into the conventional CUSUM and developed a model of risk adjusted CUSUM or RACUSUM. It has been observed from different research works that, the CUSUM analysis were performed to monitor individual concrete quality variables (strength, slump, density etc.) against the target/expected variables to be achieved in the RMC production. Correlation monitoring using CUSUM technique hasn't been emphasized yet. In this paper, to demonstrate the need for concrete specific correlation and its monitoring, separate correlations of accelerated and normal 28-day compressive strength were established with 3 W/C and two types of cements, i.e., OPC and PPC. Next, considering the limits of batching tolerances for cement water etc., in mix, 8 extreme mixes were also prepared and implication of large variation in batching on correlation between accelerated strength and actual 28 days strength has been investigated. Using Monte-Carlo simulation 30 accelerated cube strengths have been generated and corresponding CUSUM plots for mean and ranges are obtained for a given W/C and PPC which more commonly used cement. The inferences from these CUSUM plots are compared with those obtained from actual 28 days strength obtained from simulation. Also CUSUM plots are made with simulated cube strength results considering both specimen preparation variation and batching variation to demonstrate dynamic nature of mix proportion and needs for verification, monitoring and modification of mix. Lastly the CUSUM plot for correlation is presented to demonstrate its utility.

2. Research Significance

This paper is helpful for RMC producers and contractors for implementation of scientific quality monitoring for control during the production process. It can give an insight in to the dynamic nature of concrete mix proportioning and need for verification of correlation from time to time. This paper enable examination of the validity of the correlation equation obtained for specific production process over a period of time and presents a methodology to establish new correlation.

3. Experimental work

3.1 Materials and Curing Regime

Coarse aggregate (crushed aggregate 10mm and 20mm), fine aggregate (clean and uncrushed natural river sand) complying to IS 2386:1963, Ordinary Portland Cement (OPC) of grade 43 and Specific Gravity of 3.15 confirming to IS 8112:1989, The PPC cement confirming to Indian standard IS 1489:1991, specific gravity 2.90, Potable water, Poly Carboxylic Ether super-plastisizer were used.

In this paper importance and need for concrete specific correlation between accelerated curing strength and 28 days standard curing strength in quality control is addressed, hence, in addition to standard curing for 28 days strength, an accelerated curing regime was also adopted and corresponding strength was determined. The correlation is expected to be curing regime specific, but choice of accelerated regime has no role in final monitoring and any curing regime is as good as any other curing regime. A number of different curing regimes are available in codes and literature. Many codes including IS9013: 1978, allow choice of adoption of a curing regime from a proposed set of two or more regimes. Since choice of curing regime has no particular role in the considered analysis the curing regime as per IS 9013 warm water curing was adopted in this work.

3.2 Mix proportions

Three water cement ratios (0.60, 0.50 and 0.35) are selected to account for normal concrete strength considering possible lowest to highest strength range. Mix proportions were arrived at using empirical packing density concepts. The method tries to attain maximum packing of aggregates and decrease the void content to be occupied by paste, thereby, enabling reduction of cement consumption. First packing experiments were carried out for m.s.a 10mm and m.s.a 20mm coarse aggregate, resulting in a dry aggregate mixture of aggregate designated as M_{12}, and next packing experiment was carried out for resultant M_{12} mixture of combined coarse aggregate with fine aggregates, to arrive at a maximum packing density of overall all combined aggregates designated as M_3. Then the minimum void content is calculated as unity minus estimated packing density. The minimum volumetric paste content is the void volume plus excess paste required to take care of particle interference, i.e., loosening effect and wall effect etc. Different level of excess paste contents were considered for trial mix and 2% were chosen to proceed. Finally mix proportion (control mix) is calculated for each W/C using conservation of mass per unit volume principle. The mix proportions are given in Table 1 and referred as control mix. Another set of mix proportions (modified mixes) are calculated by making minor changes in cement content water content individually, over those of control mix as shown in Table 2. Modifications of quantities were up to the tolerance limit specified in the Indian standard code of practice for batching [8]. These mixes represent mixes with extreme variation introduced during production due to tolerable batching variations.

