Research Article

Tian Su, Ting Wang, Haihe Yi, Rui Zheng, Yizhe Liu, Haoran Zhai*, and Zhanfang Huang*

Finite element analysis on the bond behavior of steel bar in salt–frost-damaged recycled coarse aggregate concrete

<https://doi.org/10.1515/rams-2021-0063>
received June 22, 2021; accepted August 22, 2021

Abstract: In this article, the ABAQUS finite element software is used to simulate the bond behavior of the steel bar in salt–frost-damaged recycled coarse aggregate concrete, and the influence of the steel bar diameter and the concrete cover thickness on the bond strength is investigated. The result shows that the calculated bond–slip curve is in good agreement with the experimental bond–slip curve; the mean value of the ratio of the calculation results of ultimate bond strength to the experiment results of ultimate bond strength is 1.035, the standard deviation is 0.0165, and the coefficient of variation is 0.0159, which proves that the calculation results of the ultimate bond strength are in good agreement with the experimental results; with the increase of steel bar diameter and the concrete cover thickness, the ultimate bonding strength of RAC and steel increases; the calculation formulas for the ultimate bond strength of specimens with different

steel bar diameters (concrete cover thickness) after different salt–frost cycles are obtained.

Keywords: salt–frost damaged, recycled coarse aggregate concrete, steel bar diameter, concrete cover thickness, numerical simulation

1 Introduction

With the vigorous development of the construction industry, concrete has been widely used as the main building material [1]. In recent years, high-performance concrete has begun to be used in civil engineering [2]. However, the concrete structure has a certain design life, and a number of waste concretes will be produced in the process of reconstruction and expansion [3]. Over 900 million tons of construction demolition waste were generated annually in Europe, the United States, and Japan [4]. In China, a large amount of construction waste is also produced annually, of which waste concrete accounts for about 34% of construction waste [5]. In China, more than 95% of construction waste is transported to the suburbs for stacking or land-filling [6], which not only occupies a large number of land resources but also causes a series of environmental problems [7].

With the increase in the demand for concrete, the exploitation of natural sand and stone continues to increase [8]. The contradiction between the increasing demand for concrete and the aggregate crisis has become increasingly prominent [9], so construction waste needs to be reused [10]. In recent years, many new green building materials have begun to be used in building structures. Recycled aggregate concrete (RAC) technology is a technology that uses crushed recycled aggregate as coarse or fine aggregate to produce new concrete [11]. RAC is a sustainable green concrete [12], which not only solves the problem of waste concrete treatment but also effectively reduces the exploitation of natural sand and gravel resources and is beneficial to improve environmental pollution [13].

* **Corresponding author: Haoran Zhai**, Shandong Hi-Speed Urban & Rural Development Group Co. Ltd, Jinan, Shandong, 250014, China, e-mail: 1294191132@qq.com

* **Corresponding author: Zhanfang Huang**, Department of Civil Engineering, School of Civil and Architectural Engineering, Shandong University of Technology, Zibo, Shandong, 255000, China, e-mail: huangzhanfang@163.com

Tian Su: Department of Civil Engineering, School of Civil and Architectural Engineering, Shandong University of Technology, Zibo, Shandong, 255000, China, e-mail: sutian@sdut.edu.cn

Ting Wang: Department of Civil Engineering, School of Civil and Architectural Engineering, Shandong University of Technology, Zibo, Shandong, 255000, China, e-mail: wangtingcivil@163.com

Haihe Yi: Department of Civil Engineering, School of Civil and Architectural Engineering, Shandong University of Technology, Zibo, Shandong, 255000, China, e-mail: yihaihe@126.com

Rui Zheng: Department of Civil Engineering, School of Civil and Architectural Engineering, Shandong University of Technology, Zibo, Shandong, 255000, China, e-mail: 854886846@qq.com

Yizhe Liu: Department of Civil Engineering, School of Civil and Architectural Engineering, Shandong University of Technology, Zibo, Shandong, 255000, China, e-mail: LYZ100lyz@hotmail.com

In addition, freeze–thaw damage of concrete structures is very common in cold regions [14]. After freeze–thaw damage, the durability of the concrete structure decreases, which will affect the normal use of buildings [15]. In cold regions, concrete structures in seaport and coastal structures will be destroyed by the salt–frost cycle [16]. The damage degree and the development speed of salt–frost damage are more serious than the ordinary freeze–thaw damage [17].

