OBSERVATION OF RECYCLED AGGREGATE STRUCTURE USING X-RAY CT

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ABSTRACT

The use of low quality recycled aggregates in concrete reduces performance and increases variation. Therefore, it is important to examine the performance and safety of concrete using low quality recycled aggregates from a variety of perspectives. This study applied X-ray CT and image analysis to examine the structure of recycled aggregates in order to explore how X-ray CT may be applied to recycled aggregate concrete. It was found that recycled aggregates from different sources showed widely varying X-ray CT absorption values, which makes it difficult to carry out further analyses unless there are clear differences in the material phases. However, it is possible to estimate the amount of residual mortar through segmentation between the solid and void phases.

Keywords: Recycled aggregate, X-ray CT, aggregate quality, water absorption, segmentation.

1. INTRODUCTION

Concrete waste can be reused as recycled aggregates in new concrete but, in general, concrete using recycled aggregates has lower performance then that using natural aggregates unless a large amount of energy is invested in the aggregate recycling process. In order to minimize the environmental impact of concrete, it is better to utilize lower quality recycled aggregates, but past research has shown that as the quality of recycled aggregates decreases the amount of residual mortar increases and thus the properties of the recycled aggregate and recycled aggregate concrete become more varied (Henry et al., 2011). Therefore, it is important to examine the performance and safety of recycled aggregate concrete from a variety of perspectives.

X-ray CT is one method for quantifying crack formation and failure method, but no research work has applied X-ray CT analysis to recycled aggregate concrete. Thus, this paper takes the first step by examining the structure of recycled aggregates alone in order to better understand how the wide variation in recycled aggregate properties may affect the application of X-ray CT to studying the properties and performance of recycled aggregate concrete.

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2. EXPERIMENTAL PROGRAM

2.1. Characteristics and properties of recycled aggregate specimens

This study examined two main characteristics of recycled aggregates: the source and the water-cement ratio (W/C) of the parent concrete. For W/C, the volume of residual mortar attached to the aggregate was also studied. The characteristics of the selected recycled aggregate specimens are summarized in Table 1 and 2. In the case of the specimens by source, aggregates were selected such that they had similar size; in the case of the specimens by W/C and mortar volume, aggregates were selected such that they had similar size and the volume of residual mortar was qualitatively judged based on visual inspection. The water absorption was also evaluated for the series of aggregates with varying W/C (Figure 1).

Table 1: Specimen characteristics by source

	Average diameter (mm)			Average weight (g)		
Size	Source A	Source B	Source C	Source A	Source B	Source C
Large	13.33	14.17	13.50	3.223	3.198	2.656

Table 2: Specimen characteristics by W/C and mortar volume

	Average diameter (mm)			Average weight (g)		
Mortar volume	W/C = 30	W/C = 50	W/C = 70	W/C = 30	W/C = 50	W/C = 70
Low	12.65	14.68	13.67	2.602	3.208	3.436
Medium	13.99	14.92	14.02	3.218	2.901	2.874
High	13.23	13.94	14.92	2.658	3.333	3.038

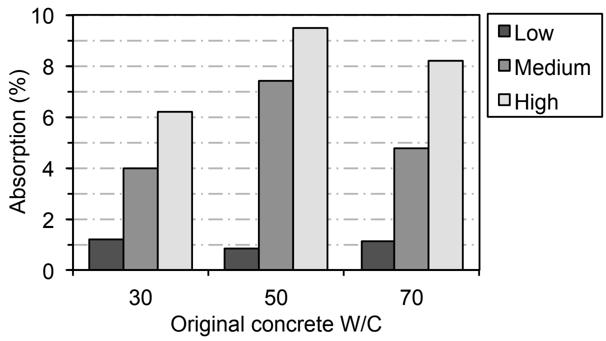

Figure 1: Water absorption of specimens by W/C and mortar volume

2.2. Image acquisition using X-ray CT

X-ray CT 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) with 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. This technique is particularly useful for identifying and quantifying void space inside a specimen, as air does not significantly absorb X-ray energy and thus can be clearly differentiated from solid material. Specific applications in the concrete field include pore structure characterization and freeze-thaw damage (Sugiyama et al. 2010; Promentilla and Sugiyama 2010).

