# A COMPARISON OF THE BOND CHARACTERISTICS IN CONVENTIONAL AND SELF-COMPACTING CONCRETE, PART II: CODE PROVISIONS AND EMPIRICAL EQUATIONS

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**Abstract**

Self-compacting concrete (SCC) is a highly workable concrete that flows through complex structural elements under its own weight. It is cohesive enough to fill the spaces of almost any size and shape without segregation or bleeding. This makes SCC become more practical wherever concrete placing is difficult, such as in heavily-reinforced concrete members or in complicated formworks. Bond behaviour between concrete and reinforcement is a primary factor in design of reinforced concrete structures. This study presents a comparison between code provisions and empirical equations with the experimental results from the recent studies on the bond strength of SCC and conventional concrete (CC). The comparison is based on the measured bond between reinforcing steel and concrete by utilizing the pullout test on the embedded bars at various heights in mock-up structural elements to assess the top-bar effect and on single bars in small prismatic specimens; and conducting the beam tests. The investigated varying parameters on bond strength are: the steel bar diameter, concrete compressive strength, concrete type, curing age of concrete and height of the embedded bar along the formwork.

## 1. INTRODUCTION

Self-compacting concrete (also known as self-consolidating concrete) is a highly flowable, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical compaction [1]. While being highly flowable, SCC needs to be sufficiently cohesive to prevent segregation or blockage of aggregates during flowing. The enhanced cohesiveness can ensure better suspension of solid particles in the fresh concrete and therefore, good deformability and filling capability during the spread of fresh concrete through various obstacles [2-3].

However, the modified composition of SCC in comparison with CC may have some consequences on the properties of the hardened concrete. It is therefore important to ensure that all the assumptions and test results on which the structural design models are based for CC construction are also valid for SCC construction. One of the important properties of the hardened concrete is its bond capacity with the reinforcing steel. The bond strength between reinforcement and concrete is a basic phenomenon which allows reinforced concrete to behave as a structural material. Forces are transferred between the two materials by two types of actions, those that are physicochemical (adhesion) and those that are mechanical (friction and bearing action), which are activated by various states of stress. To a large extent, the relative importance of those actions depends on the surface texture and the geometry of the bars [4]. In addition, there are other factors that may influence the bond behaviour of the reinforcement. For instance those that have to do with the quality of the concrete. So, change in the mix design or the placing of the material can lead to change in the physical and mechanical properties of the material [5-6] and hence affect the steel-to-concrete bond. It has been discovered that in CC, when its fluidity is increased or sand-rich mixes are used, its bond deteriorates [7].

This study presents a comparison between code provisions and developed empirical equations with the experimental results from the recent studies on the bond strength of SCC and conventional concrete (CC). The comparison is based on the measured bond between reinforcing steel and concrete by utilizing the pullout test on the embedded bars at various heights in mock-up structural elements to assess the top-bar effect and on single bars in small prismatic specimens; and conducting the beam tests.

## 2. DATABASE FOR BOND CHARACTERISTICS MODELS

In the literature there are several analytical and numerical models which try to represent the bond stress response in the steel-concrete interface. These models that most of them based on experimental results have investigated the concrete compressive strength, concrete cover, steel bar diameter and embedment length have provided equations to calculate the average bond strength by means of linear or non-linear regressions. Table 1 shows some of the empirical equations that try to represent the bond behaviour and the code provisions used for evaluating the bond strength without transverse reinforcement. The influence of the transverse reinforcement is considered as a sum with the bond strength without reinforcement with the increase of the bond strength by the amount of stirrups in the bonded zone.

