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Concrete mix revisited

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Concrete, as on date, remains the most widely used man made construction material due to its versatility. The advent of ready mix concrete, have changed some aspects of concrete. Now, the consumer can specify the concrete of his needs without bothering about the ingredients. In the early days, concrete quality was being controlled by quality of ingredients and by the concreting process. This generally resulted in uniform quality of concrete. The development of finished product quality criteria such as strength, permeability, etc lead to the neglect of the rigorous process control. This has resulted in greater variation in properties. These variations are being taken care of statistically. Thus, greater the standard deviation, greater is the target strength. The codes recommend a margin of 10 to 12 with a confidence level of 95%. The six sigma principle gives lowest strength of 19 and highest one as 61 for M40 concrete. Thus, the variation is 42 Mpa. Naturally, this results in very high consumption of cement. The high consumption of cement not only affects the economy but also the environment.

If one analyses concrete strength results of a project round the year, then one can notice that there are seasonal variations, variations due to typical location of structure, and there is variation in day and night concreting. The concrete quality is also affected by change of source of ingredients. Apart from variation in individual characteristics of ingredients and their interaction, the variation in storage of ingredients, variation in mixing, variation in composition, can cause wide variation in concrete quality. Present codal provisions require that with every such change a new mix design be prepared. Nowadays, the volume of concreting is such that no one can stop the work. At the same time, no one can ensure uniformity of material quality. Such variation is now taken care by specifying higher standard deviation. It generally so happens that at the time of making trial mixes, good quality material is used but the material at site loses its quality due to storage, etc. Such material results in bad quality of concrete. Apart from ingredients, a number of material mixing, transportation and compaction processes are involved in concrete. It is seen that optimum quality of concrete is achieved by pairing best combination of ingredients and processes. Thus, if there is more silt in the mix, then the ill effects of silt on quality of concrete can be avoided by extended mixing of concrete. So, design of concrete mixes has to be an integrated process involving correct choice of ingredients and corresponding processes.

The foremost process involved in production of concrete is mixing of the ingredients. The intimate mixing of ingredients requires making individual ingredients to be free of their own bond. Thus, it is seen that cement stored in vertical silos often form lumps, particularly in humid and cold environment. Sometimes, they do not dissolve in water even in the presence of deflocculating admixtures. So, the water cannot reach to inner particles of cement in a lump, with the result that those particles cannot be hydrated and part of concrete remains weak and overall strength is reduced considerably. In trial mixes this eventuality is not accounted for. Similar is the case with silt or clay. It is seen that clay or silt in finely divided state helps making concrete better. If it is in the form of lumps, a lot of water remains locked in the lumps. The breaking of such lumps during compaction, more often releases the water which apparently is seen as bleeding of concrete.

Similarly, the process of transporting, requires different workability for different modes of transport. Pumped concrete requires a cohesive mix with a slump of 8 to 10 cms as a less cohesive mix with high slump (15 to 20 cms) is difficult to pump.

At our sites, the aggregates are typically stored in the open. The aggregates are exposed to stone dust during production and also to the dust created by construction activities. Once accumulated on the aggregate surface, the dust particles are difficult to remove. These particles cause blinding of pores on the surface of aggregate and prevent water absorption of aggregate. If extra water is added to the concrete to cater for water absorption of aggregates, then such blinding gives rise to additional free water causing additional slump. These dust particles then catch water in the concrete mix and feed the pores in aggregate which causes reduction in the free water in concrete resulting in loss of slump. If the aggregate, before mixing, is dry and if the percentage absorption of aggregate is high, then there is considerable loss of free water resulting in drastic reduction in workability. In such cases, cement particles at the surface of aggregate become thirsty for water and cannot be hydrated. If the dust contains chemically active clay particles, then the problem is further aggravated.

It may be noted that during mixing in the mixer, the surface dust is picked up by watery cement particles and these dust particles form an emulsion along with the cement particles and coat the aggregate surface uniformly resulting in cohesive green concrete and higher strength hardened concrete.

