# The corrosion resistance performance of reinforcing steel in autoclaved aerated concrete

Yunzhen Song*

Xiamen University Tan Kah Kee College, Zhangzhou, Fujian Province, China

*songyz@xujc.com

**Abstract.** Autoclaved aerated concrete (AAC) possesses advantages such as lightweight, excellent thermal insulation, and good seismic resistance, making it widely utilized as the wall material in building structures. However, the interior environment of AAC is neutral or weak alkaline, which makes the reinforcing steel inside prone to corrosion. Existing methods to enhance the corrosion resistance of reinforcing steel in AAC are relatively limited, and the impact of carbonation on the corrosion of reinforcing steel within AAC has not been adequately considered. Based on this, the present study investigated the influence of carbonation on the corrosion of reinforcing steel and conducted a comparative analysis of the individual and combined anti-corrosion measures, including reinforcing steel coatings, rust inhibitor powder, and AAC coatings. The results indicate that the complete carbonation of AAC has a negligible impact on the corrosion of reinforcing steel. The effectiveness in corrosion resistance ranks from highest to lowest as follows: surface coating on the reinforcing steel > 0.5% dosage of rust inhibitor powder > surface coating on the concrete. The composite anti-corrosion treatments result in a better rust inhibition effect. This study holds significant engineering value in improving the service life of AAC structures.

**Keywords:** Autoclaved aerated concrete (AAC); Reinforcing Steel; Anti-Corrosion; Carbonation; Mass loss

## 1 Introduction

Due to the excellent properties of autoclaved aerated concrete (AAC) in terms of thermal insulation, sound insulation, and seismic resistance, it is widely used in various building structures such as partition walls, perimeter walls, and load-bearing structures [1, 2]. Meanwhile, the corrosion of reinforcing steel is considered one of the primary factors affecting the durability performance of AAC structures [3]. AAC has a relatively high porosity, which allows water and aggressive ions to easily penetrate the concrete and reach the surface of the reinforcing steel. Moreover, the internal hydration products of AAC mainly consist of 1.1 nm tobermorite, resulting in a neutral or weak alkaline microenvironment. The lack of rust resistance significantly restricts the use of AAC [4, 5]. Therefore, investigating the effects of various anti-corrosion methods on the rust

prevention of reinforcing steel inside AAC is significant. This research aims to enhance the durability performance and prolong the service life of AAC structures.

Currently, studies on improving the corrosion resistance of reinforcing steel can be broadly divided into two aspects. On one hand, efforts are made to increase the difficulty of aggressive ions/gas penetrating the concrete matrix. This includes the use of concrete surface coatings [6, 7] and the optimization of concrete mix proportions [8, 9]. On the other hand, protective measures for reinforcing steel are implemented, including steel surface coatings [10], sealing techniques [11], and rust inhibitors [12]. Rust inhibitors for reinforcing steel, whether added to the concrete mix or applied on the surface of reinforcing steel, are widely used in engineering as an effective approach for preventing and inhibiting reinforcing steel corrosion. They can prevent the penetration of corrosive ions/gas from the environment, thus protecting the reinforcing steel from corrosion. Steel surface coatings provide a protective barrier that isolates the reinforcing steel from the surrounding environment, thereby preventing or delaying chemical and electrochemical corrosion. However, solvent-based organic coatings are not without drawbacks, which are prone to aging and can cause significant environmental issues [13-16]. Therefore, Xu et al. [17] proposed a novel method for preparing aluminum powder-modified waterborne self-curing coatings based on zinc oxide and potassium silicate. This method can enhance the adhesion strength, alkali resistance, and impact toughness of the coating. When the content of zinc silicate is 60%, it exhibits a significant anti-corrosion effect during the corrosion process of reinforcing steel in AAC.

Overall, the current research on corrosion resistance methods of reinforcing steel in AAC is relatively limited and focused. There is significant variation in the effectiveness of reinforcing steel coatings, and the influence of carbonation on the AAC matrix and the performance of the coatings in rust prevention have not been adequately considered. Therefore, this study aims to first investigate the impact of matrix carbonation on the corrosion resistance of reinforcing steel in AAC. Subsequently, the effects of various individuals are explored or combined with corrosion resistance methods on AAC. This study is of great significance for improving the service life of AAC structures.