3.3 Number of Specimens

For an adopted W/C and cement type total 18 cube specimens were cast, 9 for standard curing and 28 days strength, and nine additional for accelerated curing and test within 24 hours. This 18 cube strength results enabled establishing correlation between accelerated and standard strength results for an individual W/C and cement combination. With 6 such combinations total 108 specimens were cast and tested as par the program. In addition, corresponding to every individual W/C and cement type 16 specimens were cast two each for a modified mix as designated in Table 2. One of these two specimens was tested after standard curing and another after subjecting to accelerated curing regime. The test results and discussions on correlation is presented in later part of the paper.

3.4 Specimen casting, curing and test

All specimens were 150mm standard size and cast in standard manner. A slump value of 125±25mm was attained in all the mixes and 0.26% by mass of cement PCE, was used for W/C of 0.35 mix. In all accelerated curing tests, specimens were 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 were tested at 28 day age as par standard procedure prescribed in IS 516: 1959 in a 250 ton capacity compression testing machine.

Table 1: Mix proportion of control mix

Cement	W/C	Water content (W) kg/m^3	Cement Content (C) kg/m^3	Fine aggregate content kg/m^3	10 mm down coarse aggregate kg/m^3	20 mm down coarse aggregate kg/m^3
OPC	0.35	174.5	498.5	729.0	437.5	656.0
	0.50	203.5	407.0	729.0	437.5	656.0
	0.60	217.5	363.0	729.0	437.5	656.0
PPC	0.35	167.5	479.0	729.0	437.5	656.0
	0.50	197.0	394.0	729.0	437.5	656.0
	0.60	211.0	352.0	729.0	437.5	656.0

 doi:10.20944/preprints202207.0207.v1

Table 2: 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 and ΔW by +1% simultaneously	M3
	Water (W)	ΔW by +1%	M4
		ΔW by -1%	M5
		ΔC and ΔW by -1%	M6
	Sand (S)	ΔS by +2%	M7
		ΔS by -2%	M8

4. Accelerated curing and 28 days strength correlation

In figures 1(a) to 1(f), plots between 24 hours accelerated and 28 days standard strength are shown for combinations of OPC and W/C 0.35, OPC and W/C 0.5, OPC and W/C 0.6 and; PPC and W/C 0.35, PPC and W/C 0.5, PPC and W/C 0.6, respectively. The slope intercept and square of correlation coefficient, r^2 values for the linear equations of the form f_{28}(standard)=m× f_1(accelerated)+c; are given in Table 3. The both slopes and intercepts vary widely from each other and apparently possibility of single correlation for all mixes does not seem to exist. The r^2 values are reasonably acceptable except for PPC with W/C 0.6. These may be due to low sample size of 9 used in correlation. To verify the same 30 additional results were obtained through Monte Carlo simulation by generating normal random number with mean and standard deviations 9 experimental results. Since the cubes were cast simultaneously, same set of random numbers were used to simulate 30 additional pairs of f_1 and f_{28}, but using respective experimental mean and standard deviations. The r^2, i.e., square of correlation coefficient improved significantly, but the m and c changed only marginally. This analysis further confirmed that correlation depends on cement type and W/C as well.