3. SPECIMEN CROSS SECTION IMAGES

3.1. Effect of recycled aggregate source

Cross section images of the recycled aggregate specimens from varying sources are shown in Figure 2. For the Source A specimen, it is not possible to differentiate between the recycled aggregate phases; furthermore, it appears that the aggregate contains materials with a high X-ray absorption, as indicated by the light flecks in the image. In contrast, it is easy to observe the different material phases for the Source B specimen. The original coarse aggregate and fine aggregates clearly contrast with the paste phase, and their lighter shade indicates that the aggregates are composed of a high-density material (possibly limestone). Finally, the original aggregate in the Source C specimen can be visually identified but the shades of the aggregate and paste appear very similar. From these images, it can be concluded that the variation in original source materials strongly affects the ability to identify the phases and structure of recycled aggregates when using X-ray CT.

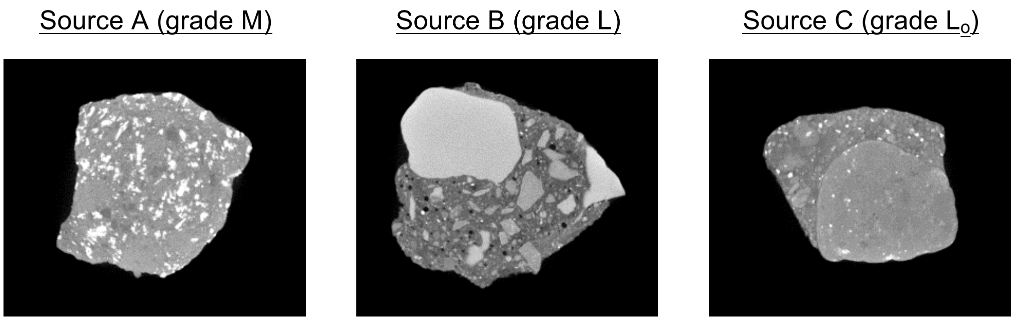

Figure 2: Cross section images by source

3.2. Effect of parent concrete W/C ratio and residual mortar volume

Figure 3 shows the cross section images for recycled aggregate specimens by W/C ratio and volume of residual mortar. For W/C=30, the grey shade is similar between the core aggregate and the residual mortar, although the border between the two can be visually identified. The difference between the core aggregate and residual mortar appears to become clearer as the W/C ratio increases – although this may be partially due to the greater number of air voids in W/C=70 relative to W/C=50 – which makes it easier to identify the aggregates. The increase in residual mortar can be seen to lead to an increase in air voids in the recycled aggregate, along with a decrease in size of the original aggregate relative to the total size of the recycled aggregate. Overall, observation of the recycled aggregate structure may be affected by the relative density of the residual mortar compared to the original aggregates as well as the presence of air voids in the residual mortar.

