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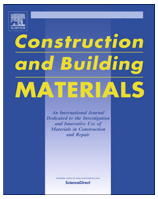

Repairs by fly ash concrete to extend service life of chloride-exposed concrete structures considering environmental impacts

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HIGHLIGHTS

- Repairs by fly ash concrete on chloride-exposed concrete structures are assessed.
- Time-dependent model of surface chloride and diffusion coefficient is used.
- Model of CO_2 emission from concrete production and repair processing is developed.
- Present value of carbon price transformed from the amount of CO_2 is predicted.
- Threshold ratio of diffusion coefficient of original to repair concrete is also defined.

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ABSTRACT

This study proposes a quantitative method to assess the corrosion-free service life and the environmental impact in terms of CO_2 and carbon price due to repairs by replacing cover concrete with fly ash concrete on chloride-exposed concrete structures. The study takes advantage of the Crank–Nicolson based finite difference approach to simplify the assessment. Using the approach, the service life and the repair time for corrosion-free condition of concrete structures can be predicted. At the time of repairs, the CO_2 occurs due to concrete production and replacement processing, and can be assessed using a CO_2 emission model developed here. And, the amount of CO_2 is transformed into the carbon price. From the study, it can be concluded that the increase of the amount of fly ash in repair concrete by 15% causes the reduction of the cumulative CO_2 and carbon price by as high as 58% and 41%, respectively. The ratio of the diffusion coefficient of original concrete to that of repair concrete can be calculated, and its threshold ratio is defined. If the ratio is larger than the threshold ratio, deeper depth of repairs causes shorter extension of corrosion-free period. Furthermore, the threshold ratio apparently decreases with repair depth.

1. Introduction

Very large amounts of wastes are being produced all around the world [1]. In many countries, fly ash which is a by-product from coal power plants is known as one of the wastes causing environmental impacts in the form of air and water pollution. In particular, it is currently found that the amount of fly ash production increases up to 600 million tons per year [2]. In the past, the most common method to manage fly ash was to dispose in landfills. However, this method was unsatisfactory in the situation where excessive amount of fly ash was produced. This led to a huge issue for fly ash management. Hence, another method was necessary.

In the present, one of the methods to reasonably remedy the issue is to reuse fly ash. For years, the research topic on using fly ash to replace for cement in concrete has been intensively studied. And, the properties of fly ash concrete were subsequently reported, e.g., compressive strength, chloride resistance etc. [3,4]. This method is gaining attention, because it not only reduces the disposal area but also helps reduce the environmental impacts produced in cement production process. In particular, it is able to reduce the environmental impact in the form of the climate change resulting from the CO_2 emission in two processes, i.e., calcinations, and generation of electrical power in cement plant [5]. Furthermore, it was reported that replacement for cement by 10% of fly ash can theoretically reduce the amount of CO_2 in the cement production process as high as 25% [6]. It should also be noted that if the large amount of fly ash is available and there is a useful destination, such as partial cement replacement in concrete, the little amount of the environmental impact should be assigned to fly ash. However, in some countries, the amount of fly ash is not enough. And, there is a need of fly ash in order to achieve better

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concrete performance, e.g., in marine environment. If this is the case, the large impact of coal fired electricity production needs to be allocated to fly ash. More details on this can be found elsewhere [7,8]

Although the reuse of fly ash in concrete is found to be useful, the performance in fly ash usage is also of interest. When fly ash is used in concrete structures exposed to marine environment, chloride attack is considered as one of the main factors in their deterioration process. Whenever the critical (or threshold) amount of chloride ions at the surface of reinforcement is reached combining with the condition of having enough oxygen and moisture, reinforcement corrosion may take place resulting in the deterioration of concrete structures. This could not only adversely affect their safety and serviceability, but also shorten their service life [9]. Hence, the long-term performance of concrete structures has to be assessed to avoid structure reconstruction which causes very large amount of environmental impacts [10]. If the long-term performance is unsatisfactory, a proper repair and maintenance action must be applied [11–13]. Although a repair or maintenance action is applied, it is unavoidable that the environmental impacts can occur. When concrete structures are repaired by replacing cover concrete with fly ash concrete, the environmental impacts in terms of the CO_2 can occur during the production of fly ash concrete and the processing of cover concrete replacement. As a result, the assessment of the amount of CO_2 in cover concrete replacement is necessary in order to satisfy low-carbon society.