Table 1: Analytical bond models

| Reference | Bond strength equation | Units |
|---|---|---|
| Orangun et al. [8] | $\tau_u = \left[1.22 + 3.23\frac{c}{d_b} + 53\frac{d_b}{l_d}\right]\sqrt{f_c'}$ | Psi units |
| Kemp and Wilhelm [9] | $\tau_u = \left[0.55 + 0.24\frac{c}{d_b}\right]\sqrt{f_c'} + 0.191\frac{A_t\, f_{yt}}{s\, d_b}$ | SI units |
| Kemp [10] | $\tau_u = 232.2 + 2.716\frac{c}{d_b}\sqrt{f_c'}$ | Psi units |
| Chapman and Shah [11] | $\tau_u = \left[3.5 + 3.4\left(\frac{c}{d_b}\right) + 57\left(\frac{d_b}{l_d}\right)\right]\sqrt{f_c'}$ | Psi units |
| CEB-FIP [12] and Huang et al. [13] * | $\tau = \begin{cases} \tau_{\max}(s/s_1)^{\alpha} & 0 \le s \le s_1 \\ \tau_{\max} & s_1 < s \le s_2 \\ \tau_{\max} - (\tau_{\max} - \tau_u)(s - s_2/s_3 - s_2) & s_2 < s \le s_3 \\ \tau_u & s_3 < s \end{cases}$ | SI units |
| Harajli [14] | $\tau_u = \left[1.2 + 3\left(\frac{c}{d_b}\right) + 50\left(\frac{d_b}{l_d}\right)\right]\sqrt{f_c'}$ | Psi units |
| Pillai et al. [15] | $\tau_u = \left[0.1 + 0.25\frac{c}{d_b} + 4.2\frac{d_b}{l_d} + 0.024\frac{A_{tr}\, f_{yt}}{s\, d_b}\right]\sqrt{f_c'}$ | SI units |
| Barbosa [16] | $\tau_u = 19.36\, s^{0.51}\, (f_c' < 50\, MPa)$, $\tau_u = 32.58\, s^{0.48}\, (f_c' \ge 50\, MPa)$ | SI units |
| Harajli et al. [17] | $\tau_{\max,\,plain} = 0.75\sqrt{f_c'}\left(\frac{c}{d_b}\right)^{2/3}$ | SI units |
| Bae [18] ** | $\tau_{\max} = A\left(\frac{c}{d_b}\right)^{B} \times (f_c')^{\alpha}$, $\alpha = \begin{cases} 0.58 & Deformed\ \mathrm{Re}bar \\ 0.21 & Plain\ \mathrm{Re}bar \\ 0.45 & GFRP\ \mathrm{Re}bar \end{cases}$, embedment length $<15\, d_b$ in mm | SI units |

*

| CEB-FIP [12] | Confined concrete | Unconfined concrete | Huang et al. [13] | High strength concrete | Normal strength concrete |
|---|---|---|---|---|---|
| $s_1$ (mm) | 1.0 | 0.6 | $s_1$ (mm) | 0.5 | 1 |
| $s_2$ (mm) | 3.0 | 0.6 | $s_2$ (mm) | 1.5 | 3 |
| $s_3$ (mm) | Distance between ribs | 1.0 | $s_3$ (mm) | Distance between ribs | Distance between ribs |
| $\alpha$ | 0.4 | 0.4 | $\alpha$ | 0.3 | 0.4 |
| $\tau_{\max}$ | $2.5\sqrt{f_c'}$ | $2.0\sqrt{f_c'}$ | $\tau_{\max}$ | $0.4\, f_{cm}$ | $0.4\, f_{cm}$ |
| $\tau_u$ | $0.4\ \tau_{\max}$ | $0.15\ \tau_{\max}$ | $\tau_u$ | $0.4\ \tau_{\max}$ | $0.4\ \tau_{\max}$ |

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| | LWSCC | | | NWSCC |
|---|---|---|---|---|
| Constant | Deformed | GFRP | Plain | Deformed |
| A | 0.85 | 0.48 | 0.3 | 0.74 |
| B | 0.17 | 0.68 | 0.88 | 0.52 |

## 3. RESULTS AND DISCUSSIONS

Table 2 summarizes comparison of the bond strength experimental results of the Zhu et al. [19], Almeida Filho et al. [20], Hossain and Lachemi [21] and Lachemi et al. [22] with predicted bond strength by using Orangun et al. [8], Kemp and Wilhelm [9], Kemp [10], Chapman and Shah [11], Harajli [14], Pillai et al. [15] and Bae [18] models.

