Advantage of particle packing model in designing self compacting concretes

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HISTORY

For several years Japan was facing acute shortage of manpower in construction Industry. Moreover durability of structures built, was a major topic of interest, and it was established that adequate degree of compaction gave more durable concretes. But reduction in manpower increased reduction in quality of construction work. A solution which could compact concrete without need of manpower was being thought of, to overcome this issue. Okamura in 1986 proposed concrete which itself did not need any vibration and which got itself compacted into every corner of formwork by its own weight. Ozawa, Okamura & Maekawa first made prototype of self compacting concrete in 1988, and since then it has been gaining popularity world wide.

SUSTAINABILITY

Concrete is a green sustainable material owing to its capability to act as a safe sink for major industrial pollutants, and also as an easily available material as compared to other construction options. But, lately it has been realised that due to increase in demand of concrete, Ordinary Portland Cement (OPC) has reached the highest levels of production, which is the most polluting industry per se. Moreover, in order to provide for cement in construction industry, the reserves of limestone also are depleting fast. On the other hand incorporation of self compacting concrete into construction, with designing procedures available now, will lead to faster and higher consumption of OPC, as Self compacting concrete requires higher cementitious content as compared to Conventional Vibratable Concrete (CVC). On the other hand, if particle packing methodology is used, it is highly possible in many cases that SCC properties are achieved in concrete with lesser or equal amount of OPC as compared to CVC for same grade. Again the reason for this being, compaction of concrete affects the concrete strength to a huge extent, and thus to achieve similar strength in SCC, it has been found that OPC contents can be optimised to achieve the required strength. Moreover, correct interpretation of minimum cement content clauses in IS 456, will be necessary, as extra cement gets added many a times just to meet the paste content requirement, which could have been avoided by adding fly ash or other cementitious materials, as replacement of fine aggregates. Thus a mix design procedure is much needed in case of self compacting concrete, which keeps cement content to the minimum possible to achieve the required strength.

CHALLENGES IN DESIGNING SELF COMPACTING CONCRETE WITH EXISTING METHODS

EFNARC Method has laid down guidelines for mix proportion, following which one may get self compacting properties. The method is very easy though, may not perform universally. The guidelines for designing the SCC as per EFNARC guidelines are:

Water Powder (-150 microns) Ratio by volume: 0.8 to 1.1

Total Powder Content: 160 to 240 litres

Coarse Aggregate Content: 28-35% of Concrete, i.e. 280-350 litres per m3,

Water Content< 200 Kg/m3

In this case, the methodology does not take into account the aggregate particle size distribution, to get the required properties. Thus, when aggregates with very high voids are available, the self compacting properties achieving becomes a challenge with this method and cited below is an example, as to how change in aggregate property resulted in change in concrete performance when both mixes were based on exactly same guidelines and the materials used except for the coarse aggregates, which had high flakiness index in one case, whereas good shape factor in another. Thus a model which can predict the void content of aggregate mixture at different proportions for given aggregates has been developed and was tested for degree of accuracy, in which R square value found was 92%. The Model outcome is represented on a 2 dimensional heat map, and it has to be interpreted as shown in Figure 1.

In the heat map of Figure 1 each colour represents a range of void content, as shown in the given legend. So to find the void content for intersection of vertical 70 line and horizontal 60 line (marked on the heat map) just check the colour which is similar to colour against 34.19 in Legend, meaning the point has void content between 34.39 to 39.05%. Now the proportion of that point is 70% of 20 mm (numbers at bottom are percentage of 20 mm in total aggregates), 60% of fine aggregate in remaining 30% aggregates (numbers on R.H.S are percentage of fine aggregate in aggregates remaining after deducting 20 mm percentage) i.e. 18% of total aggregate, and remaining 10 mm to make total of 100%, thus 12% 10 mm of total aggregates.

