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A local bond stress-slip model for reinforcing bars in self-compacting concrete

P. Desnerck, G. De Schutter & L. Taerwe
Ghent University, Ghent, Belgium

ABSTRACT: The force transfer in reinforced concrete is provided by the concrete-to-steel bond. This phenomenon has widely been studied for conventional vibrated concrete (CVC). For self-compacting concrete (SCC) however less test results are available. To fill in this lack 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 by means of "beam-test" specimens. During testing the bond stress-slip response was recorded. From the test results it can be seen that the maximum bond strength of SCC is slightly higher than for CVC when small bar diameters are studied. For larger bar diameters the difference becomes smaller. Comparison of the test data with bond models indicated that the bond clauses underestimated the bond strength for SCC as well as for CVC. Therefore an adjustment of the bond model has been made.

1 INTRODUCTION

Reinforced concrete is far from homogeneous. It is built up of steel and concrete and the concrete itself is not homogeneous neither. Reinforced concrete elements are basically designed so that the concrete can carry the compressive stresses and the steel can resist the tensile stresses. Therefore a good force transfer between the two materials is necessary which can only be achieved by an interaction between both materials, which is provided by bond between the reinforcement bars and the concrete.

The bond has an important influence on the behaviour of reinforced elements in the cracked stage. Crack widths and deflections are influenced by the distribution of bond stresses along the reinforcement bars and by the slip between the bar and the surrounding concrete.

Due to the importance of the interaction between steel and concrete a lot of research has been done in the past. In all these projects the main focus was on the reinforcement bar, its geometrical characteristics and how these characteristics influence the bond strength. With the appearance of new concrete types, such as steel-fibre reinforced concrete and high strength concrete, questions arose about the bond strength achieved with these concrete types, and the main focus of the research on bond shifted to the concrete and its composition (Martin 2002).

The same questions can be formulated for self-compacting concrete. A concrete type which, in fresh state, has the ability to flow under its own weight, fill the required space or formwork completely and produce a dense and adequately homogeneous material without a need for compaction (De Schutter et al. 2007). The advantages are clear: no need for vibration of the concrete, a higher quality of the finished element, reduced construction times, … . The self-compactability is achieved by adding a superplasticizer to the mixture and by reducing the amount of coarse aggregates. Although self-compacting concrete (SCC) is a relatively new material, already a lot of research has been done on the durability and the workability of the concrete type (De Schutter et al. 2008). Less studies have been focussing on the mechanical properties and more in particular the bond aspects.

Some programs have been carried out to determine the force transfer between concrete and reinforcement in self-compacting concrete. These studies show that the bond strength of steel in SCC is not lower than for conventional vibrated concrete (CVC), and may be even higher in some cases (Almeida et al. 2008, Chan et al. 2003, Zhu et al. 2004, Dehn et al. 2004). Nevertheless there is a great scatter in the results.

To get a better insight in the difference in bond strength between conventional vibrated concrete and self-compacting concrete and to develop modified models describing the bond stress-slip behaviour, this research program has been set up.

2 EXPERIMENTAL PROGRAM

The common way to test the bond strength of rebars in concrete is by means of pull-out tests (RILEM 1973). The behaviour of these types of specimens is quite different from that in reinforced elements subjected to bending.

The beam test specimen suggested by RILEM recommendation RC6 part 1 (RILEM 1973) is more suitable to evaluate the bond strength of reinforced elements subjected to bending. The specimen, consisting of 2 half-beams, is loaded on top introducing bending moments in the beam. In this way a more realistic stress distribution inside and around the bar is created.

2.1 *Materials*

Three types of concrete have been used: 2 powder-type self-compacting concretes and one conventional vibrated concrete. More details about the mixing procedure and the used materials can be found in (Desnerck 2008). The mix proportions and concrete strengths are summarized in Table 1.

Table 1. Mix design for SCC and CVC mixes.

Materials (kg/m³)	SCC1	SCC2	CVC1
CEM I 52,5 N	360	360	300
Sand 0/4 mm	853	853	640
Gravel 2/8 mm	263	263	462
Gravel 8/16 mm	434	434	762
Limestone filler	240	300	-
Water	165	165	165
Superplasticizer	3.6	3.0	-
f_{ccub} (N/mm²)	71.7	62.1	58.4
f_c (N/mm²)	63.7	57.5	51.8
$f_{ct,fl}$ (N/mm²)	7.2	6.8	6.2
$f_{ct,sp}$ (N/mm²)	5.0	4.4	4.1

The self-compacting concrete SCC2 has a comparable 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.

