Application of X-Ray CT Scanning to Characterize Geomaterials Used in Transportation Construction

Clinton Halverson
Department of Civil, Construction and Environmental Engineering
Iowa State University
394 Town Engineering Building
Ames, IA 50011
cahal@iastate.edu

David J. White
Department of Civil, Construction and Environmental Engineering
Iowa State University
476 Town Engineering Building
Ames, IA 50011
djwhite@iastate.edu

Joseph Gray
Center for Nondestructive Evaluation
Iowa State University
215A ASC Building II
Ames, IA 50011
jngray@iastate.edu

ABSTRACT

Conventional visual evaluation techniques (i.e., microscopy) of geomaterials are limited to the inspection of two dimensional surfaces, leaving internal three-dimensional characteristics ambiguous or resulting in costly slice-by-slice assembly to generate three-dimensional representations. Improved X-ray–computed tomography (X-ray CT) technology now allows a sample to be analyzed nondestructively and viewed in three dimensions. The outcome is the unique ability to obtain quantitative results from volumetrically imaging a sample's complete structure. Application of this technology is enabling a new area of research in the characterization of geomaterials used in transportation construction (e.g., concrete and soils).

Much valuable information can be gathered from CT scanning technology. Cracks can be mapped in soil samples to quantify spatially the planes and angles of failure. Porosity can be determined throughout sand and gravel samples. Air voids and aggregate segregation can be mapped in portland cement concrete. In pervious concrete, void matrixes can be analyzed for clogging, connectivity, and size.

A state-of-the-art CT scanning chamber was used to develop the images, and post-processing computer programs were implemented to interpret data for evaluation of geomaterials. This paper summarizes research techniques and describes the hardware and procedures required to conduct CT scanning for geomaterial applications. Finally, example images illustrating volumetric files are presented for various geomaterials.

Key words: geomaterials—nondestructive testing—X-ray–computed tomography

Proceedings of the 2005 Mid-Continent Transportation Research Symposium, Ames, Iowa, August 2005.

INTRODUCTION

X-ray computed tomography (X-ray CT) offers the field of material engineering the unique ability to view internal characteristics of specimens nondestructively and is applied in this paper to study various geomaterials (e.g., concretes and soils). This technology is made possible by using measurements of x-ray attenuation, which is a function of material density. In short, the product of this type of analysis is the creation of volumetric maps of variations in material density. The process works by positioning a sample inside an x-ray fan beam and projecting its shadow onto a special camera or detector that translates x-ray energy into electrical current (see Figure 1). As the sample is rotated inside the x-ray fan beam, this shadow is translated into a two-dimensional cross-section. By measuring several of these cross-sections at small intervals, the cross-sections can be stacked one upon another to form a three-dimensional digital representation of variations in sample density. True microfocus X-ray CT utilizes x-ray beam sources with spot sizes of only two to five microns and can produce volumetric digital files with effective pixel sizes of a few microns (Zhang et al. 2003).

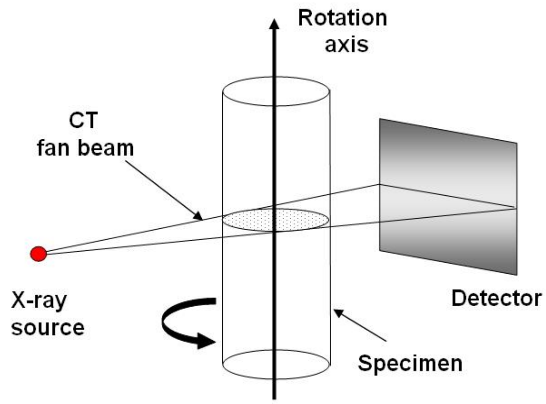


Figure 1. X-ray CT scanning setup

X-ray CT has been used recently in such applications as wetting phase displacement characteristics in porous media (Ham and Willson 2005); porosity distribution in rocks (Bashar et al. 2005); detection of large (over 40 cm^3), very dense (metal), and very low density (foam) inclusions in concrete (Diagle et al. 2005); spatial distribution of water, air, and soil solid phases throughout a soil sample (Rogasik et al. 1999); detection of disturbance zones in fine sand resulting from insertion of a cone penetration (Ngan 2005); characterization of fine-grained sand (0.22-mm mean diameter) after traditional axisymetric (triaxial) compression failure (Alshibli et al. 2000); and analysis of fracture geometry in rock that has failed under tension (Walters et al. 2005).

