BOND STRENGTH OF REINFORCING BARS IN SELF-COMPACTING CONCRETE: EXPERIMENTAL DETERMINATION

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ABSTRACT

In reinforced concrete structures, understanding the bond mechanism is of great importance for the design (anchorage lengths, load bearing capacity, crack width, …). Therefore this phenomenon has widely been studied for conventional vibrated concrete. For self-compacting concrete (SCC) however few test results are available and in practice the standards for conventional vibrated concrete (CVC) are applied to self-compacting concrete as well.
To fill in this lack of knowledge and to develop adapted standards for predicting the bond of reinforcement in SCC, an experimental program has been set up. The bond strength of reinforcement bars with different diameters has been tested for 1 conventional vibrated concrete and 2 self-compacting concretes. The testing method, by means of "beam-test" specimen, was based on RILEM RC6 part 1. During testing the free end slip of the bars and the applied load were recorded. The bar diameters ranged from 12 mm to 40 mm.
From the test results it can be seen that the maximum and characteristic bond strength of self-compacting concrete is as high as for conventional vibrated concrete, or even slightly higher. The bond strength decreases however for increasing bar diameters, and the decrease seems to be a little larger for specimen made of SCC. The slip corresponding with the maximum bond strength increases for increasing bar diameters.

INTRODUCTION

The main principle of reinforced concrete is the combined action of the concrete and its embedded reinforcement. This action is produced by bond stresses at the interface between the two materials. The bond strength influences in a significant way anchorage lengths and load bearing capacity of the concrete members, but also crack widths and crack spacing. Due to its important role in the design, an extensive number of tests to determine the force transfer between steel and concrete has been performed for conventional vibrated concrete (CVC) in the past.
Nowadays self-compacting concrete (SCC) is used more frequently. The bond strength introduced in calculations however, is based upon regulations and recommendations validated for conventional vibrated concrete. Some research programs have been carried out to determine the force transfer between concrete and reinforcement (1-4) in self-compacting concrete. These studies show that the bond strength of steel in SCC is not lower than for conventional vibrated concrete, and may be even higher in some cases. Nevertheless there is a great scatter in the results. Therefore an experimental study has been set up to determine the influence of the main factors on bond strength and to get a better insight in the difference in bond strength between CVC and SCC.

EXPERIMENTAL PROGRAM

In this research program the bond strength has been tested by means of "beam-test" specimens, as described in RILEM RC6 part 1 (5). Three types of concrete have been tested of which 2 self-compacting concretes. The bond length has been chosen to 5 times the bar diameter ϕ for all tested reinforcement bars.

Materials

A conventional vibrated concrete (CVC1) has been chosen as reference mix. The tested self-compacting concretes were designed to achieve a concrete with the same W/C ratio as the conventional vibrated concrete (SCC1), and one self-compacting concrete with the same compressive strength (SCC2).
For all the mixes a Portland Cement (CEM I 52,5 N) was used. A natural sand 0/4 mm and 2 types of gravel (2/8 mm and 8/16 mm) were chosen as aggregates. The proportion of each aggregate was the same for the two self-compacting concretes, but the amount of large aggregates was substantially smaller for the self-compacting concrete (56.9% of the amount for the conventional vibrated concrete).
For the self-compacting concrete a superplasticizer, Glenium 51 concentration 35%, has been used as well as a limestone filler. The amount of fine materials (filler and cement) is the same for both SCC's i.e. 600kg/m³.
The mix proportions are summarized in Table 1.

Materials (kg/m³)	CVC1	SCC1	SCC2
CEM I 52,5 N	360	360	300
Sand 0/4 mm	640	853	853
Gravel 2/8 mm	462	263	263
Gravel 8/16 mm	762	434	434
Limestone filler	-	240	300
Water	165	165	165
Superplasticizer Glenium 51	-	3.60	3.00
Water / cement ratio	0.46	0.46	0.55

Table 1: Mix Design

The mixes were prepared in batches of around 200 litres from which approximately 100 litres were intended for the beam-test specimen and the other 100 litres for standard concrete control specimens. After 1 minute mixing of the dry materials, water was added and mixing continued for 3 minutes in the case of conventional vibrated concrete. For the self-compacting concrete the superplasticizer has been added 30 seconds after the water and the mixing continued for 3 minutes as well.
After casting the specimens were stored at a constant temperature of 20 ± 2 °C and relative humidity of 95 ± 5 %. After 3 days the specimen were demoulded and stored in the same controlled environment until testing.
In this research program 5 different nominal diameters of the embedded reinforcement bars were chosen: 12, 20, 25, 32 and 40 mm. The nominal diameter ϕ, the yield stress f_y and tensile strength f_u as well as the maximum rib height and relative rib area f_R of the different reinforcing bars, are summarized in Table 2.

