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Study of Bond Properties of Steel Rebars with Recycled Aggregate Concrete. Analytical Modeling

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The results of analytical analysis of interfacial bond stress-slip behavior of steel bars embedded in recycled aggregate concrete (RAC) are reported in this paper. Significantly large data from the laboratory pullout tests of specimens were analyzed including the specimens tested by the author. A bond stress-slip constitutive law is proposed for the steel rebars embedded in RAC. The experimental stress–slip responses of specimens were compared with the theoretical predictions. An existing model in the literature was employed for determining the ascending branch of the bond stress–slip curve. Based on the differences in the observed and predicted responses, a modified expression to capture the descending branch of the bond stress–slip curve was proposed. The results of the modified expression correlated well with the observed data of samples tested by the author and those reported in the existing literature.

Keywords: strain compatibility, stress–slip response, constitutive law, bond strength, pullout specimen, recycled aggregates, deformed bar.

Notation

NAC – natural aggregate concrete
RAC – recycled aggregate concrete
SD – standard deviation
τ – interfacial bond stress
$\tau_{\max}$ – maximum interfacial bond stress
c – concrete cover
c_0 – distance between the ribs of the reinforcing bar
d_b – diameter of bar
f_c – concrete compressive strength
l_d – rebar embedment length
s – rebar slip
$s_{\max}$ – maximum rebar slip

Introduction. The design of reinforced concrete (RC) structures assumes a perfect bond between steel bars and concrete for the estimation of load capacity and structural deformation. The deformation capacity of RC members and their load redistribution capacity in statically indeterminate structures are directly influenced by the bond. Bond forces are developed at the steel–concrete interface in RC members at the application of load to prevent slip of reinforcing bars which ensures strain compatibility between steel and surrounding concrete. This assumption of strain compatibility is valid only in regions of low interfacial bond stresses. With an increase in the applied load, the capacity of steel–concrete interface to transmit stresses from concrete to the bar weakens (owing to the damages to the surrounding concrete), which reduces bond stresses. For the regions near a crack, steel strains differ from concrete which invalidates the assumption of strain compatibility. As a result, relative displacement occurs between concrete and reinforcement, which is termed as rebar slip (s). This slip causes a redistribution of stresses, which results in increased structural deformation and reduced the load capacity, as compared to that determined using the perfect bond assumption. A rapid degradation of structure stiffness could be resulted, which greatly influences crack width and deflection of RC members.

A significant amount of research has been conducted over the past several decades to study the bond behavior of steel bars using natural aggregate concrete (NAC) [1–16]. Different bond stress-slip laws have been proposed by the researchers [17–22] for determining strength of bond, end anchorages and lap splices of steel rebars. The application of recycled aggregate concrete (RAC) in structural applications requires sufficient investigations for its wider acceptability and use. Presently, the studies related to bond behavior of steel bars embedded in RAC are limited [23–29]. In particular, bond stress-slip constitutive laws for RAC have not been studied to the same level as for NAC.

This paper presents studies related to investigating analytical bond stress-slip behavior of steel bars with RAC. The experimental data of pullout specimens tested by the author were employed for the comparison of analytical and observed behaviors. The details of these experiments and their results are presented in the companion paper [30]. The interfacial bond stress-slip constitutive laws in the existing literature were considered to predict the bond behavior of experimentally tested pullout specimens which indicated limitations of these laws for use with RAC. A modified expression has been suggested as an exponential function (with rebar rib spacing as a variable) to capture the descending branch of the stress–slip curve. The validity and effectiveness of the proposed model was studied with reference to the available experimental studies in the literature by various researchers. The resulting data demonstrated the improved ability of the proposed equation to predict bond stress-slip behavior of steel bars embedded in different types of RAC.

1. **Problem Statement**. Recycling of waste concrete provides an effective alternative to deal with the issue of its disposal. The aggregates obtained from waste concrete can be used in the production of RAC. Most of the research on RAC has been focused on studying the material behavior in plain concrete [31–38]. Structural application of RAC requires investigation from different aspects including its bond behavior with steel bars. In general, bond behavior of steel bars in RC members is represented by an interfacial bond stress–slip relationship. A reliable stress-slip constitutive law is essential for numerical models of RC structures for correct estimation of stresses and strains in concrete and steel which influence structural deformation characteristics (which, in turn, affect crack width and spacing) and load-carrying capacity.

