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Analysis of cracking in high-strength cementitious materials under heating and re-curing using X-ray CT

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ABSTRACT

The healing of cracks formed during high temperature exposure plays an important role in the performance recovery of concrete damaged by fire, but it is necessary to better understand the cracking behavior under heating and re-curing. This research applied X-ray microtomography and image analysis techniques to non-destructively examine the internal microstructure of high-strength cementitious materials and to clarify the changes in crack characteristics due to heating and water re-curing. Results showed that, in cement paste, radial cracks formed during heating due to shrinkage by dehydration and these cracks grew larger and new cracks formed during re-curing due to expansion by rehydration. In concrete, cracks formed around aggregates due to incapability in thermal expansion, but water re-curing reduced the total crack space. Better crack recovery in concrete relative to cement paste may be due to the lower cement content and the restraining effect of aggregates.

Keywords. Fire damage, cracking, water re-curing, X-ray CT, high-strength concrete

INTRODUCTION

Although concrete generally exhibits good fire resistance, exposure to high temperatures can lead to a reduction in overall structural performance including decreased load-carrying capacity, durability and fire resistance. These are caused by the dehydration of the cement paste as well as the incapability in thermal expansion between the cement paste and coarse aggregates, which lead to weakened matrix strength, coarsened pore structure, and extensive cracking. Explosive spalling has also been observed to occur in concrete materials with dense microstructures such as high-strength concrete (Phan, 2002).

Repair operations are necessary to restore performance and typically involve the removal of damaged areas and the casting of a patching material (Tovey, 1986). Unfortunately, these operations require intense labor for removal, produce waste material that must be disposed of, and consume resources in replacing the damaged areas. A repair method that utilizes the existing concrete rather than a new patching material could provide a more economical, environmentally-friendly repair option which reduces the extent of labor-intensive repairs, thus saving energy and labor costs and reducing waste generation and resource consumption.

Re-curing of fire-damaged concrete in water has been found to restore strength and durability performance through the reduction of pore space and regeneration of hydration products from the rehydration of calcium hydroxide as well as the hydration of unhydrated cement particles (Crook & Murray, 1970; Sarshar & Khoury, 1993; Lin et al., 1996). Water supply is of particular importance for recovery, as the rate of rehydration is higher in such cases (Poon et al., 2001). Furthermore, while high-strength concrete has been found to perform differently under fire loading, it has also been shown to have better recovery under re-curing due to its dense microstructure (Poon et al., 2001). Recovery of durability has been attributed to the filling of pore space and healing of cracks as well as the consumption of calcium oxide during rehydration, which reduces the potential for harmful carbonation, but the instability of healed crack areas may limit the strength recovery (Henry et al., 2011).

As the formation and healing of cracks has been found to strongly contribute to the damage and recovery of fire-damaged concrete, it is necessary to better understand the cracking behaviour under heating and re-curing conditions. In this research, X-ray microtomography (X-ray CT) is utilized to non-destructively examine the internal structure of fire-damaged high-strength cementitious materials with the goal of characterizing the formation and change in cracks due to heating and water re-curing by applying image analysis techniques.

EXPERIMENTAL PROGRAM

Overview. An overview of the experimental program is shown in Fig. 1. Each step of the program will be introduced in detail in the following sections.

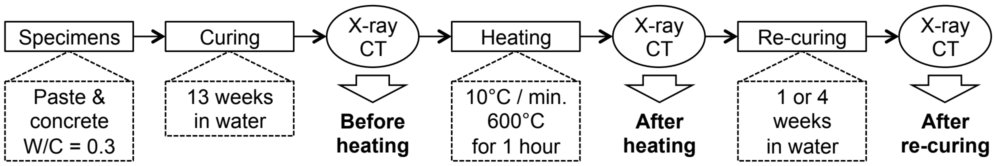


Figure 1. Overview of the experimental program

Specimen preparation and curing. Both cement paste and concrete were prepared with a water-cement ratio (W/C) of 0.30, a very low W/C typical of high strength cementitious materials. Ordinary Portland cement was used as the binder in both mixes. After casting, cylinders (100 x 200 mm) were sealed and cured in the molds for 24 hours, then removed and placed in water curing at 20°C for four weeks. The cylinders were then removed from water curing and 20 mm cores were extracted from the center of the cylinder. These cores were cut into 20 mm segments which were then returned to water curing for another nine weeks. Total curing time from casting to heating was 13 weeks (91 days) in order to achieve a high degree of hydration similar to that of concrete structures in service.