## 2    Materials and Methods

### 2.1    Experiment materials

The cement used in this study is an early-strength ordinary Portland cement (P.O. 42.5R) with a density of 3.15 g/cm$^3$ and a specific surface area of 358.6 m$^2$/kg, meeting the requirements of standard GB 175-2020 [18]. Class I fly ash is utilized as the primary source of silica phase in the production of AAC, with a fineness of 0.235% and a specific surface area of 55.7 m$^2$/kg, meeting the requirements of standard GB/T 1596-2017 [19]. The main chemical composition of cementitious materials is presented in Table 1. The anti-corrosion materials of reinforcing steel used in this study are produced by Jinan Tudor Building Materials Co., Ltd, including rust inhibitor powder, oil-based reinforcing steel coatings, and water-based concrete coatings. The origin and reference standards of other materials are shown in Table 2.

**Table 1.** Chemical composition of cementitious materials.                (%)

| Materials | CaO | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | MgO | K$_2$O | SO$_3$ | LOI |
|---|---|---|---|---|---|---|---|---|
| P.O. 42.5R | 60.26 | 15.43 | 7.99 | 5.36 | 1.91 | 0.13 | 0.58 | 3.53 |
| Fly ash | 2.656 | 55.708 | 32.792 | 4.429 | 0.235 | 1.541 | 0.65 | 1.51 |

**Table 2.** The origin and standards of raw materials.

| Materials | Origin | Standards |
|---|---|---|
| Limestone | Junhui Calcium Industry Co., Ltd. | JC/T621-2009 [20] |
| Desulfurized gypsum | Huadebao Aerated Concrete Factory | JC/T 407-2008 [21] |
| Aluminum paste | Huayi Chemical Co., Ltd. | JC/T 407-2008 [21] |

## 2.2    Experimental process and design

The mix proportion of specimens is fly ash: cement: lime: gypsum = 71: 16: 10: 3, with a water-to-material ratio of 0.56. The test specimens are divided into two types: cubes with dimensions of 100 mm × 100 mm × 100 mm and prisms with dimensions of 40 mm × 40 mm × 160 mm, as shown in Figure 1(a). The cube specimens are used to test the influence of protective layer thickness on the corrosion resistance of reinforcing steel, while the prism specimens are used to test the influence of anti-corrosion treatments (rebar coatings, rust inhibitor powder, and AAC coatings). Each experimental group consists of three specimens, and the ends of the specimens are encapsulated with epoxy resin to avoid the influence of end corrosion on the experimental results. The type of rebar inside the AAC is Φ8.

In this study, the influence of the carbonation of AAC is first explored on the corrosion level of reinforcing steel. The specimens were divided into non-carbonated and carbonated groups. The carbonation test involved a $CO_2$ concentration of 20%, an environmental temperature of 55±5 °C, and a carbonation period of 7 days to achieve complete carbonation. Furthermore, the thickness of the protective layer is crucial to prevent premature corrosion of reinforced concrete structures. When the protective layer is too thin, it cannot effectively inhibit the infiltration of moisture and corrosive ions from the surrounding air onto the reinforcing steel surface. Therefore, concrete specimens of carbonated groups with protective layer thicknesses of 20 mm, 35 mm, and 50 mm were prepared.

Subsequently, to ensure that all specimens are at the same moisture level, specimens were dried at 60 °C for 12 hours before conducting the accelerated corrosion test. The temperature and humidity cycle for the accelerated corrosion test is presented in Table 3, and the total duration is 28 days. After an accelerated corrosion test, the concrete covering the reinforcing steel was removed, and the reinforcing steel was washed using a 10% hydrochloric acid solution. Then, the reinforcing steel surface was rinsed repeat-

edly with pure water to remove any residual hydrochloric acid. The appearance of rebars before and after acid cleaning is depicted in Figure 1(b). The corrosion of the reinforcing steel was characterized by weighing the mass loss of the reinforcing steel before and after the acid cleaning using an electronic analytical balance.



