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Development of the corrosion-filled paste and corrosion layer at the steel/concrete interface

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ABSTRACT

This study investigated four types of concrete that had deteriorated by wet–dry cycles coupled with DC power. The thicknesses of the corrosion-filled paste, T_{CP}, and the corrosion layer, T_{CL}, were measured by SEM in backscattered electron mode. A sudden increase of T_{CP} near the inner crack is observed. As T_{CL} grows, T_{CP} develops gradually until T_{CL} reaches a certain value, afterwards T_{CP} remains nearly unchanged. Considering the inner cracks, which reflects the actual situation, k_T and T_{CP}^{max} in the $T_{CP} - T_{CL}$ model grow with increase of recycled aggregates replacement; while the rule is contrary if excluding the inner cracks.

1. Introduction

Steel corrosion in concrete is a major cause of durability problems for reinforced concrete structures [1–3]. As the steel corrodes, it gradually produces tensile stress on the surrounding concrete because the volume of the corrosion product is approximately two to six times that of the original steel [4]. Once the tensile stress accumulates enough, inner cracks occur. With the steel corrosion increasing, the cracks develop gradually from inner cracks to outer cracks. Once the cracks penetrate through the concrete cover, i.e., outer cracks, the steel will be in an abominable condition, leading to the rapid deterioration of the structure.

To quantitatively predict the critical steel corrosion on the occurrence of the concrete surface cracking, the three-stage model was proposed by Liu and Weyers [5] which has been widely accepted [6–18]. According to this model, the development process of cracking is divided into three stages. Stage 1: the corrosion products fill the pores at the steel/concrete interface. The corrosion products will not produce stresses on the surrounding concrete until all of the pores have been filled. Stage 2: the corrosion products accumulate at the steel/concrete interface, producing stresses on the concrete cover. Stage 3: corrosion-induced cracks occur gradually; in this stage, a portion of the corrosion products fill the cracks.

The three-stage model assumes that the corrosion products fill the corrosion-induced cracks [5,15–18] in Stage 3. However, through experimental studies of different specimens, the authors have found that the corrosion products do not fill the crack before the crack reaches the outer surface of the concrete cover [19,20]; therefore, Stage 3 is not necessary to consider in the corrosion-induced concrete surface cracking model [19,20].

Stage 1 and Stage 2 are related to the corrosion products filling the pores and accumulating at the steel/concrete interface. In previous studies, the steel corrosion accumulating at the steel/concrete interface was called the ‘corrosion layer (CL)’ [19,21] and the concrete zone around the steel bar filled by corrosion products was called ‘corrosion-filled paste (CP)’ [19,21] or the ‘corrosion accommodating region (CAR)’ [22]. ‘Paste’ means the mixture made of cement, aggregate and water, i.e. concrete, around the steel bar. In this study, the corrosion layer (CL) and corrosion-filled paste (CP) are used to describe these two regions separately.

With respect to the development of CP (in Stage 1) and CL (in Stage 2), previous research assumed the development of CL falls behind the development of CP [5,15,18]. Quite a few studies [19–26] have proven the existence of CP, but more quantitative experimental research is needed to study the thickness of CP and its variation with the growth of steel corrosion. The authors have studied CP [19] and found that the average CP thickness increases as the CL thickness grows. This result shows that the penetration of corrosion products into the porous zone of concrete and the formation of a corrosion layer at the steel/concrete interface proceed simultaneously after the initiation of steel corrosion, and not separately as previously assumed. However, when CL reaches a certain value, the average CP thickness has no obvious growth trend. Based on this experimental result, the relation between the thickness of CP (T_{CP}) and the thickness of CL (T_{CL}) is modelled in Fig. 1 [19].

This model can be expressed mathematically as [19]:

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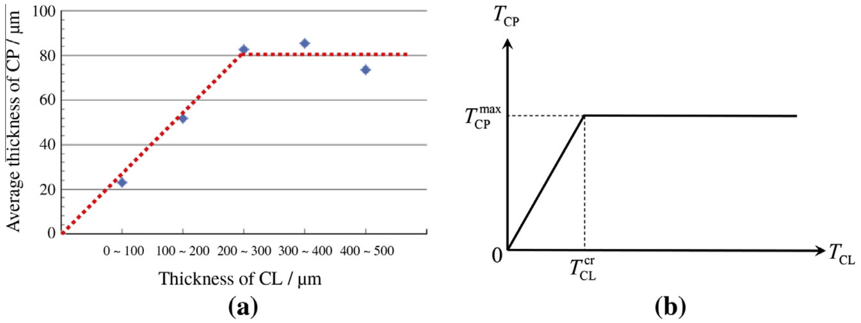

Fig. 1. Relation between T_{CP} and T_{CL} in authors' previous work. (a) Tested thickness of "corrosion-filled paste (CP)" for different corrosion layer (CL) thicknesses. (b) Proposed model of relation between T_{CP} and T_{CL}.