Heating and re-curing. Fire exposure was simulated using an electric furnace with a temperature control program. The rate of heat increase was set at 10°C per minute until the target exposure temperature of 600°C was reached, after which it was maintained for one hour. After removal from heating, specimens were allowed to cool at room temperature for one hour then placed in water re-curing with conditions similar to the initial curing period. Re-curing was carried out for one week for concrete and four weeks for cement paste.

Image acquisition using X-ray microtomography. X-ray microtomography is a powerful technique for investigating the three-dimensional (3D) microstructure of a material. As summarized by Promentilla and Sugiyama (2010) and Landis and Keane (2010), the concept of X-ray microtomography is similar to that of Computed Axial Tomography (CAT or CT) scans in the medical field, in which a 3D digital image is reconstructed from a series of two-dimensional (2D) images or "slices." Each voxel (3D pixel) within the 3D digital image has an associated X-ray absorption value which can be correlated to material density, and thus the internal structure can be determined based on the arrangement of the voxels in a 3D space. The resolution of the image can vary from the sub-micron scale or a few microns (for CT systems using synchrotron radiation with a parallel and monochromatic beam) to tens of microns (for microfocus radiation with a cone beam). There is, however, a trade-off, in that the maximum sample size for the higher-resolution systems is limited to less than a few millimeters, whereas specimens on the scale of a few centimeters may be used with lower resolution systems. In the concrete field, X-ray CT has been applied to a variety of research areas including pore structure characterization and freeze-thaw damage (Sugiyama et al., 2010; Promentilla and Sugiyama, 2010).

In this research, a desktop microfocus CT system was used for acquiring the 3D images. The set-up (Fig. 2) consists of a microfocus X-ray emitter, a rotation table, an image intensifier (II) detector with CCD camera, and an image processing unit (Promentilla et al., 2008), and power settings of 130 kV and 124 μA were used for scanning. Image acquisition was carried out before heating, after heating, and after one (concrete) or four (cement paste) weeks of water re-curing. As illustrated in Fig. 3, the focus area for data acquisition was approximately 11 mm in height, 20 mm in diameter, and roughly centered on the specimen. In this area, 351 slices (33 microns) thick were obtained. Each slice was 1024 by 1024 pixels in size, with each pixel 20 microns by 20 microns, for a voxel size of 20 x 20 x 33 microns.