a b c

 doi:10.20944/preprints202207.0207.v1

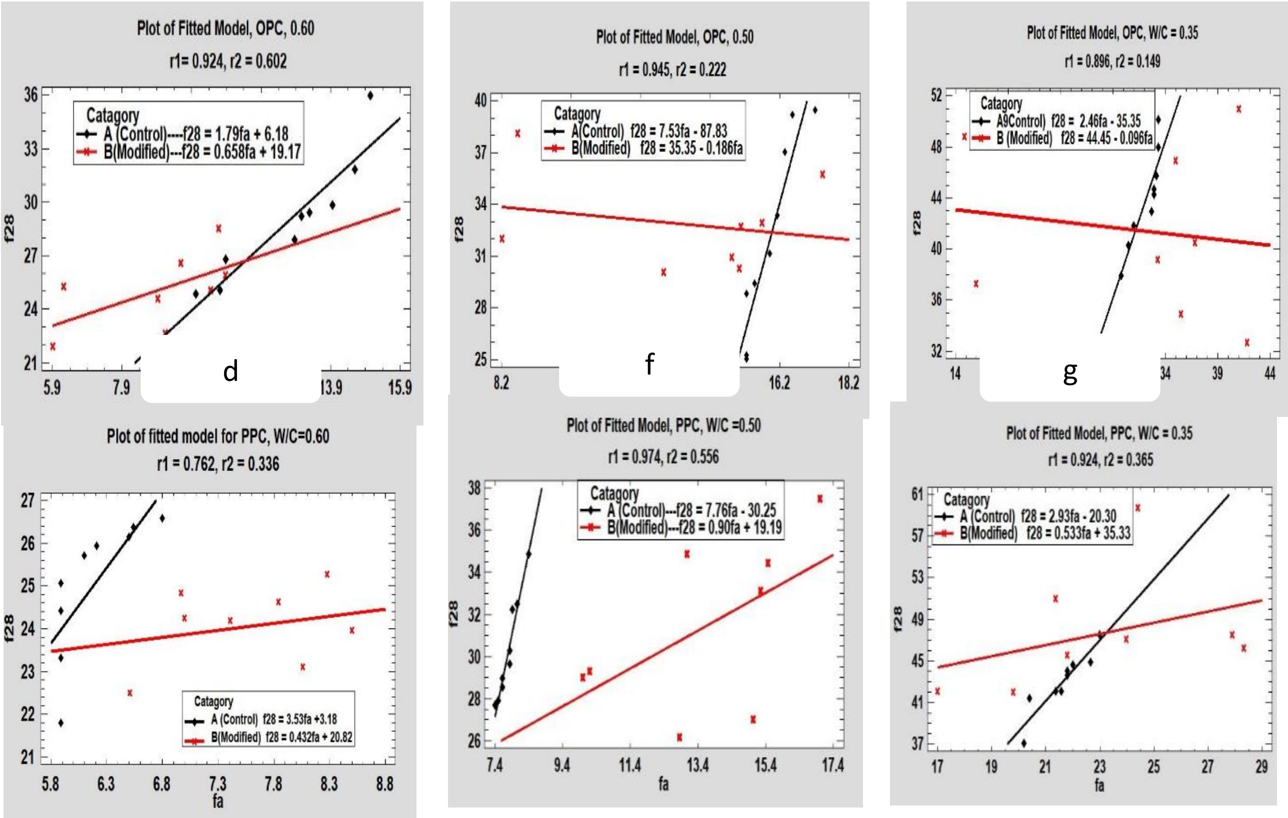

Fig.1: Clustered plot of the control and modified mixes for W/C of 0.60 (a), 0.50 (b) and 0.35 (c) of OPC and 0.60 (d), 0.50 (e) and 0.35(f) of PPC mixes respectively

Table 3: Coefficients Linear regressions equation and r^2

Cement	W/C	Actual (9 specimen)			Actual and simulated (39 results)		
		M	C	r^2	M	c	r^2
OPC	0.35	2.47	-35.3	0.80	2.69	-42.6	0.96
	0.50	7.53	-87.8	0.89	7.86	-93.2	0.97
	0.60	1.79	6.18	0.85	1.91	4.78	0.95
PPC	0.35	2.93	-20.3	0.85	3.12	-24.51	0.97
	0.50	7.70	-29.6	0.96	7.92	-31.47	0.99
	0.60	3.53	3.18	0.58	4.37	-1.98	0.89

Complete compressive strength results of all the specimens for control concrete for both OPC and PPC and all three W/C are given in Table 4 and (Table 4.1 in thesis) test results for modified mixes are given in Table 5 (Table 4.2 in thesis). The 8 pairs of modified mix results and 17 pairs of modified and control mix results both for all six cases exhibited poor correlations ($0<r^2<0.4$) indicating reliable correlation can be established only at the laboratory control level.

Table 4: Summary of test results for the control concrete

Cement	W/C	Curing regime	1	2	3	4	5	6	7	8	9	Ave. strength
			Compressive strength (MPa)									
OPC	0.60	*20hr*	10.02	10.72	10.89	12.86	13.07	13.29	13.95	14.60	15.04	12.71
		28 day	24.84	25.06	26.80	27.90	29.20	29.42	29.85	31.82	35.96	28.98
	0.50	*20hr*	15.25	15.25	15.25	15.47	15.91	16.13	16.34	16.56	17.22	15.93
		28 day	25.06	25.28	28.85	29.42	31.16	33.34	37.05	39.22	39.44	32.09
	0.35	*20hr*	29.80	30.45	31.00	32.69	32.91	32.91	33.12	33.34	33.34	32.17
		28 day	37.92	40.32	41.84	42.93	44.24	44.67	45.76	47.97	50.12	43.97
PPC	0.60	*20hr*	5.89	5.89	5.89	5.89	6.10	6.21	6.50	6.54	6.80	6.19
		28 day	21.79	23.32	24.41	25.06	25.71	25.93	26.15	26.37	26.59	25.04
	0.50	*20hr*	7.41	7.50	7.63	7.63	7.84	7.84	7.92	8.06	8.40	7.80
		28 day	27.68	27.89	28.55	28.98	29.64	30.29	32.25	32.47	34.87	30.29
	0.35	*20hr*	20.20	20.40	21.36	21.57	21.79	21.79	22.01	22.66	23.00	21.64
		28 day	37.05	41.40	42.06	42.06	43.58	44.02	44.67	44.89	47.51	43.03