The bond behavior of steel bars with concrete can be studies by using pullout tests and the results could be used to obtain interfacial bond stress–slip relationship. Prince and Singh [23, 29] and Xiao and Falkner [25] carried out pullout tests on specimens made with RAC and suggested use of Eqs. (1) and (2) to predict bond stress-slip failure envelope. Equation (1) has been suggested by Harajli [19] and is used for determining the ascending branch of the envelope. To capture the descending branch of stress–slip response of pullout specimens, Eq. (2) is employed, which was introduced by Guo [22]:

$$\bar{\tau} = (\bar{s})^{a}, \tag{1}$$

$$\bar{\tau} = \frac{s}{b(\bar{s}-1)^{2}+\bar{s}}, \tag{2}$$

where $\bar{\tau}$ and $\bar{s}$ are the bond stress and slip, respectively, normalized to their respective peak values, and a and b are constants.

The major shortcoming of Eqs. (1) and (2) is the determination of values of a and b which vary for different types of pullout specimens. The values of both these constants were calculated by the authors in references [23, 25, 29] from regression analyses of their own experimental data. This is no surprise that differing values of a and b have been reported by these authors in the aforementioned studies which vary based on the factors such as level of RCA addition, and the type and diameter of the employed rebars. As a result, reported values of a and b are applicable only for the specimens tested by these authors and may not provide satisfactory results for conditions of specimens different than those used by these researchers. These limitations of Eqs. (1) and (2) restrict their use considerably in practical applications. Consequently, it is necessary to establish a realistic bond stress-slip constitutive law, which is generic in nature and is easy in its implementation.

2. **Interfacial Bond Stress-Slip Constitutive Law**. Ciampi et al. [39] suggested the local interfacial bond–slip relationship for pullout mode of bond failure as shown in Fig. 1. The correct prediction of $\tau_{\max}$ is crucial for the determination of accurate crack spacing. Based on the relationship in Fig. 1, Harajli [19] proposed Eq. (3) for the estimation of $\tau_{\max}$ for the pullout failure of steel bars embedded in normal strength concrete. Figure 2 compares the data of observed and predicted $\tau_{\max}$ (Eq. (3)) for few of the specimens tested by Rafi [30]. It can be seen in Fig. 2 that a good correlation exists between the two data for most of the samples. The value of R^2 (Fig. 2) is assessed as 0.80. A T-test was also conducted on the datasets (Fig. 2) to determine their similarity. The results for one- and two-tail of the T-test provided a nearly zero p-value with a Pearson correlation coefficient of 0.89, which strongly suggests that both data are strongly correlated:

$$\tau_{\max} = \lambda \sqrt{f_c}, \qquad (3)$$

where $\lambda = 0.78(c/d_b)$ and c is the concrete cover.

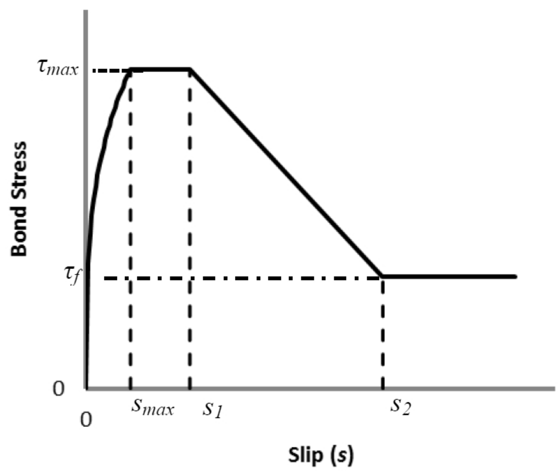

Fig. 1. Envelope for interfacial bond stress–slip response for pullout bond failure.