The comparison between Zhu et al. [19] bond stress from experimental results with predicted bond stress by using available models show that, for $d_b$=12 mm, $l_d$=120 mm the Bae model [18] shows good agreement with the experimental results although the Chapman and Shah [11] have been predicted good results too. Also, for $d_b$=20 mm, $l_d$=120 mm the Chapman and Shah [11] predicted bond stress is more accurate comparing with the experimental results. The predicted results of other models are underestimated bond stress.

Comparison of the pullout tests for $d_b$=10mm, $l_d$=50 mm and $d_b$=16mm, $l_d$=80 mm experimental results of Almeida Filho et al. [20] with bond stress models are shown that the Orangun et al. [8], Chapman and Shah [11] and Bae [18] models have more accurate predictions while the predictions of Chapman and Shah [11] overestimate the results. The other models underestimate the bond stress mostly. Also, comparison of the beam tests for $d_b$=10mm, $l_d$=100 mm and $d_b$=16mm, $l_d$=160 mm with experimental results of Almeida Filho et al. [20] are shown that the Orangun et al. [8], Chapman and Shah [11] and Bae [18] models have good results but the predictions of Orangun et al. [8] model underestimates and the predictions of Bae [18] model overestimates. Comparison of the bond stress at the bottom (left, right and middle) of the Hossain and Lachemi [21] horizontal specimens with the bond stress models are shown that Orangun et al. [8], Chapman and Shah [11], Harajli [14], Pillai et al. [15] and Bae [18] models have been predicted the good results but the Chapman and Shah [11] model overestimate and the Bae [18] is underestimation. For the horizontal specimens bond stress at the top (left, right and middle) experimental result and vertical specimens (top, middle and bottom) bond stress with comparing with models, the comparisons show that Orangun et al. [8], Chapman and Shah [11], Harajli [14], Pillai et al. [15] and Bae [18] models predict good results but the Orangun et al. [8] and Chapman and Shah [11] models are overestimation and the Bae [18] underestimates the results.

Figure 1 to 3 show the comparison of the bond-slip models between the Valcuende and Parra [4], Hassan et al. [23] and Desnerck et al. [24] experimental results.

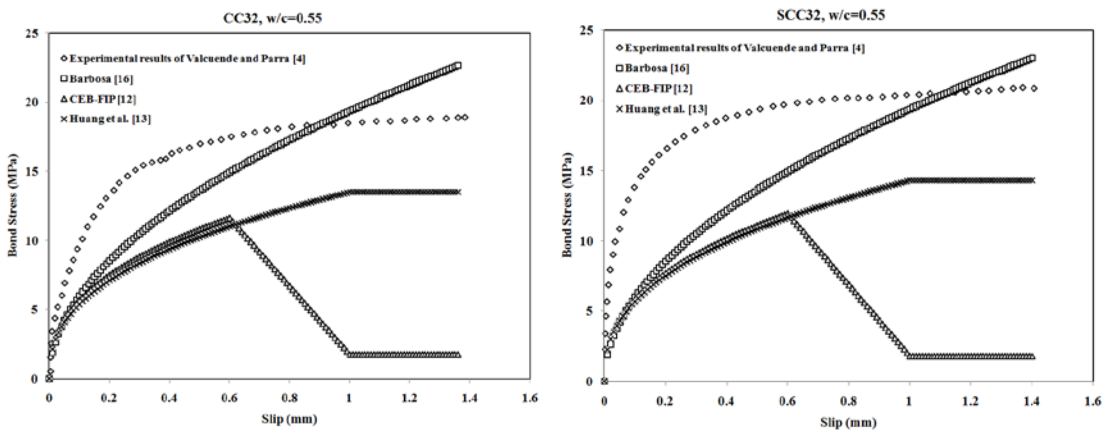


Figure 1: Comparison of the bond-slip models with Valcuende and Parra [4] results

