Quality control and mix design practice in India and sustainable concrete

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In this article, statistical quality control (SQC) used for concrete production, followed globally, is highlighted. The lack of such practice in bulk of concrete construction in India and its implication on wastage of cement is discussed. One of the common practice in India is to prescribe certified mix proportion for concrete. It is highlighted that such conservative practice is detrimental to development of concrete technology in the country. Further, it is pointed out that adoption of concrete as a major product rather than cement, mechanization, adoption of SQC and plant based control rather than prescriptive approach to concrete production will go a long way towards sustainable concrete in India.

CONCRETE QUALITY CONTROL PRACTICE IN INDIA

In India, formal structural concrete is produced and being used since the time of 'Gateway of India' i.e., the first RCC structure constructed in the decade of 1920s. Technology of production and casting of concrete, as well as, material science of concrete has evolved exponentially since then. Modern concrete is extremely versatile in rheological performances in fresh state also in mechanical and durability performances in hardened state. Industrialized production of concrete structural elements is also possible with high level of accuracy and compliance to specification through appropriate statistical quality control (SQC). India is the second largest producer and consumer of cement and hence also the second largest consumer of concrete as a nation; but, production technology and modern scientific quality control system is yet to be adopted in a large scale across the country. While in case of infrastructure projects e.g., bridges and dams, modern construction practices are often adopted, however in buildings such practices are seldom applied [1]. Sustainable concrete requires minimizing the resource usage for specified performance and that demands adoption of SQC system [2,3].

Quality control of any production system has three steps, a) forward control, b) immediate control and c) retrospective control, the last one involves quality monitoring. Internationally, in many countries, as a mandatory practice, these steps are applied to ready-mix concrete (RMC) production and production at pre-cast plant as well [4,5]. Forward control encompasses (i) testing of all ingredients, i.e., cement, aggregates, admixtures and water etc., at plant. This is to ensure that the material satisfy the required specifications within limits and do not contribute unnecessarily to undue large variation in concrete properties. (ii) Proportioning of mix specific to the material for specified performances. (iii) Maintenance of mixer machines, batching plant etc., (iv) periodic calibration check of the load cells of the weighing machine and dispenser for admixtures etc., i.e., all verifications and checks prior to actual concrete production. Immediate control refers to testing during production e.g., slump measurement at plant and also slump loss at delivery point, visual observation etc. The retrospective control is performed through SQC using Control (Shewhart) Chart and CUSUM method. The concrete differs from other material in this case as specification of concrete is associated with 28 days strength, hence application of SQC can delay the corrective measures as outcome would be known only after testing at 28 days. To overcome this short coming, accelerated curing of concrete is adopted and 28 days strength is estimated from accelerated strength test through established correlation. The correlation is concrete specific and is again monitored continuously, and; corrections are applied in case of any deviations from used correlation. CUSUM method is generally adopted for retrospective control of RMC in many countries. The details of the procedure are available in textbooks and literature [4-7]. To illustrate some of the aspects of CUSUM method, it is presented in the following paragraph.

CUSUM method in case of concrete is applied to (i) mean, (ii) range as a measure of standard deviation and also to (iii) correlation between predicted strength from accelerated test and actual 28 day strength. Test on concrete cubes subjected to accelerated-curing is performed say at 2 or 3 day age.