Note that the values of λ for the bars employed in the study conducted by Rafi [30] are 12.6, 9.4, and 7.4, respectively, for the bars of 12, 16, and 20 mm in diameter. The value of λ equal to 2.5 was recommended by the fib Model Code [40] for the pullout failure of deformed bars in good bond conditions with concrete. ACI 318R-14 [41] and CSA standard [42] imply the λ values of $0.34(c/d_b)$ and 0.52, respectively, for uncoated deformed bars of diameter not excceding 20 mm, which are embedded in less than 300 mm-thick

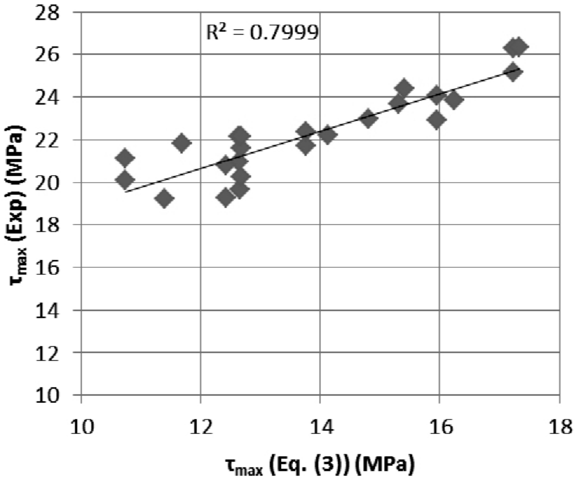

Fig. 2. Observed [30] and predicted maximum interfacial bond strength.

normal-weight concrete below the bar. It becomes apparent from the aforementioned values of λ for the employed bars that all the above codes underestimate $\tau_{\max}$ significantly. Note that the recommendations for λ given in ACI 318R-14 [41] and CSA standard [42] are based on beam tests in flexure as opposed to pullout tests. Nevertheless, (as is seen in the above) the λ value in fib Model Code [40] (which is based on pullout tests) is more conservative than in ACI 318R-14 [41]. For example, the least c/d_b value in the presented paper is 9.5 which yields a λ of 3.23 as per ACI 318R-14 [41]. In comparison, fib Model Code [40] suggests 2.5 which will provide less $\tau_{\max}$ than that by ACI 318R-14 [41].

The ascending branch of the failure envelope in Fig. 1 is expressed using Eq. (4) as suggested by Harajli et al. [43]. Using the data of experimental bond tests of the steel bars, Harajli [19] suggested $\tau_f = 0.35\tau_{\max}$, $s_{\max} = 0.15c_0$, $s_1 = 0.35c_0$, and $s_2 = c_0$ (Fig. 1), where c_0 is the distance between the ribs of the reinforcing bar:

$$\tau = \tau_{\max}\left(\frac{s}{s_{\max}}\right)^{0.3}. \tag{4}$$

Equation (4) has been used to trace the stress–slip curves of the samples employed by Rafi [30]. Figure 3 compares the data of observed and predicted bond stress–slip response of a few pullout specimens. The details of the specimens are given in Table 1. The notation of the specimen is as follows: the first two numbers indicate the percentage of RCA replacement, the second letter (P) represents a pullout specimen. This is followed by the bar diameter, while the letter in the end indicates the bar type, such as D for hot-rolled deformed and T for cold-twisted ribbed bar. For example, 10P12T is a pullout specimen made with a 10-percent replacement of RCA using a cold-twisted ribbed bar of 12 mm in diameter. It is seenin Fig. 3 that the ascending branch of the predicted curve correlates closely with the observed response. On the other hand, the predicted descending branch of the bond stress-slip law (Fig. 1) is significantly deviated form that observed during the experimental testing of samples.

The descending branch of a bond stress–slip envelope indicates the bar ability to provide a frictional resistance beyond $\tau_{\max}$. Rafi [30] reported the ductile behavior of pullout specimens in the post-peak regions of bond stress–slip response. It is noted from the observed response of the bars in Fig. 3 that the descending branch of the bond stress–slip

