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Quantification of steel-concrete interface in reinforced concrete using Backscattered Electron imaging technique

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HIGHLIGHTS

- A accurate method for quantification of steel-concrete interface is developed.
- A new thresholding method to separate porous band at the interface is proposed.
- The size of porous band at the steel-concrete interface is not uniform around the steel bar.
- The water to cement ratio can significantly affect the size and the non-uniform distribution of the porous band around the steel bar.

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ABSTRACT

Research on quantification of the size and porosity of the interface between the reinforcing steel and concrete is limited in the current published literature. This paper presents a reliable and accurate method for quantification of steel-concrete interface using the technique of Backscattered Electron (BSE) imaging. Details of sample preparation procedure designed to minimize the damage to the steel-concrete interface due to grinding and polishing are presented. A new thresholding method to separate porous band at the interface from steel and cement pastes is proposed. It is found that there is a relatively wide porous band with large pores and voids near the steel-concrete interface. It is also found that the size of porous band around the steel bar is not uniform, and that the water to cement ratio can significantly affect the size and distribution of porous band at the interface. Quantification of steel-concrete interface as proposed in this paper is of importance in crack prediction of corrosion-affected reinforced concrete structures.

1. Introduction

The interface between steel and concrete is an area with high porosity containing porous band and voids. The geometry and porosity of this interface area have a significant role in the degradation, durability and serviceability of reinforced concrete (RC) structures [1,2]. The size of this porous zone plays an important role in crack prediction of corrosion-affected RC structures [3]. Due to corrosion, the expansive corrosion products would first fill this zone. But before this area is fully filled, no pressure is exerted on concrete. This stage is commonly referred as the “free expansion” stage. Apparently larger size of this area is in favour of increasing the time to crack initiation of concrete [4,5], which leads to prolongation of service life of corrosion-affected RC structures. Furthermore, large crystals of calcium hydroxide depositing at the steel-concrete interface would affect the chloride ingression mechanisms and chloride threshold level [6–9]. In addition, corrosion products accumulated at the interface degrade the bond strength [10,11].

Despite the importance of interface area, few studies on the geometrical microstructure of the steel-concrete interface are available in the literature. With limited information, it is often assumed that the steel-concrete interface has a similar property as the interfacial transition zone (ITZ), which is the interface between cement paste and aggregates. In most of the predictive models for corrosion-induced concrete cover cracking in which the size of steel-concrete interface is considered, e.g., [5,12–14], it has been assumed that this area has uniform thickness of about 10–20 μm around the steel bar, which is nearly the same size as the ITZ investigated by other researchers [15–17].

Also, few experimental studies on the identification of geometric characteristics of the steel-concrete interface can be found in the literature. Söylev and François [18] used a video microscope with a low magnification to investigate micro-defects at the

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steel-concrete interface. With this technique, they observed some gaps beneath the horizontal steel. However, the gap sizes at the interface were not further determined in their study. Mohammed et al. [8] reported that there is a visible gap at the steel-concrete interface forming under the steel bars oriented perpendicular to the casting direction, the size of which varies from several hundred micrometres to the order of a millimetre. The size of images used in their study is in the order of 1.0 mm.

Back Scattered Electron (BSE) imaging technology is an advanced technique which has been used to observe the microstructures in cement and concrete since the work done by Scrivener and Pratt [19]. BSE imaging has the advantage of distinguishing the phases, e.g., hydrated cement pastes, anhydrous cement pastes, aggregates, pores, ITZ and cracks, of a flat-polished concrete sample. Each of the phases of concrete has its own greyscale range and brightness contrast in BSE images [17,20–23]. As a result, quantification analysis of the phases of concrete as well as reinforced concrete needs to be performed on BSE images [1,24–27].

Glass et al. [24] used 200 μm steel ribbons in concrete samples to observe the steel and concrete interface microstructure using BSE imaging. However, this size of steel ribbons cannot represent the interface in real RC structures. Horne et al. [1] used 9 mm steel bars in the study of the microstructure of steel-concrete interface, but 9 mm is usually the size of mesh. In most large-scale RC structures, the steel bars larger than 12 mm in diameter are normally required [28]. Moreover, only two locations, the top and bottom sides of the steel, are quantitatively analysed in their study. This appears to be inadequate to represent the whole steel-concrete interface around the steel bar. A thorough quantitative measurement should be conducted for the entire interface area around the steel.