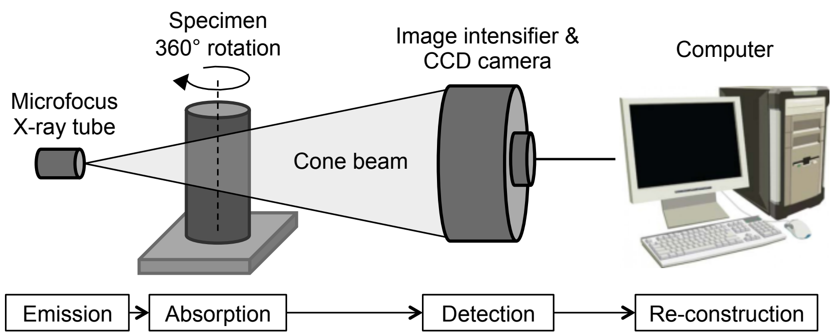


Figure 2. Set-up for X-ray CT image acquisition

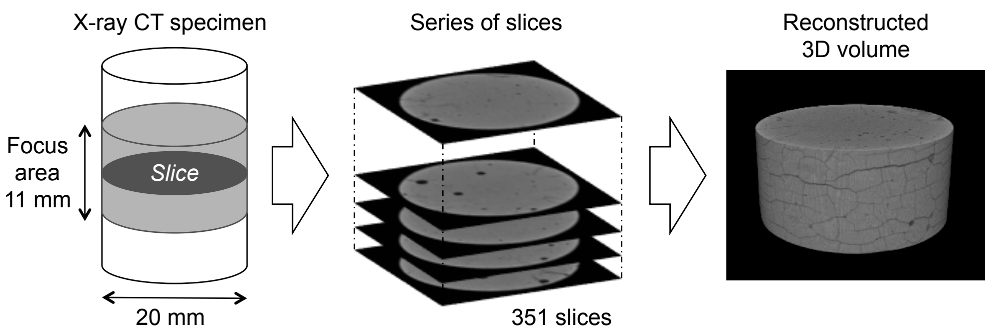


Figure 3. Details of X-ray CT specimen and 3D digital image reconstruction

RESULTS & DISCUSSION

Images of specimens after heating and re-curing. First, the conditions of the cement paste and concrete specimens were investigated by examining the cross-sectional images from before heating, after heating, and after re-curing at various heights. Fig. 4 shows the images from the cement paste specimen. Heating can be seen to induce radial cracks in the specimen due to shrinkage, which is driven by the dehydration of the C-S-H gel and portlandite. The radial cracks can be seen to grow after 28 days of water re-curing, in addition to the growth of new cracks which bridge between the ends of the heating-induced cracks. Although crack recovery under water re-curing was expected, this crack growth may be driven by the rehydration of lime, which is accompanied by an increase in volume.

