COMPRESSIVE, BOND AND SHEAR BEHAVIOUR OF POWDER-TYPE SELF-COMPACTING CONCRETE

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For the design of structural elements, the mechanical behaviour plays a crucial role. The way forces are transferred in the material and deformations are build up, determines to a high extent the dimensions of the different components. For several decennia, the behaviour of concrete under different kind of loads (compression, tension, shear, etc.) is being investigated. Recently new types of concrete were developed for specific applications or with special properties: high strength concrete, lightweight concrete, fibre reinforced concrete, ultra high performance concrete, etc. The mechanical behaviour of these concretes often differs from that of conventional vibrated concrete (CVC).

One of the more recent developments is self-compacting concrete (SCC). This concrete type has, in contrast to more conventional concretes, no need for external vibration energy to be compacted. In this way, savings on the energy consumption, a reduction of the physical pressure on the craftsmen, a limitation of the noise nuisance, etc. can be achieved.

To obtain these properties a few modifications in the composition of the concrete are necessary. One of the methods to achieve self-compaction is the reduction of the coarse aggregate content and an increase in the amount of powder. In this way, a powder-type self-compacting concrete is produced.

As the mechanical behaviour of a material covers a wide range of different facets, the focus in this study has been on three aspects: the behaviour under uni-axial compression, the shear behaviour and the bond of reinforcing bars to the surrounding concrete.

1 Experimental program

When concrete elements are subjected to increasing axial loads, internal stresses and strains are build up. The relationship between stresses and strains is represented in stress-strain diagrams. When concrete is considered, it is noticed that for increasing strains, stresses reach a maximum after which the material fails gradually. For further increasing strains, decreasing stresses are measured.

The stress-strain behaviour of self-compacting concrete was measured on cylindrical specimens with slenderness (ratio of height to diameter) of 3.0 or 3.6 according to the RILEM recommendations. During the experiments the specimens were subjected to a continuously increasing deformation. The axial deformations in the central part of the specimen, the circumferential deformation and the stress applied to the specimen were recorded. Special care was given to the steering signal to allow for the measurement of the so called ‘strain-softening’ behaviour (descending branch of the stress-strain diagram).
From the obtained results it can be seen that the peak strain (strain at the moment the compressive strength is reached) at different ages and concrete strengths for SCC is higher than for conventional vibrated concrete (CVC). The modulus of elasticity is slightly lower, however the difference is not significant.

Figure 1 - Crack formation in SCC specimens subjected to uni-axial loading

Besides the influence of limestone filler, the use of blast furnace slag, fly ash and silica fume has been investigated. For almost all tested compositions, the peak strain of SCC was higher than those of CVC. The largest peak strains were measured for self-compacting concrete containing limestone filler. The values for the concrete compositions with fly ash, silica fume or blends of these supplementary cementitious materials were slightly lower. The lowest values were found when blast furnace slag was used as addition.

Besides the modulus of elasticity, the peak strain and the compressive strength, also the toughness can be derived from the stress-strain diagram. The toughness is defined as the area underneath the entire stress-strain diagram and, in this way, a measure for the energy absorption capacity of the considered concrete. The toughness of self-compacting concrete showed to be slightly higher than for conventional vibrated concrete. The largest difference was found for the ascending branch, whereas the surface underneath the descending branch was comparable.

A second aspect that has been studied is the bond behaviour of reinforcing bars in self-compacting concrete. The developed bond strength plays a crucial role in the determination of anchorage lengths of reinforcing bars. When higher bond strengths are achieved, the designer can propose to reduce the anchorage length and so the applied amount of steel.

In literature, different test results are found for the bond strength in self-compacting concrete. Sometimes these studies deliver contradictory results, but internationally it...
seems to be agreed that the bond strength in self-compacting concrete is slightly higher than in conventional vibrated concrete. Although, most studies are limited to tests on only one or two different bar diameters.

In this study, the bond strength has been analysed by means of ‘beam-test’ specimens for two self-compacting concretes and one conventional vibrated concrete. Six different reinforcement bar diameters were used, ranging from 12 mm to 40 mm.

A clear influence of the bar diameter on the measured bond strength is noticed for self-compacting concrete: for increasing bar diameters, the bond strength is decreasing. For larger diameters (32 and 40 mm), the difference between the values measured for conventional vibrated concrete and those for self-compacting concrete are small. On the other hand, for small diameters the bond strength for self-compacting concrete is significantly higher than for conventional vibrated concrete.

In concrete elements of relatively larger dimensions, the bond strength is decreasing with increasing height of the reinforcement bar. This phenomenon is called the ‘top-bar’ effect. In the case of conventional vibrated concrete, it is known that significant reductions can be found for bars at the top. A same observation is made during the experiments on reinforcing bars embedded in column elements of 1.8 m high. For bars placed in the upper part of the column a reduction with more than 50% is measured. For self-compacting concrete the reduction is remarkably lower and between 0% and 33%.