At Iowa State University's Center for Nondestructive Evaluation (CNDE) complete microfocus X-ray CT systems have been created, including the development of customized software for data acquisition, volumetric file reconstruction, and visualization. A 64-node Linux is used in the CT reconstruction. The chamber used for these scans utilizes a 130-kilovolt microfocus X-ray tube capable of 2.5-micron resolution and 1400x1400x500-voxel (3D resolution unit) data volumes. Because all software was designed by developers at the CNDE, the unique ability to alter and add to software is available (Zhang et al. 2005).

PROBLEM STATEMENT

The Department of Civil, Construction and Environmental Engineering at Iowa State University conducts research on various construction materials used in transportation engineering. In the evaluation of these materials, both quantitative and qualitative characterization of internal structure is of significant importance. This paper illustrates images from 3D volumetric files, explains the importance and implications of such images, and describes future analysis techniques planned for the evaluation of various construction materials. It also outlines a post-processing technique used to improve image quality of computer-processed X-ray CT data.

MATERIALS AND METHODS

Results from four different materials are described in this paper: silt subject to compression loading, geogrid-reinforced quartz sand, self consolidating concrete (SCC), and pervious concrete.

Silt

The silt used in this study has a mean particle diameter of 24 microns. Samples prepared for this analysis were consolidated using a computer-controlled pressure chamber and then failed in triaxial compression. Samples were compacted into 2-in. x 2-in. x 4-in. (5.1-cm x 5.1-cm x 10.1-cm) cylindrical molds using three lifts of drop hammer compaction. The specific example illustrated in this paper was consolidated to 250 kilopascals (36.3 psi) from lateral water pressure while disallowing vertical expansion. After consolidation equilibrium was reached, vertical pressure was introduced until sample failure occurred.

After sample creation and triaxially induced failure, samples were allowed to dry. X-ray CT analysis consisted of obtaining a three-dimensional volumetric file of 640x640x340 voxels in size, resulting in a cross-sectional resolution of 0.010 mm x 0.010 mm and a vertical resolution of 0.25 mm (the distance between slices). The scan was conducted at 130 kV and 0.1 mA.

Self-Consolidating Concrete

SCC is developed to provide good workability without causing problematic settlement or requiring vibration for consolidation. Through the development process of new mixes, it is important to monitor aggregate settlement and void distribution throughout a sample to ascertain a homogenous distribution of all material phases. That need is met nondestructively by using X-ray CT, allowing the samples to be used for subsequent testing (e.g., compressive strength, freeze-thaw).

SCC samples were created by simply pouring cement into a 3-in. x 3-in. x 6-in. (7.6-cm x 7.6-cm x 15.2-cm) cylindrical mold and allowing cement to cure. In the design of SCC, it is important to keep the densities of aggregate and cement similar so aggregate settlement does not occur (Wang 2003). Since objects with equivalent densities exhibit equivalent x-ray attenuation throughout their volumes, mapping variations in densities can be challenging. Also, cement cylinders have a high density (specific gravity of 2.3 +/-) and a relatively thick diameter so samples attenuate X-rays easily, making imaging difficult, especially towards the center of the cylinders. It was found that by sending higher voltage and current through the X-ray tube, the increase in electrical power increased the number and energy of X-rays passing through the sample, improving the crispness of aggregate edges and allowing data from the center of the samples to be gathered.

The SCC sample illustrated in this paper was scanned to obtain a three-dimensional volumetric file of 640x640x310 voxels in size, resulting in a cross-sectional resolution of 0.16 mm x 0.16 mm and a vertical resolution of 0.49 mm. Scanning was conducted at 130 kV and 0.45 mA. Also, a copper filter consisting of 0.005 inches of metal was placed over the end of the X-ray tube to attenuate low-energy X-rays that absorb easily in the exterior of a sample’s volume and result in erroneously high density values towards sample edges.

