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Multigrade, Multivariable Cusum Control Charts for Control and Monitoring of the Concrete Production

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Abstract: *Concrete is one of the widely used material in infrastructure construction industries. So it is necessary to improve the efficiency of a concrete production process when ever possible. Statistical process control can be applied to gain information about variation in the concrete manufacturing process. Control charts, especially Cumulative Sum (CUSUM) chart can be implemented to monitor the various processes involved in the production of concrete. This paper studies the application of Multigrade, Multivariable CUSUM control chart for early detection of shifts in the concrete production process. The presented system determines if the monitored process is out of control by employing the multigrade approach and attempts to identify the possible causes for the out of control situation by employing multivariable approach. By identifying the causes of the out of control process, the concrete producer can improve the manufacturing process to a greater degree of accuracy.*

Keyword: *Concrete technology, Statistical quality control, Control chart, CUSUM.*

Introduction

CUSUM is an abbreviation of cumulative sum and it is the cumulative sum of differences from a target value that is of interest in the detection of change. The cumulative sum (CUSUM) control chart system measures performance relative to design intentions. British Standard BS5700 describes the CUSUM technique as being several times as effective as standard Shewhart charts in the detection of change (British Standards Institution, 1984). They are particularly effective at showing exactly when a change took place. Detection can be expressed by mathematical analysis of cumulative differences or by graphing the cumulative sums. The graphical method is easy to implement and use. Control charts can be applied to construction industry, especially in RMC plants to monitor a range of product characteristics such as cube/cylinder strength, consistence/slump, w/c ratio; constituent materials such as aggregate grading; cement strengths or production accuracy. It assists detection of changes in these properties, and indicates when action should be taken to increase the probability of meeting the specification or to reduce the materials cost of the concrete (Day, 2006).

A requirement that is absent from most concrete production specifications is that concrete shall be produced under an approved control system. But ISO 9001 certification establishes that the producer is correctly operating his nominated control system, but not whether that system is effective in the early detection of change (International Standards Organization, 1993). Also, There are drawbacks to

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the existing method of assessment of conformity of mean strength adopted in EN 206-1 including not following the CEN Guidance on the evaluation of conformity (Day, 2006). It is believed that control charts would provide an alternative and better means of ensuring that the characteristic strength is achieved and it is a method that follows the CEN Guidance.

Research Significance:

Physicist Walter A. Shewhart first developed the application of statistical techniques to manufacturing process (Shewhart, 1931). He concluded that data from physical processes typically produce a normal distribution curve, also known as Bell curve. Shewhart identified two types of variations that can happen in a process. One is natural variations which are inherent in the process and cannot be eliminated; another is special variations which are due the change in underlying process and can be eliminated.

After the end of Second World War, W. Edwards Deming became the prominent researcher of Shewhart's work. He helped war torn Japanese manufacturing industry as an industrial consultant by spreading Shewhart's thinking and subsequently championing it in industrial quality control (Deming, 1982).

CUSUM or cumulative sum control chart is a sequential analysis technique proposed by E. S. Page (Page, 1954). Page referred to a quality number θ, by which he meant a parameter of the probability distribution; for example, the mean. He devised CUSUM as a method to determine changes in it, and proposed a criterion for deciding when to take corrective action. After that Barnard developed a visualization method, the V-mask chart, to detect both increases and decreases in θ (Barnard, 1959).

The concept of natural and special variations is relevant to concrete production at a RMC plant. Natural variations exist in the process due to variation in the raw materials such as aggregate grading, chemical composition etc, batching accuracy, plant performance, sampling and testing etc. Special causes of variations could be due to changed constituent materials being used, weigh-scales losing accuracy, a new batcher, problems with testing equipment etc. CUSUM technique was first used for concrete QC in the UK in the 1970s but graphs were neither multigrade nor multivariable. Ken W. Day was drawing non-CUSUM multivariable quality control charts in 1953 and was already looking into CUSUM when the more advanced RMC development came to his attention and was incorporated into his model (Day, 2006). UK CUSUM is still not multivariable but does now use a type of multigrading which is different to Ken's (Gibb & Harrison, 2010). Day's contribution has been to use the previous average value as the target and, by this means, to enable the results from hundreds of grades of concrete to be combined into a single graph. Then he plotted other variables such as density, slump, concrete temperature and also such items as sand specific surface and various cement characteristics on the same graph axes. If one of these "related variables" shows a change point at exactly the same point as a change in strength, then it is almost certainly the cause of the strength change (Day, 2006). The European Ready Mixed Concrete Organization has proposed a standard procedure to concrete production process in accordance to EN standard (Gibb & Harrison, 2010). This procedure was proposed as an alternative method of assessment of conformity in the revision of EN206-1. While its acceptance as a CEN Technical Report is currently under review, some factors dominating concrete quality control has been ignored, such as the effect of time and temperature, Air content, Density etc. While the ERMCO procedure employs multigrade method, definitely it is a strength based univariable system which fails to take into consideration the combined effect of multivariate approach.

It has been observed after reviewing available literature of past decades, substantial work has been done in process and automation industry, but very minimal work has been done in construction industry. This paper tries to establish a modified model for CUSUM control charts applicable to RMC industry based on the now proposed ERMCO procedure, giving emphasize on combined multigrade-multivariable approach.

