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Quantitative comparison of chipping- and hydrodemolition-induced microscopic damage evolution in concrete substrates

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HIGHLIGHTS

- Chipping- and hydro-demolishing-induced damage in concrete samples was evaluated.
- The damage depth induced by surface chipping is about 4 cm.
- The hydro-demolished concrete substrate does not undergo severe damage.
- The chipped-core strength is merely 40 % of that of the hydro-demolished core.

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ABSTRACT

The present study quantitatively evaluates the severity of chipping- and hydrodemolition-induced damage in concrete substrates. The concrete substrate layer was removed with a pneumatic breaker (BR) or a waterjet (WJ). The X-ray computed tomography (CT) method was used to microscopically investigate the porosity, crack width and its connectivity in the concrete substrates. This analysis indicates that damage depth was significantly greater in the concrete samples prepared with the BR, compared with the WJ. After this analysis was completed, additional concrete material was placed on these surfaces with these different preparation methods. Subsequently, concrete bending tests were performed on sample cores obtained from these prepared concrete blocks. From these tests, the flexural strength and fracture surface location were examined. Combining the above-mentioned results, it is concluded that concrete chipping and removal with the BR can severely damage the concrete substrate contrasted with the WJ, thus resulting in a decrease in its flexural strength.

1. Introduction

It is increasingly common to strengthen and repair concrete that has undergone aged deterioration at construction sites, by placing new concrete onto the deteriorated, pre-existing concrete substrate [1,2]. Significant effort has been made in examining and characterizing the strength of repaired concrete, i.e. the bond strength between an existing concrete substrate and a newly placed concrete material for repair [3–15]. Early studies concerning concrete-to-concrete bonding strength for repairing a deteriorated concrete surface date back to the last century (e.g. [14,16]). In these studies, different concrete surface removal techniques were employed to examine how the bonding strength is affected by surface preparation methods [15], including sandblasting, chipping, grinding, and hydrodemolition. It was then clarified that such surface removal techniques could cause microcracks on the prepared surface, generating a weakened plane. Also, it was found that the roughness of the prepared surface plays a key role in the evolution of the bonding strength between the old and newly-placed concrete as the roughness is directly associated with the frictional resistance of the surface [13,17,18]. In light of these findings, a significant effort has been made in investigating the influence of the roughness of an existing concrete substrate surface [4,8,10,12,19–21] while comparing different concrete removal techniques and surface preparation methods. Such previous studies have shown that the surface roughness of a concrete substrate certainly influences the adhesion of repaired concrete. However, as discussed in the studies [5,10], its effect is occasionally quite

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obscure, giving inconsistent results among the previous studies. Garbacz, Courard and Konstana [5] concluded that the influence of near-surface cracks on the adhesion of a repaired concrete structure is considerable, which is in accordance with the discussions made in other studies [14,15].

In the practice of concrete repair, the surface of deteriorated concrete is commonly removed with a pneumatic breaker (BR) between 10 and 30 kg or a waterjet (WJ) [22]. Image analyses with a fluorescent method conducted in a previous study [23] revealed that although it is straightforward to remove the deteriorated concrete surface with such a BR, BR-induced vibration generates micro-fractures in the concrete substrate, eventually decreasing its strength. On the other hand, bending strength tests performed in a previous study indicate that the hydro-demolished concrete surface yields sufficiently high bond strength between a concrete substrate and a new layer when the removed concrete thickness is more than 5 mm [24]. This same conclusion was found in other studies (e.g. [14,15]). As described above, substantial efforts have been made in assessing the influence on concrete surface removal on the deterioration of the concrete substrate and the bond strength with a new concrete layer. It should be noted however, that the quantitative evaluation of damage in a concrete substrate inflicted by BR- or WJ-induced vibration and pressure has not yet been adequately conducted. Also, it is still challenging after adding repair materials to investigate the degree of concrete deterioration and to assess deterioration depth in the concrete substrate.

