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Quantitative analysis of concrete property under effects of crack, freeze-thaw and carbonation

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HIGHLIGHTS

- Experiment scheme was designed based on orthogonal method.
- Combined influences of carbonation, F-T cycles, chloride penetration and cracks on concrete properties were investigated.
- Compressive strength of concrete possesses negative correlation with times of F-T cycles.
- Crack width possesses the most significant effect on rebar corrosion.

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ABSTRACT

Bridge structures are exposed to vehicle loading and aggressive environments, damage of concrete will inevitably occur. In this study, influences of crack, freeze-thaw (F-T) cycling and carbonation on mechanical property and durability of reinforced concrete were investigated. Concrete prism specimens with rebars were prepared. Corresponding experimental arrangement was obtained based on orthogonal design method, and nine groups of reinforced concrete samples were tested. These samples were firstly loaded to produce cracks with different widths. Secondly, they were retained in cyclic F-T testing machine. Spalling mass and compressive strength were measured and evaluated for concrete under different crack widths and F-T cycles. Then concrete samples were exposed to carbon dioxide (CO_2) gas pressure. Finally, chloride induced corrosion of rebar was tested and combined effects of crack, F-T cycling and carbonation on rebar corrosion were demonstrated based on range analysis (RA), analysis of variance (ANOVA) and Spearman's rank correlation coefficient method (SRCCM), respectively. The results reveal that crack and F-T cycles all increase the spalling mass of concretes, whereas reduce their compressive strength. Crack presents more significant effect on rebar corrosion compared with F-T cycles and carbonation.

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1. Introduction

Reinforced concrete (RC) is one of the most widely used materials for bridge construction. Compressive strength of concrete is an important factor for mechanical performance of RC bridge, while corrosion of rebar is an important problem which reduces its durability [1,2]. In practice, effects of penetration of chloride ions, carbonation of concrete, F-T cycles or external loads can cause concrete damage, corrosion of rebar, and eventually collapse of bridge [3]. In general, the high alkalinity of concrete pore solution can be used as passive layer to protect rebar against corrosion. However, the passive layer will be weakened because of effects from penetration of chloride ions, carbonation of concrete and F-T cycles. As the corrosion proceeds, rust appears. Rust possesses greater volume, which induces cracks of concrete cover. Meanwhile, reinforced concrete will form internal cracks because of material shrinkage and repeated loading. These phenomena will threaten the safe operation of bridge [4,5]. Therefore, investigations on mechanical property and durability of structure in aggressive environments are important to be pursued.

Carbonation of concrete occurs naturally in RC bridge at a rather low yet invasive rate, which is the chemical reaction of portlandite and calcium hydroxide ($Ca(OH)_2$) in cement with CO_2 [6]. Some comprehensive reviews of concrete carbonation have been given on mechanism [7,8], modeling [9], mitigation [10] and industry implication [11]. Besides, the reaction of concrete carbonation depletes the hydroxyl ions (OH^{-1}) and reduces the pH of concrete. It makes steel bar lose its stable alkaline condition and leads to a

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high steel corrosion rate under the action of unfavorable ions [12]. Current researches reveal that carbonation influences the diffusion of chloride ions, and then the rebar corrosion caused by chloride ions [13–15].

F-T cycling is one of the most harmful phenomena for concrete, which has been investigated for many years. The main mechanisms of F-T damage have been identified [16]. F-T cycling can lead to not only superficial spalling, but also serious internal cracking. Consequently, the elastic modulus and compressive strength of concrete decrease and penetration of chloride ions increases [17–19]. Therefore, concrete loses its resistance to mechanical loading and harmful environmental conditions.

In addition, chloride penetration-induced corrosion of rebar in RC concrete is a serious threat to durability of structures [20]. Once the chloride concentration around the surface of rebars exceeds a certain threshold value, the rebars will undergo the depassivation process. Corrosion process is initiated when the chloride ions (Cl^-), oxygen (O_2) and water are sufficient [3]. Lambert et al. [21] demonstrated that chloride ions deteriorate durability of RC structures because of leading to steel corrosion. Experimental investigation by Shaheen and Pradhan [22] revealed that the range of passive region of steel reinforcement decreases with increasing in free chloride concentration for concrete made by both ordinary Portland cement and Portland pozzolana cement.