Table 5: Summary of compressive strength test results for the modified concrete

Cement	W/C	Curing regime	*M1*	*M2*	*M3*	*M4*	*M5*	*M6*	*M7*	*M8*	Ave. strength
			Compressive strength (MPa)								
OPC	0.60	*20hr*	10.89	10.46	10.68	9.15	9.59	8.93	6.23	5.92	8.98
		28 day	25.93	25.06	28.55	22.66	26.59	24.62	25.28	21.92	25.07
	0.50	*20hr*	17.43	15.69	15.04	12.86	14.82	15.08	8.23	8.67	13.48
		28 day	35.74	32.91	30.29	30.07	30.94	32.69	32.01	38.14	32.85
	0.35	*20hr*	41.84	40.97	36.83	35.00	35.52	33.34	16.03	14.94	31.81
		28 day	32.69	50.99	40.53	46.85	34.87	39.23	37.26	48.81	41.40
PPC	0.60	*20hr*	8.50	7.84	8.06	6.97	8.28	7.41	7.00	6.51	7.57
		28 day	23.97	24.62	23.10	24.84	25.28	24.19	24.25	22.50	24.09
	0.50	*20hr*	17.00	15.47	15.04	15.25	13.07	12.86	10.20	10.00	13.61
		28 day	37.48	34.43	27.02	33.12	34.87	26.15	29.32	29.00	31.42
	0.35	*20hr*	28.33	23.97	27.89	24.41	21.36	21.79	19.80	17.00	23.07
		28 day	46.20	47.07	47.51	59.71	50.99	45.55	42.00	42.12	47.64

A close look in to Table 4 indicates that 28 days cube compressive strength reduces with an increase in W/C as expected according to Abram's law $f=a/(b^{W/C})$. PPC and OPC exhibited nearly same trend and similar cube strength results as shown in Figure 2. However, the accelerated strengths although exhibit similar trend, the rate of accelerated strength development are higher for OPC than that of PPC. The ratio of average accelerated strength to 28 days standard strength expressed as percentage for control mixes and those for modified mixes are plotted in Figure 3 and Figure 4 respectively. It is clearly evident from these figures that the correlation between standard strength and accelerated strength is dependent on W/C and cement type. It may be noted that the constants of the equations are significantly different

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 July 2022 doi:10.20944/preprints202207.0207.v1

than m=1 and c=12.65 given for a typical correlation (f_{28}=12.65+f_1) in IS 9013 (1978). It is expected as the correlation was developed in 1970 at CRI (NCCBM), cement of those days was quite different, further computational capability available those days was quite limited, besides the correlation coefficient also seems to be unknown and not reported.