Besides the concrete type, the steel bar diameter has been varied. In this research program, 5 different nominal diameters of the embedded reinforcement bars were chosen: 12, 20, 25, 32 and 40 mm.

2.2 *Specimen details*

To test the bond strength of reinforcing bars in the different concrete types, the standard "beam-test" geometry, as described in the RILEM recommendation, is used. The specimen dimensions depend on the bar size. Three types of specimen are used depening on the bar diameter. A type I specimen is used for tested reinforcing bars with a diameter smaller than 16 mm. A type II is used for bars between 16 mm en 32 mm, and a third type is used for bars equal to or larger than 32 mm. An example is given for a type I specimen (Fig. 1).

The prescribed bond length is 10 times the bar diameter ϕ. However this leads to yielding, and in some cases even rupture, of the reinforcement bar before reaching the ultimate bond strength. Therefore most of the specimens are cast with a bond length of 5 times ϕ.

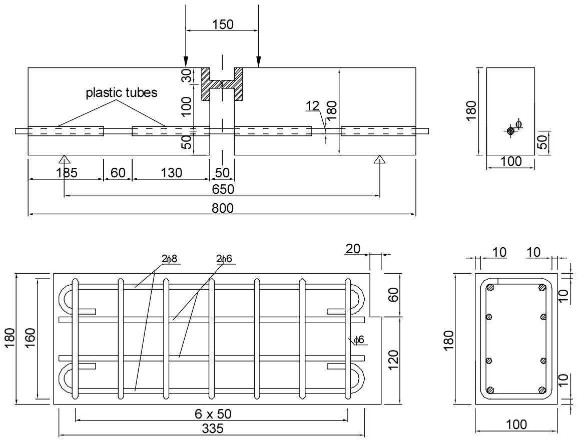

Figure 1. Size and reinforcement of beam test specimen type I (dimensions in mm).

2.3 *Testing procedure*

During the tests, the specimens were loaded at a constant rate corresponding to an increase in steel stress of 30 N/mm² per minute.

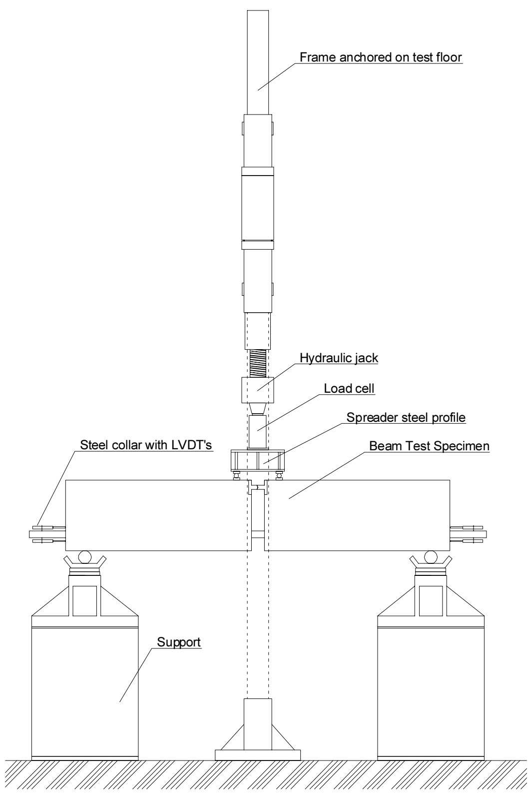

Figure 2. Test set-up for beam test specimen.

For all specimen types, the actuator was positioned in the centre of the specimen and the total load P was transferred by means of a spreader steel profile to each half-beam (Fig. 2). A load 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.

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.

2.4 *Test results*

From the obtained test results, values of the bond stress along the surface of the bonded reinforcing bar can be derived. The formulas to calculate the total force acting in the reinforcing bar depends on the geometry of the specimen used.