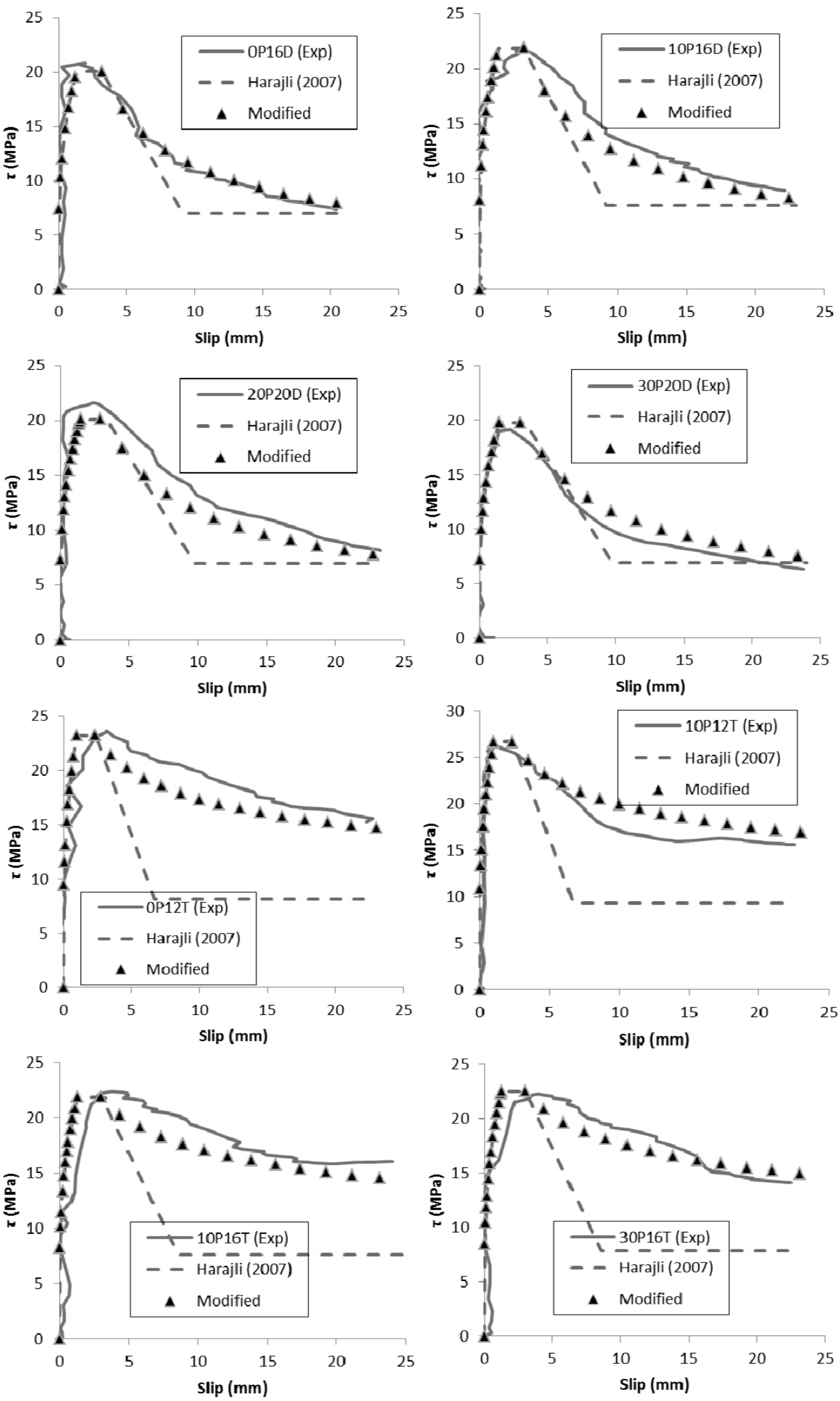

Fig. 3. Observed and predicted interfacial bond stress–slip response.

Table 1

Properties of Pullout Specimens Experimentally Tested by Rafi [30]

Specimen	f_c, MPa	c/d_b	c_0, mm	τ_{max}, MPa	s_{max}, mm
0P16D	24.09	9.4	9.2	20.93	2.00
10P16D	28.54	9.4	9.2	21.69	2.87
20P20D	33.09	7.4	9.7	21.59	0.22
30P20D	31.82	7.4	9.7	19.28	1.46
0P12T	21.64	12.6	6.7	23.70	3.07
10P12T	28.54	12.6	6.7	26.32	0.60
10P16T	28.54	9.4	8.6	22.37	2.62
30P16T	30.12	9.4	8.6	22.23	1.99

response follows an exponentially decreasing trend, which explains its deviation from the proposed straight line relationship in Fig. 1. Harajli [19] suggested Eq. (5) for capturing the descending branch for splitting the bond failure of specimens:

$$\tau = \beta\tau_{max}\left(\frac{s}{s_{max}}\right)^{-0.5}, \tag{5}$$

where β is taken as 0.65 for normal strength concrete as suggested by Harajli [19].