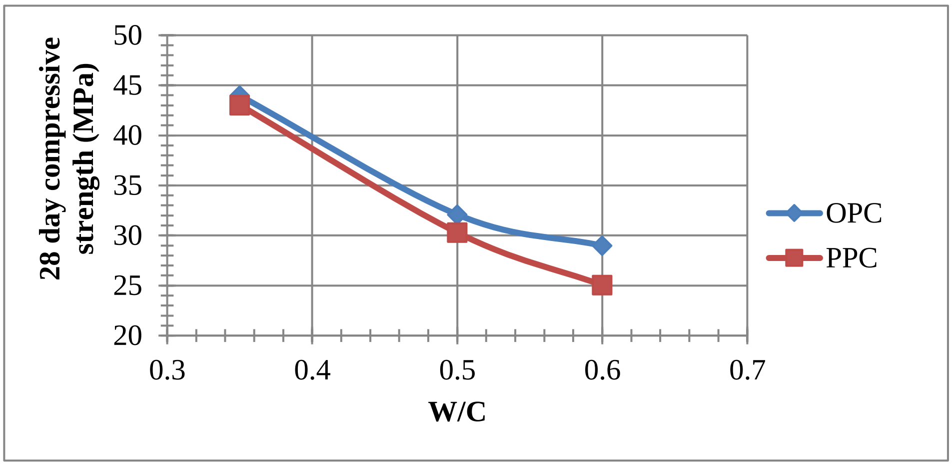

Fig.2: Plot of average 28 day compressive strength Vs W/C for control concrete

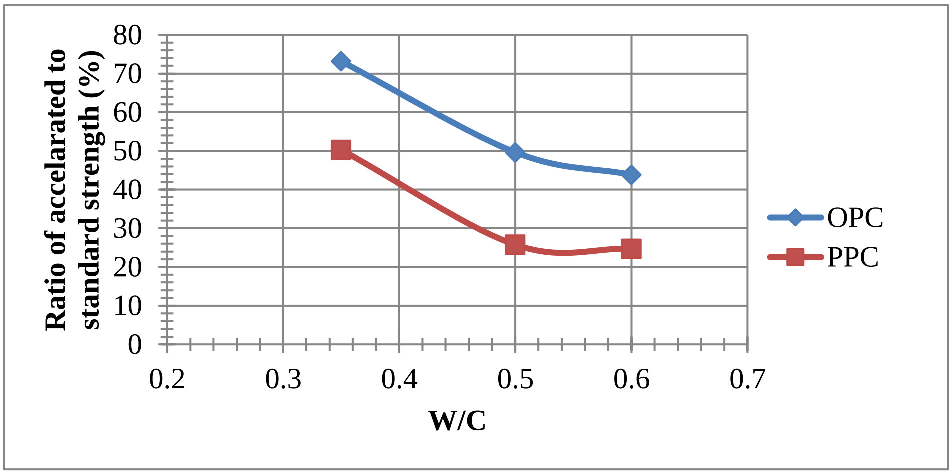

Fig.3: Plot of ratio of accelerated to standard 28 day compressive strength Vs W/C for control concrete

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 July 2022 doi:10.20944/preprints202207.0207.v1

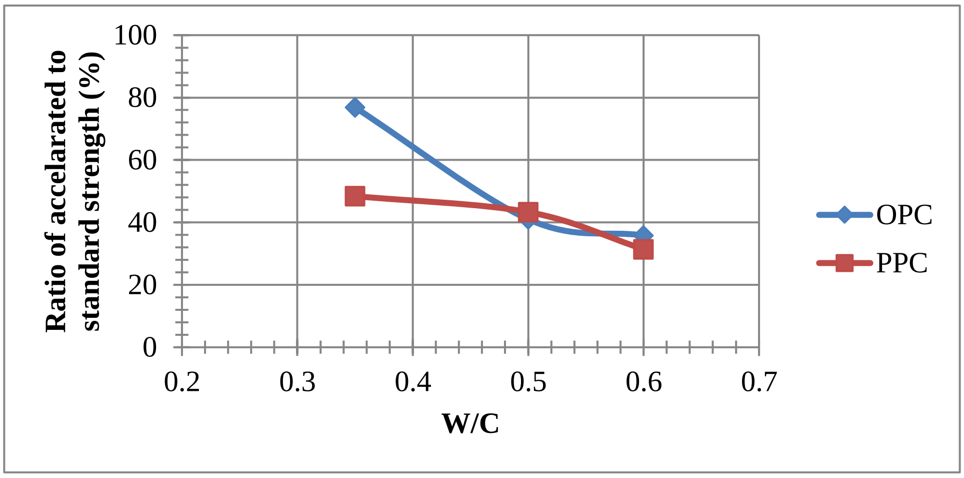

Fig.4: Plot of ratio of accelerated to standard 28 day compressive strength Vs W/C for modified concrete

5. Discussions on strength correlation

Strength of weakly bonded particulate systems like concrete is governed by weakest link, i.e., porosity and pore sizes [9-13] given by form of equation -1 below.