ϕ [mm]	f_y [N/mm²]	f_u [N/mm²]	Max rib height [mm]	f_R [-]
12	622	740	0,99	0.0473
20	641	750	1,90	0.0717
25	515	585	1,59	0.0454
32	530	643	2,54	0.0602
40	540	632	2,70	0.0665

Table 2: Characteristics of the Tested Reinforcing Bars

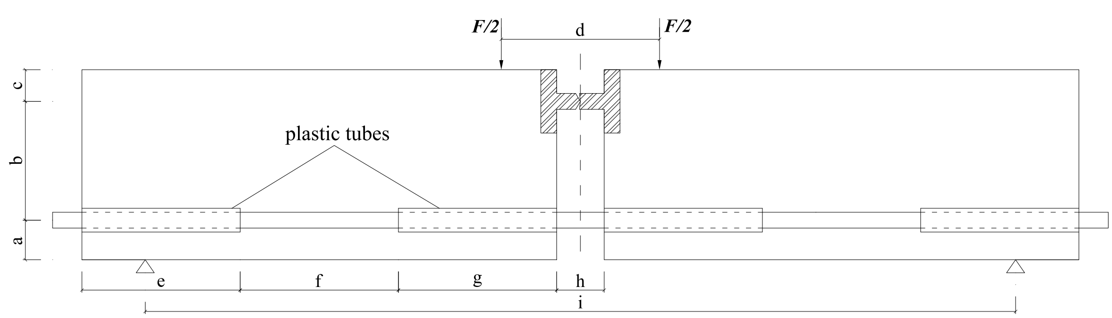
"Beam Test" Specimen

Three types of specimen were used according to the diameter tested. For bars diameter 12 mm a specimen type I and for bars diameter 20 and 25 mm a specimen type II has been used. For the largest diameters 32 and 40 mm an even larger specimen has been cast. The dimensions of the specimen can be seen in figure 1. All beams are composed of 2 parts or half-beams. At the bottom the tested reinforcing bar connects the 2 half-beams. While at the top a steel hinge is placed. This hinge has been secured to the beam 14 days before testing by using a traditional mortar.

The bond length has been limited to 5 times the bar diameter ϕ instead of 10 times as described in RILEM recommendations. The prescribed bond length, leads to rupture of the reinforcement bar before reaching the maximum bond strength, as described in earlier publications (6). The bond length has been controled by putting plastic tubes over the remaining parts of the bar.

In all cases the actual bond length started at 230 mm from the centre of the beam (200 mm inside the concrete) except for the type I specimen where the bond length started at a distance of 160 mm from the centre of the specimen. To limit the influence of the bar geometry, all bars are placed in the same way: the longitudinal ribs at mid-height.

To avoid splitting failure an auxiliary reinforcement cage consisting of plain mild steel bars has been placed according to RILEM RC6 part 1.



	ϕ [mm]	a [mm]	b [mm]	c [mm]	d [mm]	e [mm]	f [mm]	g [mm]	h [mm]	i [mm]
Type I	12	50	100	30	150	215 - 5.ϕ	5.ϕ	160	50	650
Type II	20 & 25	50	150	40	200	400 - 5.ϕ	5.ϕ	200	60	1100
Type III	32 & 40	75	200	55	200	670 - 5.ϕ	5.ϕ	200	60	1600

Figure 1: Dimensions of the Beam Test Specimen

Test Setup

During testing the specimens were loaded at a constant rate corresponding to an increase in steel stress of 30 N/mm². For all types of specimen, the actuator was positioned in the centre of the specimen and the total load F was transferred by means of a spreader steel profile to each half-beam. A pressure cell measured the load applied to the specimen during the test.

The slip of the bar, at its free end, was recorded using 3 linear variable differential transducers (LVDT) on both sides of the specimen. These LVDT's were secured to the bar by means of a steel collar.

Loading continued until the slip at one end of the specimen reached 3 mm. For the half-beam with 3 mm slip the bar was fixed in a clamping device so that the test could be continued without further slip at this side of the specimen. Loading continued until the slip at the second half of the specimen exceeded 3 mm as well.

RESULTS

Concrete Properties

The properties of the fresh and hardened concrete were determined. For the self-compacting concrete the slump flow and V-funnel time were measured before casting of the specimen. For the conventional vibrated concrete only the slump was measured.

The compressive and tensile strength of the concrete were determined at 28 days. For the compressive strength, cubes with sides of 150 mm were used (f_{ccub}) and cylinders with a height of 300 mm and a diameter of 150 mm (f_c). The splitting tensile strength $f_{ct,sp}$ and the flexural strength $f_{ct,fl}$ were measured on prisms with a length of 600 mm and a height of 150 mm. The mean results of all tests are summarized in table 3.

	CVC1	SCC1	SCC2
Slump (mm)	36	-	-
Slump flow (mm)	-	750	730
V-funnel (s)	-	11.9	13.2
f_{ccub} (N/mm²)	57.3	70.3	63.3
f_c (N/mm²)	50.7	65.1	57.0
$f_{ct,fl}$ (N/mm²)	6.0	6.9	6.5
$f_{ct,sp}$ (N/mm²)	3.8	4.8	4.2

Table 3: Properties of Fresh and Hardened Concrete

The self-compacting concrete SCC2 has a comparative compressive and tensile strength as the conventional vibrated concrete CVC1, as was intended. The first self-compacting concrete SCC1, with the same W/C ratio, has a significantly higher strength.