Some scholars have conducted a number of research studies on the frost resistance of RAC. Most scholars found that the frost resistance of RAC was inferior to the conventional aggregate concrete (CAC) [18]. Cheng *et al.* [19] investigated the influence of the amount of recycled aggregate on the frost resistance of RAC and found that as the amount of recycled aggregate increased, the frost resistance of RAC gradually decreased. Zhui and Li [20] investigated the influence of the water absorption rate of recycled aggregate on the frost resistance of RAC and pointed out that the higher water absorption rate of recycled aggregate seriously affected the frost resistance of RAC. Li [21] conducted an experimental study on the frost resistance of RAC in water and 3.5% NaCl solution and compared it with that of CAC. The test results show that whether in clean water or in a 3.5% NaCl solution, when the water/cement ratio was the same, the frost resistance of RAC was significantly inferior to that of CAC. However, some scholars also believe that the frost resistance of RAC was equivalent to that of CAC or even better than that of CAC [22]. Cao *et al.* [23] pointed out that when the replacement rate of recycled coarse aggregate was less than 50%, the basic mechanical properties of RAC were similar to those of CAC. Fan [24] found that when the replacement rate of recycled aggregate was 33%, the frost resistance of RAC was the best, which was similar to CAC. It can be seen that there are still different opinions on the research on the frost resistance of RAC.

In addition, the bond behavior of concrete with steel bar is the basis for ensuring that the two materials work together [25], and the freeze–thaw cycles and the salt–frost cycles inevitably influence the bond behavior of steel bar in concrete. Ji *et al.* [26] investigated the bond behavior of CAC specimens with different diameters (12, 16, and 20 mm) after freezing and thawing cycles through the center pull-out test. The test results show that the bond strength of CAC decreased after freeze–thaw cycles, while the slip increased. Hanjari *et al.* [27] also found that the stiffness of the ascending phase of the bond–slip curve decreased with the increase of freeze–thaw damage. Xu *et al.* [28] conducted an experimental study on the

bond behavior between steel bars and CAC with different strength grades after freeze–thaw cycles and arrived at similar conclusions. Petersen *et al.* [29] used the dynamic elastic modulus of concrete as a judgment index for freeze–thaw damage of concrete, and investigated the bond behavior between steel bars and CAC after freeze–thaw cycles.

With the continuous deepening of the research on RAC, the bond behavior between RAC and steel bar began to attract the attention of scholars and researchers. Shang *et al.* [30], Wang *et al.* [31], and An *et al.* [32] investigated the bond behavior of the steel bar in RAC after the freeze–thaw cycle and found that the bond behavior of RAC was inferior to CAC. Shang *et al.* [33] conducted an experimental study on the bond behavior of the steel bar in RAC after freeze–thaw cycles in different solutions (fresh water and seawater). The test results show that the bond strength loss in freshwater was less than that in seawater, while the increase of peak slip in freshwater was also less than that in seawater. Ren *et al.* [34] found that the bond behavior of steel bar in RAC after salt–frost cycles decreased with the increase of the steel bar diameter.

In recent years, finite element software has begun to be used in engineering analysis. Chen [35] not only simulated the pull-out test of concrete and steel bars by introducing the cohesive bond model but also simulated the entire stress process of reinforced concrete beams through the extended finite element method and then analyzed the bond behavior between concrete and steel bars. Reinhardt *et al.* [36] made a more detailed division of concrete and steel bar elements and used the proposed nonlinear constitutive relationship to analyze the stress failure process of concrete specimens. Wang *et al.* [37] used finite element methods to analyze the influence of concrete strength, anchorage length, and steel bar diameter on the bond behavior of steel bar in RAC. Cao [38] used ANSYS finite element analysis software to simulate the bond behavior of steel bar in RAC after freeze–thaw cycles, and the numerical simulation results are in good agreement with the experimental results. However, numerical simulations of the bond behavior of the steel bar in RAC after salt–frost cycles are relatively rare.