Geogrid-Reinforced Sand

Clean sand is a common foundation material in construction because of its high permeability. Sand has high strength when laterally supported, but has very little strength in tension or without lateral support due to its lack of inter-particle cohesion. Therefore, mats composed of interwoven synthetic polymer-coated fibers (geogrids) can be implemented to provide tensional strength to a sand structure and disallow expansion, thwarting failure zone development. X-ray CT can be used to characterize spatially the dead, dilated, and shear domains (Oda 1972) present in compressed sand samples, both with and without geogrid reinforcement.

Sand samples were prepared using ottawa silica sand, a clean subrounded to rounded sand. Sand was sieved and only sand retained on #8 and #10 sieves was used, resulting in a mean particle diameter of 2.42 mm.

In order to produce cohesionless samples for triaxial compression, sand was compacted into its 2.8-in. x 2.8-in. x 5.6-in. (7.1-cm x 7.1-cm x 14.2-cm) cylindrical mold fitted with a flexible latex membrane. Compaction was completed by hand tapping the mold’s sides until 860 grams of sand settled inside with a porous stone at both ends, resulting in an initial void ratio of 0.65, which was found to be the maximal degree of compaction achievable by hand tapping. If geogrid reinforcement was added, the quantity of sand required was reduced accordingly to allow consistent void ratio. Samples were then confined using an internal vacuum until liquid pressure could be provided from the triaxial testing apparatus. Once samples were failed under triaxial compression, the experiment was halted and all instruments remained static while the sample was impregnated with EPO-TEK 301 resin from an impregnation chamber. EPO-TEK 301 has been shown to be optimal for freezing samples in place because it exhibits low viscosity (100 cps at 25^{o}C), cures at room temperature, and has minimal shrinkage during curing (linear shrinkage of about 1.5%) (Jang et al. 1999). Samples were allowed to cure for 24 hours prior to removal.

CT scan of the epoxy sand sample illustrated in this paper consists of creating a volumetric file of 640x640x380 voxels in size, resulting in a cross-sectional resolution of 0.16 mm x 0.16 mm and a vertical resolution of 0.35 mm. Scan was conducted at 130 kV and 0.11 mA. Also, a 0.005-inch copper filter was used to attenuate problematic low-energy X-rays. Post processing was then implemented, as described in the section entitled “Methodology for Post-Processing Three Phase Media.”

Pervious Concrete

There are many uses for pervious concrete, such as in water retention. In the development of pervious concrete, it is important to understand liquid transport through its interconnected void spaces. X-ray CT provides a means to analyze pore continuity and flow channel dimensions to gain an understanding of how to achieve an optimal void network.

Samples of pervious portland cement concrete were created by pressing the concrete mix into a 3-inch (7.6-cm) diameter cylindrical mold so that sample weights consistent with that created by slip form paving were achieved. Samples were extruded after curing and the top and bottom sawed off to obtain a 3-inch–tall (7.6 cm) cylinder of pervious concrete.

The pervious concrete sample illustrated in this paper was scanned to produce a volumetric file dimensioned as 640x640x310 voxels, resulting in a cross-sectional resolution of 0.15 mm x 0.15 mm and a vertical resolution of 0.25 mm. Scans were conducted at 130 kV and 0.11 mA. Also, a 0.005-inch copper filter was used to attenuate problematic low-energy X-rays.

METHODOLOGY FOR POST-PROCESSING THREE PHASE MEDIA

Cross-sections of samples digitally imaged using X-ray CT are grids composed of values that represent densities. These values are presented using voxels. It is useful in many instances to be able to post-process these voxel arrangements to filter out unwanted effects and to organize data in a way to simplify further analysis. Therefore, a method of post-processing volumetric files has been devised to satisfy the following three criteria:

1. Remove beam hardening effects caused by using a white X-ray spectrum of wave energies
2. Remove unwanted erroneous patterns (artifacts)
3. Identify different phases within a sample volume