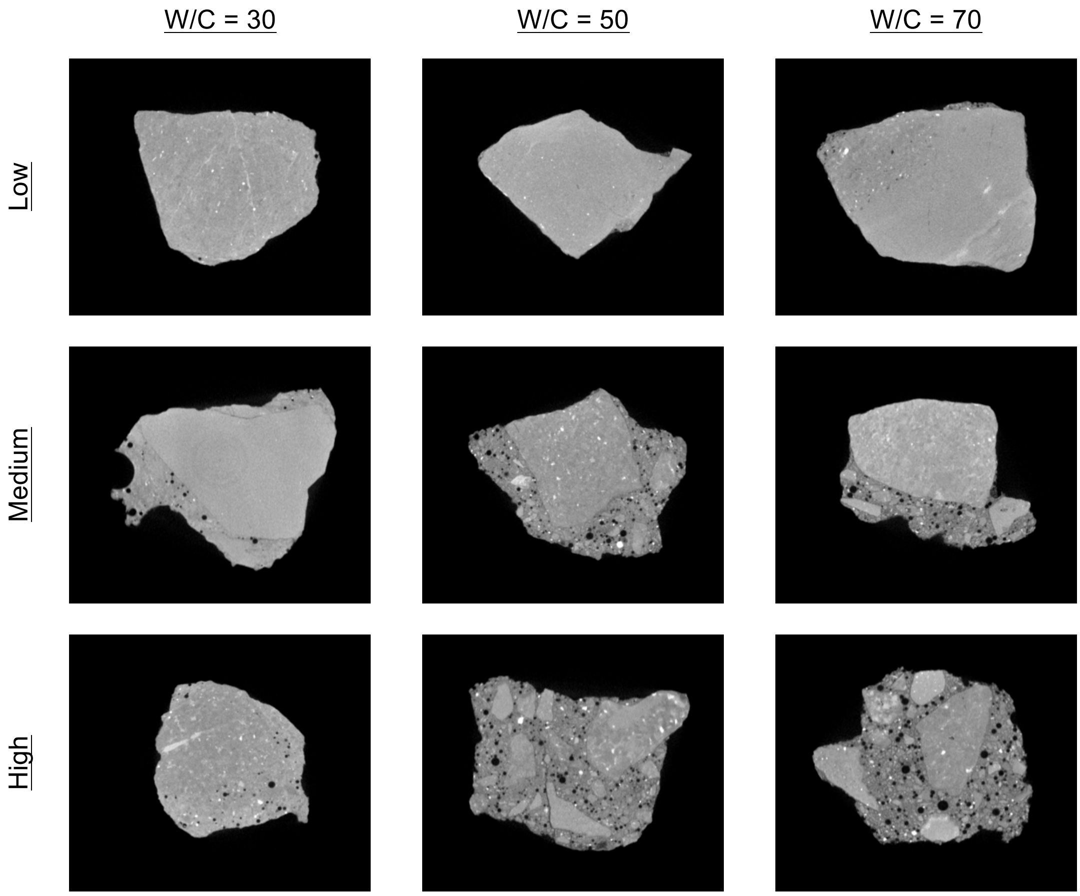

Figure 3: Cross section images by W/C and mortar volume

4. IMAGE ANALYSIS

4.1. Examination of CT numbers

One method for analyzing the cross section images is by examining the variation in CT number along a selected line segment. A notable change in CT number indicates a change in material density. Figure 4 shows the change in CT number along selected line segments for size different aggregates. For the Source A aggregate, the CT number is generally between 350 and 400, except for two spikes where the line segment crosses the high density materials. For the Source B aggregate, the CT number clearly varies as the segment crosses the different material phases. For the Source C aggregate, the CT number of the mortar phase can be seen to be slightly lower than that of the aggregate phase, but they are much more similar than in the case of the Source B aggregate. For the three aggregates by W/C with high volume of residual mortar, the largest change in the CT number occurs when the line segment intersects an air void, and there does not appear to be a large difference in CT number between the aggregate and mortar phases.