The objective of this article is to simulate the bond behavior of steel bar in salt–frost-damaged RAC through ABAQUS finite element software, investigate the influence of the steel bar diameter and the concrete cover thickness on the bond strength and obtain the calculation formulas for the ultimate bond strength of specimens with different steel bar diameters (concrete cover thickness) after different salt–frost cycles.

2 Material properties and selection of the unit type

2.1 Material properties of RAC

The aggregate properties and the design mixture proportions of RAC can be found in ref. [39]. Concrete is a non-uniform material, which is composed of coarse aggregate, fine aggregate, cement, and water. The material properties are inevitably different from that of CAC due to the change of the coarse aggregate. The constitutive relation of recycled concrete under uniaxial compression is as follows [40]:

$$y = \begin{cases} ax + (3 - 2a)x^2 + (a - 2)x^3, & x \leq 1 \\ \frac{x}{B(x - 1) + x}, & x \geq 1 \end{cases} \quad (1)$$

$$B = -9 \times 10^{-6}n^3 + 0.0024n^2 - 0.1689n + 4.2712$$

$$x = \frac{\varepsilon}{\varepsilon_c}, \quad y = \frac{\sigma}{\sigma_c}$$

where n is the number of freeze–thaw cycles; ε_c is the maximum strain; and σ_c is the stress corresponding to maximum stress.

The mechanical performance parameters of RAC are as follows:

The uniaxial compressive strength of RAC is [41]

$$f_c = 0.76f_{cu}. \quad (2)$$

The uniaxial tensile strength of RAC is [41]

$$f_{sp} = 0.24f_{cu}^{0.65}. \quad (3)$$

The elastic modulus of RAC is [41]

$$E_c = \frac{10^5}{2.8 + 40.1/f_{cu}}. \quad (4)$$

The mechanical parameters of RAC are shown in Table 1.

2.2 Material properties of the steel bar

The force mode of the steel bar simulated in this article is the uniaxial force state, and the double-line model is selected for analysis, which is mainly composed of the elastic phase and the fully plastic phase. The stress–strain curve of the steel bar is as follows:

$$\sigma_s = E_s \varepsilon_s \quad (\varepsilon \leq \varepsilon_y) \quad (5)$$

$$\sigma_s = f_y \quad (\varepsilon_y \leq \varepsilon \leq \varepsilon_s) \quad (6)$$

The mechanical performance parameters of the steel bar and stirrup is shown in Table 2.

2.3 Unit type of RAC and steel bar

The solid elements are selected in ABAQUS software to simulate RAC. The solid element is a three-dimensional solid element with eight nodes, each of which contains three degrees of freedom. By defining the damage model, the nonlinear problem of recycled concrete can be analyzed [42]. The truss elements are selected in ABAQUS software to simulate the steel bars.

2.4 Unit type of spring

In this article, a separated model is selected to investigate the bond–slip between RAC and the steel bar. Therefore, it is necessary to introduce transition elements at the interface between RAC and steel bars. In ABAQUS software, a double-spring connection element is generally

Table 1: Mechanical parameters of RAC

Number of salt–frost cycles	Uniaxial compressive strength (MPa)	Uniaxial tensile strength (MPa)	Elastic modulus (GPa)
0	33.67	2.82	26.9
25	32.15	2.74	26.7
50	30.78	2.66	26.4
75	28.96	2.56	25.9
100	26.14	2.39	25.2
125	21.36	2.10	23.7

Table 2: Mechanical parameters of the steel bar

	Diameter (mm)	Tensile strength (MPa)	Yield strength (MPa)	Elastic modulus (GPa)	Poisson's ratio
HRB400	18	645	499	200	0.30

used to numerically simulate the bond and slip between concrete and steel bars so as to transfer the shear and shear forces between two points. The spring element in ABAQUS mainly includes three element forms: Spring 1, Spring 2, and Spring A.

Because the truss element is used to simulate the steel bar in RAC, Spring 2 element is used to define the spring element between points. Spring 2 element can define the relative displacement and degree of freedom in any direction. It should be pointed out that the Spring 2 unit is a linear spring unit, and the Inp file needs to be modified to obtain the required nonlinear spring unit.