Beam Hardening and Artifacts

Beam hardening effects are caused by lower energy X-rays being preferentially absorbed in the exterior regions of a sample. During CT reconstruction, it is assumed that a constituent of a sample, say aggregate found in a concrete sample matrix, has consistent ability to attenuate X-ray photons (absorption coefficient) regardless of location inside a sample volume. This assumption is invalid if there are different photon energies present, such as those produced by a white bremsstrahlung source, in which case lower energy photons are absorbed more readily than higher energy photons. The lower energy X-rays therefore tend to become attenuated close to a sample's edge before reaching a sample's deeper interior. The effect is that regions located closer to the edge are depicted during reconstruction as having erroneously higher densities than centrally located regions. This effect can be seen by viewing voxel intensities located along a line drawn across a cross-section of a volumetric data file (Figure 2a) and looking at the trend in voxel values along that line (Figure 2b). It can be seen that at the edge of the sample, voxel intensities tend to have a higher value than those in the central region. An artifact can also be seen where a ring of higher intensity has been depicted outside the sample edge. This artifact is caused by overloaded X-ray receptors on the detector.

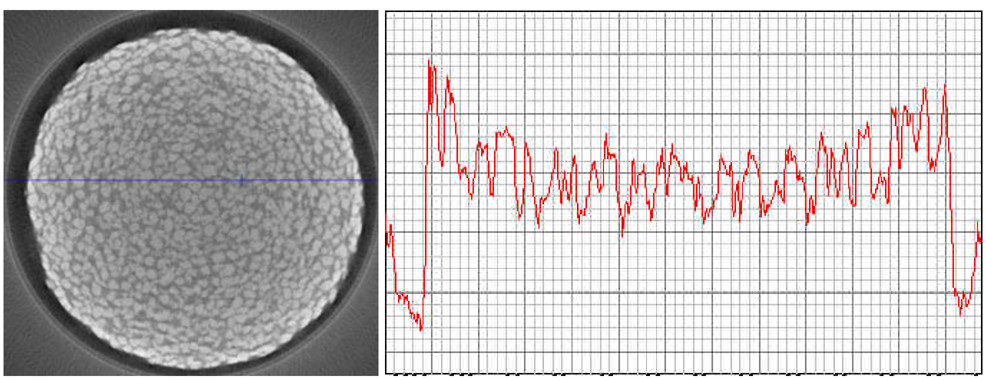


Figure 2. (a) Original sand slice and (b) histogram of intensities along the horizontal line

Identification of Phases

By identifying different phases within an X-ray CT–produced digital volume, it is possible to run computer algorithms based on voxel intensity values that could not be successful otherwise. In the case of the sample illustrated in this paper, an epoxy-impregnated sand sample is processed. It has the following three phases: air, sand, and epoxy. If air had a voxel value of zero, epoxy had a voxel value of no less than one, and sand particles had corresponding voxel values greater than those of epoxy, then the three phases could be easily identified. It would be possible to use the presence of air, now identified as having a voxel value of zero, as a means for a computer program to locate sample edges. By providing a threshold between the voxel intensity that splits epoxy regions from sand regions, a program could map the areas corresponding to those phases. Note that this may originally be impossible because epoxy voxel values (the height of the histogram troughs) at the sample edge can be higher than sand voxel values (the height of the histogram peaks) in the center of the sample (Figure 2b).

Process Steps

The first step proposed for processing the digital volume files is to split the volume into cross-sections to allow two-dimensional analysis. Once this is done, there are a slew of cross-sections that may be stacked to form a volumetric file (Figure 2a).

The second step is to use a program to identify the trend of the beam hardening artifact. This can be done by finding the maximum values found in different sections of a grid set throughout the image area and smoothing those values together to make a two-dimensional picture of the peak value trends (Figures 3a, 3b). This process can be repeated several times and averaged together to obtain a more accurate representation of the beam hardening trend.

Once the beam hardening artifact trend has been found and presented in an image (Figure 3a), its effect can be removed by subtracting the trend from the original image. In doing this, simultaneously the abnormal ring-shaped artifact will be lowered in voxel intensity.