Multigrade, Multivariable Cusum Control Charts:

The term Multigrade refers to the technique where the results from a number of different grades to be plotted as part of the same graph line. Multigrade CUSUM's are designed to incorporate concretes from different compressive strength classes in the same CUSUM system. This is obtained by adjusting the results from other grades so that they may be analyzed as though they were results from a selected basic grade.

The term Multivariable relates to including graphs of other variables such as density, workability, and temperature; tests on constituent materials such as cement strength and sand grading, and also average pair difference of 28 day results to detect any deterioration in testing quality on the same display as concrete strength. The concept is that changes in concrete strength will be mirrored in, and so confirmed and explained by, changes in one or more of the other variables.

The principle here is to plot the strength CUSUM and try to find another variable that shows a coincident change point. The CUSUM for change points can be examined mathematically but it is less reliable in comparison to graphical approach. So possible solution would be writing a program or using statistical analysis software that carries out the whole process automatically and simply announces (a) that a change point has occurred and (b) which material is the cause. In CUSUM charts, the central line does not represent a constant mean value but is a zero line for the assessment of the trend in the results. The CUSUM system is used for monitoring trends in mean strength, standard deviation and the relationship between early-age and 28 day strengths (Gibb & Harrison, 2010). CUSUM chart for individual control parameters are also drawn to detect the responsible parameter causing the shift.

(i) CUSUM M. for the control of mean strength;

To monitor mean strength, 28 day strengths are either determined or predicted from early-age strengths. The target mean strength (TMS) is subtracted from each result to obtain a difference. As results become available, the differences are cumulatively summed to form the CUSUM M. A positive difference indicates that the result in question is greater than TMS. A negative difference indicates that the result is lower than TMS. If the average strength is greater than TMS, then the slope of a plot of CUSUM M vs. result number will be positive, or upward to the right. Similarly, a negative or downward slope indicates that the mean strength is below TMS (Cement & Concrete Institute, 1997).

(ii) CUSUM R (range), for the control of standard deviation;

When applying CUSUM techniques to the standard deviation (SD) of concrete strengths, use is made of the relationship between SD and the range of successive pairs of results. It can be shown statistically that the mean range of successive pairs of a large number of results approximates to the SD of those results multiplied by 1.128. Thus, the target mean range = 1.128 x target SD. A CUSUM R chart can then be plotted for the difference between the actual range and the target mean range (TMR). Upward slopes indicate SD greater than target mean; whilst downward slopes indicate SD lower than target. To simplify the calculation, the target range is normally rounded to the nearest 0.5 N/mm^2 unless computers are used (Cement & Concrete Institute, 1997).

(iii) CUSUM C, for the control of correlation;

Normally, concrete strength at 28 days is specified and a CUSUM system can be used to monitor 28 day results as they become available. However, the producer may wish to detect changes in concrete strength performance earlier than possible using this method. Predicted strengths are commonly estimated from the strengths of cubes cured by the standard method for seven days, but predictions based on accelerated tests may be used. The predicted 28 day strength can then be used in the CUSUM calculations and subsequently confirmed, or the prediction modified, on the basis of actual 28 day results received at a later date (Cement & Concrete Institute, 1997).

(iv) CUSUM I, for individual control parameters;

A CUSUM for each individual concrete quality control parameter such as slump, density, water content, air content etc proves helpful in determining the parameter causing shift in the main reference variable such as concrete strength. In this paper, CUSUM I for pouring temperature of concrete has been presented. It is reported by ACI committee 305 that problems in hot weather conditions could be experienced in both the fresh and hardened concrete. In the fresh state, problems with the use of chemical admixtures have also been reported, as some chemicals become incompatible and are less effective at higher temperatures (Schindler & McCullough, 2002). Possible problems in both fresh and hardened concrete will likely to be (ACI 305, 2000)-

- Increased water demand.
- Increased rate of slump loss and corresponding tendency to add water at the job site.
- Increased rate of setting, resulting in greater difficulty with handling, compacting, and finishing.
- Increased difficulty in controlling the entrained air content.
- Decreased 28 day and later strengths resulting from higher water demand, higher concrete temperature or both at time of placement or during the first several days.
- Decreased durability resulting from cracking.
- Increased potential for reinforcement corrosion.

So, it is clear that monitoring individual temperature parameter will provide insight into the effect on the strength. However, other individual concrete quality parameters such as density, air content, and water content should also be monitored to find out whether they might cause a change.

For a large construction project where concrete pouring may take place over many days or weeks, a large set of test data will accumulate and each test result (based on an average of two cube tests) can be compared with the specified mean and characteristic values. The controlling compressive strength is based on a concrete family and all test results are converted to the equivalent value of a selected reference concrete such as C32/40. The analysis is based on early age test results such as on 7 day strength data, as the risk of waiting until 28 days to identify a loss of control is unacceptable. The predicted 28 day strength is calculated from the early age test result and this is used in the CUSUM until the actual 28 day strength is available (Gibb & Harrison, 2010). If 7 day test data are used, an adverse trend will be detected three weeks earlier than waiting for 28 day strength data. In order to confirm that the correlation factor is correct, a CUSUM C may be run on the differences between actual and predicted 28 day strengths. If the CUSUM C is positive then the system is underestimating the 28 day strength and if negative it is overestimating the 28 day strength. When a significant trend is detected, a new correlation relationship is determined. The CUSUM M for mean strength using predicted results will need to be recalculated as the system has effectively been under or over estimating for a period of time and it may be significantly adrift. The plot of range need not be re-determined because the correlation change will affect all results similarly except for the range straddling the point of correlation change. The relationship between 7 and 28 day strength is affected by the variation in cement properties, improper curing, and cement types, for example the strength gain between 7 and 28 days of a concrete made with a CEM I cement will be less than for an equivalent concrete made with CEM III/B cement. Concretes with different cement types should therefore be either controlled by separate control systems or the difference in correlation between different cement types considered in the corrections that are applied within the concrete family. Retarding admixtures might also affect the 7 & 28 day strength ratio (Gibb & Harrison, 2010).