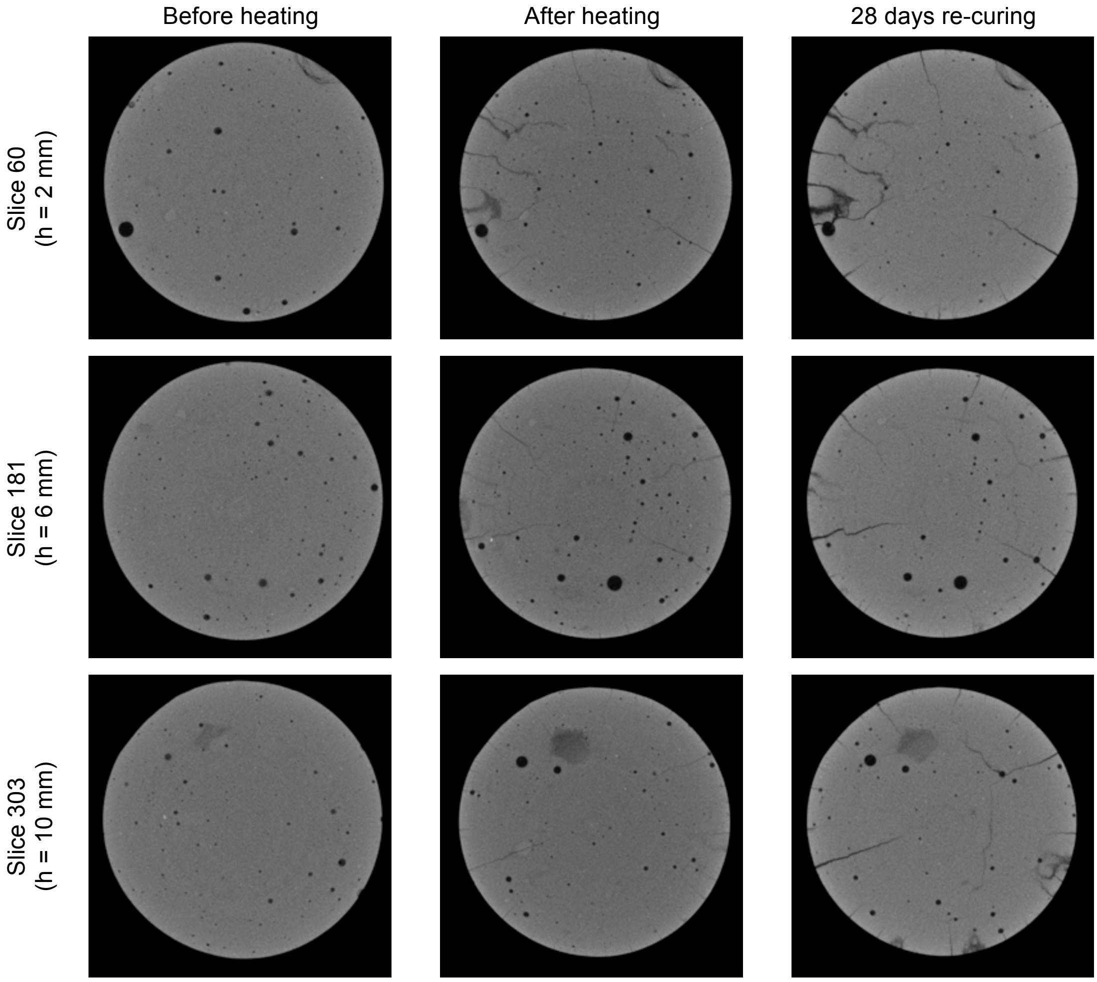


Figure 4. Cross sections at various heights of cement paste specimen

Fig. 5 shows the cross-sectional images of the concrete specimen. Unlike the cement paste specimens, the heterogeneous composition of the concrete specimen makes it more difficult to visually identify the cracks formed by heating as well as the change in cracking due to water re-curing. However, close examination shows that the majority of cracks appear to occur in the mortar-aggregate interface, most likely due to the incompatibility in thermal expansion between the aggregates and the mortar. Furthermore, the large size of the coarse aggregates relative to the specimen size may have an effect on the crack formation behavior. Unlike the cement paste, cracks formed by heating did not appear to grow due to water re-curing, which could be attributed to the restraining effect of the aggregates as well as the lesser volume of cement in the concrete specimen relative to the cement paste specimen.