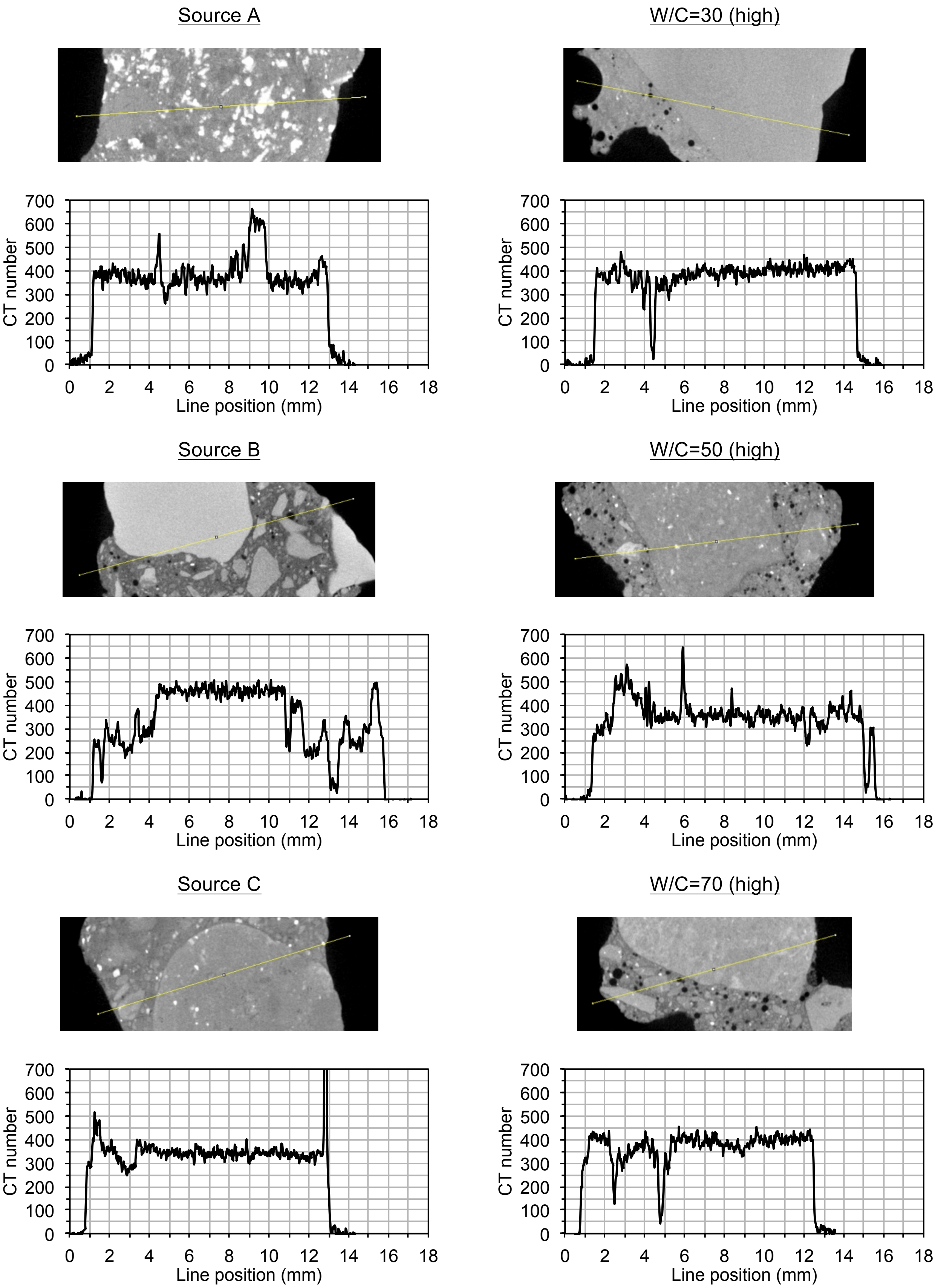

Figure 4: Variation in CT number along selected line segments

4.2. Analysis of phase volume

Among the different recycled aggregate specimens, only the Source B specimen showed a distinct and quantifiable difference between all three material phases (voids, cement paste, and aggregates). Therefore, in order to analyze the recycled aggregate structure and quantify the material phases, threshold segmentation was applied to the Source B specimen. As illustrated in Figure 5, void and solid phases could be separated 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. The same process could be applied to separate the aggregates and paste from the original grey-scale image using a different threshold value.