The present study conducts image analysis with an X-ray micro-computed tomography (CT) scanner and also performs concrete bending tests to evaluate chipping- and hydrodemolition-induced damage in concrete substrates, to replicate the repair of an aged, deteriorated concrete. The X-ray CT method [25–27] reconstructs three-dimensional (3D) images of pores and fractures inside the concrete without destructing it, thus allowing for quantitatively evaluating internal concrete damage. For the quantitative evaluation, various parameters representing characteristics of pores and fractures are employed. The present study computes three parameters based on the image analysis, namely porosity index representing pore ratio, burn number denoting fracture width, and medial axis [28,29] related to the connectivity of fractures. These parameters were used in a previous study [25] in order to evaluate damage and deterioration taking place in a cylindrical concrete sample subjected to a uniaxial loading. Another study [30] investigated the influence of surface chipping with a BR on the integrity of a concrete substrate, based on these parameters, and ascertained that BR-induced damage extends 4 cm in depth from the chipped surface. The study demonstrated the effectiveness of these parameters in evaluating BR-induced damage in the concrete substrate. The present study employs the same method to evaluate not only chipping-induced damage but also hydrodemolition-induced damage. This study aims to clarify the resultant damage from removing concrete via chipping or hydrodemolition. This was achieved by analysing the micro-fractures produced from vibration- and pressure-induced surface deterioration. A comparison of WJ and BR methods was then made in terms of microscopic damage taking place in the internal structure of the concrete substrates.

Bending strength test is defined as a method to assess the flexural strength of concrete, according to Japanese Industrial Standard (JIS) A 1106. According to JIS, the cross-section of a concrete block shall be 100 mm × 100 mm or 150 mm × 150 mm, and the block length shall be 4–5 times that of the edge length of the cross-section. The dimensions are considered almost the same as that stated in European Standard (150 mm × 150 mm × 750 mm). The test is widely employed for confirming the properties of concrete, designing concrete placement and concrete mix ratio, and evaluating the strength of concrete floor and pavement [31,32]. The present study uses cylindrically-shaped core samples from concrete blocks that have been prepared by placing concrete onto a concrete substrate after removing the surface with either the BR or the WJ. These specimens are prepared by drilling into the concrete block perpendicularly to the chipped and hydro-demolished surfaces. The obtained cores are then used to perform bending tests designed for a sample with a cylindrical cross section [33,34], although several standards defined by JIS suggest a core sample with a rectangle shape. The experimental results are subsequently analysed in terms of their flexural strength and failure plane location.

In the following sections, first a description of the X-ray micro-CT scanner as well as the CT image analysis method is provided. Next, the concrete block preparation is explained, showing information on its mixture proportions, dimensions, and the surface removal method. Then, based on the CT image analysis, the quantitative evaluation of near-surface damage is conducted for the concrete core samples that were obtained from these concrete blocks. To repair these concrete blocks new concrete was placed on the surfaces of the existing concrete blocks. Core samples were then obtained from these blocks, which included the boundary between the existing concrete and the new layer. Using these core samples, bending tests were performed. Finally, a discussion on the mechanism of microscopic damage evolution caused from the concrete chipping and removal is made by combining the results obtained from the bending tests and the CT image analysis.

2. X-ray CT scanner system

2.1. X-ray CT scanner

The present study employs an X-ray micro-CT scanner and its specifications are shown in Fig. 1(a) and in Table 1, respectively. More detailed info is found in the reference [25].

2.2. X-ray CT image and CT value

Fig. 1(b) shows the cross section of a concrete core sample. The cross section constructed with the X-ray CT method is composed of voxels, and each voxel is given a CT value. The definition of CT value is given in the reference [25]. Since an X-ray absorption coefficient is proportional to material density, the CT value represents the density in an analogous way. A material with high density is colored in white in a CT image, while a low-density material appears black in the image. Based on this, it is possible to distinguish aggregate from mortar visually in a concrete block. Table 2 shows the specific scanning conditions that the X-ray CT images were taken. These CT images were subsequently used in this study.

3. Image analysis method

3.1. Analysis method

The present study employs a commercial software, ExFact analysis for porous/particles (Nihon Visual Science Inc.). This software re-constructed and configured the CT images from the core samples. Thus, the 3D structure of the core samples, consisting of fractures and pores, was able to be analysed and evaluated. The detailed principles of this software is described in the study [35].

Using the above-mentioned software, three parameters, namely porosity index, burn number, and medial axis, are computed to assess a degree of deterioration of concrete substrates. These parameters are derived from the procedure shown in Fig. 2. Specifically, 3D images were first re-constructed from a series of X-ray CT images. Next, a threshold to distinguish pores from aggregate and