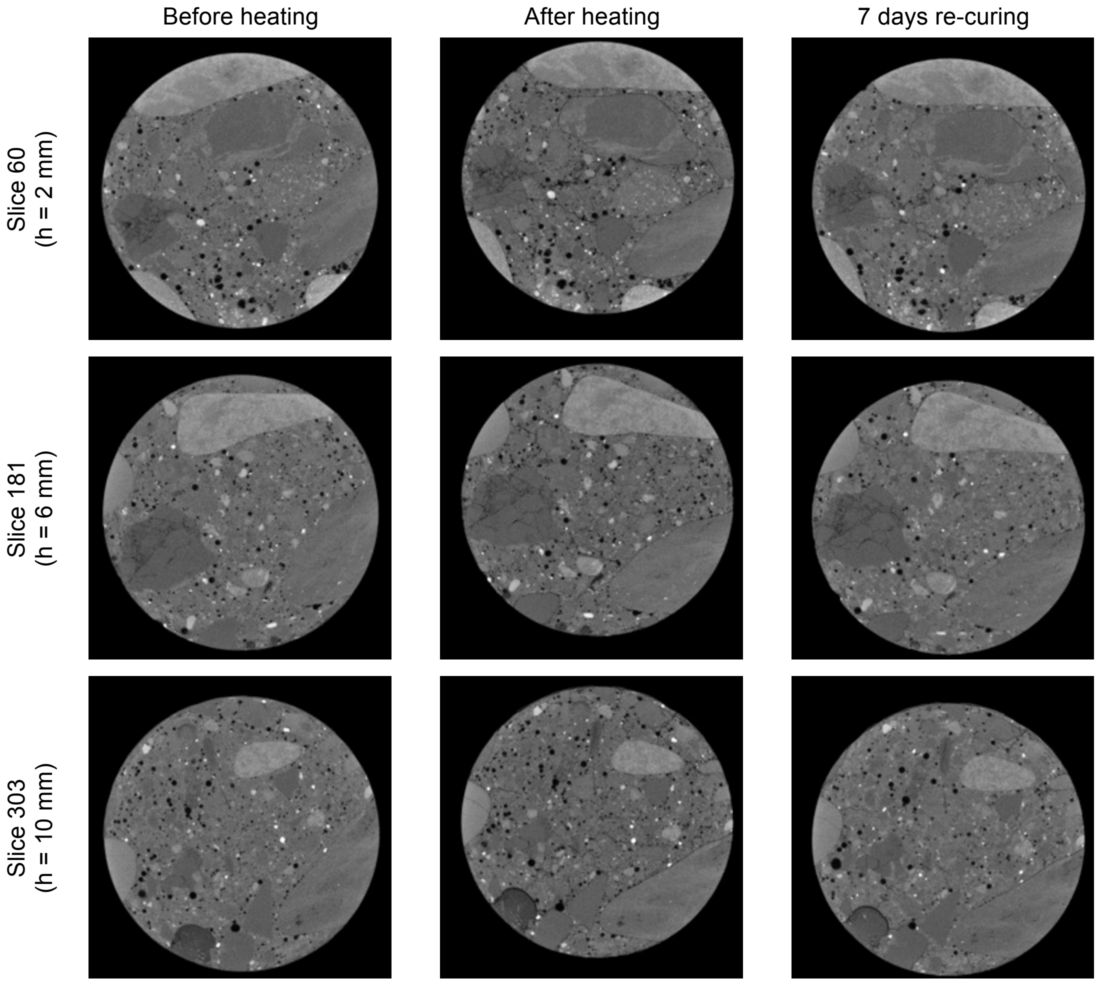


Figure 5. Cross sections at various heights of concrete specimen

Characterization of 2D cracks in cement paste. In order to quantitatively characterize the observed cracking behavior in the cement paste specimen, two crack sections were arbitrarily selected in each of slices 60, 181, and 303 (2, 6, and 10 mm from the bottom of the specimen, respectively). The crack width was calculated based on the X-ray absorption value of a series of line segments which intersect the crack, as shown in Fig. 6 and was carried out at the same crack section both after heating and after re-curing to clarify the effect of heating and water re-curing on the crack characteristics.

The results are shown in Fig. 7. For all specimens, water re-curing was found to increase crack width, although the scale varied by crack section. In crack section #2 for slices 60 and 181, re-curing resulted in only a small increase in crack width, and the change was fairly similar regardless of depth from surface. For crack section #1 in slice 60, however, water re-curing greatly increased the crack width near the surface of the specimen, with a much smaller increase further from the crack surface. Finally, for crack section #1 of slices 181 and 303, the largest increase in crack width was found to occur in the mid-range of the crack, with smaller increases both nearer and further from the surface.