3 Finite element modeling

The corresponding finite element model is established according to the size of the specimen in ref. [39]. Then the concrete model and the steel bar model are assembled, and the spring element at the contact position of the steel bar element and the concrete element (the spring element type set at this time is linear spring unit) are set.

The mesh size of the concrete element in this article is $10\text{ mm} \times 10\text{ mm} \times 10\text{ mm}$, and the mesh length of the steel bar element is also 10 mm , so as to ensure that the steel bar element nodes and the concrete element nodes overlap, which is convenient for setting the nonlinear spring unit. The model after meshing in ABAQUS is shown in Figure 1.

The loading end of the concrete is fixed during the pull-out test [39]. Therefore, the loading end of the concrete is fully constrained (the six degrees of freedom are constrained) during the finite element analysis. In addition, the steel bar is only allowed to produce displacement along the pulling direction. The displacement load is applied by amplitude to ensure the convergence of the results.

Figure 1: Model after meshing.

Firstly, the unit numbers of the concrete and the steel bar in the contact area of concrete and steel bar are found and then the linear spring element in the contact area is set as a nonlinear spring element by modifying the Inp file. The loading simulation process is consistent with the loading process of the pull-out test in the literature [39].

4 Results and analysis

4.1 Model verification

The finite element calculation results of the bond-slip curve of RAC and steel bar after salt-frost cycles are compared with the experiment results in ref. [39], as shown in Figure 2.

It can be seen from Figure 2 that for the rising section of the bond-slip curve, the experiment curve and the calculation curve are in good agreement. However, for the descending section of the bond-slip curve, there is a certain difference between the experiment curve and the calculation curve, and the bond stress of the experiment curve decreases faster than the calculation curve. The reason is that the specimen has split cracks when it reaches the ultimate load, resulting in a rapid decline in the bonding force.

In addition, the following is also the reason for the difference between the test curve and the simulation curve: the finite element analysis assumes that the concrete material is isotropic, while the actual concrete material is an-isotropic; the non-linear spring element cannot truly reflect the complex bond-slip mechanism of concrete and steel bar.

It can also be seen from Figure 2 that with the increase in the number of salt-frost cycles, the peak bond stress continues to decrease and the peak slip continues to increase, which are consistent with the experiment results in ref. [39].

The comparison of the finite element calculation results (τ_{us}) and the experiment results (τ_{ue}) of the ultimate bond strength is shown in Table 3.

It can be seen from Table 3 that the mean value of the ratio of the calculation results (τ_{us}) to the experiment results (τ_{ue}) is 1.035, the standard deviation is 0.0165, and the coefficient of variation is 0.0159. From the above three indicators, the calculation results of the ultimate bond strength are in good agreement with the experimental results, which proves the rationality of the numerical simulation.

Figure 2: Comparison of calculation results and experiment results: (a) 0 cycle of salt frost, (b) 25 cycles of salt frost, (c) 50 cycles of salt frost, (d) 75 cycles of salt frost, (e) 100 cycles of salt frost, and (f) 125 cycles of salt frost.

Table 3: Comparison of calculation results (τ_{us}) and experiment results

Salt–frost cycles	τ_{us} (MPa)	τ_{ue} (MPa)	τ_{us}/τ_{ue}
0	15.02	14.70	1.022
25	14.55	14.10	1.032
50	13.86	13.20	1.050
75	12.06	11.96	1.008
100	11.00	10.40	1.058
125	8.81	8.49	1.038

4.2 Influence of the steel bar diameter on the bond strength

The influence of the steel bar diameter on the bond strength is studied by setting the steel bar diameter to 16, 18, 20, and 22 mm and calculating the ultimate bond strength of the specimen after the salt–frost cycles, as shown in Figure 3.

It can be seen from Figure 3 that the ultimate bond strength of the specimens with different steel bar diameters decreased with the increase of the salt–frost cycles. The ultimate bond strength increases with the increase of the steel bar diameter, which is consistent with the results in ref. [39]. The reason is that the contact area between the concrete and the steel bar increases with the increase of the steel bar diameter, which leads to an increase in the ultimate bond strength. However, Zhao [43] and Pour and Alam [44] found that the bond strength decreased with the increase of the steel bar diameter. The reasons for this difference are as follows: Zhao [43] and Pour and Alam [44] both pointed out that the reason for the increase in the bond strength of specimens with small steel bar

Figure 3: Bond strength of the RAC specimen with different steel bar diameters.

diameter is the increase in the number of steel bar transverse ribs, and the finite element simulation is carried out in this article as the transverse ribs of the steel bar were not considered.

