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Evaluating the effect of external and internal factors on carbonation of existing concrete building structures

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HIGHLIGHTS

- Empirical model was modified to assess carbonation of concrete building structure.
- Effect of both external and internal factors on carbonation was considered.
- Concentration of CO_2 and surface coating significantly influenced the carbonation.

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ABSTRACT

Carbonation is one of the key factors that affect the durability of reinforced concrete structures. This research investigated the carbonation of existing concrete building structures located in a coastal city (Shenzhen, China) under subtropical maritime monsoon climate. The relationship between carbonation depth and external influencing factors (e.g. temperature, humidity, concentration of CO_2, and surface coating) as well as internal factor (reflecting concrete characteristics e.g. compressive strength) were analyzed. In addition, a prediction model was modified from the existing empirical models with an attempt to evaluate the carbonation risk in existing concrete structures. Test results showed that the carbonation level of indoor ends was higher than that of outdoor ends due to the higher average concentration of CO_2 at indoor ends as well as presence of surface coating at the outdoor ends. The natural carbonation depth was found to have a negative correlation with the compressive strength of concrete and thickness of mortar cover. When the thickness of mortar coating was over 8 mm, no carbonation was observed in existing concrete structures having an age of up to 25 years. Finally, the predicted results from the modified model, which took into account the influence of both internal and external factors, agreed well with tested data. Hence, the modified model can be used to predict the carbonation in existing concrete structures with/without surface coatings to benefit the durability design of existing building structures.

1. Introduction

Carbonation is one of the key factors that affect the durability of reinforced concrete structures [1]. According to available literature [2], the estimated global corrosion costs about 3.4% of the global gross domestic product (GDP). Concrete carbonation is a neutralization reaction between the carbon dioxide from the atmosphere and the cement hydration products (e.g. calcium hydroxide), which could lower or diminish pH value of pore solution. At low pH value, the passive protection film on the steel surface breaks down and lead to the corrosion of reinforcement, which eventually results in cross-section reduction of reinforcement and cracking or spalling of concrete cover. Hence, the service life of structures decreases significantly [3,4]. The existing literatures [5–8] confirm that the factors of natural carbonation of concrete can be divided into external and internal conditions (concrete characteristics). The external factors mainly include temperature [5], humidity [6], CO_2 concentration [7], and surface coating [8] while the internal factors consist of water cement ratio [9], cement content and type [10] etc. These factors play an important role in the carbonation process of concrete. It is also known that the natural environment is usually more complicated than the laboratory

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environment. For example in [5], it was found that the exposure conditions (temperature, humidity, wetting-drying cycling, and freeze-thaw cycling, etc) varies with time. Thus, in comparison to the laboratory data, the measured carbonation data in existing concrete structures exposed to a natural environment is more representative and precise for the development of prediction models.

Traditionally, the most commonly used carbonation model is based on Fick's first law [11] as expressed in Eq. (1).

$$X(t) = K\sqrt{t} \tag{1}$$

where $X(t)$ is the carbonation depth at time t (mm); K is carbonation coefficient (mm/year$^{0.5}$) and t is the exposure time to CO_2 (year). Various researchers [11,12] demonstrated the feasibility of the model by studying the carbonation depth of concrete exposed to natural environment. For example, Han et al. [11] revised K by including more influencing parameters (environmental conditions and concrete characteristics) and re-developed the carbonation prediction model. According to available literatures [11,13], the developed models can be classified into two categories, water to cement ratio model and compressive strength model. The model based on water to cement ratio [11], which is closely related to physical and chemical process of concrete carbonation, appears to in good agreement with the carbonation rate. For instance, the carbonation model proposed by Jiang et al. [14] is based on water to cement ratio and is as follows,

$$X(t) = 839\cdot(1-RH)^{1.1}\cdot\sqrt{\frac{\frac{W}{C\cdot\gamma_c}-0.34}{\gamma_{DH}\cdot\gamma_c\cdot C}\cdot C_o}\cdot\sqrt{t} \tag{2}$$

where $X(t)$ is the carbonation depth at time t (mm); RH is the relative humidity (%); W is water content (kg/m^3); C is cement content (kg/m^3); γ_{DH} is a coefficient to reflect degree of hydration; γ_c is the coefficient for cement type; C_0 is the concentration of CO_2 (%); t is the exposure time to CO_2 (year). The model presented above has a stronger theoretical basis; however, it has following limitations. Firstly, the water to cement ratio is a significant parameter that can be used to determine the performance of concrete. However it cannot be used to fully reflect the quality of concrete; Secondly, it is difficult to determine the water to cement ratio in most of the existing concrete structures. Thus, the models based on compressive strength [11] was developed since for the existing concrete structures it is easy to be determine the compressive strength. Moreover, the compressive strength model can be used to reflect the impact of water to cement ratio, construction level, and curing conditions on the concrete quality. Therefore, based on Fick's first law of diffusion [11], and by taking into account meteorological survey data and testing results, Jiao et al. [15] proposed the following model,