The mean bond stress can be calculated by assuming the force F_s in the reinforcing bar to be transferred to the concrete in the cylindrical zone of the embedment length l_d:

$$\tau_d = \frac{F_s}{l_d.\pi.\phi} = \frac{\sigma_s}{4.k} \qquad (1)$$

by writing l_d as $k.\phi$ and σ_s the tensile stress in the reinforcing bar. This stress is, as mentioned earlier, a function of the applied total load P and the geometry of the specimen.

$$\sigma_s = \beta.\frac{P}{A_s} \qquad (2)$$

The factor β can be determined from the specimens dimensions and has a value of 1.25 for specimen type I (diameter 12 mm), 1.50 for specimen type II (diameters 20 and 25 mm) and 1.75 for specimen type III (diameters 32 and 40 mm).

Two values are of major interest: the ultimate bond strength τ_R and the so-called characteristic bond strength τ_M. The ultimate bond strength is defined as the bond stress corresponding to the ultimate load recorded during testing. The characteristic bond strength is calculated as the mean value of the bond stresses corresponding to a slip of 0.01 mm, 0.10 mm and 1.00 mm. Both values differ for the two halves of the specimen.

2.4.1 *Influence of the concrete type*

The main goal of the study is to compare bond strengths for self-compacting concrete with those for conventional vibrated concrete. In figure 3 one of the recorded bond stress – slip curves (mean of 4 measurements) is plotted for bar diameter 20 mm and different concrete compositions. In table 2 the values of the characteristic bond strength and the ultimate bond strength are given for all specimen types as well as the standard deviation (DEV).

Table 2. Test results for beam tests with bond length of 5ϕ.

	τ_M [N/mm²]	DEV [N/mm²]	τ_R [N/mm²]	DEV [N/mm²]
SCC1-12	18.13	0.99	27.82	3.17
SCC1-20	14.94	0.77	24.07	1.84
SCC1-25	12.80	0.81	19.39	1.27
SCC1-32	11.24	0.59	20.49	1.07
SCC1-40	9.71	0.55	19.86	0.93
SCC2-12	15.77	1.47	25.70	2.93
SCC2-20	13.31	0.25	21.54	1.56
SCC2-25	12.10	0.29	18.60	2.03
SCC2-32	10.65	0.28	19.77	0.85
SCC2-40	8.81	0.29	17.48	0.44
CVC1-12	13.45	0.73	19.88	0.75
CVC1-20	12.96	0.53	19.46	0.82
CVC1-25	11.14	0.94	16.28	1.50
CVC1-32	9.67	0.28	18.10	1.00
CVC1-40	8.13	1.22	16.61	2.09

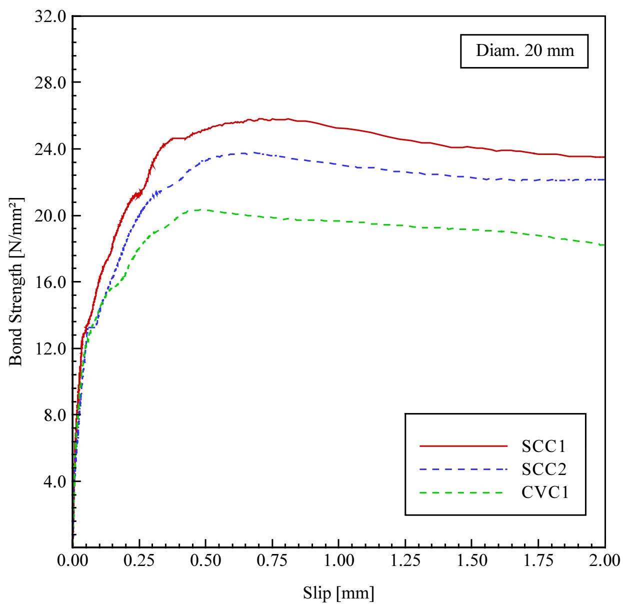

Figure 3. Bond stress – slip diagram for bar diameters 20 mm.

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 bar diameters 12 mm for which a significant difference between the 2 concretes is noticed. The difference for the ultimate bond stress τ_R is somewhat larger. For all tests on SCC2, τ_R is above the ultimate bond stress of CVC1.

When the bond stress-slip relations of the different concrete types are plotted for tests on specimen with a reinforcing bar of 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 higher compressive strength) at all stress levels, resulting in a steeper curve. For bar diameters of 40 mm the curves for SCC2 and CVC1 are almost identical for small slip values, while the bond stress level for SCC1 for the same slip is higher. For all other diameters, the bond stresses for the SCC2 specimens are higher for the same slip as recorded for the CVC1 specimens. In some cases the stresses even approach the values for SCC1.