$$f_c = Kc\frac{1-P}{\sqrt{r_{0.5}}} \qquad (1)$$

Where, f_c is the compressive strength, K is a constant along with other properties of pore free matrix, depends also on elastic modulus and surface energy of pore free solid, c is related to cement/cementitious content expressed as a fraction. P is the porosity and $r_{0.5}$ is the median pore radius or mean distribution radius. The P and $r_{0.5}$ are related to W/C, degree of hydration and specific gravity of cement, in addition $r_{0.5}$ is also related mean particle size of cement [10-14]. The relationship of P, $r_{0.5}$ with W/C, degree of hydration and cement particle size is complex and not linear. Elastic modulus and surface energy may again depend in a complex manner with nature of hydration product. Hence ratio f_1/f_{28} cannot be constant and hence, depends on cement used and also on W/C, thus is likely to be concrete specific. There is a need to establish the correlation at site and monitor the same and modify/reestablish as required. Past research on accelerated curing also demonstrated existence of many reported correlation, even considering maturity concepts [15]. The proposed practice by ready mix concrete associations and practice reported in other literatures thus recommends continuous monitoring of correlation through CUSUM and modifications as required [16-18]

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 July 2022 doi:10.20944/preprints202207.0207.v1

5. CUSUM plot of correlation in Quality Control

The CUSUM analysis of correlations has been performed in this section. First, the correlation developed for the control OPC mix with W/C =0.5 is performed (C_0) which is (f_{28} =7.86f_a -93.2) is assumed and the CUSUM analysis is performed for correlation. Generating a set of normally distributed random numbers with mean (15.93 MPa) and standard deviation (0.7) of 0.5 W/C with OPC a hypothetical set accelerated test results (f_1) generated, similarly with another set of random numbers with mean (32.09 MPa) and standard deviation (5.54) of 0.5 W/C with OPC a hypothetical set actual test results (f_{28}) generated and the corresponding CUSUM plot for correlation is shown in Figure 5 and V-mask with decision interval 8.1×5.54=44.87 and gradient 5.54/6=0.915 shown.

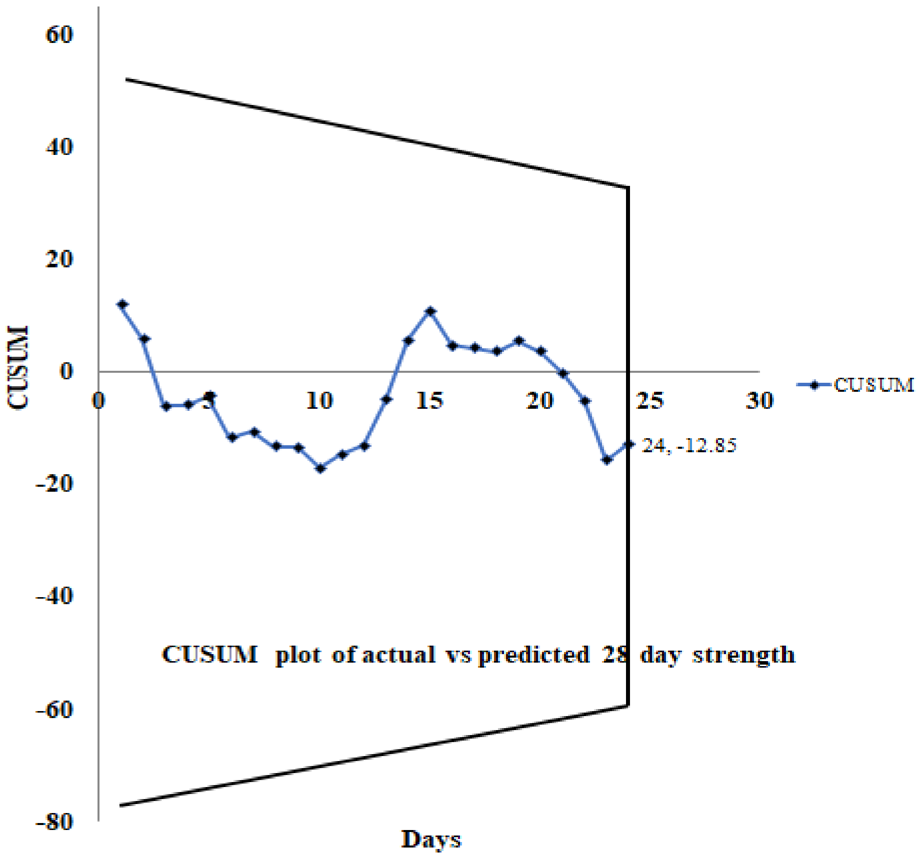

Fig.5: CUSUM plot for correlation (f_{28} =7.86f_a -93.2) for OPC control mix and W/C of 0.50

6. Conclusions

Generally, one can make inferences from the CUSUM plot that correlation is sensitive to change in mix proportions. The experimental investigation or demonstration result of this paper can be concluded with the following points.

