Corrosion-Induced Deterioration of Reinforced Concrete

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Steel corrosion in reinforced concrete structures is critical to structural performance and also causes spalling of concrete cover, which poses a risk to occupants and any other person passing under the structure. It is well established that corrosion is initiated after the depassivation of the steel surface caused by the carbonation of the cover concrete and chloride ingress. For real structures in the field, it has been reported that corrosion was unlikely to be observed when the concrete was directly kept from moisture exposure, even when carbonation reached the reinforcing steel; however, corrosion can occur because of rainfall moisture and other sources.

In this study, he cover depth effect on corrosion-induced deterioration on-site in different Asian countries was surveyed focusing on the water penetration rather than the classical corrosion factors, such as carbonation and chloride ingress, and then to experimentally and numerically investigate the threshold of water penetration and drying in cover concrete to support the survey findings.

Keywords: reinforced concrete bridge ; reinforcement corrosion ; corrosion-induce deterioration ; water penetration ; cover depth ; drying and wetting conditions

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1. Overview

Reinforced concrete bridges were visually surveyed in Japan, Thailand, and Vietnam to study the deterioration caused by internal steel corrosion under different climates, focusing on the concrete cover depth. Spalling or cracking arising from corrosion is likely where water is supplied. According to prior studies and our surveys, a concrete cover depth of more than 40 mm was found to prevent spalling, regardless of environmental conditions and structure age. Because water supply at steel is a key corrosion factor, it was hypothesised that under natural conditions, the water penetration in concrete would remain at a depth of approximately 40 mm. Our laboratory study examined water penetration under drying and wetting conditions. The results also suggested that under periodic rainfall conditions, the threshold of water penetration was not exceeded. The numerical study indicated maximum moisture evaporation to facilitate oxygen diffusion occurred at a depth of approximately 30–40 mm unless the concrete was exposed to continuous drying for more than one month. It was experimentally and numerically concluded that an adequate cover depth of greater than 40 mm could inhibit moisture and oxygen penetration at the steel, which supported the survey findings of cover depth effect on a high resistance to corrosion-induced deterioration despite an increase in service life.

2. Background and research significance

Steel corrosion in reinforced concrete structures is critical to structural performance and also causes spalling of concrete cover, which poses a risk to occupants and any other person passing under the structure. It is well established that corrosion is initiated after the depassivation of the steel surface caused by the carbonation of the cover concrete and chloride ingress. In practical design, the risk of corrosion is generally assessed based on the carbonation rate and chloride diffusion to determine the design cover depth [1][2][3]. The supply of both water and oxygen is necessary for the initiation of corrosion after depassivation. Tuutti [4] investigated the effect of relative humidity (hereafter referred to as "RH") during the propagation stage of corrosion, considering chloride ingress and diffusion of O_2, and observed a lower corrosion rate in carbonated concrete with a decreased RH. Similarly, Gonzalez et al. [5] reported an environment with a low RH (50%) can limit the corrosion rate even when carbonation occurs and chloride ions are present in the mortar. Furthermore, Glass et al. [6] concluded that high RH and chloride presence significantly increased the risk of corrosion in carbonated mortars. Moreover, Stefanoni et al. [7] summarised the key factors affecting the corrosion rate of reinforcement in carbonated concrete and concluded that the most important parameter for steel corrosion is the exposure condition, which changes the pore saturation.

It has been classically known that carbonation is one of the keys to initiate corrosion. For real structures in the field, it has been reported that corrosion was unlikely to be observed when the concrete was directly kept from moisture exposure, even when carbonation reached the reinforcing steel; however, corrosion can occur because of rainfall moisture and other sources [8][9]. Ishibashi et al. [10] and Maehara and Iyoda [11] reported that moisture supply is more likely to cause spalling in reinforced concrete. In Japan, the effect of water penetration on corrosion has been considered [12][13], along with carbonation assessment in the design specifications to utilise blended cement, reported to have a higher carbonation rate than concrete without mineral admixtures [14][15][16]. The simple design water penetration rate determined by the water-to-binder ratio, which is proportional to the square root of time based on the Lucas–Washburn equation, is used to calculate the penetration, assuming short-term penetration in a practical way [12][13]. The design cover depth to prevent corrosion in service life is determined by taking into account the age when water penetrates the steel position, as well as the carbonation progress and chloride ingress.

It is known that the total water uptake in unsaturated concrete is initially proportional to the square root of the elapsed time, but it is gradually retarded [17], which is also observed in porous materials other than cementitious materials [18]. Recently, McDonald et al. [19] explained the anomalous water sorption in cement pastes by considering the dynamic porosity based on the 1H nuclear magnetic resonance results, and the proposed mechanism was verified by a transport model in three types of pores with a variable porosity fraction according to the water saturation. Previous studies have shown the effect of water infiltration on corrosion in reinforced concrete for both laboratory specimens and real structures; however, the infiltration mechanism in concrete is anomalous, leading to difficulty in determining the moisture behaviour in concrete, especially under outdoor drying and wetting conditions.

In reality, because the water penetration rate can be affected by climate, such as ambient temperature and precipitation, the effect of cover depth on the deterioration of reinforced concrete by corrosion with water penetration in tropical regions can be different from that reported in Japan. In addition, the water penetration is gradually retarded, as reported previously, which might prohibit water from penetrating deeply. Hence, the objective of this study is to examine and compare the effect of cover depth on the deterioration of reinforced bridges by steel corrosion under different climate environments in Japan, Thailand, and Vietnam. The concrete cover depth was measured using a non-destructive method focusing on the spalling or cracking caused by the corrosion of the internal reinforcement. Subsequently, one-dimensional water penetration in concrete with different cover depths under drying and wetting conditions was experimentally studied, and an experimental method was proposed to focus on the electivity change before and after wetting at each depth. The experimental results are also discussed based on the numerical analysis of the drying process in the capillary and gel pores. The significance of this study is to survey the cover depth effect on corrosion-induced deterioration on-site in different Asian countries focusing on the water penetration rather than the classical corrosion factors, such as carbonation and chloride ingress, and then to experimentally and numerically investigate the threshold of water penetration and drying in cover concrete to support the survey findings.

3. Conclusions

In this study, the corrosion-induced deterioration of reinforced concrete bridges in Japan, Thailand, and Vietnam was visually surveyed, and the cover depth in the members around the deterioration was measured and compared to those without deterioration. In addition, the water infiltration in specimens with different cover depths under drying and wetting cycles was examined to measure the specific electric resistance. The findings and suggestions of this study are summarised as follows:

(1) Corrosion-induced deterioration in bridges was frequently observed where water was continuously supplied from rainfall and other means, regardless of climatic region and member type.

(2) Reinforced concrete members with cover depths exceeding 40 mm, except in a few cases, were protected from visible spalling by corrosion in all surveyed countries, regardless of the boundary conditions and construction year.

(3) It was experimentally found that water penetration, owing to wetting for a few days after drying for approximately 1 or 2 weeks, cannot exceed 40 mm in the case of W/C = 45% and mild drying at 20 °C.

(4) The numerical simulation indicated that significant time (>1 month) was required to dry relatively large capillary pores at depths of more than 40 mm. It is suggested that the capillary pores in the cover concrete with a depth of over 40 mm may be mostly saturated owing to the natural periodic rainfall, leading to the difficulty of water and oxygen penetration into the reinforcement to cause corrosion, despite an increase in service life as indicated in the field survey.

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