(a)                  (b)
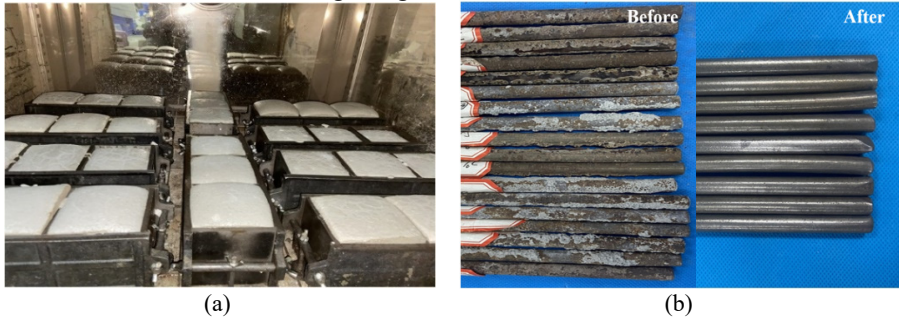
**Fig. 1.** Accelerated corrosion tests: (a) AAC specimens; (b) rebars after acid cleaning.

**Table 3.** The temperature and humidity cycle for the accelerated corrosion test.

| Stage | Temperature (°C) | Relative humidity (%) | Duration (h) |
|---|---|---|---|
| 1 | $25 \pm 5$ | $\geq 95$ | 2.5 |
| 2 | $25 \pm 5 \rightarrow 55 \pm 5$ | $\geq 95$ | 0.5 |
| 3 | $55 \pm 5$ | $\geq 95$ | 2.5 |
| 4 | $55 \pm 5 \rightarrow 25 \pm 5$ | $\geq 95$ | 0.5 |

The experimental conditions for the accelerated corrosion test are designed as shown in Table 4. It includes the individual and combined treatments of rust inhibitor powder, reinforcing steel coating, and concrete coating. The designation R0 is a non-carbonized test group, while all other test groups have been carbonized. R refers to the untreated control group. C1, C2, and C3 represent the test groups of rust inhibitors with concentrations of 0.2%, 0.3%, and 0.5% respectively. H1 refers to the test group using concrete coating alone, and G1 represents the test group using steel coating alone. CH1, CH2, and CH3 are the test groups by combining three concentrations of rust inhibitor powder with concrete coating, while CG1, CG2, and CG3 represent the test groups by combining three concentrations of rust inhibitor powder with steel coating. HG refers to the test group by combining concrete coating and reinforcing steel coating. Q1, Q2, and Q3 represent the test groups by combining three concentrations of rust inhibitor powder with both concrete coating and reinforcing steel coating.

**Table 4.** The experimental conditions for the accelerated corrosion test.

| ID | Individual | ID | Dual | ID | Triple |
|---|---|---|---|---|---|
| R0 | non-carbonized | CH1 | 0.2% inhibitor + concrete coating | Q1 | 0.2% inhibitor + concrete coating + steel coating |
| R | control group | CG1 | 0.2% inhibitor + steel coating | | |
| C1 | 0.2% inhibitor | CH2 | 0.3% inhibitor + concrete coating | Q2 | 0.3% inhibitor + concrete |

| | | | | | |
|---|---|---|---|---|---|
| C2 | 0.3% inhibitor | CG2 | 0.3% inhibitor + steel coating | | coating + steel coating |
| C3 | 0.5% inhibitor | CH3 | 0.5% inhibitor + concrete coating | Q3 | 0.5% inhibitor + concrete coating + steel coating |
| H1 | concrete coating | CG3 | 0.5% inhibitor + steel coating | | |
| G1 | steel coating | HG | Steel coating + concrete coating | | |