The design of the mask consists of determination of the appropriate gradients and decision intervals which is based on statistical probabilities and they are linked to the standard deviation of the plant (Figure 1).

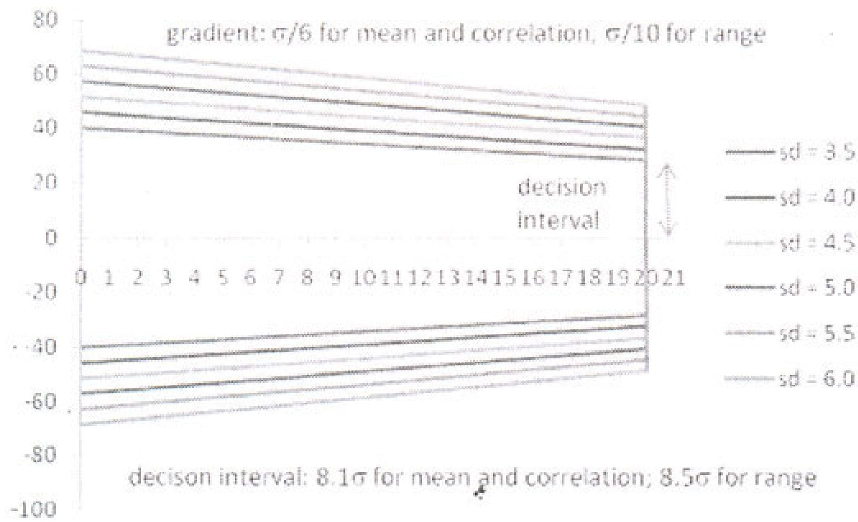

Figure 1: Design of V-mask (Gibb & Harrison, 2010)

Result and Discussion :

The following example is taken from the now proposed ERMCO procedure to simply illustrate the CUSUM process that can be applied to a concrete plant controlling its production based on a family of mixes (Gibb & Harrison, 2010). The control system is based on a reference concrete described in Table 1 which is also the main concrete produced at the plant. The control cement content is the current level that the CUSUM identifies as necessary to produce the target strength of the reference concrete.

Table 1: Reference Concrete Mix and Family parameters

Parameters	Family parameters range	Reference Concrete Mix
Compressive strength	C16/20 to C45/55	C32/40
Aggregate size and type	Gravel only, 20 mm or 10 mm	20 mm gravel
Cement Type	CEM III/A only	CEM III/A
Slump	25 mm to 150 mm	70 mm
Water reducing admixture	With or without admixture	None
Control cement content		320 kg/m^3

The CUSUM control chart construction is divided into two phases, Multigrade and Multivariable.

MULTIGRADE phase:

A key relationship needed in the CUSUM analysis is the main relationship between cement content and strength (Figure 2), which not only allows mixes to be transposed to an equivalent to the reference concrete, but is also used to determine the size of correction to be applied when the CUSUM indicates change has occurred.

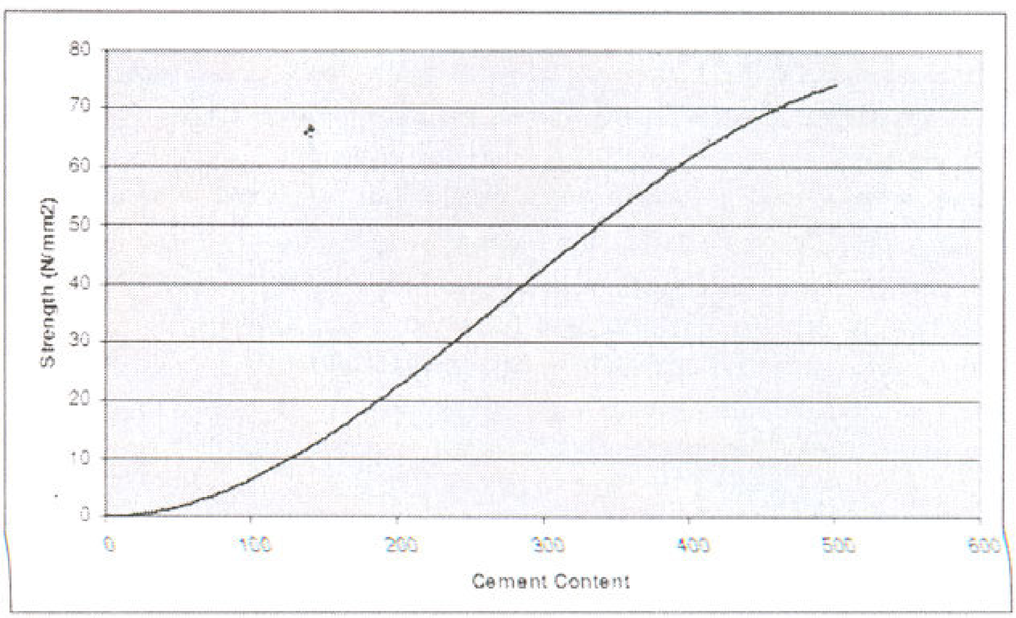

Figure 2: Main relationship between cement content and strength (Gibb & Harrison, 2010)