Based on some trial and error calculations, Eq. (5) has been modified in order to trace the descending branch of the pullout samples employed in the studies presented. The modified expression is given by Eq. (6):

$$\tau = \tau_{max}\left(\frac{s}{s_1}\right)^{\alpha}. \tag{6}$$

Note that β is taken as 1 in Eq. (6). The observed data of 24 different types of samples reported by Rafi [30] was analyzed to study the variations in τ for different values of α through an iterative process. As mentioned earlier, the frictional component of bond plays a vital role in the determination of descending part of bond stress–slip response; this component is influenced by the rib characteristics of the bar. As a result, α was considered to be a function of c_0. This allows the use of Eq. (6) for steel bars with different geometries of rebar deformation. Based on the aforementioned data analysis, the value of α was obtained as $-0.05c_0$ and $-0.03c_0$ for the hot-rolled deformed and cold-twisted ribbed bars, respectively. Fig. 3 illustrates the descending branch of the curves as predicted by Eq. (6). A good correlation exists between (Eq. (6)) and the observed response in Fig. 3.

3. **Validation of Model**. In order to assess the effectiveness and reproducibility of Eq. (6), a sizeable amount of observed data of pullout specimens made from RAC available in the literature was analyzed and the analytical results obtained from Eqs. (4) and (6) (in conjunction with Eq. (3)) were compared with the recorded data. The details of few selected studies and necessary parameters are given in Table 2. It is noted in Table 2 that f_c values range from 27–50 MPa. Similarly, c/d_b and c_0 are also different than those employed in the experimental testing program reported by Rafi [30]. Figure 4 compares the results of analytical and experimental bond stress–slip responses for the studies in Table 2.

