Self-Compacting Concrete

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Every so often a new development emerges which makes a significant change to the practice of making concrete. The advent of self-compacting concrete (SCC) has been hailed as one such development. SCC could be described as a highly flowable concrete that fills all areas of the formwork and consolidates fully under its own self-weight, irrespective of the presence of congested reinforcement and without segregation.

While it may appear that the addition of a conventional superplasticiser to concrete has the same characteristics as SCC, in fact the admixture (usually a modified acrylic polymer or a polycarboxylate ether) which enables the concrete to be self-compacting has several important distinguishing effects which sets it apart as a new advancement. No compactive effort is required to remove the entrapped air and, despite the concrete's high deformability, it has a strong resistance to segregation, even when flow is restricted by obstructions.

In using conventional concrete, we have always been conscious of the need to compact the concrete fully because the consequences of not doing so, in terms of strength and durability loss and the expense of making good or repair, are severe. The process of providing mechanical vibration takes time and personnel, needs supervision, is unhealthy (due to the potential for "white finger" syndrome, insomnia and occupational deafness) and an environmental nuisance (due to disruptive noise).

SCC was developed initially in Japan in the early 1990's as a response to a need to improve quality and shorten construction times by increased automation on several major projects. Indeed, today a high percentage of all concrete poured in Japan is SCC, with increasing usage in Europe, particularly in Scandinavia. SCC in precasting(1) appears to have potential for the greatest efficiencies, especially where the quality of finish is an issue. There are also reported cases of using SCC for pumping(2), tremieing(2) and with fibres(3) without difficulty. In particular, the self-compaction and flowing characteristics allow concrete to be pumped in at the bottom of vertical elements, filling from the bottom upwards. The UK Concrete Society has established a Working Party on SCC and a major collaborative research program in Europe (4) has recently finished investigating its potential.

Nowadays, in many countries, there are reports of the benefits of SCC(5). By eliminating the need for vibration, shorter construction times (as much as 20% in some cases) and lower overall costs have been recorded in improved health and safety conditions. The increase in material costs varies from country to country, but can range from as little as €5/m³ (in Sweden) to as much as €20/m³ (in the UK(2)). It has been shown that labour costs (for formwork, concreting and remedial work) and program time reductions more than compensate for the increase in material costs. On the other hand, although formwork re-usage should be improved, formwork pressures may be increased due to the speed of placement, which is especially relevant for high lifts.

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Properties required of SCC

It is understood that three properties are demanded of SCC in its fresh state for it to be successful:

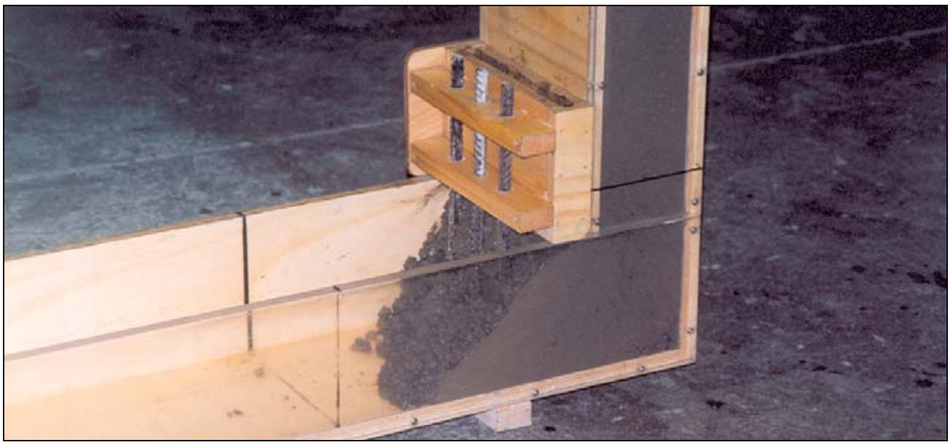
a) Filling Ability - the concrete must flow into all areas of the formwork under its own self-weight;
b) Passing Ability - the concrete must flow through obstructions, such as congested reinforcement, without becoming blocked;
c) Stability - segregation must not occur - the concrete must be cohesive.