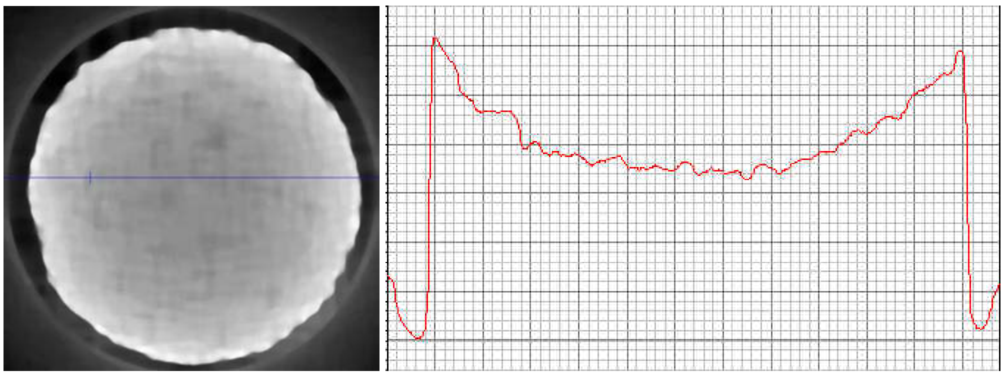


Figure 3. (a) Result of smoothing technique and (b) histogram of intensities

The ring artifact should now be of low enough intensity to be removed by assigning all voxel values below a certain intensity (an intensity below the lowest voxel value inside the sample area but above the highest voxel value of the artifact) a new voxel intensity of 0. This cutoff can also be useful, as it can define the edge of the sample volume. Now by assigning all areas without voxel values of 0 a voxel value of 1, you have effectively separated your air phase from your epoxy and sand phases (see Figure 10).

Now that the trend line of the beam hardening artifact has been identified, the ring artifact outside the sample area has been removed, and the air phase has been identified, it is just a means of taking the original image (Figure 2a), subtracting from it the trend of the beam hardening artifact (Figure 3a), and assigning all areas depicted as air an intensity value of 0; a final image is thus produced (Figure 4a). Note that troughs in the voxel intensity histogram near the edge of the sample volume are now well below the peak values near the sample's central region (Figure 4b).

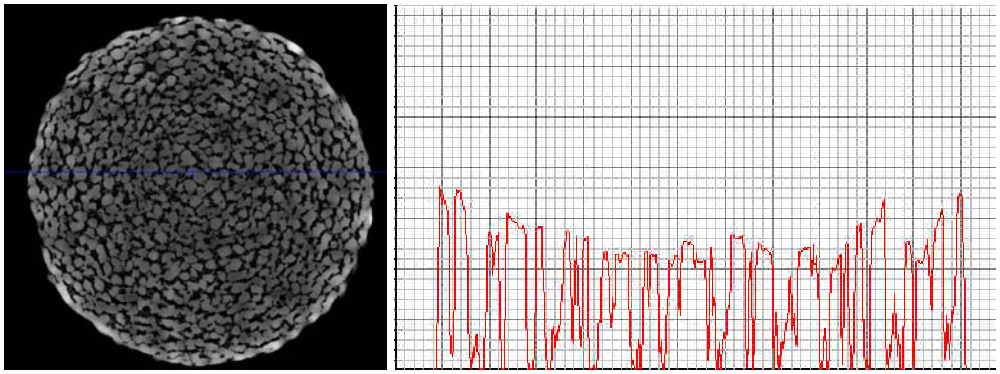


Figure 4. (a) Resulting image of post-processing and (b) histogram of intensities

Now that an image that can be easily processed has been produced, the same process can be reiterated for each slice of a volumetric file, and the slices may be combined into a new volumetric file. In order to decipher between sand and epoxy phases, a threshold voxel value can be assumed to be that which separates the two phases. By using a program to count the number of voxels below and above this threshold (excluding the value of 0, since it indicates air), it is possible to achieve a representation of how much sand and epoxy volume resides inside the sample, assuming the utilized threshold is correct. These phase volumes can be compared to actual measured volumes, and the threshold value may be adjusted accordingly until actual and measured volumes agree. Now that the threshold voxel value separating epoxy and sand has been identified, computer programs may readily process volumetric files and identify the three phases found inside the digital sample volume.

It should be noted that while the processing explanation is lengthy, once a program has been developed to process the X-ray CT–generated slices, it should be rather simple to operate.