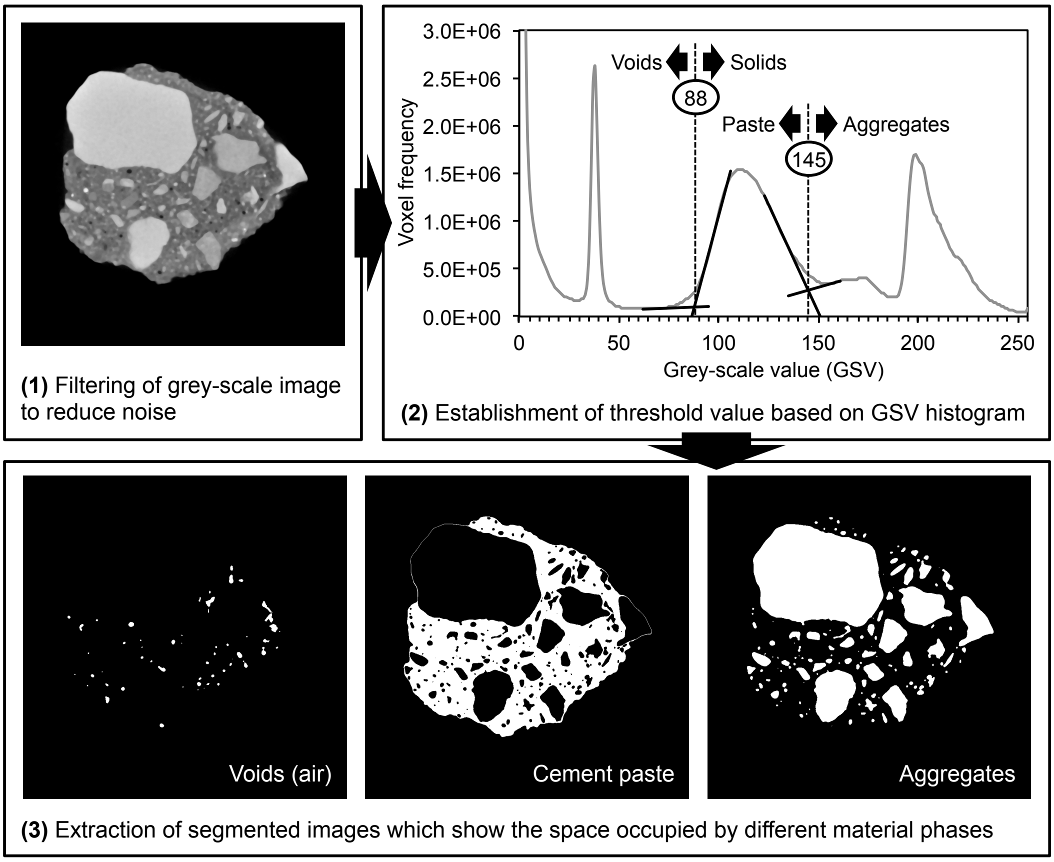

Figure 5: Segmentation method for identifying different material phases

After carrying out the segmentation, the stack of binary 2D images was used to reconstruct the 3D volume occupied by each material phase. These reconstructions are shown in Figure 6, along with their volume fraction. For the Source B specimen, air voids were found to occupy just 2.0% of the aggregate volume, with cement paste and aggregates occupying 49.2% and 48.8%, respectively. Void space appears to occur primarily in the volume occupied by the cement paste, with no void surfaces occurring in the boundaries around the largest aggregates. A fine layer of paste can be found to coat each of the aggregates exposed or protruding from the recycled aggregate surface.