In its hardened state, the primary requirement is that the compressive strength must be optimized through the achievement of full compaction under its own self- weight. Many tests have been done by coring cast elements with highly congested reinforcement and verifying that the strength is equivalent to mixes to which mechanical vibration has been applied; usually marginally higher compressive strengths with better uniformity is achieved. Further, from an aesthetic viewpoint, the uniformity of compaction thus achieved improves the quality of finish (there are fewer defects such as grout loss, honeycombing and blow holes), and the impermeability of the cover concrete is expected to enhance durability.

Despite the lower coarse aggregate content, shrinkage and creep are not increased and bond is marginally improved due to better densification in the interfacial transition zones around the reinforcing bars(6) and especially the elimination of any voidage under bars due to plastic settlement.

Mix design

The need to achieve high fluidity while increasing the cohesiveness seems to represent conflicting requirements. The first alteration to the mix usually involves utilising a much higher quantity of fines (typically at least 50% sand is used) to obtain stability, with lower coarse aggregate content to reduce interparticle friction. The normal rules apply concerning maximum aggregate size and the gap between the reinforcing bars, irrespective of concerns about blocking due to congestion of reinforcement. It is difficult to achieve appropriate fluidity and viscosity by changing the grading of the sand alone and either an active cement



'L' Box Test: Conventional Concrete Coagulates Around the Reinforcement Bar

Rheodynamic Concrete Demonstrates Flow Charestics

SCC Bypasses Reinforcement Bar

replacement ingredient (such as slag or ash) or a filler (such as limestone powder) is added in relatively large quantities, depending on the local economics and availability. Typically, changing a normal C30/35 mix to a self-compacting mix might demand the addition of over $200kg/m^3$ of limestone filler to the original cement content of $300kg/m^3$. Furthermore, while the SCC admixture can be made to produce flowing and cohesive concrete by adjusting the fines content (particularly that passing the 150μm sieve), the increased water demand which the filler (or cement replacement) and additional sand generates means that the water content is critical to obtain good flow. In these circumstances, it is not easy to avoid segregation without adding a viscosity modifier. Special training is required to design, produce, transport and place SCC(7). However, a wide range of mixes can be made to meet the required properties. It is essential to undertake trials on proposed mixes using locally available materials.

Testing

The main outstanding problem in relation SCC(4) is there is no accepted standard test for establishing the workability of the fresh concrete. There is no independent authoritative guidance on an appropriate test which could be specified to scientifically establish fully the fresh properties of SCC (incidentally, no such test exists for normal concrete either!) The most common tests will be described here briefly, followed by an explanation as to why recent research may have a solution to the shortcoming of the existing tests. Considering the requisite properties of SCC, as described above, there are a number of tests which can either quantify some aspect of the concrete's behaviour or which give a qualitative evaluation of some of those properties.

Slump Flow(5): This test is the most common because it uses a standard slump cone to give an indication of the filling ability and, to some extent, the cohesion. Without tamping the concrete, the cone is filled with concrete and removed and, subsequently, the concrete spreads over the flat smooth surface. Typically, the diameter, df, of the subsequent disc of concrete ranges from 600 to 700mm, although it is not a particularly sensitive test. The time to reach a diameter of 50cm is recorded as T50 and is considered an indication of viscosity. It is desirable to have a high df value combined with a low T50. It is useful to observe whether either grout/paste has separated at the edge (usually associated with a segregated pile of coarse aggregate in the middle) - if the concrete has not segregated, then the coarse aggregate can be seen to be spread evenly across the disc, especially right to the edge.

L-box(5): This test primarily measures the passing ability by observing any tendency to block the flow when a reservoir of concrete passes an obstruction (three closely spaced reinforcing bars) under gravity into an open channel. As the concrete flows, the time required to pass along the channel is recorded at specific distances from the reservoir (an indication of viscosity) and the ability to self-level is observed by comparing the final height of concrete as a ratio (normally between 0.8 and 1.0) of that at the end of the channel to that remaining in the reservoir. The cohesiveness of the mix can also be observed as the concrete flows along the channel floor.