Self-compacting concrete allows new placement techniques. Whereas the casting into the formwork of conventional vibrated concrete is only possible from above, for self-compacting concrete pumping from the bottom or the side of the formwork becomes possible. To study the influence of the flow pattern inside the formwork on the bond strength, a wall element of 4 m in length and 2 m in height has been cast with SCC pumped from aside through a valve. At different heights and at different distances from the inlet, reinforcing bars were embedded. The test results showed no significant influence of the distance to the inlet on the bond strengths, or a reduction in the top-bar effect. However, it is recommended to perform further research into this topic.
At last, the shear strength of self-compacting concrete has been studied. Due to the modification in the composition of a powder-type self-compacting, the amount of coarse aggregates is lower than for conventional vibrated concrete. Internationally it is assumed that this reduction leads to a reduction in the aggregate interlock of the concrete. The aggregate interlock is the phenomenon in which the aggregates pointing out at one side of the crack face are interlocking with the other side of the crack to transfer shear forces. One of the possible test methods to quantify the aggregate interlock is the use of push-off specimens.

Tests were performed on Z-shaped specimens cast with four different conventional vibrated concretes and four self-compacting concretes. The reinforcement ratio of the shear plane has been varied between 0.40% and 2.65%. For different concrete strength classes, the shear strength of SCC was on average 15% higher than for CVC with comparable compressive strength and reinforcing ratio.

Figure 3 - Push-off test set-up

Different possible causes for these observations were sought. On the one hand, the influence of the reduction in coarse aggregate content has been studied. Tests were repeated with a conventional vibrated concrete which had a coarse aggregate content which was comparable with that of self-compacting concrete. The measured shear strengths turned out to be close to those of the reference concrete. As a result, the influence of the reduction in the amount of coarse aggregates is small.

On the other hand, the improved matrix quality and bond between the aggregates and the matrix (as observed for self-compacting concrete) can lead to a higher resistance to crushing of the concrete matrix. By means of tests on vibrated self-compacting concrete, the quality of the interfacial transition zone between aggregates and matrix was reduced. The shear strengths turned out to be 10% lower, which indicates a significant influence of this aspect on the shear strength.

The final investigated influencing factor is the dowel action of the provided reinforcing bars. As the bond strength of reinforcing bars in self-compacting concrete is higher than that in conventional vibrated concrete, the contribution of dowel action to the overall shear resistance of both concrete types can be different. A reduction of the bond length of 80 mm in the zone close the shear plane has a limited influence on the shear strength. On the
other hand, a reduction of the bond length with 400 mm leads to a decrease in some cases of more than 15%. This decrease can be attributed to the higher deformation capacity of the reinforcing bar.

2 Modeling

The second part of the research dealt with the comparison of the obtained test results with mathematical models available in literature. For each of the three aspects a modified model was derived to predict the behaviour of powder-type self-compacting concrete.

The stress-strain diagram of conventional and high strength concrete has been studied and modelled by several researchers in the past. Those models often differ only in, for example, the values of a few parameters. Comparison of the models with the measured diagrams of self-compacting concretes revealed that the existing models did not allow for a good prediction of the behaviour. One of the determining factors turned out to be the prediction of the peak strain. In several models the peak strain is considered independent from the compressive strength of the concrete and the used additions. Only in a few cases the compressive strength is incorporated.

The model proposed for self-compacting concrete, as given in this study, is based on the Sargin-formulation. This model uses a ratio of two second order polynomials to estimate the stress-strain behaviour. By modifying the formula for the peak strain and the limit strain (strain corresponding to a stress reduction to 50% of the compressive strength), a much better correspondence has been achieved.

Regarding the modelling of the bond stress – slip diagram, different formulations already exist. Most of these equations are based on the model of the fib Model Code. For the prediction of the diagram of self-compacting concrete, it is found that the fixed slip values, taken for the slip which corresponds to the ultimate bond strength, doesn’t correspond to the experimental results. Therefore a varying slip values is proposed as a function of the clear rib distance of the reinforcing bar. The value of the ultimate bond strength itself, turned out to be a function of the compressive strength of the concrete, the coverage on the tested rebar and the bar diameter. Those three aspects are incorporated in the proposed equations.

The regulations found in ACI318 and Eurocode 2 for the top-bar effect, were found to be applicable for self-compacting concrete. However, for conventional vibrated concrete the reduction in the bond strength was often higher than predicted by the codes and so an unsafe value is obtained. Additional research for conventional vibrated as well as self-compacting concrete seems necessary.

Finally, a comparison was made between the theoretical shear strengths and the experimental determined values. The equations taken from literature and standards provide a wide range of possible values for the shear strength of initially cracked or uncracked concrete. The model developed by Mattock shows good correspondence with the test results of the conventional vibrated concrete elements. A small modification of the lower limit to that provided by ACI318 can lead to slightly better predictions. In this way, the underestimation is on average 16%.
For self-compacting concrete the best correspondence is found with the values obtained from the equation proposed by Walraven. However, this model does not apply an upper limit accounting for the over-reinforcement of the shear plane by large reinforcement ratios. Because of this, for high reinforcement ratios, the shear strength is significantly overestimated. By the application of an upper limit, as found in the model of e.g. Mattock, a mean underestimation of the shear strength of 16% is obtained.

In general it can be concluded that the considered powder-type self-compacting concretes are performing equally or even slightly better with respect to the, in this project, investigated aspects: compression, shear and bond. However, it remains necessary to further investigate some of the aspects to obtain a more in-depth and fundamental understanding of the material. Often this insight will broaden and/or nuance the accepted concepts with respect to conventional vibrated concrete as well.