2.4.2 *Influence of the bar diameter*

When the results of all test are compared, it can be seen that an increase in the bar diameter results in a decrease of τ_M and τ_R. As the concrete strength influences the bond properties of the concrete, the bond stress is normalised by the root of the compressive strength:

$$\tau_{R,n} = \frac{\tau_R}{\sqrt{f_c}} \tag{3}$$

In Figure 4, $\tau_{R,n}$ is plotted for all concrete mixes and tested bar diameters.

The differences in the normalized ultimate bond strength for the conventional vibrated concrete and the self-compacting concrete is largest for bar diameters of 12 mm. The difference becomes smaller for higher bar diameters, but the results for self-compacting concrete are higher in all cases. There are no significant differences between the normalized ultimate bond strength of SCC1 and SCC2, except in case of a 40 mm reinforcement bar.

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

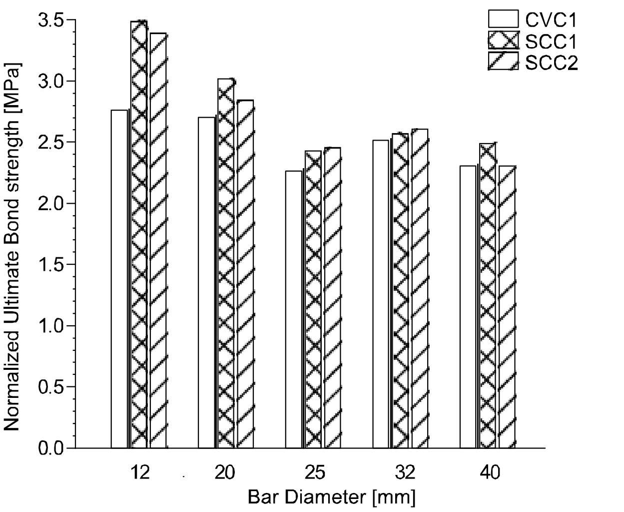

Figure 4. Normalized ultimate bond strength for different diameters and concrete compositions.

2.4.3 *Crack pattern*

After testing the crack pattern appearing on the surface of the specimen was recorded. No big differences between the crack pattern for CVC1 and the self-compacting concretes SCC1 and SCC2 were noticed. In almost all cases the crack pattern was limited to the zone in which actual bond between the reinforcing bar and the concrete was possible, so along the bonding length.

An example of one of the crack patterns of the specimen is given in Figure 5.

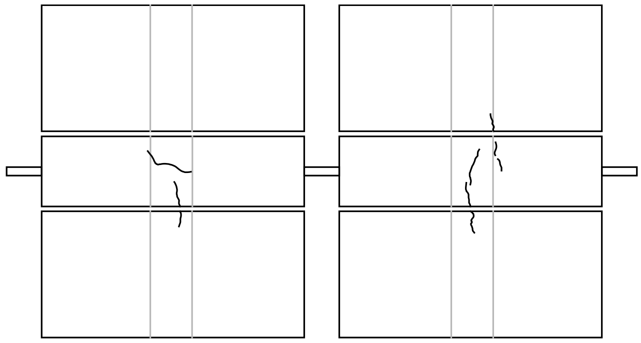

Figure 5. Crack pattern for one of the specimen of CVC1 with bars 12 mm diameter.

3 PREDICTION MODELS

In literature a lot of models to predict the ultimate bond strength, corresponding slip and equations to describe the bond stress-slip behaviour can be found. In these models several parameters such as bar diameter, concrete cover, concrete compressive strength, … are incorporated.

All equations have been established by linear or non-linear regression on test results with varying parameters, but mostly for conventional vibrated concretes with compressive strengths in the range between 20 and 50 MPa. Few tests have been done on high strength concretes with compressive strengths above 60 MPa. The compressive strengths of the concretes used in this research project are all around 60 MPa or higher for the SCC1 mixture.

