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Structural behaviour of powder-type self-compacting concrete: Bond performance and shear capacity

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ABSTRACT

An experimental test program was carried out to investigate the bond and shear performance of powder-type self-compacting concrete (SCC). In order to examine the bond strength of reinforcement in concrete, pull-out tests (according to RILEM recommendation RC6 part 2) were performed. In total, 72 pull-out specimens were tested, cast with different concrete mixtures and rebar diameters (8, 12, 16, and 20 mm). It was found that SCC shows normalized characteristic bond strength values as high as or higher than vibrated concrete (VC). In addition, as the bar diameter increases, larger bond strengths are measured, with the highest values for bars with diameter 12 or 16 mm. When larger diameters up to 20 mm are used, a decrease in bond performance is noticed. To study the shear behaviour, four-point bending tests were executed. Small SCC and VC beams were cast with different reinforcement ratios (1.0%, 1.5%, and 2.0%) and tested with different shear span-to-depth ratios (from 1.5 to 3.0), with a total of 102 beams. A slightly decreased shear capacity is observed for SCC. Also, higher ultimate shear stresses are recorded when higher reinforcement ratios or smaller shear span-to-depth ratios are applied.

1. Introduction

Self-compacting concrete (SCC) is becoming increasingly used in civil engineering. Powder-type SCC differs from vibrated concrete mixtures (VC) by the increased amount of fine aggregates and fillers, and the addition of a superplasticizer which increases the workability. As a result, SCC is capable of flowing under its own weight and completely filling the formwork. Also a dense and adequate homogeneous material is achieved without the need of compaction. Therefore, it can be used to cast narrow, complex formworks, even in the presence of dense reinforcement [1,2]. Today, the fresh properties and durability behaviour of SCC are thoroughly investigated in literature, while the mechanical properties – such as bond and shear behaviour – are less reported. Because of this lack of information regarding structural performance of SCC members, this material is still not confidently used by designers and engineers in the construction industry, despite the many advantages, such as increased productivity, reduced labour and higher quality of the structure [3].

Reinforced concrete (RC) is a composite material, designed to resist compressive stresses (concrete) and tensile stresses (reinforcement steel). To achieve an effective RC structure, a good bond between concrete and reinforcement steel is necessary to enable force transfer between both materials. In literature, many test results of pull-out tests show that the bond strength of SCC is as high as or higher than VC [4–12]. Depending on the quality and the compressive strength of the concrete, the bond strength of SCC is about 5–40% higher [6–8]. This increased bond performance can be attributed to a reduced formation of bleed water under the reinforcement bars due to the absence of compacting equipment [7–9]. In addition, previous tests with bar diameters ranging from 12 to 40 mm showed a significant size effect on the bond strength: for smaller bar diameters, higher bond stresses are found [10,11]. As opposed to pull-out test, similar results regarding bond performance are achieved when beam tests are conducted to examine the bond behaviour between concrete and reinforcement steel [12]. Only smaller slip values are measured when the compressive strength of the concrete increases when beam tests are applied.

Concerning the bearing capacity of SCC beams, there is some concern among researchers and designers that they may not be strong enough in shear. Because of the use of fine aggregates and a smaller amount of coarse aggregates, a weak interlock mechanism is expected. Kim et al. [13] already confirmed this statement after experimentally determining lower fracture reduction factors – and thus less aggregate interlock – using SCC. In the research by Hassan et al. [14], an up to 17% reduction in shear strength was found in SCC beams subjected to shear failure. Additionally, the ultimate shear load grew with the increase of longitudinal reinforcement and/or decrease in beam depth. However, Lachemi et al.

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[15] indicated a difference in shear capacity of only 5% between SCC and VC. Taking into account a large scatter on the test results, this makes it hardly convincing that SCC has a poor shear resistance compared to VC. Desnerck [16] also pointed out that any potential reduction in the shear strength of hardened SCC due to reduced aggregate interlock may in reality be outweighed by the overall gain in matrix quality, including the interfacial transition zone (ITZ). By means of push-off tests, normalized ultimate shear strengths of SCC up to 15–20% higher than for VC were measured in some cases. However, when SCC is modified to become a mixture requiring compaction by reducing the content of superplasticizer, a decrease in ultimate shear strength of 8% is found due to vibration. From these results, it is not possible to conclude that SCC shows worse shear behaviour than VC.

In order to validate or elucidate the findings mentioned above, this paper evaluates the bond and shear performance of SCC. Pull-out tests are performed to examine the bond-slip behaviour between concrete and reinforcement steel with different diameters (8, 12, 16, and 20 mm). To investigate the shear capacity of SCC, four-point bending tests are carried out on small concrete beams without stirrups. The influence of different parameters such as concrete type, shear span-to-depth ratio, and reinforcement ratio is examined.

2. Experimental program

2.1. Mix design

Self-compacting concrete (SCC) and vibrated concrete (VC) were used to cast 72 pull-out specimens and 102 reinforced concrete beams. Three SCC mixtures (SCC1, SCC2, and SCC3) and one VC mixture (VC1) were made in the laboratory. One SCC and one VC mixture (SCC4 and VC4) were supplied by a ready-mix concrete company in different batches (batch a and b).

