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The development of a quantitative concrete core tomography protocol for the design of concrete mixes

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ABSTRACT : This is a study of the application of computer tomography in the study of concrete cores. A laboratory protocol is presented for testing concrete cores using a medical CT scanner. The protocol includes extensive software implementation for transferring data from CT computers to workstations, for removing various imaging artifacts from the concrete images and for performing automated image processing of concrete cores. Preliminary results are presented for estimating the system resolution and detectability. It is demonstrated that computerized axial tomography can be used effectively in evaluating the interior structure of concrete/aggregate mixes and for estimating various mass and fractions in the mix. Also, applying edge--detection in tomograms may prove to a very useful tool for calibrating and validating consitutive models used in finite--element codes to simulate crack formation during earthquake loading..

1 Introduction to computer tomography

Computer tomography is a non–invasive laboratory technique for imaging the interior of objects with complex internal geometry. The method attempts to relate changes in the penetration of a particle or photon beam through an object to the density of the object. It uses a particle or photon beam source and a detector array to obtain data and then a dedicated processor for data reconstruction and another dedicated processor for the display.

The entire procedure can be described as follows. A thin plane layer of a three–dimensional object –referred to as a slice– is isolated by the sunchronized movement of the beam source and the detector array. During the synchronized motion of the beam detector assembly, beam projection data are obtained for the particular image plane from many different angles. These changes in the beam intensity (from the source to the detector) are related to the nonuniformities and to the inhomogeneities in the interior of the slice. The reconstruction of the image of the interior structure of the slice relies on a basic principle of topology which requires that given an infinite number of single beam projection data though a two–dimensional surface, then it is possible to derive the exact distribution of the attenuation coefficient of the beam for the entire volume.

To appreciate the operation and nomenclature of computer tomography, consider a beam of intensity I_0 incident upon a homogeneous object of width d and uniform density ρ. The intensity of the beam after it has penetrated the object is $I_{\text{transmitted}}$, and it is a function of d, ρ and I_0; it is given by :

$$I_{\text{transmitted}} = I_0 e^{-k(\rho)d} \qquad (1)$$

The parameter $k(\rho)$ is referred to the attenuation coefficient of the object and it is directly related to its density. When the object is inhomogeneous, i.e., $\rho = \rho[x, y, z]$, then the intensity after penetration depends on the distribution of densities of the various inhomogeneities which the beam encountered in its path. In this case the transmitted intensity is given by

$$I_{\text{transmitted}} = I_0 e^{-\int_{\mathcal{L}} k(\rho[x,y,z])dl}. \quad (2)$$

$\mathcal{L}$ is the total path length and dl is the differential element along the path. In a conventional CT scanner, the detector signal is averaged over a short period of time and then digitized. Since the reference I_0 is known, measuring $I_{\text{transmitted}}$ provides the value of $log(I_{\text{transmitted}}/I_0)$ which then provides $\int_{\mathcal{L}} k(\rho[x,y,z])dl$ along the path $\mathcal{L}$. Given a large number of projections, one obtains a sufficient number of values of $\int_{\mathcal{L}} k(\rho[x,y,z])dl$ so that one obtains an approximate map of $k(\rho[x,y,z])$ throughout the two–dimensional plane. Image reconstruction algorithms are then used to assign different grey level intensities to ranges of values of $k(\rho[x,y,z])$ and then a two–dimensional grey-scale image is produced on a computer monitor. Figure 1 shows a schematic of a third generation scanner x-ray scanner imaging a patient's head. The detectors array provides one data array for $log(I_{\text{transmitted}}/I_0)$ for every angle of the x–ray tube assembly.

In practice, absolute values of the attenuation coefficient k are not calculated; instead the processor assigns integer values –known as CT numbers and linearly related to the Hounsfield numbers– to the attenuation coefficient. The CT number is related

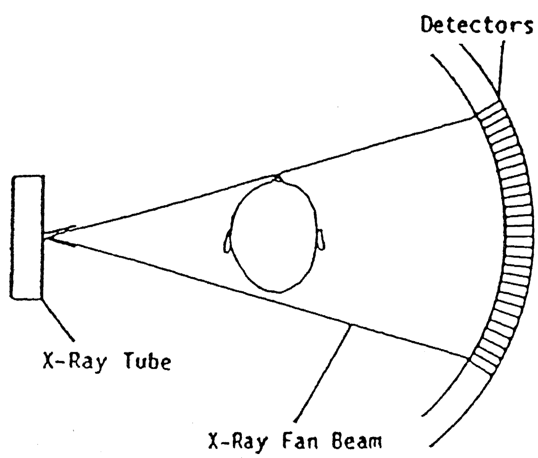

Figure 1 A schematic of a third generation CT scanner imaging a patient's head.

to the attenuation coefficient by the equation

$$\text{CT} = 1000[\frac{k_{\text{concrete}}}{k_{\text{water}}} - 1]. \quad (3)$$

Notice that the CT number is essentially the relative difference of the attenuation coefficient of the material with the attenuation coefficient of water; the larger the difference in densities between the material and water the higher the CT number is. Also notice that if a material has an attenuation coefficient which is very close to that of water, then the imaging system will not be able to resolve any water–filled voids inside the material. Computer tomography works best when the inhomogeneities in the material have large differences in their attenuation coefficients.