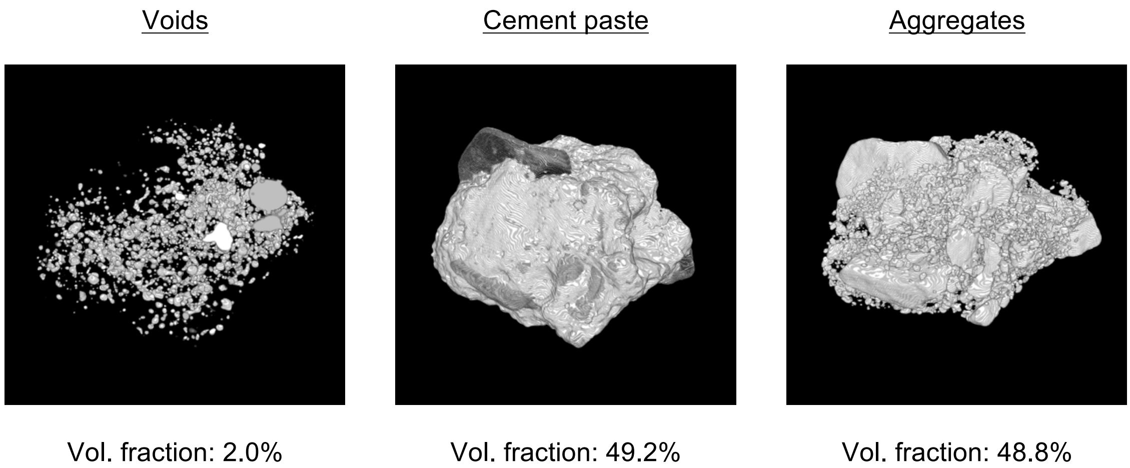

Figure 6: 3D reconstruction of material phases and their volume fraction

4.3. Analysis of void volume and comparison with water absorption

In the case of specimens with varying W/C ratio and residual mortar volume, the amount of air voids appeared to increase as both the W/C ratio and residual mortar volume increased. The segmentation method in Figure 5 was thus applied to quantitatively examine the volume of voids in each aggregate, with the results shown in Figure 7. For all three W/C ratios, the void volume fraction can be seen to increase as the volume of residual mortar increased. In the case of W/C=50, however, it appears that the aggregates with “medium” and “high” volumes of residual mortar had similar void volumes, which illustrates the difficulty in qualitatively assessing the volume of residual mortar by inspection alone. Furthermore, as each aggregate varies in size and composition, it is difficult to clarify whether the void volume actually increases as W/C ratio increases.

Figure 8 plots the void volume against the water absorption for the nine specimens. A linear relationship with a very high correlation (R^2=0.97) can be observed, which shows that void volume can be correlated to other aggregate properties independent of the W/C ratio. However, this calculation is affected by the resolution and noise of the acquired images, and it is necessary for future research to clarify the effect of these factors on the void volume.

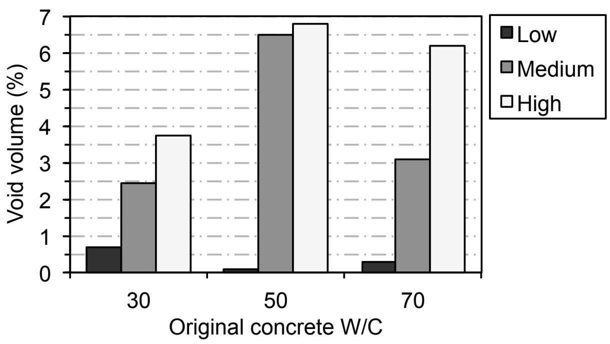

Figure 7: Calculated void volume by W/C and mortar volume

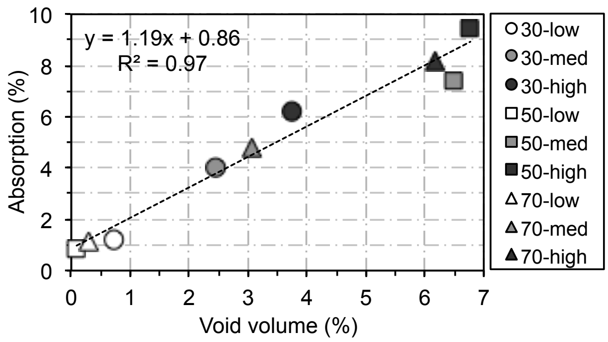

Figure 8: Relationship between calculated void volume and water absorption

5. CONCLUSION

It was found that recycled aggregates from different sources show widely varying X-ray CT absorption values due to the variation in their source materials, which makes it difficult to carry out image analyses unless there are clear differences between the original mortar and original aggregates. However, when focusing only on the difference between solids and air voids, it is possible to apply segmentation to roughly estimate the amount of residual mortar by examining the relationship between the volume of air voids and the water absorption of the aggregates. For future studies focusing on crack formation and failure mechanism, materials with different densities should be used in the recycled aggregates to help facilitate image analysis methods.

6. ACKNOWLEDGMENTS

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