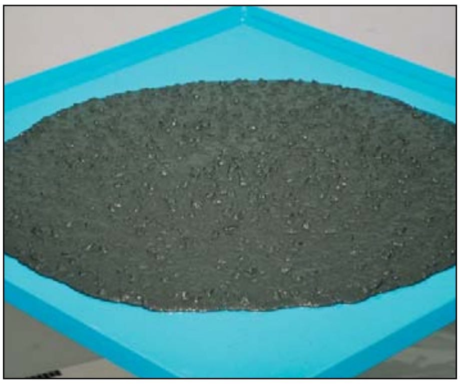
Other tests include the J-Ring (where an arrangement of bars surrounds the slump cone), the U-box (similar to the L-box except the open channel is replaced by another empty reservoir, making the whole apparatus U shaped) and the V-funnel (a hopper into which the concrete is poured and passes through an orifice). All are variations of the same theme, each assessing different aspects of the three basic requirements of flow, passing ability and stability. Each gives some information but does not give a complete picture. How the constituents might be modified to alter the properties seems to be more a question of trial and error than science. However, recent research in the area of rheology (the science of flow of materials) may provide us with an acceptable universal solution to the absence of standardisation amongst the preponderance of tests, none of which is satisfactory.

Rheology and SCC:

It has long been accepted[(8)] that normal concrete can be defined in fundamental rheological terms by just two parameters, the yield value, τ_0 (that is, how much stress is required to get the concrete to flow) and the plastic viscosity, μ (that is, how "runny" it is when it does flow). In mathematical terms, the shear stress, τ, is related to the shear rate, γ, by

$$\tau = \tau_0 + \mu \, . \, \gamma$$

Any material, including concrete, which behaves in such a linear way is called a Bingham material. There are various devices (rheometers, viscometers, two-point workability test, etc) for measuring these parameters reliably, all of which are laboratory based. For example, the most popular method in these islands is the two- point test in which the torque required to rotate an impeller in concrete is linearly proportional to the speed of rotation of the impeller, analogous to the equation above. On-going research work at Trinity College[(8)] in Dublin is developing an affordable hand tool for measuring rheological properties of normal and SCC concrete on site and this should prove to be a practical step forward in quality control terms.



The concrete has an exceptional slump.

However, and this is enormously significant, these rheological tests measure scientifically the basic flow characteristics of fresh concrete. In so doing, the test can discern clearly between different concretes, can identify changes to the mix constituents and, more importantly, can allow the mix designer to select constituents to achieve the desired flow properties. In this way, it has been shown[(9)] that a cohesive SCC mix can be designed for a particular application without recourse to lengthy and repetitive trial mixing (although, of course, the mix design would need to be confirmed by a trial mix prior to a full scale pour).

For example, the requirements for fresh concrete to have a high ability to flow and yet be cohesive seem to contradict each other. In rheological terms, a successful SCC mix may indeed have a low viscosity (to enable flow), but then it needs a modest yield value to remain stable. On the other hand, if a SCC is viscous, it will need to have a very low yield value otherwise it will not flow. If one measures the rheology of the concrete and finds that it is too viscous, one may be temped to add water - this will reduce the viscosity but also the yield value and the mix may well segregate (as well as affecting strength and the pore structure). Alternatively, say, silica fume could be added which will increase strength while reducing the viscosity and increasing the yield value. In this way, it can be seen that a strategic decision can be made on how to change the constituents of the concrete to achieve the required properties. This has been achieved in practice in a number of large scale projects[(9)].

Again, it is seen that there is no unique mix to achieve the one end. But the choice of constituents should be based on a firm understanding of the consequences of the changes to the mix, founded in rheology, not on a trial an error method.

Conclusions

Self-compacting concrete has much to offer. It has proven advantages in improving quality and speed of concreting work, it leads to a better working environment and it is, on balance, cost effective in many countries. Although it has particular advantages in pre-casting and where reinforcement is congested, the fact is there are numerous reports of its successful use in day-to-day work. There are several countries which have embraced the technology, thereby creating a competitive advantage for concrete. While the issue of standardisation of the testing method has yet to be resolved[(1)], potentially by using rheology, the existing methods for testing are practical and have shown that they can lead to a successful outcome.

One of the bugbears of concrete - the need to properly compact it fully to optimise its strength, now seems to have a technical solution and, perhaps, in years to come, it might become accepted as the milestone in innovation, that many currently believe it to be.

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