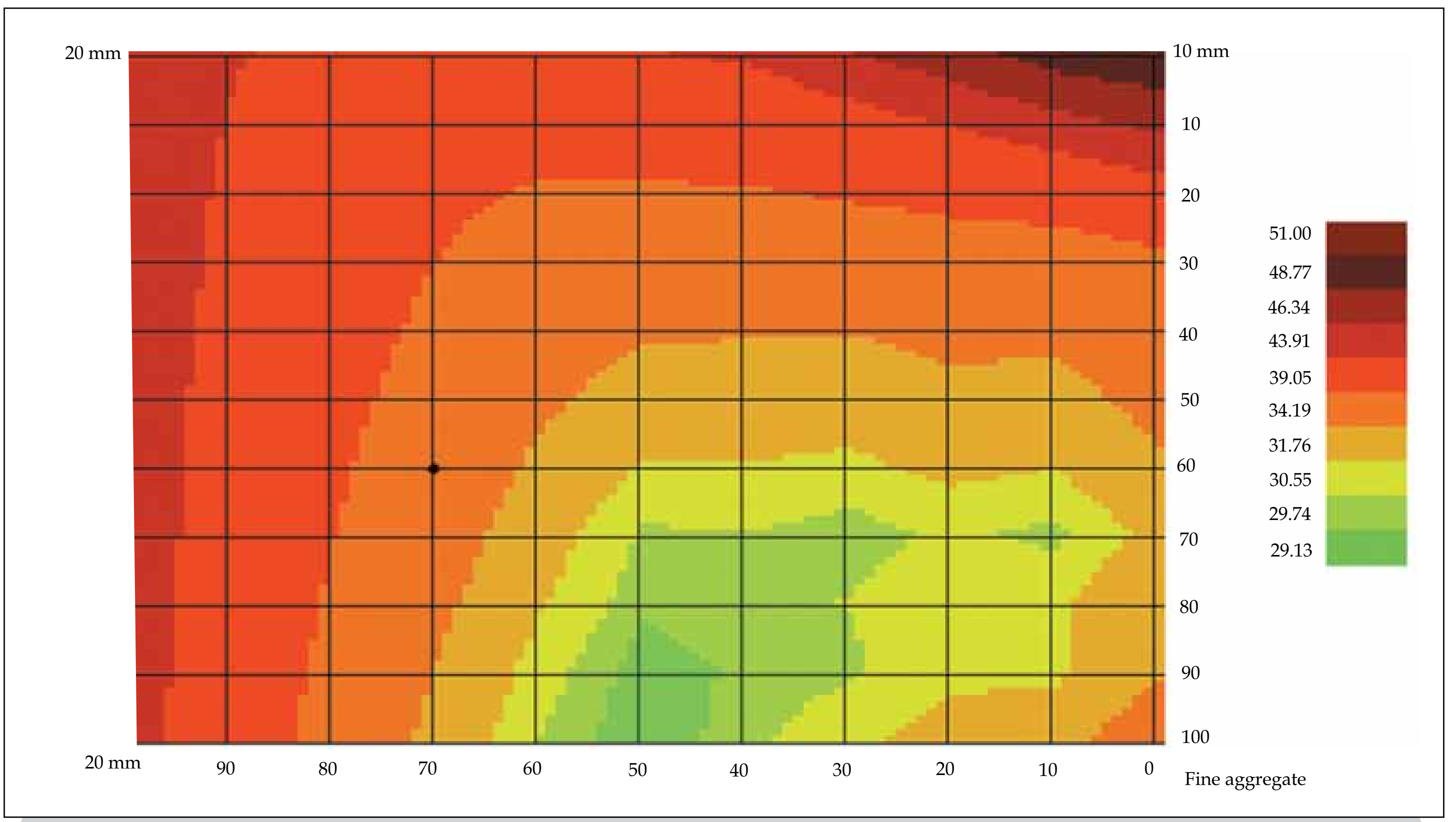

Figure 1. Sample heat map of void ratio for different combinations of aggregate

Table 1. Mix proportion

Material	Mix with first set of aggregates (M1)	Mix with second set of aggregates (M2)
Cement	340	340
Fly Ash	202	202
Water	160	160
Fine Aggregates	905	905
10 mm	740	795
Admixture (PCE based)	5.96	5.96

Water powder ratio chosen was 0.8, and water content chosen was 160 kgs/m3. Thus volume of powder found was 200 litres. This powder was divided into cement and fly ash as 340 kgs OPC and 202 kgs fly ash, and concrete mix was made with 2 different aggregates. The mix proportion is given in Table 1.