Table 2: Comparison of experimented bond stress with predicted bond stress by using models

| Bond Stress (MPa) | | | | | |
|---|---|---|---|---|---|
| **Zhu et al. [19]** | | **CC35** | **SCC35** | **CC60** | **SCC60** |
| $d_b$=12 mm, $l_d$=120 mm | | 11.18 | 13.73 | 23.41 | 34.08 |
| Predicted Bond Stress (MPa) | Orangun et al. [8] | 8.05 | 9.07 | 10.38 | 11.8 |
| | Kemp and Wilhelm [9] | 7.6 | 8.56 | 9.8 | 11.14 |
| | Kemp [10] | 5.6 | 1.6 | 6.75 | 7.46 |
| | Chapman and Shah [11] | 9.65 | 10.88 | 12.44 | 14.15 |
| | Harajli [14] | 7.55 | 8.51 | 9.73 | 11.06 |
| | Pillai et al. [15] | 7.59 | 8.56 | 9.79 | 11.13 |
| | Bae [18] | 10.48 | 12.04 | 14.07 | 16.33 |
| $d_b$=20 mm, $l_d$=120 mm | | 8.98 | 24.41 | 10.55 | 32.52 |
| Predicted Bond Stress (MPa) | Orangun et al. [8] | 7.52 | 8.48 | 9.7 | 11.03 |
| | Kemp and Wilhelm [9] | 5.53 | 6.23 | 7.13 | 8.11 |
| | Kemp [10] | 3.65 | 3.92 | 4.25 | 4.61 |
| | Chapman and Shah [11] | 9.14 | 10.3 | 11.78 | 13.4 |
| | Harajli [14] | 7.08 | 7.98 | 9.13 | 10.38 |
| | Pillai et al. [15] | 7.14 | 8.05 | 9.21 | 10.47 |
| | Bae [18] | 7.41 | 8.52 | 9.96 | 11.56 |
| **Almeida Filho et al. [20]** | | **CC1** | **SCC1** | **CC2** | **SCC2** |
| Pullout test, $d_b$=10mm, $l_d$=50 mm | | 11.56 | 14.34 | 17.05 | 18.11 |
| Predicted Bond Stress (MPa) | Orangun et al. [8] | 12.29 | 12.66 | 16.2 | 17.28 |
| | Kemp and Wilhelm [9] | 9.03 | 9.3 | 11.91 | 12.7 |
| | Kemp [10] | 6.99 | 7.16 | 8.71 | 9.18 |
| | Chapman and Shah [11] | 14.15 | 14.58 | 18.67 | 19.9 |
| | Harajli [14] | 11.52 | 11.87 | 15.19 | 16.2 |
| | Pillai et al. [15] | 11.6 | 11.95 | 15.3 | 16.31 |
| | Bae [18] | 12.12 | 12.54 | 16.7 | 17.99 |
| Pullout test, $d_b$=16mm, $l_d$=80 mm | | 10.75 | 12.93 | 21.94 | 19.23 |
| Predicted Bond Stress (MPa) | Orangun et al. [8] | 11.89 | 12.24 | 15.67 | 16.71 |
| | Kemp and Wilhelm [9] | 8.67 | 8.93 | 11.44 | 12.19 |
| | Kemp [10] | 6.66 | 6.81 | 8.27 | 8.71 |
| | Chapman and Shah [11] | 13.73 | 14.15 | 18.11 | 19.31 |
| | Harajli [14] | 11.15 | 11.49 | 14.7 | 15.68 |
| | Pillai et al. [15] | 11.23 | 103.48 | 16.15 | 15.79 |
| | Bae [18] | 11.72 | 12.13 | 16.15 | 17.4 |
| Beam test, $d_b$=10mm, $l_d$=100 mm | | 13.44 | 11.45 | 16.55 | 16.86 |
| Beam test, $d_b$=16mm, $l_d$=160 mm | | 13.2 | 11.58 | 16.95 | 17.25 |
| Predicted Bond Stress (MPa) | Orangun et al. [8] | 11.26 | 11.6 | 14.85 | 15.83 |
| | Kemp and Wilhelm [9] | 10.47 | 10.78 | 13.8 | 14.72 |
| | Kemp [10] | 8.34 | 8.55 | 10.49 | 11.08 |
| | Chapman and Shah [11] | 13.01 | 13.41 | 17.16 | 18.29 |
| | Harajli [14] | 10.53 | 10.85 | 13.88 | 14.8 |
| | Pillai et al. [15] | 10.59 | 10.91 | 13.96 | 14.88 |
| | Bae [18] | 13.61 | 14.09 | 18.76 | 19.62 |