$$\begin{cases} T_{CP} = k_T \times T_{CL}, \; T_{CL} < T_{CL}^{cr} \\ T_{CP} = T_{CP}^{max} = k_T \times T_{CL}^{cr}, \; T_{CL} > T_{CL}^{cr} \end{cases} \tag{1}$$

where T_{CP}^{max} is the maximum T_{CP} achieved, T_{CL}^{cr} is the critical value of corrosion layer thickness corresponding to T_{CP}^{max}, and k_T is the ratio between T_{CP}^{max} and T_{CL}^{cr}. The value of k_T is determined from the relation curve of $T_{CP} - T_{CL}$; according to the experimental results [19], k_T is approximately 0.3. However, it should be noted that, as the samples involved in this study are very limited (only one concrete mixture), whether $k_T = 0.3$ is suitable for any other concrete mixture still remains to be determined.

Because the thickness of CP and CL and their relation are essential for concrete surface cracking prediction induced by steel corrosion (Stage 1 and Stage 2), it is necessary to carry out more experiments with different types of concrete mixtures to further this study of CP and CL.

Therefore, the aim of this study is to observe the development of CL and CP in corroding concrete specimens and also provide quantitative descriptions of the relationship between T_{CP} and T_{CL}. To achieve these objectives, four types of reinforced concrete specimens casted with different percentages of recycled aggregate were investigated. From these four types of specimens, samples with different degrees of steel corrosion and damage were created for further observation. The steel/concrete interfaces of these samples were investigated. This study will help to better understand the progress and the mechanism of concrete cracking induced by steel corrosion.

2. Experimental program

2.1. Specimens and materials

A Recycled Aggregate (RA) concrete specimen with the dimensions shown in Fig. 2 was used in this study. Each specimen contains a 16-mm-diameter plain bar. To avoid severe corrosion of the steel at the ends of each specimen, both ends and the exposed steel bars were coated with epoxy resin. One end of each steel bar was attached to a wire that was connected to a power source, and the other end was treated with protective paint to prevent corrosion products from dissolving in the NaCl solution in which the specimens were to be submerged as described in Section 2.2.

Four types of concrete mixture proportions with different percentages of RA replacement are listed in Table 1. The 28-day compressive strengths of these RA concrete specimens measured on 150-mm cubes are presented in Table 2. A total of five specimens were cast for each type of concrete. However, three of them had been used for other studies, leaving two specimens of each type of concrete for observation and measurement as stated in Section 2.3 and 2.4. The specimens were labelled as RXXX-N, where XXX is the percentage of RA replacement, and *N* is the specimen number with that RA replacement percentage. For example, R067-2 represents the 2nd specimen with 67% NA replaced by RA.

2.2. Accelerated corrosion history

After 28 days of curing, the test specimens were wrapped in stainless steel nets with sponge material filling the spaces between the specimens and the nets. The wetting and drying cycles were coupled with DC power to accelerate the steel corrosion. Each cycle lasted for three days and consisted of a one-day wetting period followed by a two-day drying period. During the wetting period, the specimens, wrapped in the sponge material, were partly immersed in a 3.5% NaCl solution, as shown in Fig. 3, so that the sponge would remain wet and a constant current could be applied between the reinforcing steel bars (acting as anodes) in the specimens and the stainless steel nets (acting as cathodes). The current applied was 300 $\mu A/cm^2$. During the drying periods, the DC power was turned off and the specimens were removed from the sponge and exposed to air in the laboratory for two days.

After 5 cycles, longitudinal cracks were observed on the lateral side of the cylinder specimens, approximately parallel to the steel bar of the specimens. However, the cracks did not run through the entire lateral side of the specimens. Some parts of the lateral side did not show cracks.

It needs to be noted that, during the period of accelerated corrosion, some parts of the concrete cover of the specimens R033-2

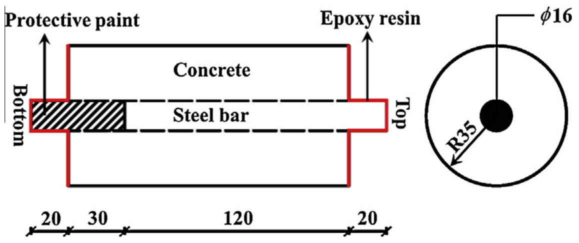

Fig. 2. Schematic of the specimen (dimensions are in mm).

Table 1
Mixture proportions of concrete specimens (kg).

Mix	Weight per 1 m^3 concrete			
	R000	R033	R067	R100
Cement	430	430	430	430
Sand	559	559	559	559
Natural aggregate	1118	745	373	0
Recycled aggregate	0	373	745	1118
Water	185	185	185	185
Supplementary water	0	5	10	15