$$X(t) = 2.56\cdot K_{mc}\cdot K_j\cdot K_p\cdot K_s\cdot K_{co_2}\cdot T^{1/4}\cdot(1-RH)\cdot RH \cdot(57.94\cdot m_c/f_{cu}-0.76)\cdot\sqrt{t} \tag{3}$$

where $X(t)$ is the carbonation depth at time t (mm); K_{mc} is the uncertainty coefficient of the model; K_j is the corner correction coefficient; K_p is the surface correction coefficient; K_s is the stress correction coefficient; K_{CO_2} is the coefficient reflecting CO_2 concentration, and $K_{CO_2} = (C_0/0.03)^{0.5}$; T is the average temperature (°C); RH is the average relative humidity (%); f_{cu} is compressive strength (MPa); t is the exposure time to CO_2 (year) [15]. The model considers the effects of both concrete characteristics and environmental conditions. Hence, it is practically significant by taking into account the compressive strength of concrete as the variable. It is pertinent to mention here that in the existing concrete building structures, plenty of concrete walls are usually covered with cement mortar and other coating materials. Moreover, it was also reported that the carbonation process is influence by the surface coating [7,16]. However, in the proposed model by Jiao et al. [15], the effect of surface coating was not taken into account. In order to involve the influence of the surface coating, Baba et al. [17] proposed a model that took into account the influence of cement mortar on the surface and is shown as follows.

$$X(t) = K\cdot\left(\sqrt{t}-D_f/K_f\right) \tag{4}$$

where D_f is the thickness of surface layers (mm); K_f is the carbonation coefficient of surface layers (mm/year$^{0.5}$). Roy et al. [16] evaluated the effect of plastering on the carbonation of a 19 year old reinforced concrete building and found less concrete carbonation when the concrete surface was covered with relatively thick mortar coating. It was concluded that coating could improve the resistance of carbonation of concretes and prolong the service life of concrete structures. However, the proposed model by Baba et al. [17] did not consider concrete characteristics and surrounding environments. Therefore, a model involving both external and internal influencing factors to predict the service life of existing concrete structures should be suggested to investigate the resistance of concrete to the coupling effect of multiple conditions.

In this research, the carbonation performance of existing building structures in a coastal city under the subtropical marine climate (Shenzhen city, China) was investigated. The relationship between carbonation and external as well as internal influencing factors was analyzed, based on which, a model modified from the existing empirical models was used to more accurately predict the carbonation behavior of concrete structures in order to benefit the durability design of existing building structures.

2. Experimental investigation

2.1. Climate conditions of Shenzhen and sampling

The core samples of building structures investigated in this research were from Shenzhen (22°27′–22°52′ N, 113°46′–114°37′ E), China, which is located in Guangdong Province in the South of China and along the South Pacific, with a typical subtropical maritime monsoon climate. In Shenzhen, summer is long with plenty of rainfall while winter is short. In terms of economy, Shenzhen ranks at 4th place in mainland China with a population of more than 10.78 million [18]. The data of Shenzhen Meteorological Station [19] shows that from 1981 to 2016, the annual average temperature, relative humidity, and rainfall was approximately 23.1 °C, 75%, and 1887.4 mm, respectively (Fig. 1). It can be seen from

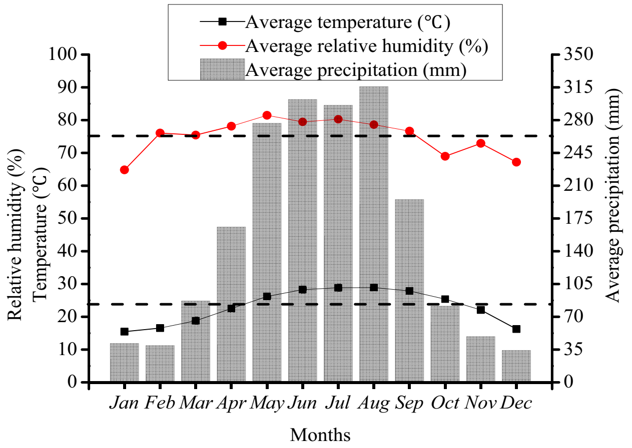

Fig. 1. Climatic chart of Shenzhen (average of temperature, relative humidity, and precipitation) (1981–2016) [19].