# 3    Results and Discussion

## 3.1    Influence of carbonation on corrosion of reinforcing steel

Comparing the corrosion of reinforcing steel between the carbonated group R and non-carbonated group R0, the mass loss rate of the carbonated group R was $5.69 \times 10^{-3}$, while the mass loss rate of the non-carbonated group R0 was $5.58 \times 10^{-3}$. The small difference between the two groups indicates that carbonation has little influence on the corrosion of reinforcing steel in AAC. This can be attributed to two factors. Firstly, AAC has a weakly alkaline pH, so the decrease in pH caused by carbonation has a minimal effect on the corrosion of reinforcing steel. Secondly, the formation of calcium carbonate crystals partially fills the internal pores, leading to a denser matrix and improved resistance against corrosion damage. Through the combined effect of these two factors, carbonation does not significantly accelerate the corrosion of reinforcing steel in AAC.

Moreover, comparing the mass loss of rebars under different protective layer thicknesses, as shown in Figure 2, it can be observed that with the increase in the thickness of the protective layer, the mass loss rate of rebars in AAC gradually decreases after the accelerated corrosion test. However, the reduction in mass loss is not significant, indicating that improving the corrosion resistance of rebars only based on increasing the thickness of the protective layer has limited effectiveness. Therefore, to accelerate the corrosion rate of rebars, subsequent studies used carbonated AAC specimens for further investigation.
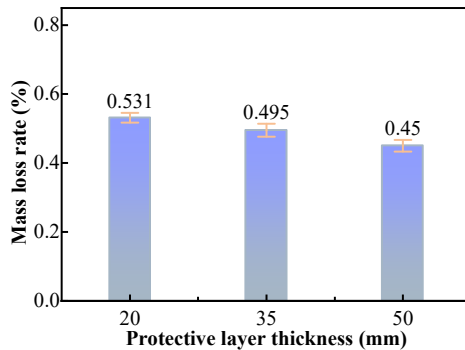


**Fig. 2.** The mass loss rate of rebars under different protective layer thicknesses.

## 3.2    Influence of the individual anti-corrosion method on rebars

**Rust inhibitor powder.**

The impact of rust inhibitor powder on the corrosion resistance performance of rebars is illustrated in Figure 3. In comparison to the control group R without any anti-corrosion treatment, the presence of rust inhibitor powder at three different dosages resulted in a noticeable reduction in the mass loss rate of rebars. Additionally, as the dosage of the rust inhibitor powder increased, the mass loss rate of rebars exhibited a continuous decrease, which indicated that the rust inhibitor powder effectively enhances the corrosion resistance performance of rebars in AAC. One of the reasons is its small particle size. With the addition of the rust inhibitor powder to AAC, the water absorption of the system increases, and a higher dosage leads to a faster thickening of the slurry. This results in a denser AAC, which slows down the rate of moisture and corrosive ions/gas from the air penetrating through the pores into the interior of the AAC. Additionally, the rust inhibitor powder can form a passive film and an adsorption film on the surface of rebars. The passive film protects the surface of rebars by inhibiting the corrosion process, while the adsorption film further reduces the corrosion rate. Through the combined effects of these mechanisms, the corrosion rate of rebars in AAC is effectively reduced. Compared with the control group R, the mass loss rate of rebars decreases by 32.86% when the dosage of the incorporated rust inhibitor powder is 0.5%. It was also observed that further increasing the dosage of the rust inhibitor powder beyond 0.3% does not significantly reduce the mass loss of rebars. Therefore, it is recommended to use an incorporation dosage range of 0.3% to 0.5% for the rust inhibitor powder.
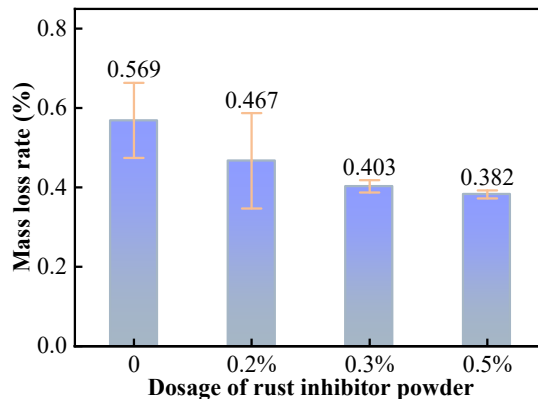