Bond Strength and Slip

For each specimen, 2 x 3 registrations of the slip versus bond stress have been made (3 LVDT's for both halves of the beam). Besides the maximum bond stress τ_R, the characteristic value of the bond stress has been calculated from the results. This characteristic value τ_M is defined as the average of the bond stresses at a slip of 0,01 mm;

0,1 mm and 1 mm. Out of the measurements the slip at maximum bond stress d_R can be determined. All results are summarized in table 4.

Mix	Bar diameter [mm]	τ_M [N/mm²]	τ_R [N/mm²]	d_R [mm]
CVC1	12	13.6	21.9	0.45
	20	13.0	19.4	0.54
	25	10.7	16.2	0.70
	32	9.6	18.0	1.64
	40	8.4	17.2	1.78
SCC1	12	17.7	27.7	0.34
	20	15.2	23.9	0.65
	25	12.2	19.3	1.01
	32	11.1	20.4	1.59
	40	9.7	19.8	1.74
SCC2	12	16.3	25.6	0.45
	20	13.4	21.5	0.64
	25	11.6	18.4	0.93
	32	10.6	19.7	1.40
	40	8.8	17.4	1.87

Table 4: Results of the Beam-Tests

Comparing the different types of concrete for the same bar diameter, CVC1 and SCC2 (which have almost the same compressive strength) have comparable values for the characteristic bond stress τ_M, except for bars diameter 12 mm where there is a significant difference between the 2 concretes. The difference for the maximum bond stress τ_R is somewhat larger. For all tests on SCC2, τ_R is above the maximum bond stress of CVC1.
When the bond-slip relations of the different concrete types are plotted for tests on specimen with a reinforcing bar with the same diameter, it can be seen that the bond strength of SCC1 is larger than those of SCC2 and CVC1 (as was expected due to the larger compressive strength) at all stress levels, resulting in a steeper curve. An example is given in figure 2 for a reinforcing bar with a diameter of 40 mm. The curves for SCC2 and CVC1 are almost identical for small amounts of slip, while the bond stress level for SCC1 for the same slip is higher.

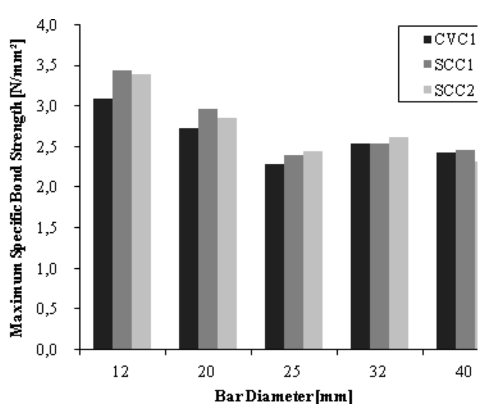


Figure 3: Comparison of the Maximum Specific Bond Strength for Different Mixes

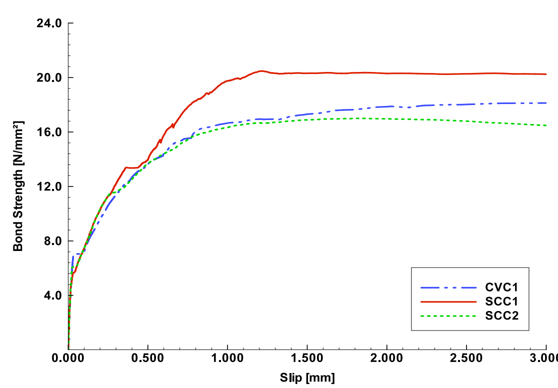


Figure 2: Bond–Slip Relation for Different Mixes and Bars diameter 40 mm

When results from all test are compared, it can be seen that an increase in the bar diameter means a decrease of τ_M and τ_R. As generally known the compressive strength has an influence on the bond properties of the concrete. Therefore in figure 2 the maximum specific bond stress, defined as the ratio of the maximum bond stress and the root of the compressive strength is plotted for all concrete mixes and tested bar diameters. The difference in specific bond strength for CVC and SCC is largest for bar diameters of 12 mm. The difference becomes smaller for higher bar diameters. There are no significant differences between the specific bond strength of SCC1 and SCC2.

By increasing the bar diameter, the slip at maximum bond stress is increasing in all cases. There is no significant difference that can be noticed between the results for self-compacting concrete and the results for conventional vibrated concrete.

CONCLUSSIONS

- From the results of the beam-tests, it can be seen that the bond strength of self-compacting concrete is as high as the bond strength for conventional vibrated concrete when large bar diameters are studied. For smaller bar diameters, the bond strength of SCC is slightly higher.
- For equal water to cement ratio the compressive strength of self-compacting concrete is higher (due to the limestone filler content), and so is the maximum and characteristic bond strength.
- The slip corresponding to the maximum bond strength is increasing for decreasing bar diameters.

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