Furthermore, Cracks cannot be avoided for a real structure, which can be caused by shrinkage, thermal gradients, corrosion of rebar, mechanical loading, etc. These cracks often become preferential paths for the ingress of external agents and lead to degradation of both durability and carrying capacity of structure [23]. Ji et al. [24] demonstrated that cracks will allow more penetration substance, such as CO_2 and chloride ions to invade into pore solution. It accelerates the carbonation process and leads to more and deeper cracks. Zhang et al. [25] found that existence of cracks changes mechanical behavior and reduces load carrying capacity of structure. Cracks also decrease distance between steel bar and external environment at the places of cracks. This situation increases the probability of steel corrosion and deteriorates durability of RC structures.

A large number of researches have been conducted, most of which focus on a single factor that influence properties of RC structures. However, structures usually suffer from a couple effects of multi-factor in natural environment. The influences are complex and synergetic instead of simple superposition by each single factor. There is a rapidly increasing amount of studies on concrete properties with multi-factor. Niu et al. [26] conducted an experimental study on concrete damage and chloride penetration under effects of carbonation and F-T cycles. Zhu et al. [3] investigated the combined effects of carbonation and chloride ingress on concrete. Kuosa et al. [27] demonstrated the synergetic effects of freeze-thaw, carbonation and chlorides on concrete deterioration. Wittmann et al. [28] examined chloride corrosion resistance and rate of chloride diffusion of concrete under alternate actions of freeze-thaw cycles and carbonation. However, many combined aspects have not been demonstrated through experimental and analytical methods in sufficient details.

In this paper, the combined influences of carbonation, F-T cycles and cracks on mechanical property and durability of ordinary Portland concrete were investigated. Experimental scheme was determined through orthogonal design. Nine groups of RC samples were tested according to the order of pre-crack, cyclic F-T, carbonation and chloride-induced rebar corrosion. Quantitative analyses including RA, ANOVA and SRCCM were conducted to evaluate and compare the effects of crack, freeze-thaw and carbonation on concrete property, respectively.

2. Materials and experiments

2.1. Materials and mixture

Q235 steel round bars with diameter 8 mm are cut into 580 mm long. Firstly, the steel bars are polished with grit silicon carbide (SiC) emery paper in order to guarantee no pit corrosion on them. Subsequently, steel bars are cleaned using 12% hydrogen chloride (HCl) solution and then immersed into $Ca(OH)_2$ solution to neutralize residual HCl liquid. Then, ethanol and acetone treatments are used to degrease surfaces of steel bars according to GB/T 50082-2009 [29]. Finally, steel bars are flushed cleanly with clear water and put into drying device at 20 °C for 4 h. Each steel bar is weighed to obtain the initial mass using sensitive balance.

PO 42.5 type Portland cement confirming the requirements of GB175-2007 [30] is used in this study. Crushed stone with diameters ranging from 2.36 mm to 26.5 mm and natural sand with fineness modulus of 2.7 are adopted as coarse and fine aggregates, respectively. The mixture proportions of concrete are listed in Table 1. Slump result of concrete is tested to be 40 mm, which indicates that the mixture is with favorable cohesiveness and meets the requirement of GB 50164-2011 [31].

2.2. Specimen preparation

Specimen used in this study is composed of concrete and two steel bars. Dimensions of specimen and relative positions between concrete and rebar are shown in Fig. 1. The concrete mixtures were prepared in the laboratory by a pan mixer. Prisms of $300 \times 150 \times 150$ mm were cast in steel moulds and compacted by vibrating table. They are allowed to cure at 20 °C and 95% relative humility (RH) and removed from the moulds after 24 h curing. Besides, waterproofing treatments of smudging the silicone sealant on steel bars and binding them up with waterproof tape must be used for the exposed parts of steel bars to resist the corrosion from water and oxygen in curing room (shown in Fig. 2). All specimens are cured under normal curing condition (20 °C and 95% RH) for 28 days before further tests.

2.3. Experimental methods

2.3.1. Scheme design

Orthogonal design of experiment is an effective approach to deal with the test including multiple factors and levels, which can reduce the number of required experiments and achieve reasonable results [32]. It has been adopted by many researchers to improve work efficiency and obtain the optimum level group [32–35]. In this study, three factors prevalent in concrete situated in higher latitudes including crack width, F-T cycle and carbonation time are considered, and each one has three levels. The choices of values for three factors are essential to determine the influence degrees of factors. According to the statistics of China Meteorological Administration (CMA), average times of F-T cycles are 74 in one year for central south, north and northeast regions of China, whose extreme low temperatures range from −40 °C to −10 °C. Based on current research [36], one time of fast F-T cycle in indoor test used in this study is equivalent to 15 times of natural F-T

Table 1
Mixture proportions of concrete.

Materials	Nominal proportions (kg/m^3)
Cement	349
Water	185
Fine aggregate	517
Coarse aggregate	1269

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