The ultimate bond strengths of the specimens with different steel bar diameters were fitted, respectively, and the results are as follows:

$$d = 16 \text{ mm: } \tau_{u,n} = -0.0502n + 15.019, \quad R^2 = 0.9738 \quad (7)$$

$$d = 18 \text{ mm: } \tau_{u,n} = -0.0497n + 15.657, \quad R^2 = 0.9503 \quad (8)$$

$$d = 20 \text{ mm: } \tau_{u,n} = -0.0495n + 16.141, \quad R^2 = 0.9326 \quad (9)$$

$$d = 22 \text{ mm: } \tau_{u,n} = -0.0472n + 16.539, \quad R^2 = 0.9186. \quad (10)$$

The formula for calculating the ultimate bond strength of specimens with different steel bar diameters can be expressed as

$$\tau_{u,n} = -a_d n + b_d \quad (11)$$

The parameters a_d and b_d of specimens with different steel bar diameters are shown in Figure 4.

The relationship between the parameter a_d (b_d) and the steel bar diameter d was fitted:

$$a_d = 0.0005d + 0.0579, \quad R^2 = 0.7940 \quad (12)$$

$$b_d = 0.2522d + 11.047, \quad R^2 = 0.9886. \quad (13)$$

Substituting formulae (12) and (13) into formula (11), the formula for calculating the ultimate bond strength of specimens with different steel bar diameters after salt–frost cycles is

$$\tau_{u,n} = -(0.0005d + 0.0579)n + (0.2522d + 11.047). \quad (14)$$

4.3 Influence of cover thickness on the bond strength

The influence of the cover thickness on the bond strength is studied by setting the concrete cover thickness to 41, 51, and 66 mm, respectively, and calculating the ultimate bond strength of the specimen after the salt–frost cycles, as shown in Figure 5.

It can be seen from Figure 5 that the ultimate bond strength of the specimens with different cover thicknesses decreased with the increase of the salt–frost cycles. The ultimate bond strength increases with the increase of the cover thickness, which is consistent with the results in refs [44,45]. The reason is that the friction and mechanical force between the concrete and the steel bar increase with the increase of the cover thickness, which leads to an increase in the ultimate bond strength.

Figure 4: Parameters a_d and b_d of specimens with different steel bar diameters. (a) Parameter a_d ; (b) Parameter b_d .

Figure 5: Bond strength of the RAC specimen with different cover thicknesses.

The ultimate bond strengths of the specimens with different cover thicknesses were fitted, respectively, and the results are as follows:

$$C = 41 \text{ mm: } \tau_{u,n} = -0.0497n + 15.657, \quad R^2 = 0.9503 \quad (15)$$

$$C = 51 \text{ mm: } \tau_{u,n} = -0.0531n + 17.391, \quad R^2 = 0.9539 \quad (16)$$

$$C = 66 \text{ mm: } \tau_{u,n} = -0.0538n + 20.462, \quad R^2 = 0.9818. \quad (17)$$

The ultimate bond strengths of the specimens with different cover thicknesses were fitted, respectively, and the results are as follows:

$$\tau_{u,n} = -a_c n + b_c. \quad (18)$$

The parameters a_c and b_c of specimens with different cover thicknesses are shown in Figure 6.

The relationship between the parameter a_c (b_c) and the cover thickness c was fitted:

$$a_c = 0.0002c + 0.0441, \quad R^2 = 0.7882, \quad (19)$$

$$b_c = 2.4925c + 12.912, \quad R^2 = 0.9701. \quad (20)$$

Substituting formulae (19) and (20) into formula (18), the formula for calculating the ultimate bond strength of specimens with different cover thicknesses after salt–frost cycles is