Table 2: Adjustments per m³ to convert the cement content of the tested concrete to a concrete on the main relationship (Gibb & Harrison, 2010)

Parameter	Cement content of tested concrete, kg/m³	Adjustment, kg/m³
Admixture	200 to 380	+25
	380+	Use a super plasticizer
Aggregate size (for 10 mm)	**Cement content of tested concrete, kg/m³**	**Adjustment, kg/m³**
	200 to 380	-15
	380+	-10
Slump	**Target slump, mm**	**Adjustment, kg/m³**
	20	+15
	50	+10
	70	0
	100	-5
	120	-10
	150	-15

It should be noted that the relationship in Figure 2 and the adjustments in cement content due to aggregate size, slump, and admixture in Table 2 is obtained by conducting rigorous testing of vast samples for that RMC plant.

Consider the second Mix in the CUSUM Calculation from Table 4. The mix must first be adjusted for 150 mm slump with respect to 70 mm slump and for water reducing admixture (Table 2). Total adjustment to apply is (+25 – 15) = 10 kg. The adjusted cement content becomes (310 + 10) = 320 kg/m³. From Figure 2, 320 kg/m³ cement content is expected to achieve strength of 46.8 N/mm² but the reference concrete is C32/40. As the plant has a standard deviation of 3.5 N/mm² and a design margin of 2SD, the target mean strength of the reference concrete is 47 N/mm². A difference of (47 - 46.8) = 0.2 N/mm² in the CUSUM system has to be introduced to transpose the strength at the equivalent cement content to the target mean strength of the reference mix. The predicted and actual 28 day strengths are 45.3 N/mm² and 46.3 N/mm² respectively. After adjustment to equivalent cement content values of the reference concrete, these become (45.3 + 0.2) = 45.5 N/mm² and 46.5 N/mm² and the change in CUSUM M is (45.5 - 47) = -1.5 N/mm² if the predicted strength is being used and (46.5 - 47) = - 0.5 N/mm² when the predicted 28 day strength is replaced with the actual 28 day strength. Similarly, Adjustments are made to the other mixes. Once the adjustments have been made and the adjusted 28 day strength calculated, the data may be used in CUSUM control system. The presented system is analyzed with the statistical analysis program JMP. JMP provides a comprehensive set of statistical tools including statistical quality control (Carver, 2010). The CUSUM's are shown in Figures 4, 5 & 6 for run on mean (CUSUM M), standard deviation (CUSUM R) and correlation (CUSUM C) respectively. For control purposes the mixes include a prescribed concrete (P300, Mix No. 13) and a nominal mix (1:2:4, Mix No. 14).

The CUSUM M has shown that there has been a decline in the performance from Mix reference 7; therefore to bring the process back into control it is necessary to increase the control cement content. The magnitude of the increase in cement content is a function of the standard deviation of the plant and the number of results over which the change has taken place (Figure 3). The plant standard deviation is 3.5 N/mm^2 and the change occurred at Mix reference 7, but the CUSUM M first crosses the V-mask at Mix reference 9 giving a change over 9 results. From Figure 3 it can be seen that a change over 9 results gives a change in cement content of 14 kg/m^3. For simplicity, this would be rounded to 15 kg/m^3 and therefore the control cement content of the reference concrete would be increased from 320 kg/m^3 to 335 kg/m^3.

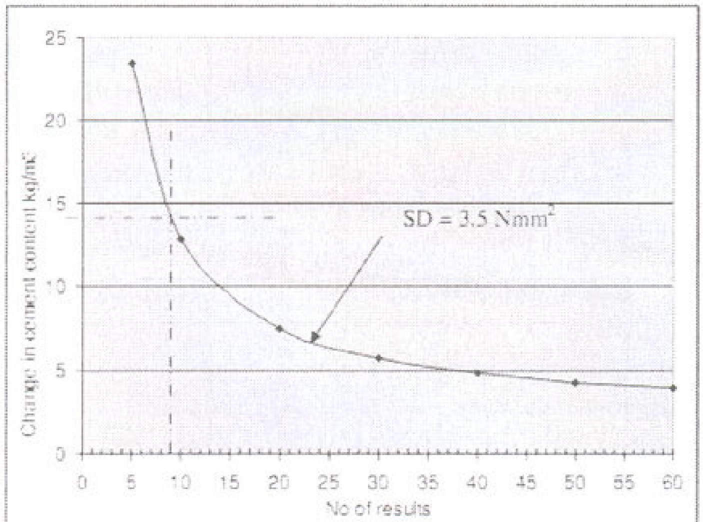

Figure 3: Strength change against No. of results (Gibb & Harrison, 2010)