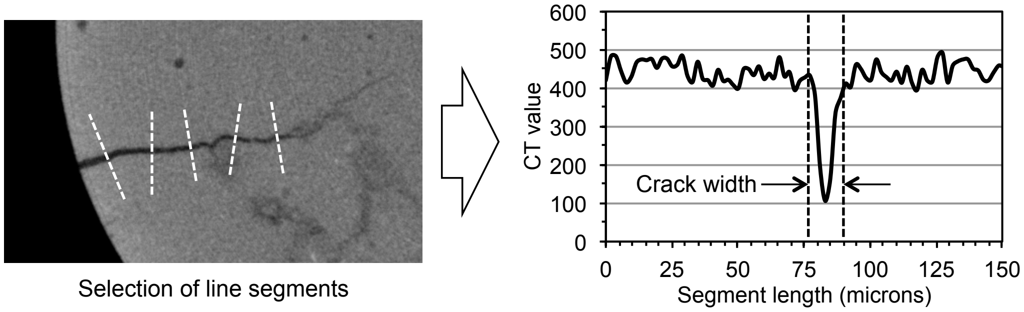


Figure 6. Method of calculating crack width

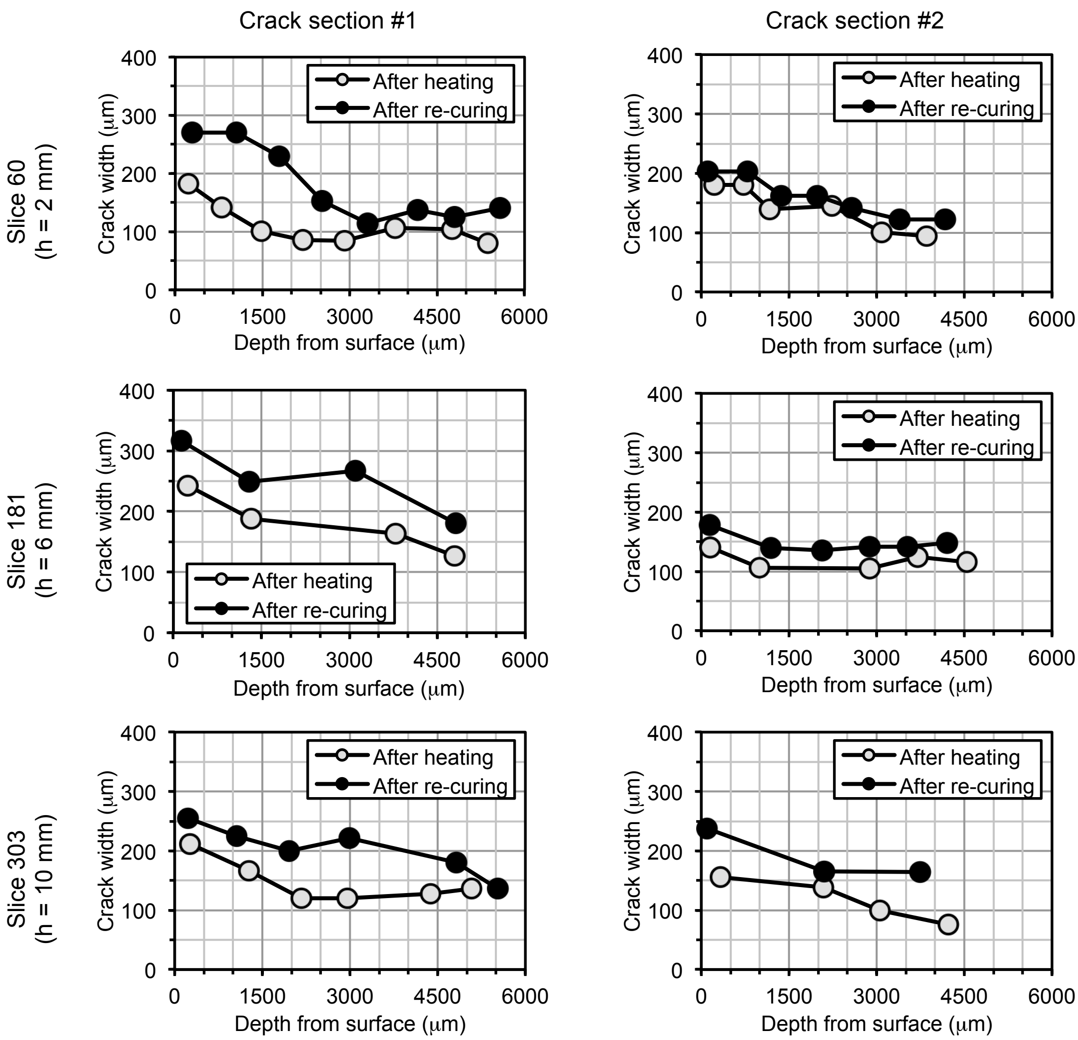


Figure 7. Change in crack width from surface for selected crack sections at various heights of cement paste specimen

The tortuosity was also calculated for each crack after both heating and water re-curing. Tortuosity is the degree of twistedness of a given path and can be calculated as the ratio of the actual path length to the shortest distance between the start and end points of the path. Therefore, a perfectly straight path would have a tortuosity of one, with greater tortuosity values indicating greater twistedness of the path. For all cracks except one (slice 60, no. 2, after re-curing) the tortuosity was calculated as 1.03, which indicates that the cracks are almost perfectly straight. The cross sections in Fig. 4 clearly showed the cracks forming in a radial direction after heating, and the tortuosity result confirms that they formed nearly straight in the x-y plane. As a result, although re-curing was found to significantly affect the crack width it did not appear to affect crack tortuosity for the selected cracks.