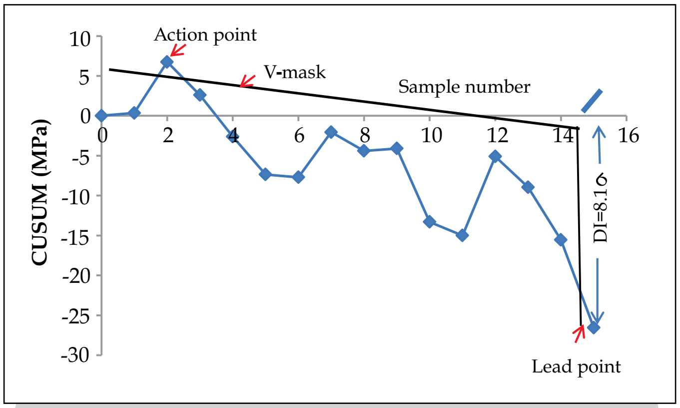

Figure 1. Typical CUSUM plot for mean

The 28 days compressive strength is then predicted from the strength obtained through the accelerated test using the above correlation. In case of CUSUM for mean, the deviation of predicted strength from target mean strength is calculated and cumulated from first sample, continuously. The trend of this cumulative sum or CUSUM is plotted against sample number as shown in Figure 1. An upward trend indicates Mean strength of the produced concrete is higher than target mean strength and is probably uneconomical. When the CUSUM trend swings around zero or X axis the concrete is designed correctly and no corrections are required. A downward trend indicates (as shown in Figure 1) that the actual concrete produced possibly does not satisfy the target mean strength requirement and proportions need to be corrected to obtain the desired strength. To identify whether trend exhibited at a particular sample point warrants correction or simply can be attributed to random occurrences, a V-mask as shown (part only) in the Figure 1 is used. The truncated V-mask is characterized by decision interval DI=8.1σ, σ being the established standard deviation (or may be estimated standard deviation 's' also) of strength, and; the gradient line with its slope as σ/6 (s/6) for mean and correlation. On obtaining a new sample data corresponding CUSUM value is calculated and plotted on the CUSUM plot and becomes the lead point as shown. The centre point of V-mask is placed on the lead point. As long as all the previous CUSUM values remain within the boundary of the truncated V-mask, no action is required. The CUSUM plot thus continuously gets elongated. When for any lead point, the CUSUM plot lays outside the boundary of the mask as shown for 15th data, it indicates a systematic deviation, as opposed to random variation, hence, correction must be applied to the mix proportions and CUSUM plot is restarted from 0 again, shown in Figure 1 from sample 15, for the modified mix. It is apparent that till 14th data as lead point no action was warranted. A simple algorithm as given below may come handy in excel spread sheet adoption of this method. Let qs_t be the CUSUM value at tth data point, then for $qs_t - qs_{(t-n)} < 0$, n=1,2,….(t-1) for majority of n in general, there is a decreasing trend for strength and; for $qs_t - qs_{(t-n)} > 0$, n=1,2,…. n, for majority of n in general, the trend is an increasing one. For former case of decreasing trend, $(qs_t + 8.1\sigma + n\sigma/6) < qs_{(t-n)}$ n=1,2,….t at any n=N indicates a systematic decrease in mean strength. The data point at N represents the action point; t-N = run length = r (say). The corresponding correction in mean strength $\Delta f_m = \{DI + r \times G\}/r = 8.1\sigma/r + \sigma/6$. The mix proportions then are to be modified for a target mean strength, increased by Δf_m. Similar exercise can be performed for correlation and range i.e., standard deviation also. Details of this method are readily available in text books [4-9]. One may have to apply such a correction either for strength or standard deviation for every 15 or 30 data points, thus determination of mix proportions for a specified grade of concrete in a project is not a one time job rather dynamic with frequent changes. Such a dynamic SQC can only be applied by doing mix proportioning at site and plant laboratory and not in any remote laboratory. A survey on long term strength data from a number of RMC plants in Delhi NCR was reported by author as co-author in an earlier paper [8]. None of the RMC plants were using CUSUM method and systematic SQC in totality. It was demonstrated through a mock exercise of CUSUM method that many of the plants were wasting cements as strength were higher than the target strength required. None of the plants were using accelerated test facilities. To the best of author's knowledge, situation in the country is no better even now and systematic SQC is not adopted in most of the concrete construction projects. Rather mix proportion is considered static and proportions are decided on the basis of mix design carried out at institutional laboratory once only in the beginning. Thus nationwide there may be serious wastage of cement that can be avoided by adoption of systematic SQC and mix proportioning at site/plant as discussed above.