A new main relation would also be adopted that relates to a control cement content of 335 kg/m^3 for a characteristic strength of 40 N/mm^2 which results in target strength of 47 N/mm^2. Table 3 shows the relationships in tabular form and from Table 4, this can be seen as a change in cement/strength code from A to B. The cement contents actually used at the plant would immediately be increased to the amount shown by the new main relationship. This changed main relationship will also lead to revised adjustments being applied to obtain the predicted cube strength of the reference concrete. These adjustments are applied from result 18 onwards (Table 4). They will also be applied to the batching of new mixes, but there will be a period where the concrete has already been batched at a cement content that is less than that now known to be necessary. During this period no more actual 28 day strength are available. However for the control of the mean strength, Mix reference 18 onwards is adjusted to the new target cement content of the reference concrete (335 kg/m^3). The CUSUM's with the additional data is shown in Figures

7, 8 & 9. Following the change in cement content to achieve the target strength, sample number 18, C32/40 70 mm slump, which is the control mix and therefore batched at the control cement content has previously not required a correction to the strength for samples 3, 4 and 7 (Table 4). However, the control cement content has now increased to 335 kg/m^3; since the mix was batched at 320 kg/m^3 before, the CUSUM M detected the need for a change, an adjustment from the new main relation needs to be applied. The same concrete was batched at Mix No. 22 but in this case the control mix cement content changes needed to compensate for the changes in mean strength and in standard deviation have already been implemented. For this reason there is no adjustment to make as the batched cement content is now (320 + 15 + 5) = 340 kg/m^3.

Table 3: Relationships between strength and cement content (Gibb & Harrison, 2010)

Cube strength, N/mm^2	Cement content, kg/m^3, for cement/strength codes		Cube strength, N/mm^2	Cement content, kg/m^3, for cement/strength codes	
	A	B		A	B
20	180.0	195.0	41	290.0	305.0
21	185.0	200.0	42	295.0	310.0
22	190.0	205.0	43	300.0	315.0
23	195.0	210.0	44	305.0	320.0
24	200.0	215.0	45	310.0	325.0
25	205.0	220.0	46	315.0	330.0
26	210.0	225.0	47	320.0	335.0
27	215.0	230.0	48	325.0	340.0
28	220.0	235.0	49	330.0	345.0
29	225.0	240.0	50	335.0	355.0
30	230.0	245.0	51	340.0	360.0
31	235.0	255.0	52	345.0	365.0
32	240.0	260.0	53	355.0	370.0
33	245.0	265.0	54	360.0	375.0
34	255.0	270.0	55	365.0	380.0
35	260.0	275.0	56	370.0	385.0
36	265.0	280.0	57	375.0	390.0
37	270.0	285.0	58	380.0	395.0
38	275.0	290.0	59	385.0	400.0
39	280.0	295.0	60	390.0	405.0
40	285.0	300.0			

The range over the adjustment between samples 17 and 18 in compressive strength is large (56.3 - 41.2) = 15.1 N/mm^2. The result before the change of mean strength is adjusted using the new main relation for the range calculation only. From the new main relationship the expected strength is 44.2 N/mm^2 and this reduces the range from 15.1 N/mm^2 to 12.1 N/mm^2.

After Mix No. 18, a change in the plant standard deviation is also detected (Figure 9). The average range is 5.3 N/mm^2 and the new standard deviation is (5.3÷1.128) = 4.7 N/mm^2. To avoid over-correcting, a decision is taken to change the standard deviation to 4.0 N/mm^2. The target strength of the reference concrete is now (40 + 2 × 4.0) = 48 N/mm^2. A 1 N/mm^2 increase requires a 5 kg/m^3 increase in the cement content (Table 4). The current control mix cement content is therefore immediately increased from 335 kg/m^3 to 340 kg/m^3 with the cement/strength relationship is unchanged.

Multivariable phase

Whenever a change is detected in the main strength CUSUM, it should be compared with all Individual controlling CUSUM to find out the responsible parameter for the change. A change in main strength CUSUM will be reflected in the responsible parameter CUSUM in which change will also be detected. The presented system shows a CUSUM I for pouring temperature data in Figure 10.

Comparing Figure 4 and Figure 10, it is clear that the effect of pouring temperature on concrete strength is prominent. The target pouring temperature is 25°C. The first four mixes shows fairly uniform pouring condition. From mix no. 5, pouring temperature increases rapidly which affect the concrete quality (ACI 305, 2000). The inferior quality is reflected in the concrete strength CUSUM M control chart. From mix no. 9, pouring temperature again returns to fair level, permitting proper controlling operations (Figure 10).

The presented multivariable system contains pouring temperature CUSUM along with the concrete strength CUSUM. From the individual pouring temperature CUSUM, the reason behind the shift in strength of concrete is confirmed and adequate measures such as increment of water content can be taken. In practical application of multivariate approach, CUSUM for other individual controlling parameter such as water content, air content, recycle aggregate etc should be constructed and monitored.