Table 2: Comparison of experimented bond stress with predicted bond stress by using models

| Bond Stress (MPa) | | | | | |
|---|---|---|---|---|---|
| **Hossain and Lachemi [21]** | | **CC** | **FA SCC** | **SC SCC** | **VMA SCC** |
| Bottom Left | | 11.33 | 11.65 | 4.5 | 7.54 |
| Bottom Middle | | 12.06 | 14.09 | 6.87 | 8.91 |
| Bottom Right | | 9.62 | 9.61 | 5 | 7.61 |
| Top Left | | 5.47 | 9.06 | 4.18 | 7.61 |
| Top Middle | | 8.8 | 11.89 | 5.81 | 9.32 |
| Top Right | | 2.52 | 8.9 | 4.68 | 8.09 |
| Top | | 2.4 | 12.75 | 5.93 | 9.8 |
| Middle | | 6.1 | 13.46 | 6.56 | 10.58 |
| Bottom | | 8.2 | 13.78 | 7.68 | 11.24 |
| Predicted Bond Stress (MPa) | Orangun et al. [8] | 11.09 | 11.99 | 9.51 | 10.44 |
| | Kemp and Wilhelm [9] | 6.1 | 6.59 | 5.23 | 5.74 |
| | Kemp [10] | 3.57 | 3.73 | 3.29 | 3.45 |
| | Chapman and Shah [11] | 13.19 | 14.27 | 11.31 | 12.42 |
| | Harajli [14] | 10.45 | 11.31 | 8.97 | 9.84 |
| | Pillai et al. [15] | 10.55 | 11.41 | 9.05 | 9.94 |
| | Bae [18] | 8.13 | 8.91 | 6.81 | 7.58 |
| **Lachemi et al. [22]** | | **NG_NS** | **BS_BS** | **BS_NS** | **ES_NS** |
| $d_b$=15 mm, $l_d$=100 mm | | 9.88 | 5.56 | 6.48 | 9.02 |
| Predicted Bond Stress (MPa) | Orangun et al. [8] | 9.66 | 10.65 | 11.94 | 18.16 |
| | Kemp and Wilhelm [9] | 9.4 | 9.08 | 9.92 | 9.97 |
| | Kemp [10] | 6.35 | 6.84 | 7.47 | 8.38 |
| | Chapman and Shah [11] | 11.21 | 12.37 | 15.4 | 12.91 |
| | Harajli [14] | 9.05 | 9.98 | 11.19 | 12.91 |
| | Pillai et al. [15] | 10.77 | 10.4 | 11.37 | 11.42 |
| | Bae [18] | 12.19 | 3.21 | 3.31 | 3.32 |
| $d_b$=15 mm, $l_d$=200 mm | | 12.41 | 7.34 | 8.47 | 10.59 |
| Predicted Bond Stress (MPa) | Orangun et al. [8] | 9.36 | 9.04 | 9.88 | 9.93 |
| | Kemp and Wilhelm [9] | 10.9 | 9.08 | 9.92 | 9.97 |
| | Kemp [10] | 7.21 | 7.02 | 7.53 | 7.55 |
| | Chapman and Shah [11] | 11.05 | 10.67 | 11.66 | 11.71 |
| | Harajli [14] | 8.76 | 8.461 | 9.25 | 9.29 |
| | Pillai et al. [15] | 8.81 | 8.51 | 9.3 | 9.34 |
| | Bae [18] | 12.7 | 3.21 | 3.31 | 3.32 |

Figure 1 shows that CEB-FIP [12] model has slightly good prediction but none of the other bond-slip models have good prediction. Figure 2 shows the Huang et al. [13] model has good prediction for CC experimental results but for the SCC, it underestimates and other models have not good predictions. In addition, Figure 3 shows that overall trend of the Huang et al.

[13] model is good but it is overestimate and the CEB-FIP [12] model overestimates and underestimates results for CC and SCC, respectively.