3.1 *Bond stress – slip relation*

A model for the bond stress- slip behaviour is required to be able to make calculations of the crack pattern, crack widths, … . Therefore a relationship has been proposed in the Ceb-Fib Model Code 1990 (Fig. 6). It consists of an increasing first branch up to the ultimate bond stress. This branch is followed by a plateau during which slip is increasing for constant bond stress, after which bond stress starts to decrease for increasing slip values. Finally a constant residual bond strength is reached which is due to pure friction between the reinforcing bar with the cracked concrete lugs and the surrounding concrete:

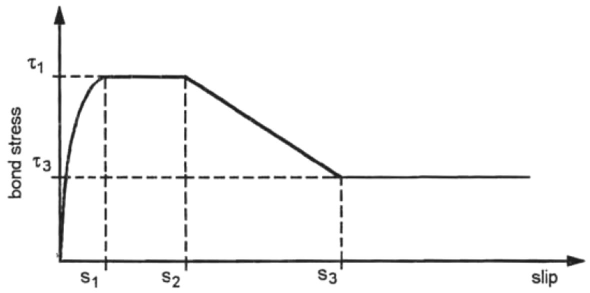

Figure 6. Prediction model for the bond stress – slip relationship according to MC90 and Huang et al.

$$\tau = \tau_1 . \left(\frac{s}{s_1}\right)^{\alpha} \quad \text{for} \quad 0 \le s \le s_1 \qquad (4)$$

$$\tau = \tau_1 \qquad s_1 < s \le s_2 \qquad (5)$$

$$\tau = \tau_1 - (\tau_1 - \tau_3) . \left(\frac{s - s_2}{s_3 - s_2}\right) \qquad s_2 < s \le s_3 \qquad (6)$$

$$\tau = \tau_3 \qquad s_3 < s \qquad (7)$$

The parameters in this model have been prescribed in the code for confined and unconfined normal strength concrete with good or other bond conditions. Huang et al. (1993) proposed values for the parameters for normal and high strength concrete under good bond conditions (Table 3 and 4).

Table 3. Values for the prediction equations according to Ceb-Fip MC90 (1999) for good bond conditions.

	Confined concrete	Unconfined concrete
s_1	1.0 mm	0.6 mm
s_2	3.0 mm	0.6 mm
s_3	distance betw. ribs	1.0 mm
α	0.4	0.4
τ_1	2.5 $\sqrt{f_c}$	2.0 $\sqrt{f_c}$
τ_3	0.4 τ_1	0.15 τ_1

Table 4. Values for the prediction equations according to Huang et al. (1996) for good bond conditions.

	High strength concrete	Normal strength concrete
s_1	0.5 mm	0.6 mm
s_2	1.5 mm	0.6 mm
s_3	distance betw. ribs	1.0 mm
α	0.3	0.4
τ_1	$0.4.f_{cm}$	$0.4.f_{cm}$
τ_3	0.4 τ_1	0.4 τ_1

Both models (CEB-Fip confined concrete and Huang high strength concrete) are compared with the measured bond stress-slip behaviour of the specimen (Figs. 7 to 9). It can be seen that the predicted values calculated with the Huang-model for high strength concrete overestimate the bond strength in all cases. For the MC90-model, the values are underestimated for small diameters and in the range of the measured values for larger bar diameters.

The bar diameter has also an influence on the slip corresponding with the ultimate bond strength as can be seen on the graphs. Both models however have fixed values of this slip value regardless the bar diameter.

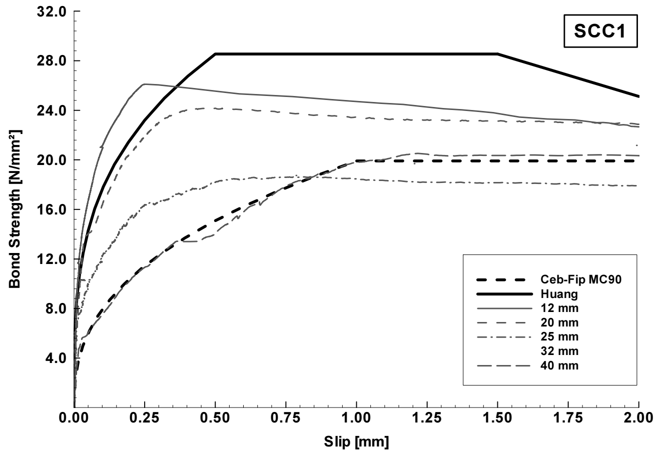

Figure 7. Comparison of measured bond stress –slip behaviour for SCC1 with prediction models.