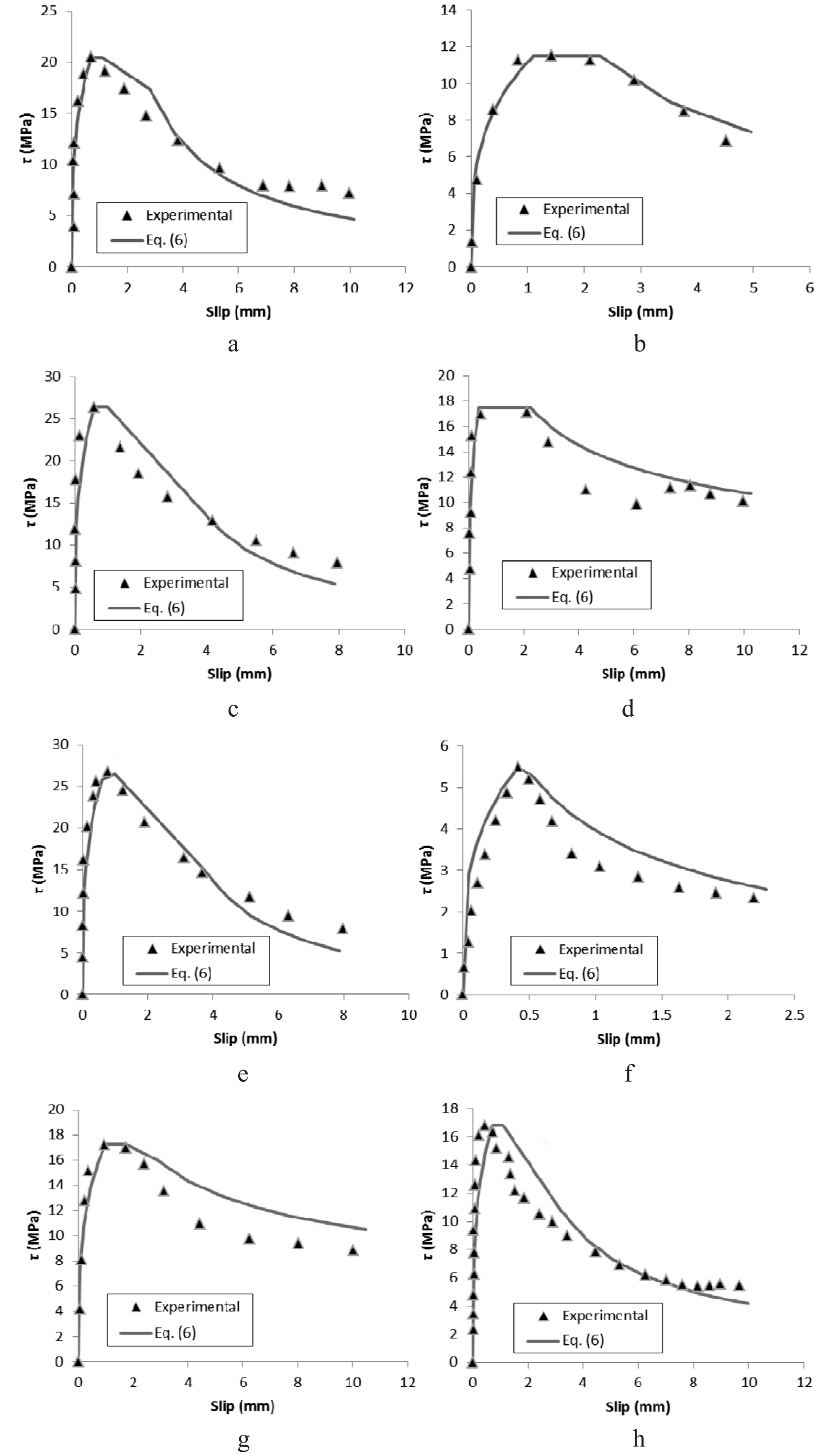

Fig. 4. Comparison of interfacial bond stress–slip responses: (a) A10R25 [23]; (b) according to [44]; (c) RCA-I100V [27]; (d) RCA-II-50 [25]; (e) RCA-I0V [27]; (f) BE-RAC2-50-375A [26]; (g) RCA-II-100 [25]; (h) A8R75-3 [23].

Table 2

Summary of Pullout Specimens Reported in the Literature

Author	Specimen	f_c, MPa	c/d_b	c_0, mm	τ_{max}, MPa	s_{max}, mm
Prince and Singh [23]	A10R25-2	28.88	4.50	6.8	20.51	0.71
Prince and Singh [23]	A8R75-3	26.16	5.75	5.4	16.81	0.62
Hameed et al. [44]	Reference	50.00	7.80	6.8	11.51	1.62
Kim and Yun [27]	RCA-I100V	29.17	5.80	6.8	26.91	0.59
Xiao and Falkner [25]	RCA-II-50	39.27*	4.50	6.5	17.24	0.47
Xiao and Falkner [25]	RCA-II-100	34.63*	4.50	6.5	17.39	1.20
Kim and Yum [27]	RCA-I0V	36.97	5.80	6.8	27.64	0.76
Butler et al. [26]	BE-RAC2-50-375A	49.40	1.50	6.8	5.48	0.42

* Cube strength.

It is seen in Fig. 4 that the analytical predictions correlate well with the observed data in all cases under study. These results prove the reliability of the proposed constitutive law (in particular, Eq. (6)), as applied to steel bars embedded in RCA. A comparative analysis of Eqs. (6) and (2) yields more simplistic form and easier application of the proposed Eq. (6). In addition, the proposed method (Eqs. (3), (4), and (6)) is free from the need of determining constants a and b in Eqs. (1) and (2).

Conclusions. This paper reported studies related to the analytical bond stress-slip behaviors of steel reinforcing bars with RAC. The analytical results were compared with the observed data from the pullout specimen tests. A bond stress-slip constitutive law is proposed, which is based on the determination of τ_{max}, and ascending and descending branches of bond stress–slip envelope. The expressions suggested for NAC in the existing literature provided a good correlation with experimentally observed τ_{max} (Eq. (3)) and the ascending part of the interfacial bond stress–slip envelope (Eq. (4)). A modified expression (Eq. (6)) is suggested to capture the descending part of the interfacial bond stress–slip envelope for the pullout failure. The proposed equation is an exponential function with a variable of reinforcing bar rib spacing. The results obtained via the modified equation match closely with the descending part of the observed bond–slip responses reported in the literature for a variety of pullout specimens.