Table 4: CUSUM Calculation

Current Standard Deviation, SD = 3.5 N/mm²

Mix description						Strength			Adjustments									CUSUM					
																		M	R		C	I	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mix No.	Strength class	Aggregate size	Target slump	Plasticizer	Batched cement content	Actual 7 day	Predicted 28 day	Actual 28 day	Total cement adjustment	Adjusted cement content (6+10)	Cement/Strength Code	Expected strength (From Fig. 3)	Reference strength	Target strength (14+2×SD)	Strength adjustment (15-13)	From predicted	From actual (9+16)	Adjusted strength (18)	Target Range (1.128×SD)	Range (From 18)	Actual — predicted 28 day (9-8)	Target Temperature	Pouring Temperature
1	C28/35	20	100	√	275	34.5	52.5	39.5	-5	270	A	37.3	40	47	9.7		49.2	49.2			-13.0	25	25
2	C32/40	20	150	√	310	41.0	62.4	46.3	10	320	A	46.8	40	47	0.2		46.5	46.5	3.9	2.7	-16.1	25	24
3	C30/37	20	70	×	320	38.0	57.8	46.8	0	320	A	46.8	40	47	0.2		47.0	47.0	3.9	0.5	-11.0	25	26
4	C32/40	20	70	×	320	37.2	56.6*	49.3	0	320	A	46.8	40	47	0.2		49.5	49.5	3.9	2.5	-7.3	25	25
5	C28/35	20	70	√	245	26.7	40.6	39.5	25	270	A	37.3	40	47	9.7		49.2	49.2	3.9	0.3	2.0	25	27
6	C25/30	20	150	√	310	41.5	63.2	53.8	10	320	A	46.8	40	47	0.2		54.0	54.0	3.9	4.8	1.0	25	29
7	C40/50	20	70	×	320	42.6	64.8	53.3	0	320	A	46.8	40	47	0.2		53.5	53.5	3.9	0.5	-0.5	25	31
8	C32/40	20	50	×	285	28.2	42.9	39.2	10	295	A	42.1	40	47	4.9		44.1	44.1	3.9	9.4	0.0	25	30
9	C28/35	20	50	×	285	30.9	47.0	40.7	10	295	A	42.1	40	47	4.9		45.6	45.6	3.9	1.5	-1.5	25	23
10	C25/30	20	120	√	360	32.8	49.9	48.8	15	375	A	57.3	40	47	-10.3		38.5	38.5	3.9	7.1	-3.0	25	24
11	C40/50	20	100	×	275	51.8	78.8	40.5	-5	270	A	37.3	40	47	9.7		50.2	50.2	3.9	11.7	1.9	25	23
12	C28/35	20	70	√	245	36.6	55.7	35.0	25	270	A	37.3	40	47	9.7		44.7	44.7	3.9	5.5	0.5	25	25
13	C25/30	20	150	√	300	28.9	44.0	37.4	10	310	A	44.9	40	47	2.1		39.5	39.5	3.9	5.2	0.5	25	24

Table 4: CUSUM Calculation (Cont'd)

Mix description						Strength			Adjustments									CUSUM					
																		M	R		C	I	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mix No.	Strength class	Aggregate size	Target slump	Plasticizer	Batched cement content	Actual 7 day	Predicted 28 day	Actual 28 day	Total cement adjustment	Adjusted cement content (6+10)	Cement/Strength Code	Expected strength (From Fig. 3)	Reference strength	Target strength (14+2×SD)	Strength adjustment (15-13)	From predicted	From actual (9+16)	Adjusted strength (18)	Target Range (1.128×SD)	Range (From 18)	Actual — predicted 28 day (9-8)	Target Temperature	Pouring Temperature
14	C32/40	20	70	×	270	37.5	57.1	37.6	0	270	A	37.3	40	47	9.7		47.3	47.3	3.9	7.8	-1.0	25	25
15	C40/50	20	120	√	360	41.4	63.0	47.3	15	375	A	57.3	40	47	-10.3		37.0	37.0	3.9	10.3	-2.5	25	23
16	C28/35	20	120	√	360	29.5	44.9	53.8	15	375	A	57.3	40	47	-10.3		43.5	43.5	3.9	6.5	1.0	25	22
17	C25/30	20	100	×	275	22.4	34.1		-5	270	A	37.3	40	47	9.7	41.2		41.2	3.9	2.3		25	20
Target Strength Not Being Achieved; Cement Content Increased; CUSUM M Reset To Zero																							
17	Adjusted					21.7	31.5			270	B	34.3	40	47	12.7	44.2		44.2					
18	C32/40	20	70	×	320	41.8	53.1		0	320	B	43.8	40	47	3.2	56.3		56.3	3.9	12.1			
Standard Deviation Increased To 4.0 N/mm2; Target Strength Increased To 48 N/ mm2; Target Range Increased To 4.5 N/ mm2; Cement Content Increased.																							
18	Adjusted					41.8	53.1			320	B	43.8	40	48	4.2	57.3		57.3					
19	C25/30	20	100	×	290	26.2	36.9		-5	285	B	37.2	40	48	10.8	47.7		47.7	4.5	9.6			
20	C28/35	20	50	×	305	28.6	39.7		10	315	B	42.9	40	48	5.1	44.8		44.8	4.5	2.9			
21	P300	20	150	√	300	24.4	34.8		10	310	B	41.9	40	48	6.1	40.9		40.9	4.5	3.9			
22	C32/40	20	70	×	340	39.5	51		0	340	B	47.6	40	48	0.4	51.4		51.4	4.5	10.5			