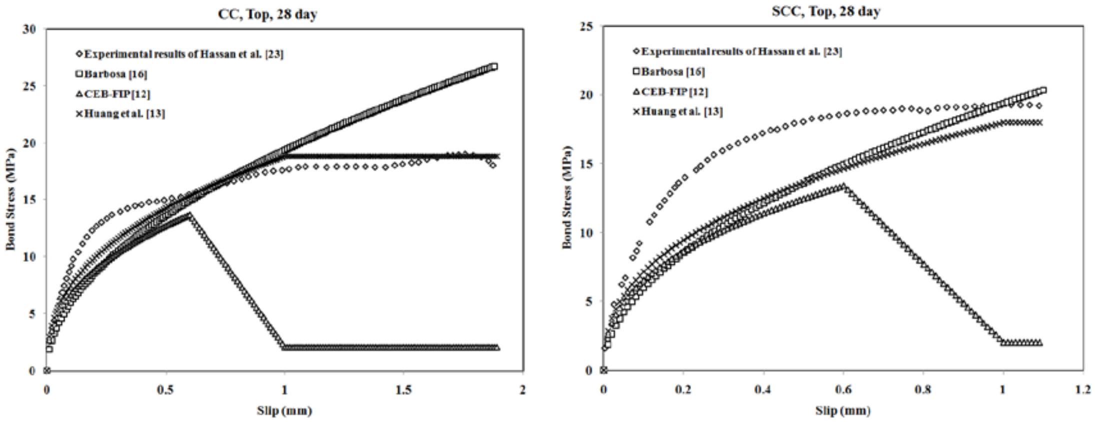


Figure 2: Comparison of the bond-slip models with Hassan et al. [23] results

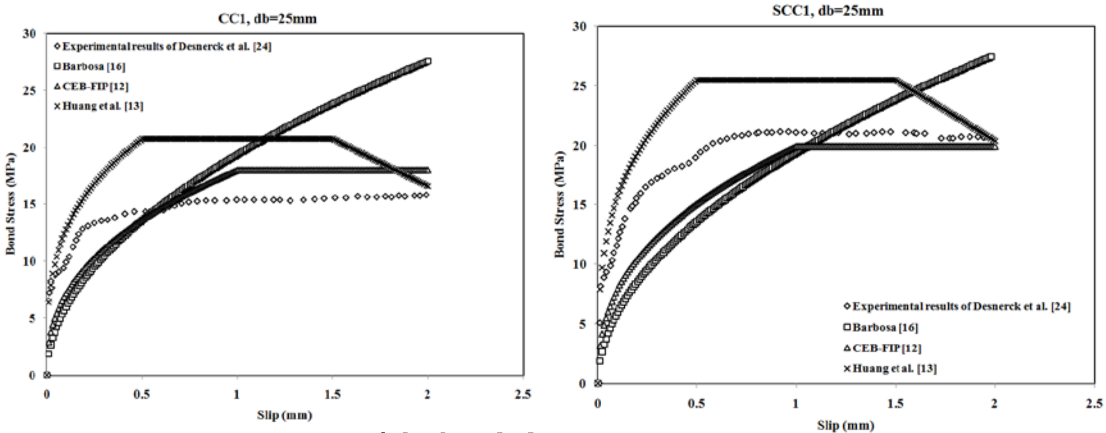


Figure 3: Comparison of the bond-slip models with Desnerck et al. [24] results

## 4. CONCLUSIONS

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

- By comparison of the Code provisions and equations can be concluded that the same procedures adopted for CC can be used for SCC, which means that bond properties of SCC are similar to the CC.
- In most comparisons the Chapman and Shah [11] and Bae [18] models are more appropriate for prediction of the bond strength when using the various experimental conditions (e.g. casting direction, $d_b$, $l_d$, pullout and beam test). Other existing equations underestimate the bond stress of both SCC and CC mixtures.
- Available bond-slip models are not appropriate for both CC and SCC bond strength prediction. However, the Huang et al. model [13] has good trend for prediction of bond strength and this model should be modified based on the experimental conditions.

## REFERENCES


[1] 237R-07, 'Self-Consolidating Concrete', American Concrete Institute, (2007).