1. D. A. Abrams, *Tests of Bond between Concrete and Steel*, Bulletin No. 71, Engineering Experiment Station, University of Illinois, Urbana (1913).
2. T. D. Mylrea, "Bond and anchorage," *ACI J.*, **44**, No. 3, 521–552 (1948).
3. A. P. Clark, "Bond of concrete reinforcing bars," *ACI J.*, **46**, No. 3, 161–184 (1950).
4. P. M. Ferguson, "Bond stress – the state of the art," *ACI J.*, **63**, No. 11, 1161–1190 (1966).
5. E. S. Perry and J. N. Thompson, "Bond stress distribution on reinforcing steel in beams and pullout specimens," *ACI J.*, **63**, No. 8, 865–876 (1966).
6. L. A. Lutz and P. Gergely, "Mechanics of bond and slip of deformed bars in concrete," *ACI J.*, **64**, No. 11, 711–721 (1967).
7. ACI Committee 408, "Opportunities in bond research," *ACI J.*, **67**, No. 11, 857–867 (1970).
8. Y. Goto, "Cracks formed in concrete around deformed tension bars," *ACI J.*, **68**, No. 4, 244–251 (1971).

9. J. Minor and J. O. Jirsa, "Behavior of bent bar anchorage," *ACI J.*, **72**, No. 4, 141–149 (1975).
10. C. O. Orangum, J. O. Jirsa, and J. E. Breen, "A reevaluation of test data on development length and splices," *ACI J.*, **74**, 114–122 (1977).
11. A. D. Edwards and P. J. Yannopoulos, "Local bond-stress to slip relationships for hot rolled deformed bars and mild steel plain bars," *ACI J.*, **76**, No. 3, 405–419 (1979).
12. P. S. Chana, "A test method to establish realistic bond stresses," *Mag. Concrete Res.*, **42**, No. 151, 83–90 (1990).
13. A. Z. Mohamad and L. A. Clark, "Bond behaviour of low-strength concrete," *Mag. Concrete Res.*, **44**, No. 160, 195–203 (1992).
14. A. Azizinamini, M. Stark, J. J. Roller, and S. K. Ghosh, "Bond performance of reinforcing bars embedded in high-strength concrete," *ACI Struct. J.*, **90**, No. 5, 554–561 (1993).
15. M. H. Harajli, "Development/splice strength of reinforcing bars embedded in plain and fiber reinforced concrete," *ACI Struct. J.*, **91**, No. 5, 511–520 (1994).
16. J. Cairns and K. Jones, "Influence of rib geometry on strength of lapped joints: an experimental and analytical study," *Mag. Concrete Res.*, **47**, No. 172, 253–262 (1995).
17. R. Eligehausen, E. Popov, and V. Bertero, *Local Bond Stress–Slip Relationships of Deformed Bars under Generalized Excitations*, Report No. UCB/EERC-83/23, Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, CA (1983).
18. L. R. Feldman and F. M. Bartlett, "Bond strength variability in pullout specimens with plain reinforcement," *ACI Struct. J.*, **102**, 860–867 (2005).
19. M. H. Harajli, "Numerical bond analysis using experimentally derived local bond laws: A powerful method for evaluating the bond strength of steel bars," *J. Struct. Eng.*, **133**, No. 5, 695–705 (2007).
20. H. Sezen and J. P. Moehle, "Bond-slip behaviour of reinforced concrete members," in: Proc. FIB Symp.: Concrete Structures in Seismic Regions (May 6–8, 2003, Athens, Greece).
21. J. M. Alsiwat and M. Saatcioglu, "Reinforcement anchorage slip under monotonic loading," *J. Struct. Eng.*, **118**, 2421–2438 (1992).
22. Z. Guo, *Strength and Deformation of Concrete – Experimental Foundation and Constitutive Relationship* [in Chinese], Press of Tsinghua University, Beijing (1997).
23. M. J. R. Prince and B. Singh, "Investigation of bond behaviour between recycled aggregate concrete and deformed steel bars," *Struct. Concrete*, **15**, No. 2, 154–168 (2014).
24. G. Metelli and G. A. Plizaari, "Effects of relative rib area on bond behavior," *Stud. Res.*, **27**, 141–163 (2007).
25. J. Xiao and H. Falkner, "Bond behaviour between recycled aggregate concrete and steel rebars," *Constr. Build. Mater.*, **21**, 395–401 (2007).
26. L. Butler, J. S. West, and S. L. Tighe, "The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement," *Cement Concrete Res.*, **41**, 1037–1049 (2011).
27. S. W. Kim and H. D. Yun, "Influence of recycled coarse aggregates on the bond behaviour of deformed bars in concrete," *Eng. Struct.*, **48**, 133–143 (2013).