Coarse aggregate content was kept at minimum level of the guideline in EFNARC, i.e. 280 litres, the reason it is different in the mixes, because specific gravity of second set of coarse aggregate was 2.84, and that of first set 2.64. Also, the coarse aggregate (10 mm NSA) in M2 had higher degree of flakiness and thus the void content was 50%, as against void content of 47% in first case. Thus void content in aggregate combination (905:740 for M1 or 905:795 for M2 which is 55:45 as per absolute volume) for M1 was 32% and for M2 it was 34%. Although this might not be a major difference, but it shows a huge difference when compared with aggregate proportion represented by minimum voids (green Patches on heat map). The results for fresh concrete properties for these mixes are given in Table 2. But more than the difference in performance test results of the different mixes, the difference can be made out in the heat maps of pictures of these concretes (Figures 2 and 3).

Table 2. Mix proportions of Mix 3

Material	Quantity (kgs)
Cement	300
Fly Ash	160
Water	160
20 mm	485
10 mm	390
Fine Aggregate	880
Admixture (PCE Based)	4.14

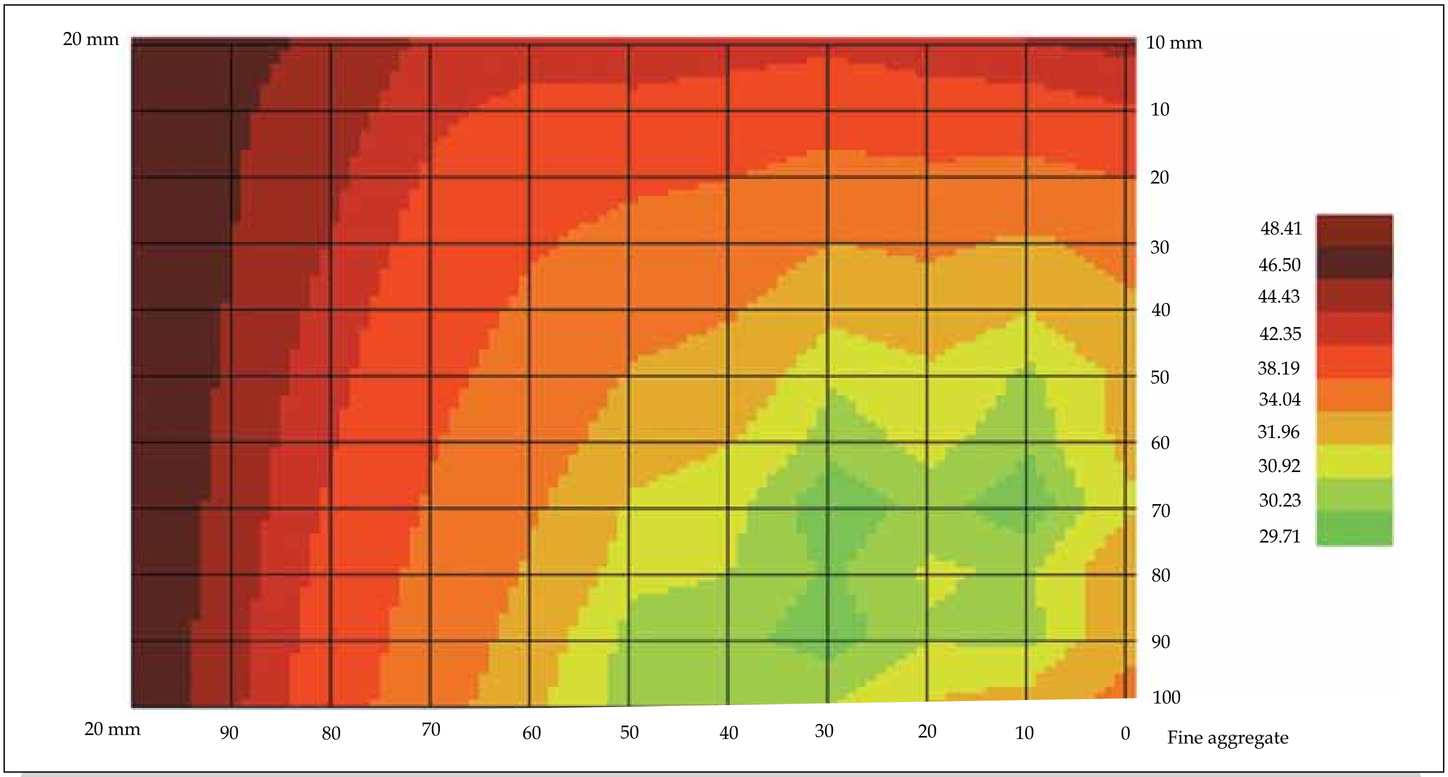

Figure 2. Void heat map with different proportions of aggregates (1st set of aggregates)