$$\tau_{u,n} = -(0.0002c + 0.0441)n + (2.4925c + 12.912). \quad (21)$$

5 Conclusion

- (1) The bond–slip finite element calculation curve of RAC and steel bars agreed well with the experimental curve; the finite element calculation results (τ_{us}) agreed well with the experiment results (τ_{ue}), which proves the rationality of the numerical simulation.
- (2) The ultimate bond strength between RAC and the steel bar increased with the increase of the steel bar diameter, and the calculation formula for the ultimate bond strength of specimens with different steel bar diameters after salt–frost cycles is obtained by fitting ($\tau_{u,n} = -(0.0005d + 0.0579)n + (0.2522d + 11.047)$).
- (3) The ultimate bond strength between RAC and the steel bar increased with the increase of the cover thickness, and the calculation formula for the ultimate bond strength of specimens with different cover thicknesses after salt–frost cycles is obtained by fitting ($\tau_{u,n} = -(0.0002c + 0.0441)n + (2.4925c + 12.912)$).

Figure 6: Parameters a_c and b_c of specimens with different cover thicknesses. (a) Parameter a_c ; (b) Parameter b_c .

Acknowledgment: The study was carried out with the support of the Doctoral Science and Technology Startup Foundation of Shandong University of Technology (420048).

Funding information: The study was carried out with the support of the Doctoral Science and Technology Startup Foundation of Shandong University of Technology (420048).

Author contributions: Tian Su: Investigation, methodology, writing – original draft preparation; Ting Wang: writing – original draft preparation; Haihe Yi: writing – review & editing; Rui Zheng: checked original draft; Yizhe Liu: checked original draft; Haoran Zhai: visualization, checked original draft; Zhanfang Huang: methodology, formal analysis.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement: The data used to support the findings of this study are available from the corresponding author upon request.

References

- [1] Sivanathan, A., Q. Dou, Y. Wang, Y. Li, J. Corker, Y. Zhou, et al. Phase change materials for building construction: an overview of nano-/micro-encapsulation. *Nanotechnology Reviews*, Vol. 9, No. 1, 2020, pp. 896–921.
- [2] Lei, D. Y., L. P. Guo, and Y. Li. The investigating on mechanical properties of ultra-high strength and ultra-high ductility cementitious composites (UHS-UHDCC). *Journal of Building Engineering*, Vol. 43, 2021, id. 102486.
- [3] Su, T., C. X. Wang, F. B. Cao, Z. H. Zou, C. G. Wang, J. Wang, et al. An overview of bond behavior of recycled coarse aggregate concrete with steel bar. *Reviews on Advanced Materials Science*, Vol. 60, No. 1, 2021, pp. 127–144.
- [4] Sadati, S., M. Arezoumandi, K. H. Khayat, and J. S. Volz. Shear performance of reinforced concrete beams incorporating recycled concrete aggregate and high-volume fly ash. *Journal of Cleaner Production*, Vol. 115, 2016, pp. 284–293.
- [5] Du, T., H. Q. Li, and Y. W. Qin. Discussion on the development of regenerative concrete in the future. *Concrete*, Vol. 4, 2002, pp. 49–50 (in Chinese).
- [6] Lu, W. and V. W. Y. Tam. Construction waste management policies and their effectiveness in Hong Kong: a longitudinal review. *Renewable & Sustainable Energy Reviews*, Vol. 23, 2013, pp. 214–223.
- [7] Tabsh, S. W. and A. S. Abdelfatah. Influence of recycled concrete aggregates on strength properties of concrete. *Construction and Building Materials*, Vol. 23, No. 2, 2009, pp. 1163–1167.
- [8] Kulatunga, U., R. Haigh, D. Amaratunga, and R. Rameezdeen. Attitudes and perceptions of construction workforce on construction waste in Sri Lanka. *Management of Environmental Quality*, Vol. 23, No. 1, 2006, pp. 57–72.
- [9] Wang, J., H. H. Yuan, X. Kang, and W. Lu. Critical success factors for on-site sorting of construction waste: A china study. *Resources Conservation and Recycling*, Vol. 54, No. 11, 2010, pp. 931–936.
- [10] Lu, W. and H. Yuan. A framework for understanding waste management studies in construction. *Waste Management*, Vol. 31, No. 6, 2011, pp. 1252–1260.
- [11] Wagih, A. M., H. Z. El-Karmoty, M. Ebid, and S. H. Okba. Recycled construction and demolition concrete waste as aggregate for structural concrete. *HBRC Journal*, Vol. 9, No. 3, 2013, pp. 193–200.
- [12] Guo, H., C. Shi, X. Guan, J. Zhu, Y. Ding, T. C. Ling, et al. Durability of recycled aggregate concrete – A review. *Cement and Concrete Composites*, Vol. 89, No. 5, 2018, pp. 251–259.
- [13] Xuan, D., B. Zhan, and C. S. Poon. Assessment of mechanical properties of concrete incorporating carbonated recycled