**Fig. 3.** The impact of rust inhibitor powder on the corrosion resistance of rebars.

**Coating treatments.**

As shown in Figure 4, comparing the effects of 0.5% rust inhibitor powder, concrete coating, and steel coating on the anti-corrosion performance of rebars, it was found that the steel coating had the lowest mass loss rate, which was $3.44 \times 10^{-3}$. Compared to control group R, the mass loss rate decreased by 39.54%, indicating the most significant corrosion resistance effect. The concrete coating showed a reduction in the mass loss

rate by 25.65% compared to the control group R, indicating some improvement in the corrosion resistance of rebars in AAC. However, compared to incorporating rust inhibitor in AAC or rebar coating, the effectiveness of concrete coating in preventing rebar corrosion is relatively inferior.
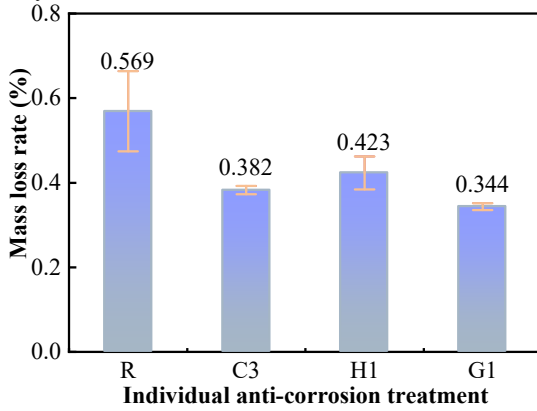


**Fig. 4.** The impact of individual anti-corrosion treatments on the corrosion resistance of rebars.

### 3.3    Influence of the composite rust inhibition methods

**Composite treatment with rust inhibitor powder and concrete coating.**
The impact of the composite treatment with three different dosages of rust inhibitor powder and concrete coating on the corrosion resistance of rebars is shown in Figure 5. Combining the results from Figures 3 and 4, it can be observed that the composite treatment exhibits a lower mass loss rate compared to a single application of rust inhibitor powder or concrete coating. Furthermore, with an increase in dosage, the mass loss rate gradually decreases. The treatment with a dosage of 0.3% and 0.5% shows better performance, with a significantly lower mass loss rate. Specifically, the composite treatment with a dosage of 0.5% results in a mass loss rate of only $3.07\times10^{-3}$, which is a 46.04% reduction compared to the control group R.
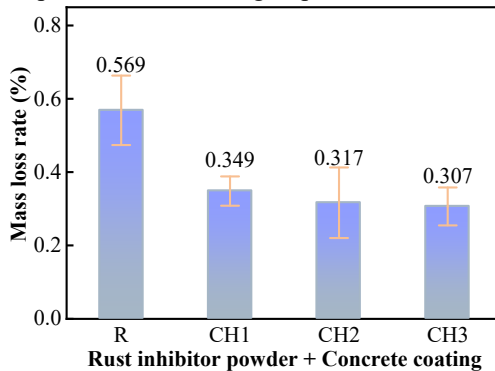