KEY FINDINGS

Silt

A vertical profile of the failed silt sample (Figures 5 and 6) shows nearly vertical cracks in the center of the sample and very little cracking towards sample edges. Obvious expansion during compression can be seen by the bulging of the sample sides. There is a large, nearly horizontal shear band formed through the sample center. This is very different than the shear planes typical of failing symmetrically consolidated samples.

Figure 5. (a) Silt sample and (b) X-ray CT cross-sections

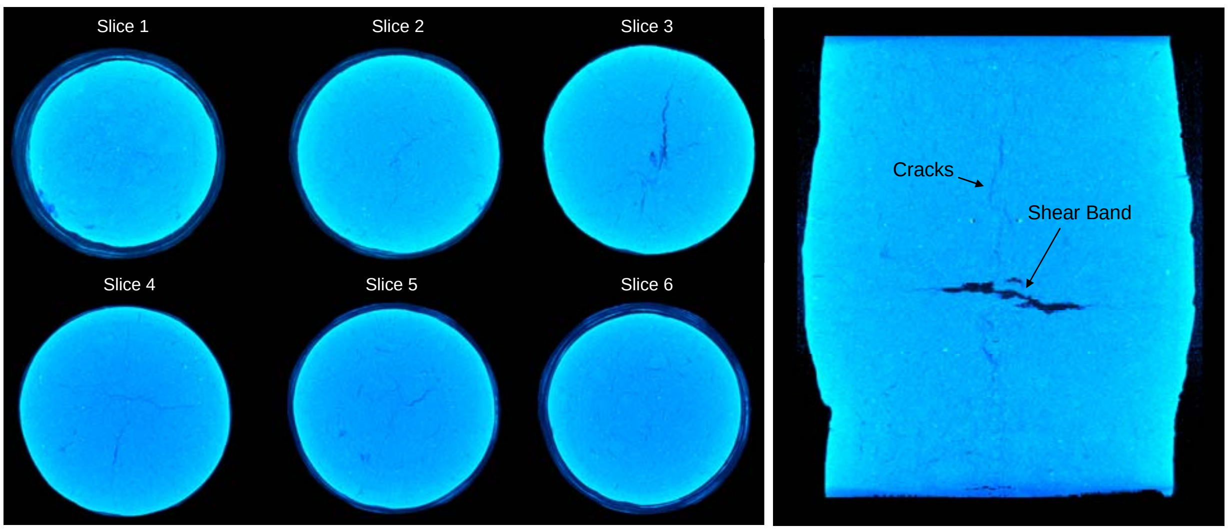


Figure 6. Silt sample vertical profile

Self-Consolidating Concrete

A profile of a SCC sample (Figure 7) shows uniform distribution of large aggregate except near the top center, where only smaller aggregate resides. This condition was present in two out of three scanned samples. As a result, it became apparent that there are edge effects thwarting aggregate settlement from concrete molds. Voids are distributed randomly throughout samples. Large voids tend to align themselves adjacent to aggregate edges, bending around their curvature.