Characterization of 2D cracks in concrete. As it was difficult to identify the cracks in the heated and re-cured concrete from the images in Fig. 5, threshold segmentation was applied to clearly visualize the cracks in the specimen. As illustrated in Fig. 8, void space (which includes both interconnected cracks and isolated air voids) could be extracted by selecting a threshold value from the grey-scale value distribution and using that value to convert a grey-scale image to a binary black and white image. Percolated cracks could then be extracted by carrying out a connectivity analysis to separate connected cracks from the isolated air voids.

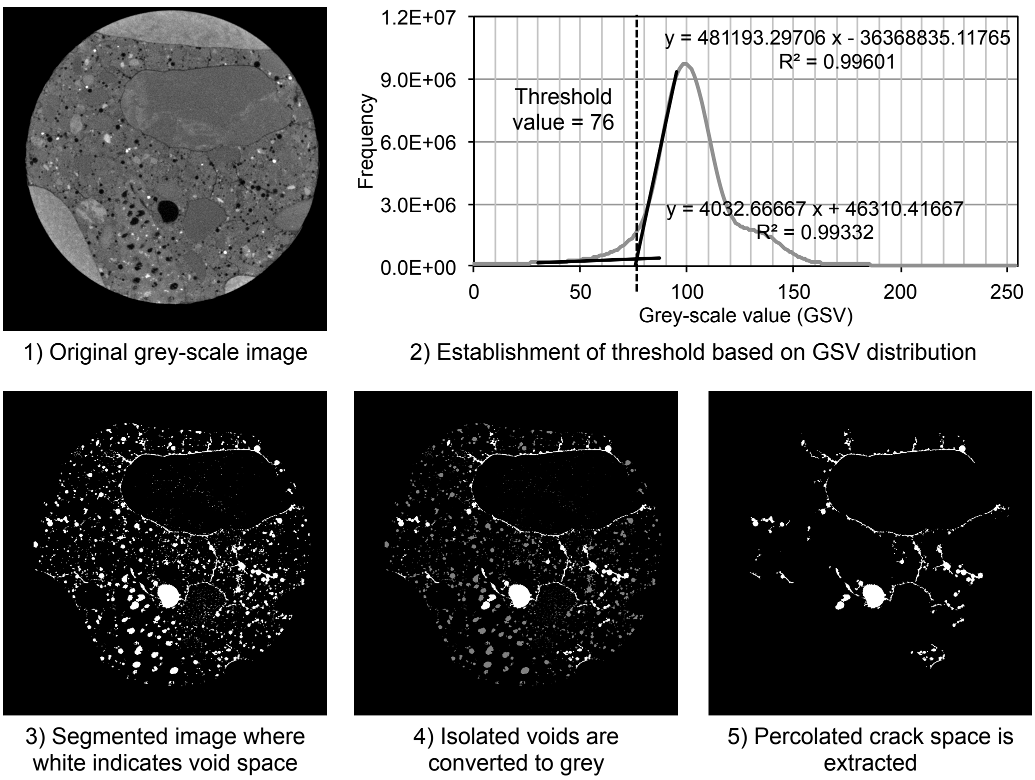


Figure 8. Method of segmentation for identifying percolated crack space

Analysis results are shown in Fig. 9 for the concrete specimen after heating and after seven days water re-curing. From these images, cracks can be clearly seen to have occurred around the largest aggregate due to heating, along with some cracking around a smaller aggregate. In addition, some bridging cracks also formed between the two aggregates as well as connected to a large air void. The effect of water re-curing is also clearly demonstrated, as the amount of crack space was significantly reduced after only seven days, with only a small fraction remaining in the aggregate-mortar interface.