**Fig. 5.** The impact of the composite treatment of rust inhibitor powder and concrete coating.

**Composite treatment with rust inhibitor powder and rebar coating.**

The second composite treatment involved sequentially applying three different dosages of rust inhibitor powder and rebar coating, as illustrated in Figure 6. After the accelerated corrosion test, a significant decrease in mass loss rate was observed. In comparison to the untreated control group R, the composite treatment of 5% rust inhibitor powder and rebar coating resulted in a 59.58% reduction in the mass loss rate. This reduction exceeds half of the mass loss rate observed in the control group R. When compared to the methods of solely adding rust inhibitor powder or using rebar coating, the composite treatment involving the combination of rust inhibitor powder and rebar coating exhibited superior rust prevention effectiveness.
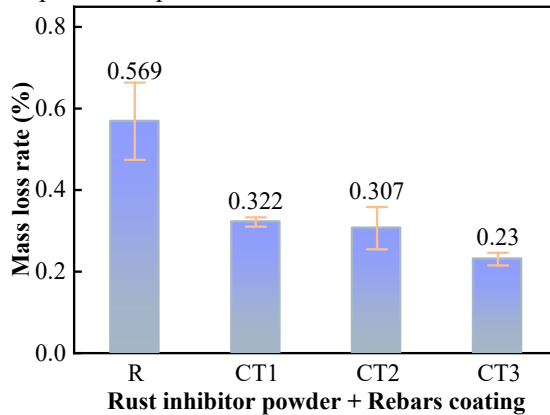


**Fig. 6.** The impact of the composite treatment of rust inhibitor powder and rebars coating.

**Composite treatment with concrete coating and rebar coating.**

The third composite treatment involves the combination of concrete coating and rebar coating. The treatment process begins by applying the coating onto the surface of the rebars. Once the rebar coating has cured and hardened, the coated rebar is embedded into the concrete. Next, a water-based concrete coating is uniformly applied to the surface of AAC twice using a brush. After the AAC specimens are subjected to alternating wet and heat tests. With the composite treatment of the two rust prevention methods, the mass loss rate of rebars is reduced to $1.19 \times 10^{-3}$, which is significantly lower compared to the individual treatment.

**Rust inhibitor powder, concrete coating, and rebar coating.**

Figure 7 represents the mass loss rate of rebars in AAC when treated simultaneously with three different dosages of rust inhibitor powder, concrete coating, and rebar coating. Compared to the control group R, all three dosages resulted in a significant reduction in the mass loss rate of rebars. When the dosage of rust inhibitor powder was 0.5%, the mass loss rate decreased to $1.13 \times 10^{-3}$, representing a reduction of 80.14% compared to the control group R. This indicates a significant rust prevention effect. The simultaneous application of the three corrosion resistance methods to the reinforcing steel in

AAC provides effective protection, effectively reducing the corrosion level of rebars in AAC. It represents the optimal solution for corrosion resistance of rebars in AAC.
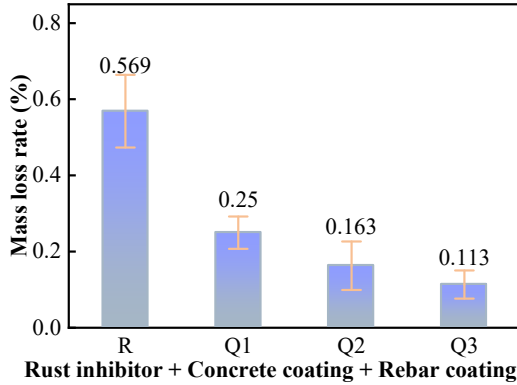
**Fig. 7.** The impact of composite treatment of rust inhibitor, concrete coating, and rebar coating.

## 4      Conclusion

Autoclaved aerated concrete (AAC) has a neutral or weak alkaline microenvironment and cannot resist corrosion from aggressive ions or gas. Therefore, anti-corrosion measures for reinforcing steel are necessary to improve the service life of AAC. This study investigated the impact of carbonation on the corrosion of rebars and explored the enhancing effects of three different rust prevention methods on the corrosion resistance of rebars in AAC. The specific conclusions are as follows:

- The carbonation of AAC has a slight impact on the corrosion performance of internal rebars. Only increasing the thickness of the protective layer does not effectively improve the corrosion resistance of rebars in autoclaved aerated concrete;
- Under complete carbonation conditions of AAC, the most effective method for preventing corrosion is to apply a coating to the rebar surface, followed by the incorporation of a 0.5% dosage of rust inhibitor powder to achieve self-sealing treatment of the concrete matrix;
- When the reinforcing steel is treated with a combination of 0.5% rust inhibitor powder, rebar coating, and concrete coating, the mass loss rate is reduced by 80.14% compared to the control group. This represents the most effective rust inhibition solution.