An experiment was conducted to see the effect of dust particles and amount of free water. All in one aggregate without - 600 micron, and water in the ratio of 12:1 (by weight) was taken. The water was added to the aggregate and stirred. It was seen that there was no free water that can come out. Then water was increased to 12 :1.5 ratios and again there was no free water. Subsequently, water was increased to 6:1 ratio and at this water content, free water was noticed. The free water was removed and the quantity of held water was equivalent to the ratio 20:1. Thus quantity of held water was considerably reduced when dust from aggregate surface was washed out. The difference in water content in the 20:1 ratio and 8:1 ratio was held by dust and when the quantity of water increased, it washed away the dust and the held water became free. In terms of W:C ratio, clear aggregate holds water equivalent to W:C ratio of 0.21, whereas the water held by dust coated aggregate was 0.525. This holding capacity kills slump and also reduces strength. This is the reason that sometimes W:C ratio of 0.5 gives higher strength than that with 0.35. If stone dust is replaced with clay, then water held would be 0.6 in terms of W:C ratio.

The effect can be statistically evaluated by designing an experiment. The experiment involves casting and testing of trial mixes. The mixes were designed with two levels of W:C ratios as shown below. Both clean aggregates and aggregates coated with dust or clay were used. The mixes so cast were then tested for slump and compressive strength.

Table 1. Design of experiment for evolving relationship between dust coating, W:C ratio, and slump and compressive strength of concrete

	Dust on surface	W:C ratio
	0.35	0.5
Clean, 0%	(1)	a
With dust coat, 100%	b	ab

Table 2. Laboratory test results of Table-1 experiment

Treatment	Slump, mm	Compressive strength, Mpa
(1)	40	55
a	110	32
b	10	33
ab	90	43

The results give the following relationship:

$$Y_1 \text{ (slump)} = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_1 x_2$$

$$= 62.5 + 37.5 x_1 - 12.5 x_2 + 2.5 x_1 x_2$$

where, $x_1 = (W - 0.425) / 0.075$, $x_2 = (S - 50) / 50$

Y_2 (compressive strength) $= 40.75 + 5.75 x_1 - 2.75 x_2 + 8.25 x_1 x_2$

When water and cement is mixed together, the water-cement paste is formed. The consistency of the paste varies as per the proportion of cement and water. It forms a plastic mass if water to cement ratio is below 0.35. As the water content is increased, it results in viscous liquid. A further increase results in a flowing mix. In the plastic mass, water is held by cement particles whereas in case of flowing mix, the cement is emulsified and forms emulsion in water. The addition of admixtures leads to further lowering of paste consistency. The paste determines the slump of concrete. The lower consistency results in higher slump but of a non cohesive type. The medium consistency results in higher slump but a cohesive mix. The addition of particles of size less than 300 micron further increases the consistency. The properties of concrete is dependent on how good the coating of aggregate surface is achieved by the cement water paste. The thickness of coating and its uniformity account for concrete workability and concrete strength apart from W:C ratio, aggregate and, type and grade of cement.

The variation in consistency with variation in admixture, water and silt content can be numerically established by the following statistical experiment:

Table 3. Design of experiment for evolving relationship between silt content, W:C ratio, admixture dosage and consistency of of cement - water paste as measured with Marsh cone

Silt content in terms of percentage of cement (S)	W:C (W)	Admixture dosage in terms of percentage of cement (A)	
		1%	2%
0	0.35	(1)	b
	0.6	a	ab
10%	0.35	c	ac
	0.6	bc	abc

The trial mix results were:

Table 4. Laboratory test results of Table-3 experiment

(1)	a	b	c	ab	ac	bc	abc
18.00	0.97	7.00	33.00	0.85	1.40	9.30	1.00

The analysis yields the following relationship:

$Y = 8.95 - 7.885 x_1 - 4.4 x_2 + 2.23 x_3 + 4.27 x_1 x_2 - 2.1 x_1 x_3 - 1.63 x_2 x_3 + 1.55 x_1 x_2 x_3$

where, Y = Time taken in minutes to empty the Marsh cone (measure of consistency)

$x_1 = (8W - 3.8)$, $x_2 = 2A - 3$, $x_3 = 0.2 S - 1$

The workability or slump of concrete is related to the consistency of cement - water paste, ambient temperature and aggregate – water ratio. To find out the numerical relationship, the following experiment was designed.