- concrete aggregates. *Cement and Concrete Composites*, Vol. 65, No. 1, 2016, pp. 67–74.
- [14] Dutta, P. K. and D. Hui. Low-temperature and freeze-thaw durability of thick composites. *Composites Part B: Engineering*, Vol. 27, No. 3–4, 1996, pp. 371–379.
- [15] Cao, D. F., K. F. Zhou, M. Zhou, W. J. Ge, and B. Y. Wang. Study on the shear behaviors of RC beams after Freeze-Thaw cycles. *Applied Mechanics and Materials*, Vol. 488, 2014, pp. 750–754.
- [16] Su, T., J. Wu, G. X. Yang, X. H. Jing, and M. Andrea. Shear behavior of recycled coarse aggregate concrete beams after freezing and thawing cycles. *ACI Structural Journal*, Vol. 116, No. 5, 2019, pp. 67–76.
- [17] Yang, Q. B. *The deicer-frost scaling of concrete*. China Architecture and Building Press, Beijing, 2012 (in Chinese).
- [18] Roumiana, Z., B. Francois, and W. Eric. Frost resistance of recycled aggregate concrete. *Cement & Concrete Research*, Vol. 34, No. 10, 2004, pp. 1927–1932.
- [19] Cheng, Y., X. Shang, and Y. Zhang. Experimental research on durability of recycled aggregate concrete under freeze-thaw cycles. *Journal of Physics Conference Series*, Vol. 870, No. 1, 2017, pp. 1–4.
- [20] Zhu, H. B. and X. Li. Experiment on freezing and Thawing durability characteristics of recycled aggregate concrete. *Key Engineering Materials*, Vol. 400–402, No. 10, 2009, pp. 447–452.
- [21] Li, X. M. *The experimental study on the bond behavior between rebar and recycled concrete after freezing and Thawing*. Master Thesis, Qingdao University of Technology, Qingdao, 2015 (in Chinese).
- [22] Yildirim, S. T., C. Meyer, and S. Herfellner. Effects of internal curing on the strength, drying shrinkage and freeze-thaw resistance of concrete containing recycled concrete aggregates. *Construction & Building Materials*, Vol. 91, No. 8, 2015, pp. 288–296.
- [23] Cao, W. L., M. B. Liang, and H. Y. Dong. Experimental study on basic mechanical properties of recycled concrete after freeze-thaw cycles. *Journal of Natural Disasters*, Vol. 21, No. 3, 2012, pp. 184–190 (in Chinese).
- [24] Fan, Y. H. *Experimental study on the influence of freeze-thaw cycle on mechanical properties of frost-resistant recycled aggregate concrete*. Master Thesis, Harbin Institute of Technology, Harbin, 2009 (in Chinese).
- [25] Lau, K. T., P. K. Dutta, L. M. Zhou, and D. Hui. Mechanics of bonds in an FRP bonded concrete beam. *Composites Part B: Engineering*, Vol. 32, No. 6, 2001, pp. 491–502.
- [26] Ji, X., Y. Song, and Y. Liu. Effect of freeze-thaw cycles on bond strength between steel bars and concrete. *Journal of Wuhan University of Technology*, Vol. 24, No. 4, 2008, pp. 584–588.
- [27] Hanjari, K. Z., P. Utgenannt, and K. Lundgren. Experimental study of the material and bond properties of frost-damaged concrete. *Cement and Concrete Research*, Vol. 41, No. 3, 2011, pp. 244–254.
- [28] Xu, S., A. Li, and H. Wang. Bond properties for deformed steel bar in frost-damaged concrete under monotonic and reversed cyclic loading. *Construction and Building Materials*, Vol. 148, No. 9, 2017, pp. 344–358.
- [29] Petersen, L., L. Lohaus, and M. P. Anna. Influence of freezing-and-thawing damage on behavior of reinforced concrete elements. *ACI Materials Journal*, Vol. 104, No. 4, 2007, pp. 369–378.