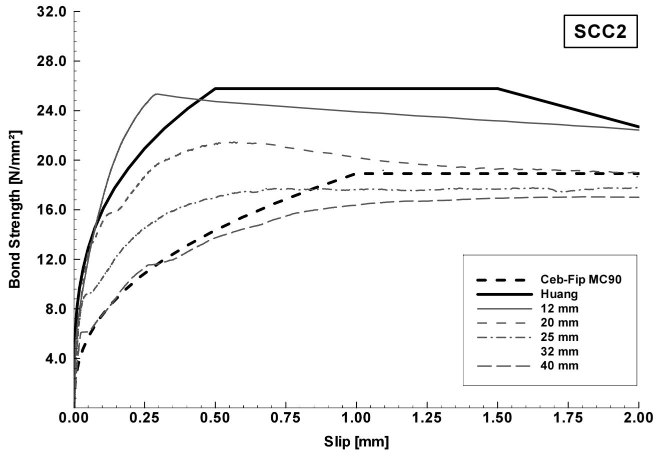

Figure 8. Comparison of measured bond stress –slip behaviour for SCC2 with prediction models.

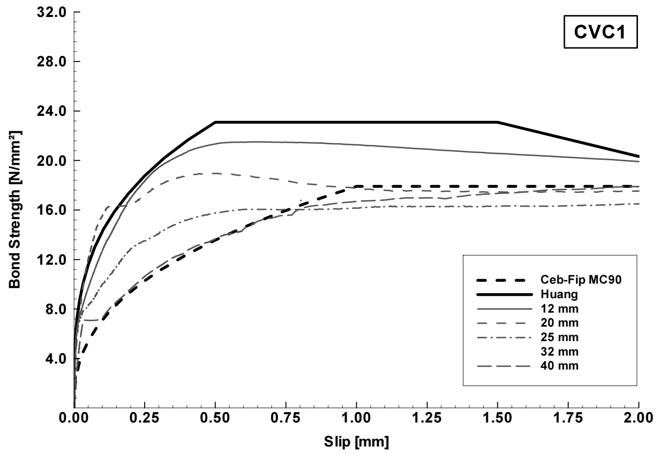

Figure 9. Comparison of measured bond stress –slip behaviour for CVC1 with prediction models.

Out of this it can be concluded that the models should be modified to take in to account the effect of the bar diameter.

3.2 *Maximum bond strength*

To get a better prediction of the ultimate bond strength more sophisticated models are necessary. Some of the models to predict the ultimate bond strength are show in table 5 with the used unit system. Key parameters in these equations are the ratio of the concrete cover c to the bar diameter ϕ, the ratio of the bar diameter to the bond length l_d and the root of the compressive strength f_c.

Table 5. Prediction models for bond strength.

Author	Equation	Units
Eligehausen	$\tau_R = 0.75.\ \sqrt{c/\phi}\ .\ \sqrt{f_c}$	SI
Esfahani*	$\tau_R = 4.73.[(c/\phi)+0.5]/[(c/\phi)+5.5].\ \sqrt{f_c}$	SI
Harajli	$\tau_R = [1.2+3.\ (c/\phi)+50.\ (\phi/l_d)].\sqrt{f_c}$	Psi
Huang**	$\tau_R = 0.45.f_{cm}$	SI
Orangun	$\tau_R = [1.22+3.23.\ (c/\phi)+53.\ (\phi/l_d)].\sqrt{f_c}$	Psi
MC 90	$\tau_R = 2.5.\sqrt{f_{ck}}$	SI

* Equation is valid for $f_c > 50$ MPa
** Equation is valid for f_c between 60 and 120 MPa

In figures 10 to 12 a comparison is made between the obtained values and the predicted ones for the different concrete mixes in a bond stress versus bar diameter diagram. It shows an underestimation of the ultimate bond strength in all cases, except for the Huang model (1996) which is developed for high strength concrete. The predicted value is sometimes only 40% of the recorded one. Some models give bond strengths independently from the bar diameter, others seems to predict the trend quite good but give values that are too low, e.g. the models by (Orangun et al. 1977; Harajli 1994). Therefore the coefficients out of the Orangun-model have been re-determined by linear regression based on the obtained results.