[2] Okamura, H., Ozawa, K., 'Mix design for self-compacting concrete', *Concrete Libr JSCE*, **25** (1995) 107–20.
[3] Ozawa, K., Sakata, N., Okamura, H., 'Evaluation of self-compactability of fresh concrete using the funnel test', *Concrete Libr JSCE*, **25**(1995) 59–75.
[4] Valcuende, M. and Parra, C., 'Bond behaviour of reinforcement in self-compacting concretes', Construction and Building Materials, **23** (2009) 162–170.
[5] Domone, P.L., 'A review of the hardened mechanical properties of self-compacting concrete', *Cement Concrete Comp*, **29**(1) (2007) 1–12.
[6] Parra, C.J., 'Experimental study of self-compacted concrete in hardened state', PhD thesis, Polytechnic University of Valencia, (2005).
[7] Martin, H., 'Bond performance of ribbed bars (pullout tests) – influence of concrete composition and consistency', In: Bartos P, editor. Bond in concrete, (1982) 89–99.
[8] Orangun, C.O., Jirsa, J.O., and Breen, J.E., 'A reevaluation of test data on development lenght and sploces', *ACI Journal Proceedings*, **74**(3) (1977) 114-122.
[9] Kemp, E.L., and Wilhelm, W.J., 'Investigation of the parameters influencing bond cracking', *ACI Journal Proceedings*, **76**(1) (1979) 47-71.
[10] Kemp, E.L., 'Bond in reinforced concrete: behavior and design criteria', *ACI Journal Proceedings*, **83**(1) (1986) 50–57.
[11] Chapman, R.A., and Shah, S.P., 'Early-age bond strength in reinforced concrete', *ACI Materials Journal*, **84**(6) (1987) 501-510.
[12] CEB-FIP, 'Structural Concrete—Bulletin No. 1.' Paris, France, (1999).
[13] Huang, Z., Engström, B., Magnusson, J., 'Experimental investigation of the bond and anchorage behaviour of deformed bars in high strength concrete', Report 94:4, Chalmers University of Technology, (1996).
[14] Harajli, M.H., 'Development/splice strength of reinforcing bars embedded in plain and fiber reinforced concrete', *ACI Structural Journal*, **91**(5) (1994) 511–520.
[15] Pillai, S.U., Kirk, D.W., and Erki, M.A., 'Reinforced Concrete Design', McGraw-Hill Ryserson, Whitby, ON, Canada, (1999).
[16] Barbosa, M.T.G., 'Evaluation of the behavior of the bond in ordinary and high strength concrete', Doctoral Thesis, COPPE/UFRJ (in Portuguese) (2001).
[17] Harajli, M., Hamed, B., and Karam, K., 'Bond-slip response of reinforcing bars embedded in plain and fibre concrete', *Journal of Materials in Civil Engineering*, **14**(6) (2002) 503-511.
[18] Bae, S., 'Mix design, formwork pressure and bond characteristics of special self-consolidating concrete', MSc Thesis, Ryerson University, (2006).
[19] Zhu, W., Sonebi, M., and Bartos, P.J.M., 'Bond and interfacial properties of reinforcement in self-compacting concrete', Materials and Structures, **37** (2004) 442-448.
[20] Almeida Filho, F.M., K.El Debs, M., H.C.El Debs, A.L., 'Bond-slip behavior of self-compacting concrete and vibrated concrete using pull-out and beam tests', Materials and Structures, **41** (2008) 1073–1089.
[21] Hossain, K.M.A., Lachemi, M., 'Bond Behavior of Self-Consolidating Concrete with Mineral and Chemical Admixtures', ASCE, Journal of Materials in Civil Engineering, **20**(9) (2008) 608-616.
[22] Lachemi, M., Bae, S., Hossain, K.M.A., Sahmaran, M., 'Steel–concrete bond strength of lightweight self-consolidating concrete', *Materials and Structures*, **42** (2009) 1015–1023.
[23] Hassan, A.A.A., Hossain, K.M.A., Lachemi, M., 'Bond strength of deformed bars in large reinforced concrete members cast with industrial self-consolidating concrete mixture', *Construction and Building Materials*, **24** (2010) 520–530.
[24] Desnerck, P., De Schutter, G., and Taerwe, L., 'Bond behaviour of reinforcing bars in self-compacting concrete: experimental determination by using beam tests', *Materials and Structures*, **43** (2010) 53-62.