- [30] Shang, H., T. Zhao, and W. Cao. Bond behavior between steel bar and recycled aggregate concrete after freeze–thaw cycles. *Cold Regions Science and Technology*, Vol. 118, No. 10, 2015, pp. 38–44.
- [31] Wang, C. X., J. X. Ling, and H. Wang. Effect of the freeze-thaw damage on the durability of recycled concrete and bonding performance of steel. *Journal of Chongqing University: Natural Science Edition*, Vol. 39, No. 2, 2016, pp. 131–139 (in Chinese).
- [32] An, X. Z., C. Yi, X. X. Wang, and X. P. Jiang. Study of bond performance between steel bar and recycled aggregate concrete subjected to freeze-thaw cycling. *Journal of Experimental Mechanics*, Vol. 28, No. 2, 2013, pp. 227–234 (in Chinese).
- [33] Shang, H., Z. Wang, Z. Peng, T. Zhao, G. Fan, and G. Ren. Bond behavior of steel bar in air-entrained RCAC in fresh water and sea water after fast freeze-thaw cycles. *Cold Regions Science and Technology*, Vol. 135, No. 3, 2017, pp. 90–96.
- [34] Ren, G., H. Shang, P. Zhang, and T. Zhao. Bond behaviour of reinforced recycled concrete after rapid freezing-thawing cycles. *Cold Regions Science and Technology*, Vol. 157, No. 1, 2019, pp. 133–138.
- [35] Chen, Q. *Numerical simulation of reinforced concrete bonding properties and beam cracks*. Master Thesis, Zhejiang University, Hangzhou, 2011 (in Chinese).
- [36] Reinhardt, H. W., J. Blaauwendraad, and E. Vos. Prediction of bond between steel and concrete by numerical analysis. *Matériaux et Constructions*, Vol. 17, No. 100, 1984, pp. 311–320.
- [37] Wang, C. X., H. G. Wei, and J. Wu. Experimental Research and numerical simulation of bond-slip of reinforced recycled concrete. *Journal of Guangxi University*, Vol. 38, No. 4, 2013, pp. 996–1002 (in Chinese).
- [38] Cao, F. B. *Experimental study on basic mechanical properties of recycled concrete after freeze-thaw cycles*. PhD Thesis, Nanjing University of Aeronautics and Astronautics, Nanjing, 2017 (in Chinese).
- [39] Su, T., J. Wu, G. X. Yang, and Z. Z. Hao. Bond behavior between recycled coarse aggregate concrete and steel bar after salt–frost cycles. *Construction and Building Materials*, Vol. 266, No. 11, 2019, pp. 673–685.
- [40] Wu, J., X. H. Jing, and Z. Wang. Uni-axial compressive stress-strain relation of recycled coarse aggregate concrete after freezing and thawing cycles. *Construction and Building Materials*, Vol. 134, No. 3, 2017, pp. 210–219.
- [41] Xiao, J. Z. *Recycled concrete*, China Construction Industry Press, Beijing, 2008 (in Chinese).
- [42] Zhang, J., Q. Y. Wang, and S. Y. Hu. Parameter verification of concrete damaged plastic model of ABAQUS. *Building Structure*, Vol. 38, No. 8, 2008, pp. 132–135 (in Chinese).
- [43] Zhao, J. *Experimental study on bond and anchorage performance of recycled concrete*, Guangxi University, Nanning, 2008 (in Chinese).
- [44] Pour, S. M. and M. S. Alam. Investigation of compressive bond behavior of steel rebar embedded in concrete with partial recycled aggregate replacement. *Structures*, Vol. 7, No. 8, 2016, pp. 153–164.
- [45] Hu, Q., W. W. Chen, and C. Y. Zou. Experimental study on bond performance of recycled concrete. *Journal of Harbin Institute of Technology*, Vol. 42, No. 12, 2010, pp. 1849–1854 (in Chinese).