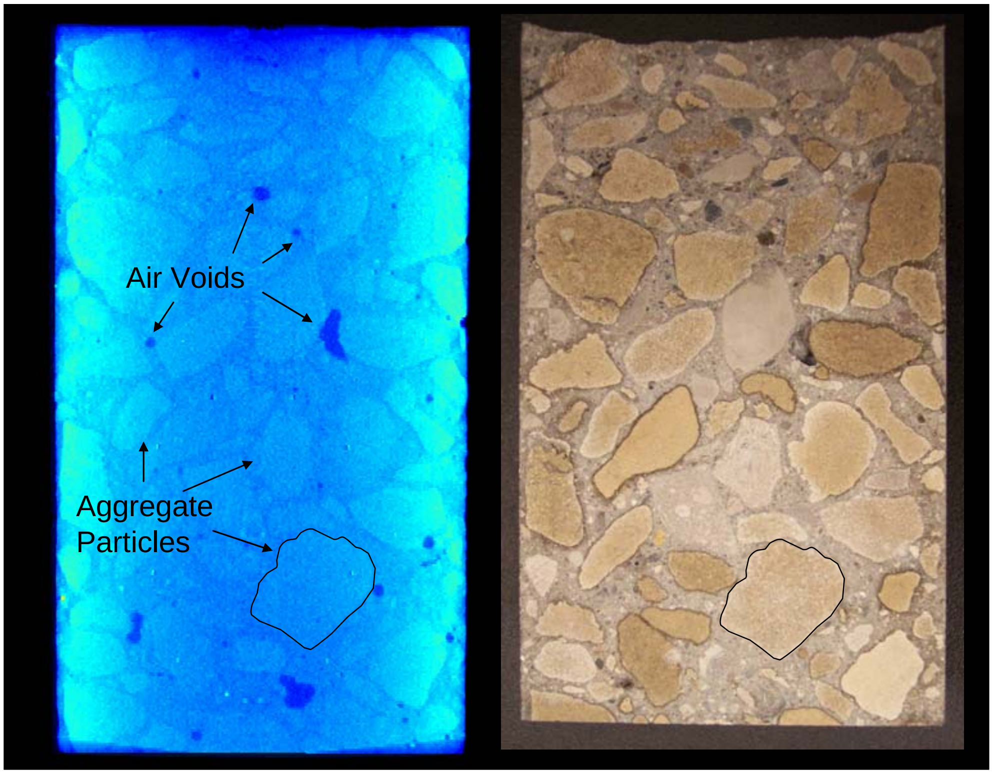


Figure 7. SCC sample vertical profile

Geogrid-Reinforced Sand

A profile view of an epoxy sand sample reinforced with three geogrids (Figures 8 and 9) is very hard to interpret using the naked eye. Therefore, the use of image post-processing such as that presented in this paper coupled with a program to determine void ratio in finite areas throughout the sample are currently being produced to better analyze these samples.

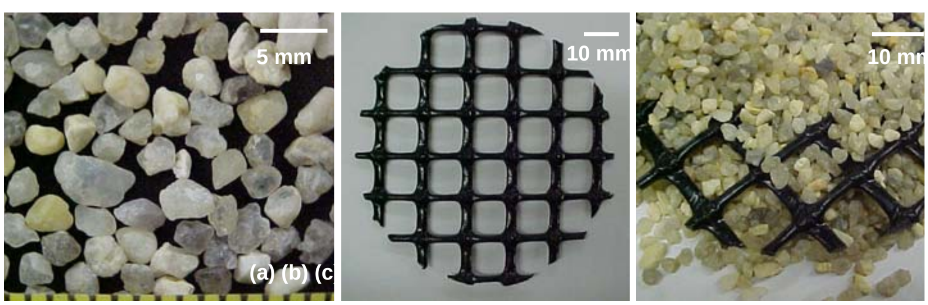


Figure 8. (a) ASTM quartz sand with D_{50} = 2.18 mm, (b) polyethylene biaxial geosynthetic reinforcement, (c) geosynthetic-reinforced sand