Table 3. Workability test results

Test	Mix 1	Mix 2	Mix 3
Slump Flow	660mm	630mm	650mm
T500	3 secs	2 secs	3 secs
V funnel	9 secs	8 secs	11 secs

Table 4. Properties of hardened state

Age	Compressive Strength M1	Compressive Strength M2	Compressive Strength M3
3 days	17.55 MPa	19.1 MPa	15.8 MPa
7 days	24.70 MPa	27.2 MPa	22.5 MPa
28 days	37.69 MPa	41.33 MPa	36.5 MPa

As per ICAR (International Centre for Aggregate Research) SCC can be made by adding paste content in aggregates equal to the void volume in compacted state plus additional 8 to 16% for spacing the aggregates (based on visual rating of aggregates for angularity and flakiness) so that they flow on their own. Hence third mix was made incorporating this concept, and aggregate proportion with minimum voids was chosen (areas marked in dark green). Aggregate set used in Mix 3 was exactly the same as in Mix 2, and additionally 20 mm aggregate was incorporated. Thus, proportion where the minimum voids was seen in the heat map, same proportion was mixed and it's void content was calculated. The proportion of aggregates with minimum voids as per the model in heat map is (intersection of 28 and 69) 28:22:50 (20mm:10mm:Fine Aggregate). The void content physically when tested was found as 29.3%, as against 29.71% predicted by this model. Thus the paste content required to make SCC was found as 293 litres plus additional 12% i.e. 35 litres totalling to 328 litres. Fixing water as 160 kgs, and OPC and fly ash in proportion of 65:35, the contents found were 300 kgs and 160 kgs respectively. If you see the powder content is much less than that used in Mix 1 and 2, but still within the margin specified by the EFNARC. Thus the mix used for mix 3 is given in Table 2. The results of fresh concrete workability tests are given in Table 3. The concrete properties in hardened state are summarised in Table 4.