After heating | 7 days re-curing

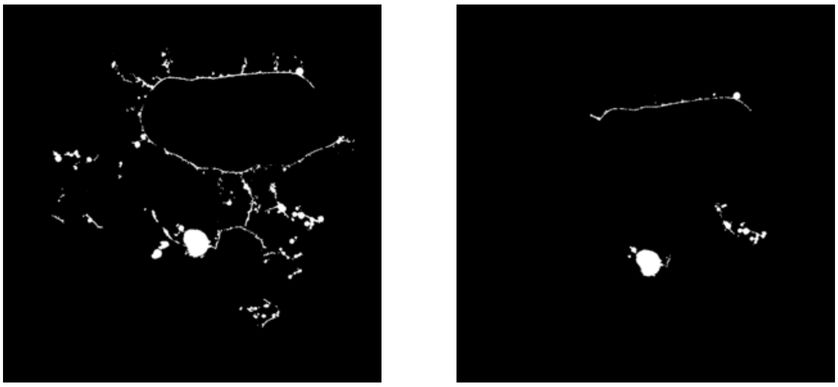
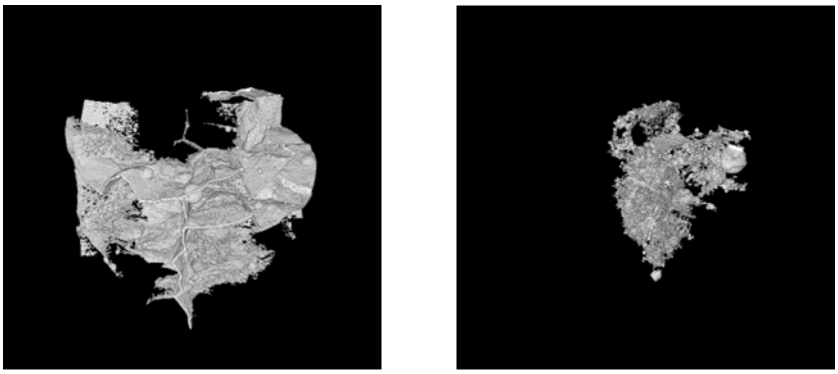


Figure 9. Comparison of percolated crack space in concrete specimen

3D reconstruction of percolated cracks in cement paste and concrete. Finally, three-dimensional images of the percolated crack space were reconstructed to understand the characteristics of the total crack volume. Fig. 10 shows the 3D reconstructed crack images for the cement paste and concrete specimens after re-curing along with characteristics of the crack volumes. For the cement paste specimen, cracks occur radially in both the horizontal and vertical directions, and are generally concentrated at the specimen's surface. The 3D crack shape of the concrete specimen is much more difficult to describe; however, it does have a higher surface to volume ratio than the cement paste specimen, which suggests that further re-curing may be more effective for reducing crack volume in the concrete specimen due to the relatively higher surface area available for healing under water supply.

Cement paste specimen (28 days re-curing)	Concrete specimen (7 days re-curing)



Cement paste specimen	Concrete specimen
Surface area (m^2): **2.3066E-03**	Surface area (m^2): **1.93E-03**
Object volume (m^3): **9.06065E-08**	Object volume (m^3): **4.60E-08**
Surface to volume ratio (m^{-1}): **2.55E+04**	Surface to volume ratio (m^{-1}): **4.21E+04**

Figure 10. Comparison of 3D crack volume and characteristics after re-curing

CONCLUSION

In this paper, the effects of heating and water re-curing on cracking in high strength cement paste and concrete were investigated using X-ray microtomography, and various image analysis techniques were applied to characterize the changes in the crack structure. It was found that, in the cement paste specimen, heating resulted in straight, discrete radial cracks due to shrinkage caused by dehydration, and these cracks grew larger in width and new cracks were formed under water re-curing due to volume expansion from the rehydration of lime. Cracks in the concrete specimen due to heating generally formed around aggregates due to incapability in thermal expansion between the mortar and aggregates, but water re-curing greatly reduced crack space due to re-curing. The difference in crack recovery under re-curing could be attributed to the higher cement content in the cement paste specimen and the restraining effect of aggregates in concrete.

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