In this study, a method to assess the amount of CO_2 and the time value of carbon price due to repairs for extending corrosion-free service life (or corrosion-free period) of chloride-exposed concrete structures is presented. For these, there are two issues to be addressed; prediction of corrosion-free service life, and assessment of the amount of CO_2 and carbon price. In predicting the service life, the behaviors of chloride diffusion before and after repairs must be considered. And, the amount of CO_2 and the carbon price must be related to repair application times. The two issues and the remedial solutions are presented as follows.

2. Finite difference for chloride transport in repaired concrete

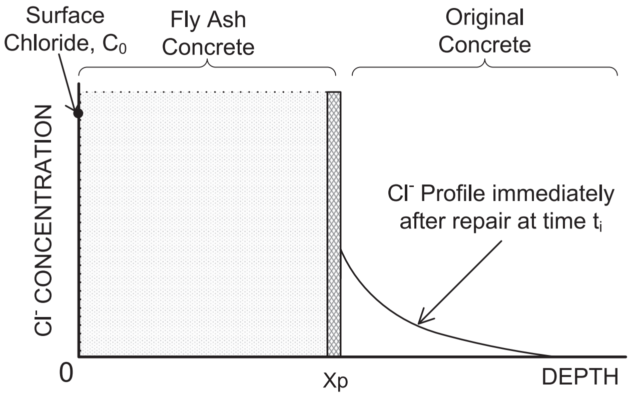
2.1. Without cover concrete replacement

The fundamental partial differential equation (PDE) for chloride ion diffusion based on Fick's second law [14] can be written as

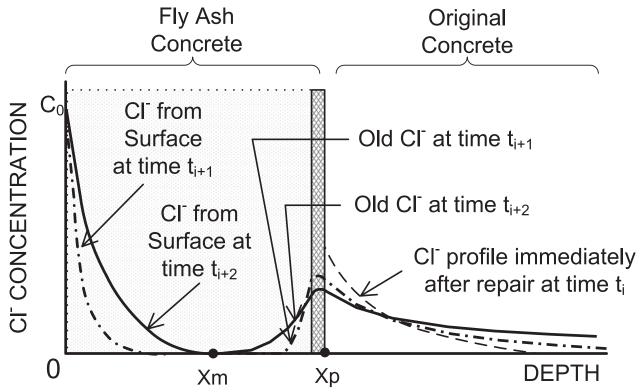
$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D \frac{\partial C}{\partial x} \tag{1}$$

where C is the chloride content as a function of position x and time t, and D is the chloride diffusion coefficient which can be either constant or in a function of x or t.

2.2. With cover concrete replacement



a) Immediately after replacement



b) After replacement

Fig. 1. Chloride profile after cover concrete replacement.

According to REHABCON [15], cover concrete replacement was defined as an action causing removal of original cover concrete and replacement by a repair material, e.g., concrete, fly ash concrete, polymer-based material etc [16,17]. In addition to this definition, the cover concrete replacement in this study is carried out, whenever the corrosion of reinforcement initiates. This initiation occurs, if the chloride content at the outer surface of reinforcement reaches a threshold (or critical) value. With the replacement as shown in Fig. 1a, the concrete is taken off as deep as the distance of x_p, called repair depth. Consequently, the chloride ions inside the taken-off concrete are also removed. After that, repair concrete, such as fly ash concrete, is replaced for the removed original concrete. Immediately after the repair, there are three principal stages as follows

1. The remaining chloride ions in the non-removed or original concrete are about to distribute to both the original concrete and fly ash concrete, so mathematical complication will be involved in solving the partial differential equation (PDE) with nonlinear initial chloride profile at the time t_i as shown in Fig. 1a.
2. When the remaining chloride ions penetrate through the original concrete and also back to the fly ash concrete [18], complicated PDE involving space-dependent diffusion coefficient will be encountered due to the difference between the diffusion coefficient of the original concrete and the fly ash concrete. These are represented in Fig. 1b. If the effect of time-dependent diffusion coefficient due to aging of concrete structures [19] is included, the problem will be more complicated. For these, the partial differential equation (PDE) for the Fick's second law [20] can be written as

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D(x,t) \frac{\partial C}{\partial x} \tag{2}$$

   where $D(x,t)$ is the chloride diffusion coefficient in a function of position x and time t.
3. When the penetrating surface chloride ions merge with the redistributing chloride ions at the point x_m at the time t_{i+2} as shown in Fig. 1b, the complication in solving the PDE is faced again. If this kind of repairs is repeated, the problem will be even more complicated.