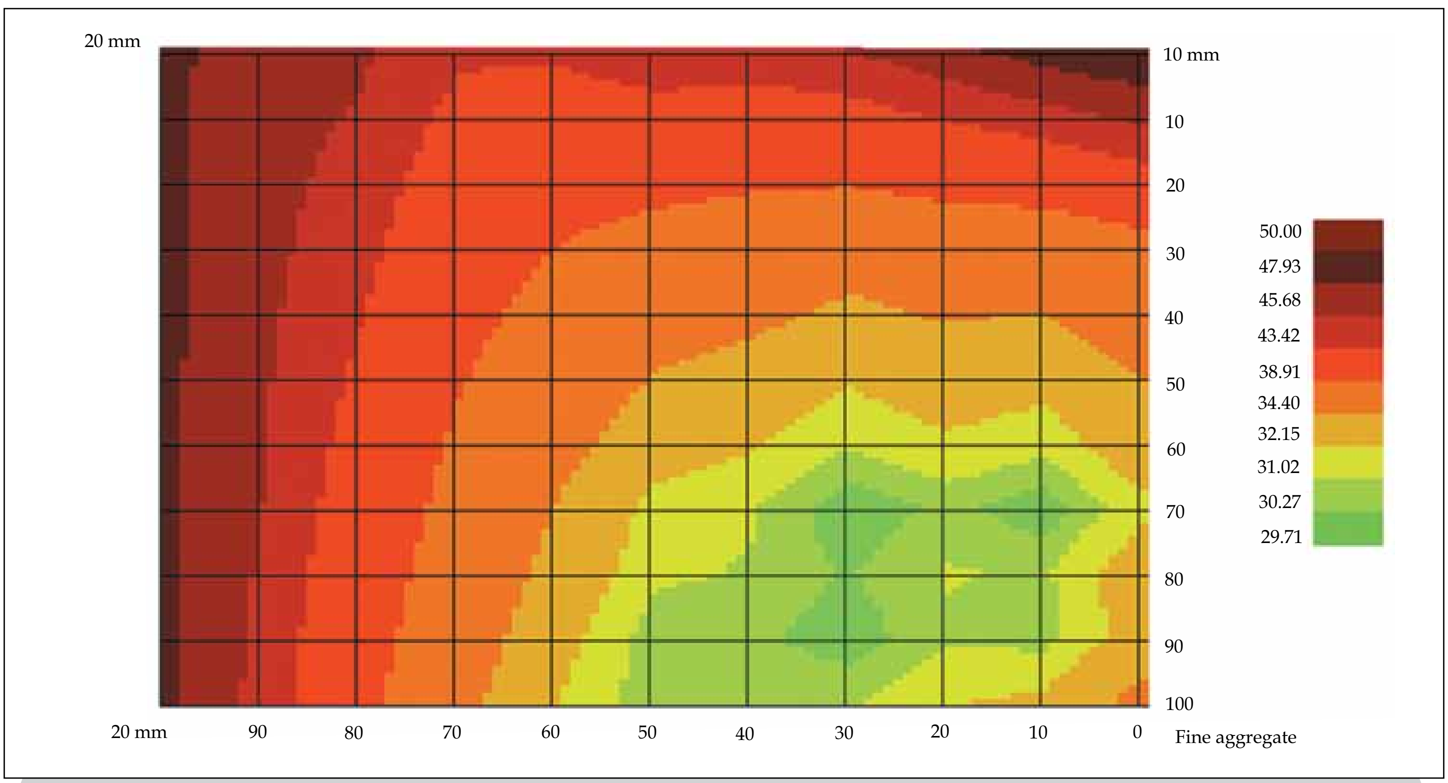

Figure 3. Void heat map with different proportions of aggregates (2nd set of aggregates)

Commentary on test results

Although the test results have shown satisfactory results in terms of test parameters of passing ability, flowing ability, it should be noted that the mix proportioned for 1 and 2 were having cement and fly ash content much higher than mix 3 which was designed on most dense aggregate packing combination. Moreover visual observation of concrete just after V funnel test in bucket, showed aggregates above the level of slurry in resting condition, meaning any slight deviation in raw material on coarser side would lead to segregation of mix, especially for mix 2. If we analyse in mix 1 the void content in aggregate combination was 32% or 320 litres, and paste content was (Cement+Fly ash+Water volume) 360 litres, thus 12.5% higher than the void content hence satisfying the ICAR criterion. Whereas in Mix 2, the void content was 34% or 340 litres and paste content being same i.e. 360 litres which was just 6% higher than the voids. Hence when comparison of pictures of mix 1 and mix 2 was done, mix 2 seemed more segregated. In mix 3 the concrete inspite of much less paste content, has shown no signs of segregation due to aggregate proportioning. It must be noted that to make mix 2 more robust, paste content would have to be increased, till the SCC looks visibly robust, and as per ICAR criterion the paste content required would be 381 litres (additional 12% paste), which translates to 369 kgs OPC, 199 kgs Fly Ash and 173 kgs water (keeping water cement ratio constant).

Figure 4. Mix 2 after passing through V funnel in the bucket

Figure 5. Mix 1 After passing through V funnel

As far as the hardened strength of concrete is seen, Mix 2 (Figure 4) gave the highest strength, reason being due to lesser content of additional paste in the voids of aggregates, points of contact between aggregates may have been higher due to which load, during compressive strength testing, passed through them. Mix 3 (Figure 6) gave the lowest strength, which could have been due to higher water cement ratio as compared to M1 & 2 on account of decrease of cementitious content. It must be noted that, for strength comparison Mix 3 cannot

Figure 6. Mix 3 after passing through V funnel

be compared with other mixes as their fresh concrete robustness was far deviating from that of Mix 3. Had percentage fill and water cement ratio of Mix 3 been same as that of Mix 2, then strengths could have been compared. In SCC it always is better to achieve a robust mix complying to all the requirements in fresh state, only after which strength should be looked upon.

CONCLUSION

EFNARC and other methods have given broad guidelines for designing of SCC, though guidelines to achieve robustness with minimal effort is missing. ICAR methodology for designing self compacting concrete proves to be a more direct approach in making SCCs robust, but methodology to optimize by achieving least void content is missing, for which one has to physically do the tedious work of finding proportion with minimum voids. The minimum void content in aggregates is different for different sources of aggregates and the proportion of aggregates also differ to get minimal voids in different sets of aggregates. Thus a practical model for predicting void content of aggregate for different proportions, is tested and has been found to be able to optimize concrete mix for achieving SCC properties.

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