28. C. Lima, A. Caggiano, C. Faella, et al., "Physical properties and mechanical behaviour of concrete made with recycled aggregates and fly ash," *Constr. Build. Mater.*, **47**, 547–559 (2013).

29. M. J. R. Prince and B. Singh, "Pullout behaviour of deformed steel bars in high-strength recycled aggregate concrete," *Proc. Inst. Civil Eng.-Constr. Mater.*, **169**, No. 1, 13–26 (2016).

30. M. M. Rafi, "Study of bond properties of steel rebars with recycled aggregate concrete. Experimental testing," *Strength Mater.*, **50**, No. 6, 937–950 (2018).

31. A. Ajdukiewicz and A. Kliszczewicz, "Influence of recycled aggregates on mechanical properties of HS/HPC," *Cement Concrete Comp.*, **24**, No. 2, pp. 269–279 (2002).

32. S. C. Angulo, P. M. Carrijo, A. D. Figneiredo, et al., "On the classification of mixed construction and demolition waste aggregate by porosity and its impact on the mechanical performance of concrete," *Mater. Struct.*, **43**, No. 4, 519–528 (2010).

33. R. M. Chakradhara, S. K. Bhattacharyya, and S. V. Barai, "Influence of field recycled coarse aggregate on properties of concrete," *Mater. Struct.*, **44**, No. 1, 205–220 (2011).

34. A. Domingo, C. Lázaro, F. L. Gayarre, et al., "Long term deformations by creep and shrinkage in recycled aggregate concrete," *Mater. Struct.*, **43**, No. 8, 1147–1160 (2010).

35. M. Etxeberria, A. R. Mari, and E. Vázquez, "Recycled aggregate concrete as structural material," *Mater. Struct.*, **40**, No. 5, 529–541 (2007).

36. M. Etxeberria, E. Vázquez, A. Mari, and M. Barra, "Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete," *Cement Concrete Res.*, **37**, No. 5, 735–742 (2007).

37. B. González-Fonteboa, F. Martínez-Abella, J. Eiras-López, and S. Seara-Paz, "Effect of recycled coarse aggregate on damage of recycled concrete," *Mater. Struct.*, **44**, No. 10, 1759–1770 (2011).

38. M. C. Limbachiya, T. Leelawat, and R. K. Dhir, "Use of recycled concrete aggregate in high-strength concrete," *Mater. Struct.*, **33**, No. 9, 574–580 (2000).

39. V. Ciampi, R. Eligehausen, V. V. Bertero, and E. P. Popov, "Analytical model for deformed bar bond under generalized excitations," in: Trans. of IABSE Colloquium on Advanced Mechanics of Reinforced Concrete, Delft, the Netherlands (1981).

40. *fib Model Code for Concrete Structures 2010*, International Federation for Structural Concrete, Federal Institute of Technology Lausanne, Switzerland, Ernst & Sohn (2013)

41. *ACI 318R-02. Building Code Requirements for Structural Concrete*, ACI Committee 318, Detroit, MI (2014).

42. *CAN/CSA-A23.3-04. Design of Concrete Structures*, Canadian Standards Association, Rexdale, Ontario, Canada (2004).

43. M. H. Harajli, M. Hout, and W. Jalkh, "Local bond stress-slip behavior of reinforcing bars embedded in plain and fiber concrete," *ACI Mater. J.*, **92**, No. 4, 343–353 (1995).

44. R. Hameed, A. Turatsinze, F. Duprat, and A. Sellier, "Bond stress-slip behaviour of steel reinforcing bar embedded in hybrid fiber-reinforced concrete," *KSCE J. Civ. Eng.*, **17**, No. 7, 1700–1707 (2013).

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