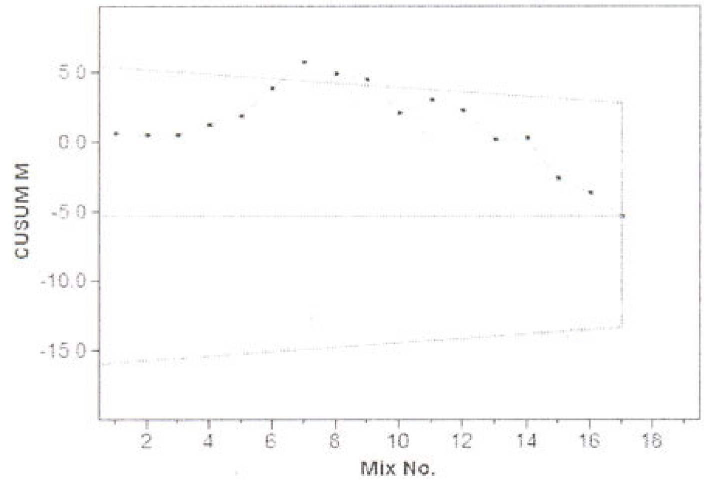

Figure 4: CUSUM M

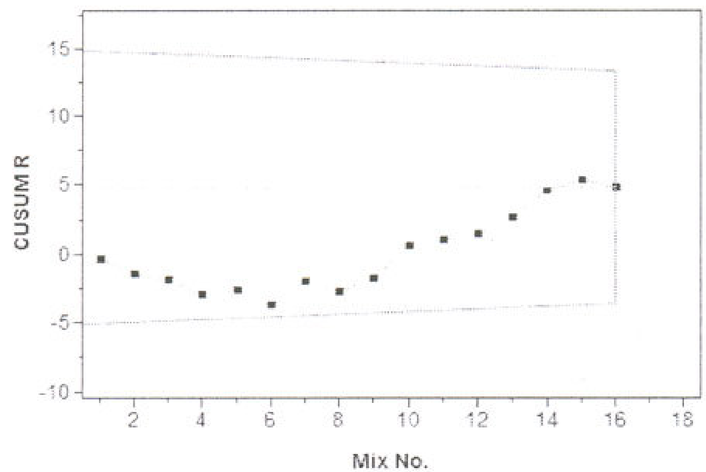

Figure 5: CUSUM R

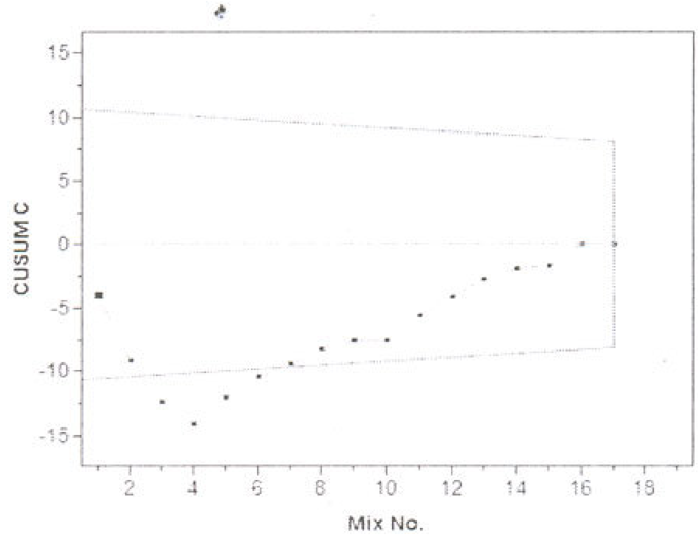

Figure 6: CUSUM C

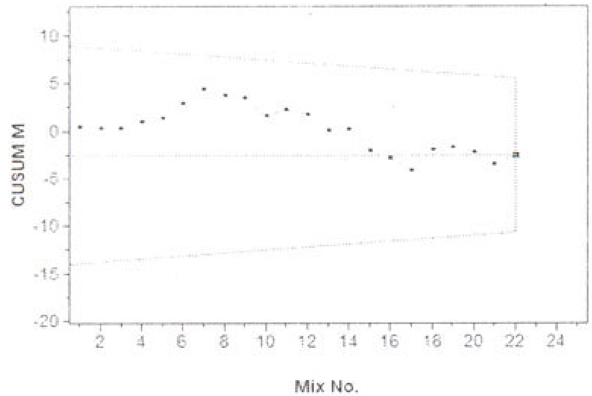

Figure 7: CUSUM M with additional Mix references

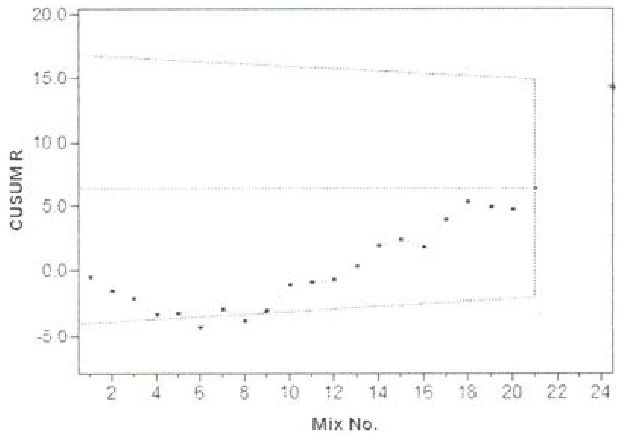

Figure 8: CUSUM R with additional Mix references

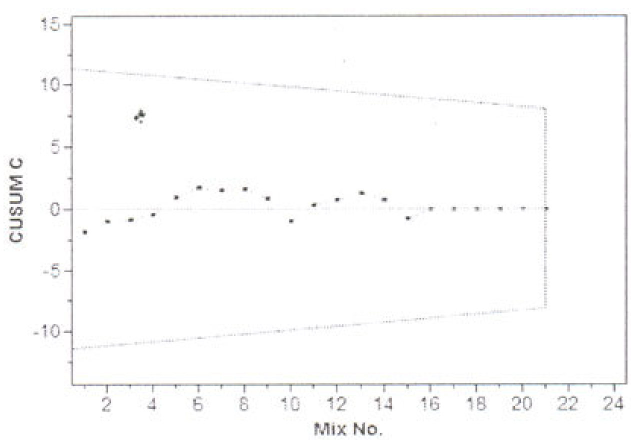

Figure 9: CUSUM C with additional Mix references

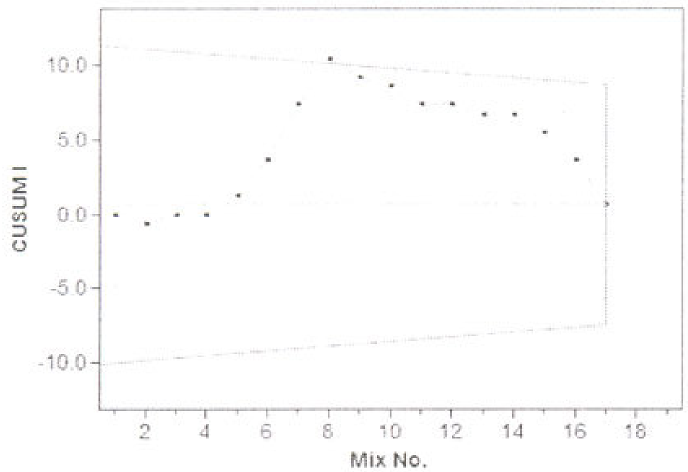

Figure 10: CUSUM I

Conclusion :

An exemplary analysis of CUSUM control chart for concrete quality controlling is illustrated in detail. It has been seen that with the application of Multigrade, Multivariable CUSUM control chart, any production process defect can easily be determined and proper remedy can be applied before significant time lapse, thanks to the use of early age concrete compressive strength. The application of individual parameter CUSUM has proved to be helpful in finding out the responsible reason behind the change. The slump CUSUM replicates the effect of temperature on the quality of concrete which is very important for hot weathered countries like Bangladesh. It is important to obtain historical data and to store present data to employ in the analysis in future. However, the use of control charts should not be treated in isolation from the rest of production control. A CUSUM graph of early age results (7 days at most, 2 or 3 days in tropical countries working a 7 day week such as in Singapore) will often show whether a change is genuine in even 3 to 5 results, especially if accompanied by a density graph plotted at 24 hours. Density data is very valuable and should be measured and entered in the system, allowing a density CUSUM to run six days ahead of 7 day strength CUSUM. Other important factors affecting concrete quality such as Water content, Recycled concrete aggregate should be taken into consideration. Control