Table 5. Laboratory test results of the experiment designed for evolving relationship between dust coating, aggregate - water ratio, ambient temperature and consistency of water - cement paste with slump of concrete

Aggregate-water ratio (Ag/W)	Ambient temperature (T), ^{o}C	Paste consistency (PC)	
		2 minutes	8 minutes
10	25	15	8
	40	12	6
15	25	10	5
	40	7	3

The analysis yields the following relationship:

Y (slump) $= 4.31 - 0.625 x_1 - 1.37 x_2 - x_3 + 0.2 x_1 x_2 - 0.5 x_1 x_3 + 3.75 x_2 x_3$

where, Y = slump in cms, $x_1 = (T - 32.5) / 7.5$, $x_2 = (PC - 5) / 3$, $x_3 = (AW - 12.5)/2.5$.

The concrete specifications generally stipulate maximum and minimum permissible values for the various ingredients. This includes the values of minimum and maximum W:C ratio, cement content, admixture content, cement strength, etc. The above equations enable one to find combined limit from individual ingredient limits. Thus, limits for cement – water paste consistency can be determined from limits of W:C ratio, admixture, and silt content of mix. Similarly limits regarding slump, paste consistency and temperature will enable to find out the limits for Ag:W. These derived limits will enable to design experiment to find concrete strength in relation to various factors like slump, cement content of mix, cement strength and water absorption of aggregate. This relationship can be evolved by trial mix with a desired initial slump. Then extreme cement content limit, available cement strength and aggregates can be worked out. The experiment may be designed in the following manner:

Table 6. Design of experiment for evolving relationship of slump retention and development of strength of concrete with aggregate absorption, cement content of mix, and cement strength

Aggregate absorption, %	Cement content, kg/m^3	Cement strength, N/mm^2	
		53	67
2	350	(1)	b
	425	a	ab
5	350	c	bc
	425	ac	abc

Table 7. Table format for recording experimental results of Table-6 experiment

Treatment	(1)	a	b	c	ab	ac	bc	abc
Strength (Immediate)								
Slump (Immediate)								
Strength (Cast after 2 hrs of mixing)								
Slump (After 2 hrs)								

The analysis of the above data would then yield the relationship. Such experiments can be conducted to see the influence of variations in ingredient levels or any of the processes on any of the characteristics of concrete. These relationships enable to achieve optimum concreting. Thus, if we consider ambient temperature, it enables to compare the effect of temperature on strength and slump and thereby the cost of processing. Similarly, mixing, transportation and compaction can be optimised by considering cost of ingredients and cost of process. Thus, the effect of silt in aggregate on the strength of concrete can be taken care of by removing it by washing and also by extending the mixing time and using additional water. Alternative processes can be chosen by optimising the cost.

The exercise so far has helped in making a choice of the ingredients, determining the need to process the ingredients and identifying the concreting process to be adopted. The concreting process include method of storage of materials, method of processing ingredients, batching, mixing, transportation, placing, compaction and curing. The final mix design is done as per stipulations and tolerances provided in the respective specifications. The specifications generally provide for minimum and maximum W:C ratio, cement content, ambient temperature, etc. The acceptance is defined by minimum workability, strength, permeability, etc. The final trial mix is done at the plant using acceptable tolerances, acceptable concreting process and acceptable ingredients. For this purpose, statistical design of experiment considering critical specifications, their natural variation and acceptability of final concrete is done. The relationship derived on that basis can be used to monitor the concrete quality. The relationship can also be used to simulate the effect of the variations on the concrete.

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