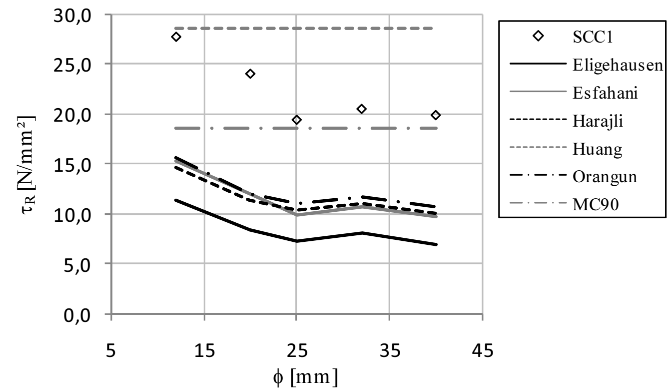

Figure 10. Bond strength versus bar diameter – comparison of models and test results for SCC1.

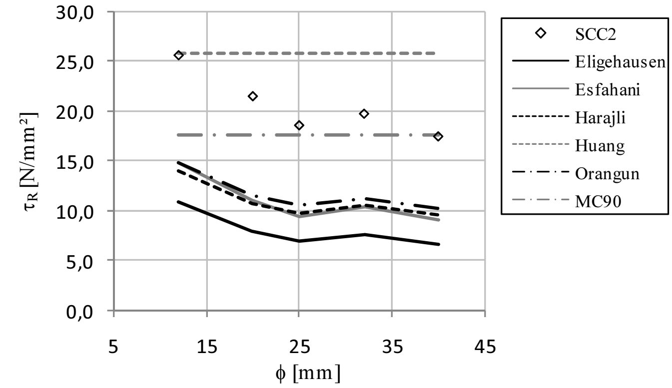

Figure 11. Bond strength versus bar diameter – comparison of models and test results for SCC2.

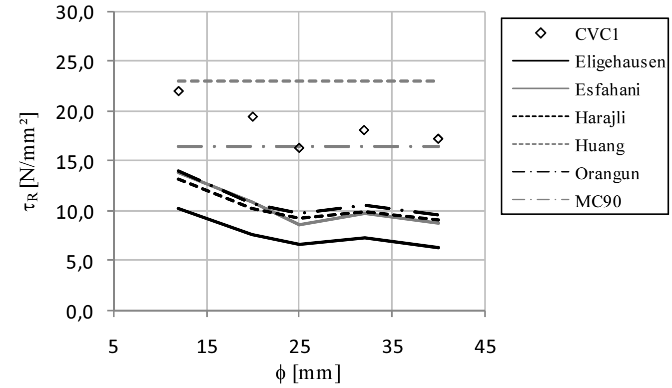

Figure 12. Bond strength versus bar diameter – comparison of models and test results for CVC1.

Due to the fact that the bond length has been kept constant in these test, the term with l_d becomes constant. The determined coefficients for both self-compacting concretes were almost identical, but the coefficients for the conventional vibrated concrete differed. The new equations are given in Table 6. The good correlation between the predicted and the measured bond strengths can be noticed in Figure 13 (for SCC mixtures).

Table 6. Modified prediction models for bond strength.

Concrete type	Equation	Units
SCC	$\tau_R = [1.77+0.49.(c/\phi)].\sqrt{f_{cm}}$	SI
CVC	$\tau_R = [1.87+0.35.(c/\phi)].\sqrt{f_{cm}}$	SI

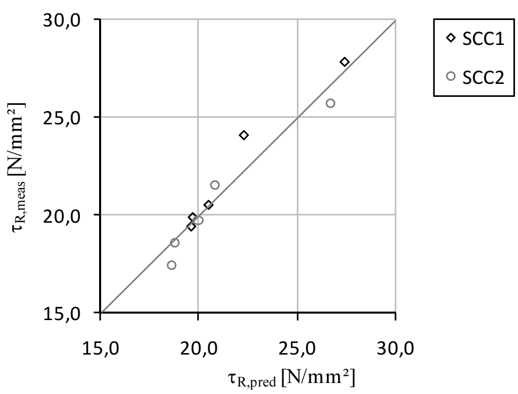

Figure 13. Correlation between measured values and predicted values for SCC with the modified equations.

3.3 *Slip corresponding to maximum bond strength*

As can be seen in Figure 7, the slip corresponding to the moment of maximum bond strength is influenced by the reinforcing bar diameter. For smaller diameters the maximum bond strength is larger but the slip is smaller.

In the bond model out of MC90, no influence of the bar diameter on the value of s_1 is noticed, although it is clearly present in the experimental results. Most authors suggest a fixed value for s_1, while others suggest values that depend on the clear rib spacing c_0. Some of the values for confined reinforcing bars are summarized in Table 7.