SCC1, SCC2, and VC1 were based on the mix designs used in the research of Boel [17] and Desnerck [16], where VC1 is a reference mixture with a compressive strength of about 60 MPa. SCC1 has the equal water/cement ratio, resulting in a higher compressive strength due to the effect of the limestone filler. SCC2 is designed to have the same compressive strength as VC1, by reducing the amount of cement, resulting in a higher water/cement ratio. SCC3 is based on a SCC mixture used in the doctoral research of Boel [17] with the water content as SCC1, but a lower W/C-factor.

For all mixtures Portland cement CEM I 52.5 N was used. Sand (0/4) and river gravel (4/8 and 8/16) were selected as aggregates and a polycarboxylic ether hyperplasticizer was used. Test SCC mixtures were made to determine the amount of superplasticizer, in order to achieve a slump flow of the fresh concrete of about 750 mm. The mix proportions of SCC1, SCC2, SCC3, and VC1 are summarized in Table 1. While making the mixtures, the dry materials were first mixed. Next, the water was added and 30 s later the superplasticizer was gradually added during 1 min. After this, the mixing was continued for 2 min, in a planetary mixer.

Table 1
Mix design for SCC and VC mixes (laboratory).

Materials (kg/m^3)	SCC1	SCC2	SCC3	VC1
CEM I 52.5 N	360	300	400	360
Sand 0/4 mm	853	853	853	640
Gravel 2/8 mm	263	263	263	462
Gravel 8/16 mm	434	434	434	762
Limestone filler	240	300	200	–
Water	165	165	165	165
Superplasticizer	3.1	2.6	3.4	–
Water/cement ratio	0.46	0.55	0.41	0.46

SCC4 and VC4 are C40/50 concrete mixes, suitable for an environment with frost, but without exposure to rain (exposure classes XF1 and XC3, according to CEN [18]), provided by a ready-mix concrete company in two different batches (a and b). For both types CEM III/A 42.5 N LA was used. The maximum aggregate size $D_{\max}$ was 8 mm for SCC4 and 16 mm for VC4. A slump flow between SF1 and SF3 was required for the SCC mixtures to obtain a good workability. For the VC mixtures, a slump S4 and flow F3 were required, but a lower workability was found for VC4a. However, no problems regarding workability were experienced.

Fresh properties were determined by the slump flow and V-funnel test for SCC mixtures and by the slump and flow test (only for VC4) for VC mixtures [19]. Hardened properties were identified by the compressive strength and tensile strength (SCC1a, SCC2, and VC1a) at 28 days. For the compressive strength, cubes (f_{ccub}) with sides of 150 mm were made. The tensile flexural strength ($f_{ct,fl}$) was measured on prisms with a length of 400 mm and a height of 100 mm by means of three-point bending tests. Afterwards, the tensile splitting strength was determined on the two remaining halves of the prisms, used to measure $f_{ct,fl}$. All cubes and prisms – together with the test specimens – were demoulded after 1 day and sealed and stored at 20 ± 2 °C until the age of testing. The mean values of the properties of fresh and hardened concrete are summarized in Tables 2 and 3 for all mixtures. Because SCC1, SCC3, and VC1 were used in two testing programs, characteristics are given for both test series (a and b). Also, the consistence and viscosity classes of the SCC and VC mixtures are mentioned [18,20].

2.2. Pull-out tests

2.2.1. Specimen type

In order to study the bond behaviour between rebars and concrete, pull-out tests are performed. Ribbed steel bars BE500S (according to EN 10080 [21]) with a diameter φ of 8, 12, 16, and 20 mm are used. For all mixtures, four test specimens with diameter 8, 12, and 16 mm are cast. Also for mixtures SCC3, SCC4, and VC4, 4 pull-out specimens with diameter 20 mm are made. According to the RILEM recommendations RC6 part 2 [22], a side of the concrete cube of at least 10 times φ is required to avoid splitting of the concrete during testing. Hence, a cube side of 200 mm is chosen for all test members. Also a bond length between steel and concrete of 5 times φ is recommended by RILEM. However, based on known bond stresses from literature, this will result in yielding of the steel reinforcement on the active (loaded) end of the specimen. Therefore, a bond length of 3.5 times φ is selected, based on calculations, in order to avoid yielding of the steel. The dimensions of the pull-out specimens are presented in Fig. 1.

2.2.2. Testing procedure

The pull-out tests are conducted in a 250 kN tensile test machine. Therefore, a construction is made to clamp the pull-out test specimens in the testing device. The tests are performed according to RILEM recommendations [22], except that the active force is applied on the reinforcement steel instead of on the concrete cube. During testing, a force of 5 kN is applied on the specimen to obtain a good grip of the claw, after which the test continues at a constant rate of 0.02 mm/s. The relative slip between steel and concrete is measured by means of two symmetrically placed lasers on the passive (unloaded) end of the rebars. The test is stopped when a slip of at least 10 mm is measured. The pull-out test set-up is shown in Fig. 2.

2.3. Four-point bending tests

2.3.1. Specimen type

To investigate the shear capacity of SCC beams, four-point bending tests are carried out on small beams without stirrups with