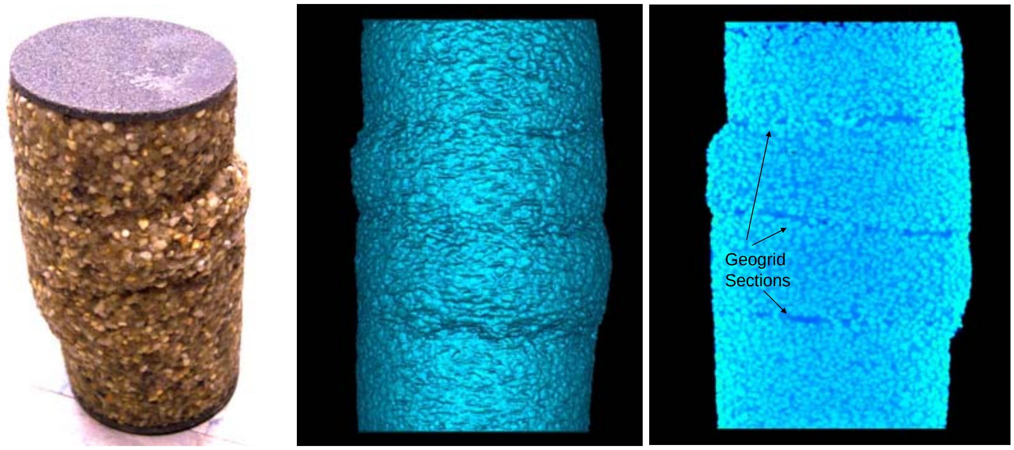
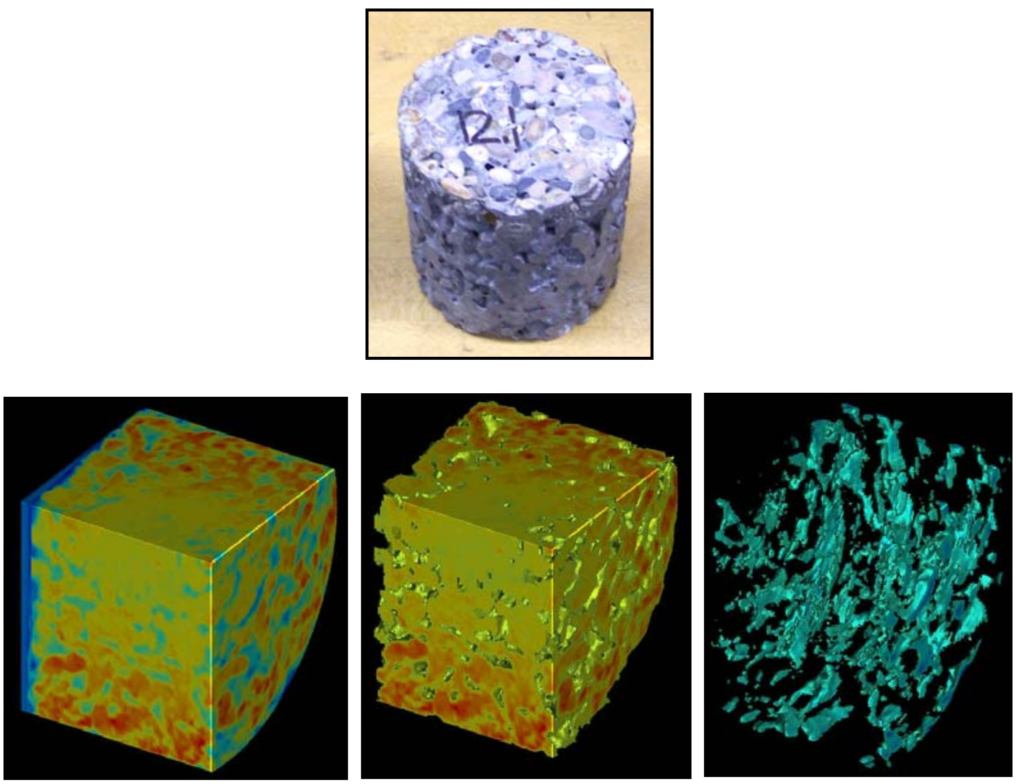


Figure 9. Epoxy sand sample vertical profile

Pervious Concrete

A horizontally tipped profile view of pervious concrete (Figure 10) shows pore spaces found within the sample. By looking through a volumetric sample, large voids that can collect fluid, referred to as nodes, and the thinner void channels connecting them, referred to as throats, can be measured and used to determine water flow through the concrete and pore space continuity, enabling better design for rapid water transport while retaining high strength.



(a) (b) (c)

Figure 10. Pervious concrete section: (a) composite sample, (b) solids component, and (c) air voids

CONCLUSIONS

X-ray CT provides a means to view the entire volume of materials used in transportation engineering. Using scanning equipment available at Iowa State University, samples consisting of laterally consolidated silt, self-consolidating concrete, sand reinforced with geogrid, and pervious concrete have been scanned and illustrated. Silt samples show cracks due to the changes in density found at failure planes. Self-consolidating concrete can be viewed to determine whether problematic aggregate settlement is occurring. Sand reinforced with geogrid can be post-processed in such a way that further computer analysis may be conducted to find void ratio distribution. Pervious concrete can have its internal void structure measured and modeled to provide a better understanding of fluid flow to aid design. By using post-processing programs and taking simple measurement, qualitative data volumes can be processed quantitatively. X-ray CT bridges the gap between unknown internal material characteristics and engineering solutions.

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