charts provide information about the process, but the interpretation of the information is not a mechanical process. All the information available to the concrete producer should be used to interpret the information and make informed decisions. The application of control chart in RMC industry of Bangladesh is badly needed as there are many RMC plants operating. Efficient and correct employment of statistical quality control methods would yield in better control over the overall manufacturing process, hence attaining maximum economy.

Bibliography:

ACI 305. (2000). *Hot Weather Concreting – Reported by ACI Committee 305.* Farmington Hills, Michigan: American Concrete Institute.

Barnard, G. (1959). Control charts and stochastic processes. *Journal of the Royal Statistical Society. Series B (Methodological)* , 239–71.

British Standards Institution. (1984). *Process control using quality control chart methods and CUSUM techniques, BS5700.*

Carver, R. (2010). *Practical Data Analysis with JMP.* Cary, North Carolina: SAS Publishing.

Cement & Concrete Institute. (1997). *Monitoring concrete strength by the cusum system.* Midrand: Cement & Concrete Institute .

Day, K. W. (2006). *Concrete Mix Design, Quality Control and Specification.* Oxfordshire: Taylor & Francis.

Deming, W. E. (1982). *Out of the Crisis: Quality, Productivity and Competitive Position.*

Gibb, I., & Harrison, T. (2010). *Use of control charts in the production of concrete.* European Ready Mixed Concrete Organization.

International Standards Organization. (1993). *Acceptance control charts, ISO7966: 1993.*

Page, E. S. (1954). Continuous Inspection Scheme. *Biometrika* , 100–115.

Schindler, A. K., & McCullough, B. F. (2002). *The Importance of Concrete Temperature Control During Concrete Pavement Construction in Hot Weather Conditions.* Washington, D. C.: Transportation Research Board.

Shewhart, W. A. (1931). *Economic Control of Quality of Manufactured Product.*