On the other hand, few BSE image processing techniques have been proposed for the phase determination and pore segmentation in concrete [23,26,29]. It seems that there is no standard method for these techniques. If a set of consistent rules is used for pore segmentation, the method for phase quantification in concrete can be reliable. As the phase determination based on BSE images can be very subjective [26], statistical analysis of results obtained from BSE images is also necessary. Another issue for BSE imaging is the sample preparation of reinforced concrete. With the requirement of a flat-polished surface, reinforced concrete samples must be cut into suitable size, and then ground and polished with minimum damage to the steel-concrete interface. However, the steel bars are easily deformed during sample preparation, complicating the observation of the steel-concrete interface. Therefore, a high-quality grinding and polishing process is needed to remove damaged surface caused by cutting, meanwhile minimizing the deformation of steel bars caused by the grinding and polishing.

Considering above discussions, it is almost certain that a reliable method is essential for observation and quantification of the steel-concrete interface. This paper presents such a method with accuracy for detail preparation of BSE samples for the measurement of porous band at steel-concrete interface. In this method, the damage due to grinding and polishing of the steel-concrete interface is minimized. Steel bars of 16 mm in diameter were used in reinforced concrete samples with a practical perspective on large RC structures. A new greyscale thresholding method is used to identify the porous band at the steel-concrete interface from BSE images. Quantitative analysis based on BSE images is conducted for the entire interface around the steel bar and the effect of w/c ratio on the steel-concrete interface is investigated. Repetition tests and statistical analysis are also carried out to verify the reliability of the quantification results from image analysis. The results for the porous band presented in this study can not only be useful for predictive models considering the microstructures of the steel-concrete interface, but also be helpful for RC mesoscale structure modelling.

2. Experiment

2.1. Test specimen

Concrete prism specimens of the size 150 mm × 150 mm × 300 mm with the three different mixes were cast. Ribbed low carbon steel bar of 16 mm in diameter was embedded in each of the specimens at the location shown in Fig. 1. The cover thickness to the bottom surface of the concrete was 20 mm. Cement used in this experiment was ordinary Portland cement. The coarse aggregates used were single sized normal weight limestone of 14 mm and the sands were medium grading river sand (<0.75 mm). Three water-cement ratios were used. The concrete mix specification is listed in Table 1. All the specimens were compacted for 10 s on vibration compacting table and water-cured for 28 days before testing.

No mineral additives and chemical superplasticizers were used in this experiment, as supplementary cementitious additives like fly ashes or silica fumes give rise to some difficulties to BSE image analysis. For example, fly ashes containing carbons make it difficult to determine the boundary lines between cement pastes and pores in BSE images [30]. On the other hand, silica fumes and superplasticizers greatly affect the consistency of cement paste and slump of concrete [31,32], which also affect the steel-concrete interface significantly.

Considering the spatial variability of the interfacial porous band, 10 mm thick slices at three longitudinal locations along the steel bar, as shown in Figs. 1 and 2(a), were cut from each prism specimen. These slices were numbered as 1, 2 and 3 from one end to the centre. Concrete slices were then core drilled into samples of 38 mm in diameter containing steel bar in the centre by core drill press. Fig. 2(b) shows three core drilled samples from slices as shown in Fig. 2(a) cut from Sample A.

In order to have statistically reliable results for each mix design three concrete samples were cast (3 × 3), and three longitudinal locations in each specimen were cut to obtain core drilled samples. In total, 27 (3 × 3 × 3) core drilled samples were prepared for BSE image analysis in this experiment. Therefore, a more statistically reliable and accurate result can be produced from the experiment.

2.2. BSE sample preparation

Core drilled samples were dried at a temperature of 25 °C and moulded by ultra-low viscosity epoxy. A vacuum was applied to the concrete-epoxy moulds for 20 min to force the epoxy into the pores in samples. Then, the samples were left to harden under a temperature of 25 °C for 24 h followed by oven drying below 60 °C for one hour. As the samples were prepared in the same temperature and humidity condition, the shrinkage of concrete caused by

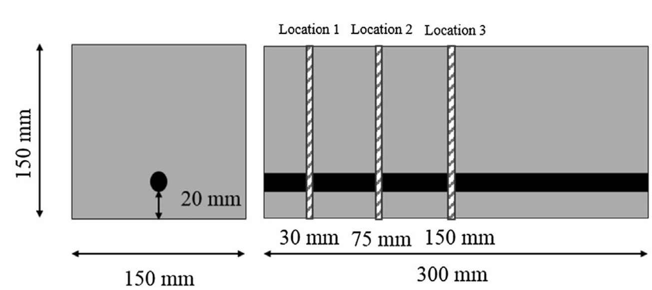

Fig. 1. Dimensions of concrete specimen.