MIX DESIGN PRACTICE

Often proportions of concrete mix in construction projects in India is done by mix design carried out at institutional or research laboratories e.g., IITs, NITs or Government research laboratories etc. with small quantity of supplied material required for tests and for making some cubes. The results of the same however, is used for a long time in the project possibly for whole project duration spanning over years, even though the material might have changed. For example, a recent request came from a reputed construction organization, for consultancy job at IIT Delhi, for testing materials for source approval and carrying out mix design for M25, M30, M35 and M40 and samples were also said to be supplied. Additionally, minimum cement contents were also specified as 330 kg/m^3, 340 kg/m^3, 350 kg/m^3 and 360 kg/m^3 respectively for M25, M30, M35 and M40 respectively. Total material supplied included 4 bags of coarse aggregates, 2 bags of M-sand; cement 2 bags each from 3 manufacturers, concrete construction quality water 5 litres and admixture of a specific make, 5 litres. The project is a large building infrastructure construction project involving office buildings in a megacity. Two interesting observations can be made from such a request. First, the total quantity of material supplied is just good enough for about maximum 9-10 cubes per grade for each brand of cement. Mix proportions decided on the basis of such small sample size is expected to satisfy the concrete specifications required over the long period of project, for a large mega project, in spite of the fact that material from the same source, even though likely to satisfy the limits, may induce significant change in fresh and strength properties of concrete. The second observation concerns the minimum cement content specified in the request. Minimum grade of concrete specified is M25, thus it is apparent that the exposure considered is moderate. Specified cement content is good 10 kg/m^3 more than that required for durability requirement in IS: 456-2000. This request for mix design is not isolated one; many reputed organizations adopt this kind of practice, more so without SQC mentioned earlier. The result is either wastage of cement or non- adherence to strength requirement.

Cement is produced from natural raw material with minimal processing except that the raw material mix fed to the plant is made homogeneous as much as possible, yet it is the only factory produced material in the concrete. Even then, for cement of the same brand both fresh property and strength of concrete is likely to vary from time to time and lot to lot. Systematic controlled aggregate production has just begun in India. Aggregate from the same source but collected at different times are likely to exhibit different packing characteristic due to variation in shape, and grading. Aggregates obtained at different times are likely to affect the concrete strength in varying manner due to variation in size, texture, elastic and surface energy properties. This variation is likely to be more for less mechanized production. Thus properties of concrete obtained on the basis of single time test cannot be extrapolated for long term use. Hence overall SQC for concrete production is desirable rather than single time initial mix design and continuing with it for the whole project.

Mix design is done to obtain the proportion of constituents that would ensure concrete of properties complying with certain specifications, economically. Thus ideally speaking mix design should have been handled as an optimization problem for cost minimization, with greater than equal to type of constraints satisfying the specifications such as slump≥specified value, strength≥target mean strength. However, well defined and unique mathematical relationships relating strength, service life or slump to proportions of ingredients of concrete are not available. This is because materials used are largely natural and not processed; variability is large and thus difficult to idealize for modeling. More than 50 empirical relationships relating to slump and to factors affecting, are reported by Popovics, [10] hence not unique and not universally applicable. Similarly, there is infinite number of curves relating strength 'f' to water to cement ratio (W/C); e.g. those recommended in DOE mix design procedure and is again not unique [11]. The strength f at any W/C can be empirically related to strength $f_{0.5}$ at W/C =0.5, through Abraham's law using the data of DOE curves as:

$$f = K_1 \times K_2^{W/C} \quad \text{... (1)}$$

where,

$$K_1 = \left[58.11 \times \ln f_{0.5} - 60.47\right]$$

$$K_2 = \left[\frac{f_{0.5}}{540.76} - \frac{1}{6371.84}\right]$$

However, there are infinite numbers of $f_{0.5}$ depending on other ingredients. Change in ingredients with time would results in change of $f_{0.5}$ and in turn would cause change in f, the change Δf would be higher at lower W/C and can be of the order 10-15% of "f" for $\Delta f_{0.5}=0.1f_{0.5}$..