Table 7. Prediction models for bond strength.

Author	Equation	Units
Harajli	$s_1 = 0.15\ c_0$	SI
Huang	$s_1 = 1.0$ mm (normal strength concrete)	SI
	$s_1 = 0.6$ mm (high strength concrete)	SI
MC 90	$s_1 = 1.0$ mm	SI
Oh	$s_1 = 1.04$ mm	SI

A comparison between the predicted values for s_1 and the experimental determined values is given in Figure 13.

None of the models gives a good prediction of the slip corresponding with the maximum bond strength. The clear rib spacing, which is increasing for increasing bar diameters, is influencing the slip values. No big differences are noticed between self-compacting and conventional concrete (except for bars diameter 40 mm), as well as no significant difference can be seen between the values for SCC1 compared to the values of SCC2 and CVC1. So it can be concluded that the concrete type (SCC or CVC) and the compressive strength of the concrete does not have an influence on s_1.

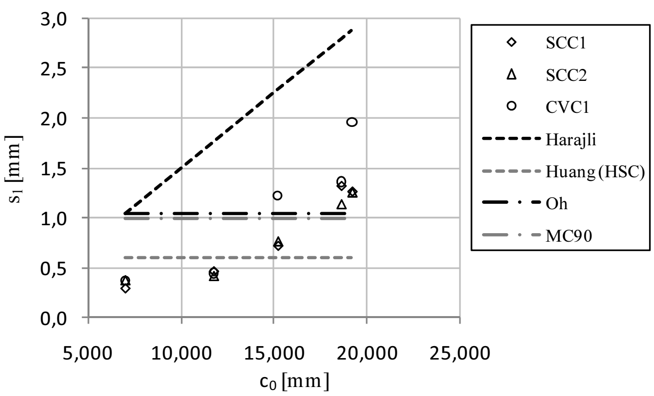

Figure 13. Clear rib spacing versus slip s_1 – comparison of models and test results.

A regression analysis has been performed to determine a good relationship between the clear rib spacing c_0 of the tested reinforcing bar and the observed slip corresponding to the maximum bond strength:

$$s_1 = c_0.(0.0035c_0 + 0.006) \tag{8}$$

The new proposed equation is plotted in Figure 14 together with the obtained test results.

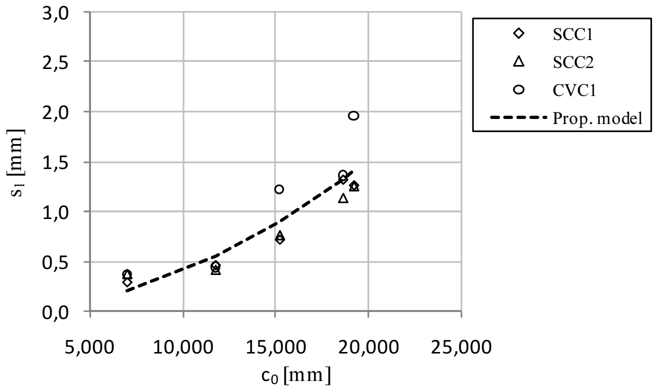

Figure 14. Clear rib spacing versus slip s_1 – Comparison of test results with new proposed model.

The equations of Table 6 and the equation (8) can now be used in the MC90 model (equation 4 till 7) to replace the expressions for τ_1 and s_1.

4 CONCLUSIONS

Based on the obtained results, the following conclusions can be made:

a. 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, with the largest difference occuring for the smallest bar diameters.

b. For equal water to cement ratio the compressive strength of the powder-type self-compacting concrete is higher (due to the limestone filler content), and so are the maximum and characteristic bond strengths.

c. The slip corresponding to the maximum bond strength is increasing for increasing bar diameters.

Considering the bond models, the following can be concluded:

a. The bond stress-slip model out of MC90 does not implement the influence of the bar diameter, resulting in a model that underestimates the ultimate bond strength for small bar diameters and approaches the values for τ_R for large bar diameters.

b. The bond stress – slip model does not take into account the influence of the bar diameter on the slip corresponding with the ultimate bond strength.

c. Almost all existing models for predicting the ultimate bond strength underestimate the actual value for SCC as well as for CVC

d. Almost all models neglect the influence of the clear rib spacing on the slip corresponding with the ultimate bond strength.

e. A modification can be made to the models to get a better prediction of the ultimate bond strength, as discussed.

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