## References

1. Yardim, Y, Waleed, A M T, Jaafar, M S and Laseima, S 2013 AAC-concrete light weight precast composite floor slab. *Constr. Build. Mater.* **40** 405-10
2. Tanner J E, Varela J L, Klingner R E, Brightman M J, and Cancino U 2005 Seismic testing of autoclaved aerated concrete shearwalls: a comprehensive review. *ACI Struct. J.* **102**(3) 374

3.  Barberton F, Baroghel-Bouny V, Zanni H, Bresson B, Malosse L, and Gan Z 2005 Interactions between chloride and cement-paste materials *Magnetic resonance imaging* **23**(2) 267-72

4.  Ferrer B, Bogas J A and Real S 2016 Service life of structural lightweight aggregate concrete under carbonation-induced corrosion *Constr. Build. Mater.* **120** 161-71

5.  Liu Y, Leong B S, Hu Z T and Yang E H 2017 Autoclaved aerated concrete incorporating waste aluminum dust as foaming agent. *Constr. Build. Mater.* **148** 140-7

6.  Almusallam A A, Khan F M, Dulaijan S U and Al-Amoudi O S B 2003 Effectiveness of surface coatings in improving concrete durability *Cem. Concr. Compos.* **25**(4-5) 473-81

7.  Pan X, Shi Z, Shi C, Ling T C and Li N 2017 A review on concrete surface treatment Part I: Types and mechanisms *Constr. Build. Mater.* **132** 578-90

8.  DeRousseau M A, Kasprzyk J R and Srubar Iii W V 2018 Computational design optimization of concrete mixtures: A review *Cem. Concr. Res.* **109** 42-53

9.  Shakhmenko G and Birsh J 1998 Concrete mix design and optimization *Proc. 2nd Int. Symp. Civil Eng.* 1-8

10. Manna M, Bandyopadhyay N, and Bhattacharjee D 2008 Effect of plating time for electroless nickel coating on rebar surface: an option for application in concrete structure *Surf. Coat. Technol.* **202**(14) 3227-32

11. Lin B L, Lu J T and Kong G 2008 Synergistic corrosion protection for galvanized steel by phosphating and sodium silicate post-sealing *Surf. Coat. Technol.* **202**(9) 1831-8.

12. Wang H, Zhang A, Zhang L, Liu J, Han Y, Shu H and Wang J 2020 Study on the influence of compound rust inhibitor on corrosion of steel bars in chloride concrete by electrical parameters *Constr. Build. Mater.* **262** 120763

13. Gao J, Li C, Lv Z, Wang R, Wu D, and Li X 2019 Correlation between the surface aging of acrylic polyurethane coatings and environmental factors *Prog. Org. Coat.* **132** 362-9

14. Lacombe C V, Bouvet G, Trinh D, Mallarino S and Touzain S 2018 Effect of pigment and temperature onto swelling and water uptake during organic coating aging *Prog. Org. Coat.* **124** 249-55

15. Kenessov B, Derbissalin M, Koziel J A and Kosyakov D S 2019 Modeling solid-phase microextraction of volatile organic compounds by porous coatings using finite element analysis. *Anal. Chim. Acta* **1076** 73-81

16. Qi Y, Shen L, Zhang J, Yao J, Lu R, and Miyakoshi T 2019 Species and release characteristics of VOCs in furniture coating process *Environ. Pollut.* **245** 810-9

17. Xu R, He T, Yang R, Da Y, and Chen C 2020 Application zinc silicate-potassium silicate coating for anticorrosion of steel bar in autoclaved aerated concrete *Constr. Build. Mater.* **237** 117521.

18. Chinese National Standard GB 175-2007 Common Portland Cement (in Chinese).

19. Chinese National Standard GB/T 1596-2017 Fly Ash used for Cement and Concrete (in Chinese).

20. China Building Materials Industry Standard JC/T 621-2021 Quicklime for Silicate Building Products (in Chinese).

21. China Building Materials Industry Standard JC/T 407-2008 Aluminum Powder Paste for Aerated Concrete (in Chinese).