There are many methods of mix proportioning and, is not unique again. Mix design is not done using fundamental mathematical models, rather is performed from simple empirical, geographical region based, charts, tables or equations, although principle and steps involved may be similar in many methods. Calculations involved are very simple and may not require more than 10 minutes when done using spread sheet in computer by a person familiar with the component ingredients. Laboratory time required rather can be high as number of trial casting and repeat tests may be involved. Thus more of physical effort than mental one, and; experience plays a strong role in mix design. This is recognized in recent IS 10260:2009; according to the recommendation prescribed in this code, the starting W/C is decided either from durability criteria or experience. Hence mix design of concrete is both art and science and can be easily done fast with lesser trials by qualified and experienced person/team in laboratories equipped with simple concrete testing facility meant for preparing cubes and testing them for compliance and acceptance. Such laboratories are readily available at RMC/site plants. There is hardly any research involved in day to day mix design and hence need not be done in remote institutional laboratories. On the other hand plant laboratories shall be capable of doing mix design and modifying the same as and when required on a regular basis as governed by CUSUM method of retrospective control of SQC. This will ensure cement saving and production of appropriate quality of concrete. This is the practice adopted in most of the nations where concrete technology has advanced to an engineered-material level.

QUALITY OF CONCRETE AND SUSTAINABILITY

Role of quality control in reducing carbon emission, reducing natural resource wastage and thus their depletion, has been elaborated in earlier papers [1] and needs no further elaboration at this stage. Mechanized and industrialized production of concrete has a major role in this regard as overall variation can be controlled to a significantly lower level of standard deviation by controlling variation of individual component factors in the processes of batching and mixing etc., through automated sensing and computer controlled production. In countries where concrete technology is significantly advanced compared to India, cement is sold less as a product compared to concrete. The cement producing companies often themselves produce aggregate from open cast mines or quarries using mechanized production method; make concrete, and; market concrete as a major product rather than cement. To a civil or structural engineer concrete is the material and not cement. Quality of concrete is more important rather than the mix used in it. Thus prescription of proportion and certification of mix is rather detrimental to the innovation and development of concrete. The practice of carrying out mix design of concrete at remote laboratories therefore is doing a dis-service to the development of concrete construction practices in India and sustainability in general, therefore shall be discontinued. A survey of investigations of rebar-corrosion distressed buildings in northern and central India published earlier revealed that internal chloride from ingredients; low cover and poor quality of concrete were the main causes of early distress exhibited in a majority of structures [12]. For many of these structures mix designs were carried out remotely and certified, in spite of that, early distress became evident.

The concrete today is quite different than yesteryears. Newer cements and cement combinations are being adopted. Bureau of Indian standard (BIS) has already adopted a code for composite cements with OPC, Fly ash and GGBFS in addition earlier cement codes, Euro codes EN 197-1:2000, recommends use of 27 combinations of cement and cementitious combinations, LC3 cement and Magnesia based cement, geo-polymers are other binder system those are being considered and adopted at various level. Other ingredients and their usage are also going through paradigm shift. Thus performance compliance of concrete shall be judged through various acceptance methods using appropriate criteria rather than compliance prescription guidelines for ingredients and mix except in some special cases. Beside cube test for strength compliance, some Indian projects had already adopted DIN 1048 part 5 (BS_EN 12390-8) water permeability through depth of penetration test for durability compliance. In-situ test for concrete performance for durability is already considered and may be the next step.

RMC plants are now there in many small and medium sized towns of the country. Adoption of total SQC and mix design and control at plant will go a long way to serve the cause of sustainability by minimizing the resource wastage.

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