1. Correlation shall be established only with laboratory prepared samples.

2. Correlation is mix specific and shall be generated at the plant/site.
3. Utility of the correlation in CUSUM is demonstrated

Notations

RMC = Ready Mix Concrete

CUSUM = Cummulative Sum

RACUSUM = Risk Adjusted Cumulative Sum

CSA = Canadian Standard Association

SD = Sample Standard Deviation

QM = Quality Monitoring

TMS = Target Mean Strength

δ = Target Standard Deviation

C_0 = Control mix correlation (Initial Correlation) = ($f_{28} = 0.7968f_a + 18.86$)

C' = Modified mix correlation (New Correlation) = ($f_{28} = 0.4467f_a + 25.03$)

References

[1] F. Walker, "Advances in Ready Mixed Concrete Technology," p. 291–296, 1976.

[2] Indian Standard, IS 9013, Method of Making, Curing and Determining Comressive Strength of Accelerated Cured Concrete Test Specimen, New Delhi: Bureau of Indian Standards, 1978.

[3] British Standards Institute, BS 1881, Methods of Accelerated Curing of Test Cubes, 1983.

[4] Canadian Standards Association, CAN/CSA-A23.2-10C-14, Accelerating the Curing of Concrete Cylinders and Determining Their Compressive Strength, 2014.

[5] J. Gohel. and D. Sarkar, "Comparative Study of CUSUM with V- mask and EWMA Control Charts for Strength Monitoring of Readhy Mixed Concrete," *International Journal of Advanced Technology in Engineering and Science*, vol. 05, no. 01, pp. 63-71, 2017.

[6] D. Sarkar and B. Bhattacharjee, "Design and Application of Multivariate CUSUM for Quality Monitoring of ReadY Mixed Concrete," *International Journal of Quality Engineering and Technology* , vol. 04, no. 02, pp. 161-179, 2014.

[7] G. Dutta. and D. Sarkar , "Design and Application of Risk Adjusted Cumulative Sum (RACUSUM) for Online Strength Monitoring of Ready Mixed Concrete," *Journal of Construction Engineering and Management* , 2008.

[8] Indian Standards, IS 4925, Concrete Batching and Mixing Plant Specification, New Delhi: Bureau of Indian Standards, 2004.

[9] R .Kumar and B. Bhattacharjee Porosity, pore size distribution and in situ strength of concrete. *Cement and Concrete Research*, January 2003. Vol. 33(1), pp.155-164.

[10] Kondraivendhan, B., and Bhattacharjee, B., "Prediction of strength, permeability and hydraulic diffusivity of OPC paste", ACI Materials Journal, V. 111, No. 2, 2014, pp.171-178.

[11] Kondraivendhan, B., and Bhattacharjee, B., "Strength and W/C Ratio Relationship of CBM revisited through pore features", Materials Characterization, V.122, 2016, pp 124-129

[12] KONDRAIVENDHAN. B and BHATTACHARJEE, B., Effect of age, w/c ratio on size and dispersion of pores in OPC paste" *ACI materials journal*. March-April 2010. Vol. 107, No. 2. pp. 147-154.

[13] Kondraivendhan B and Bhattacharjee (2013) Pore size distribution modification of OPC paste through inclusion of fly ash and sand. Magazine of Concrete Research 65(11):673-684.

[14] PATIL, S.G. and BHATTACHARJEE, B., Size and volume relationship of pore for construction materials. *Journal of Materials in Civil Engineering, ASCE*. June 2008. Vol. 20, No.: 6, pp. 410-418.

[15] V. Ramakrishnan and J. Dietz, "Accelerated Method of Estimating the Strength of Concrete," *South Dakota School of Mines and Technology*

[16] Concrete Mix Design, Quality Control and Specification, fourth edition K. W. Day, J. Aldred and B. Hudson. CRC Press, Boca Raton, FL, USA,2013,

[17] Anderson R. and Dewar J.D, Manual of Ready Mixed Concrete, 2003.

[18] Newman K. , "Advances in Ready Mix Concrete," p. xvi–xxiv, 1976