Computer tomography systems use specialized dedicated microprocessors which generate the CT number data for every pixel of a video monitor and then they employ sophisticated image reconstruction algorithms to enhance and display the final image.

The single most common beam systems in use for CT are x–ray systems; they are now ubiquitous in medicine, and they are becoming so in aerospace engineering. In medical applications the beam energies vary from 100keV to 130keV. In prototype industrial applications, these energies are about 1500keV, since higher energies are required to penetrate through denser materials. Acoustic tomography is similar to x–ray tomography, and it has found numerous applications in NDE testing; however, at present, its resolution and its sensitivity is much poorer than x–ray CT because of the diffraction of the acoustic beams. Other related computer tomography modalities include magnetic resonance imaging and positron emission tomography.

2. Introduction to concrete core tomography

To our knowledge, there exist no published reports of qualitative applications of computer tomography in concrete/aggregate studies. R. Green (1988) reported of some preliminary gamma–ray studies at the University of Texas at Austin and presents a tomogram of a section of a a concrete beam with a rebar. The photograph appears to have poor resolution, but given the various stages of reproduction from the original that it went through it is hard to comment on its quality. The use of a γ–ray based system instead of an x–ray system may have been necessary due to the higher energy required to penetrate through steel reinforcement.

The work which we will present here is an attempt to understand the CT characteristics of concrete and to generate various preliminary data sets necessary for the further progress. In particualr we will report on the following areas.

1) Demonstration of the feasibility of concrete core tomography.

2) Preliminary experiments to determine the concrete and aggregate CT number.

3) Determination of the beam hardening correction function for the CCT.

4) Implementation of the correct histogram equa ization and edge–detection analysis.

5) Determination of the system resolution, the point–spread function and the system detectability.

6) Implementation of software to perform automated edge–detection in the CCT images and calculation of the mass fraction.

7) Implementation of algorithms to provide quan titative displacement data on large scale deformations.

3. Demonstration of the feasibility of concrete core tomography

To evaluate the feasibility of x–ray tomography for imaging concrete cores we used a Phillips 220 third generation x-ray CT scanner located at Norris Hospital at USC. We have acquired considerable experience with its operation in imaging studies of asphalt pavements. (This study had been funded by the Strategic Highway Research Program (SHRP) of the National Research Council.) In our preliminary study our focus was to determine if sufficient differences in the CT numbers exist to resolve air voids, water voids, and aggregate particles inside a concrete core. Our work proceeded in two steps.

Step 1. Development of an imaging protocol. We first established a standard imaging protocol. Since CT was developed for human studies, operating parameters had to be modified to yield optimal results for concrete/aggregate cores. We determined the optimal system parameters by imaging two cylindrical concrete cores of diameter 20cm and depth 10cm. In particular we determined that an x–ray peak energy 130kVp, an intensity of 250mA , the scan time of 3msec, and a slice thickness iof 3mm produced excellent grey–scale images with good contrast. Other system parameters such as the number of repetitions, the number of projections, and the interslice spacing appear to be highly dependent on the specific application and they do not depend on the single slice data. However it appears that a $2mm$ interslice spacing is necessary to achieve uniform contrast across the entire image, as well as the desired level of detectability.

Step 2. Calibration of the CT using phantoms. After these parameters were established, we calibrated the images we obtained. The calibration was performed by using a special "phantom" which we had constructed for asphalt tomography. The phantom is a very expensive water bath with well known x–ray attenuation properties. By comparing images with the bath filled only with water and images with asphalt masses, aggregate masses and concrete masses immersed in the bath we can adjust certain hardware parameters of the CT system. This procedure has to be done at least once because the existing calibration procedures have been developed for human studies; our preliminary images were biased towards enhancing the contrast between tissue, bone, fat and water.

Our preliminary results indicated that concrete core tomography is feasible and it is possible to obtain images of superior contrast. We will present several images in further sections of the report.

4 Determination of the Aggregate and Concrete CT Numbers

In our preliminary work, we determined aggregate CT numbers by either reading off CT values from aggregates inside core; that data was able to demonstrate that significant differences exist between the CT numbers of concrete and aggregate to expect that concrete core tomography is feasible. However, we found out that the standard deviation was relatively high when we measuring the Hounsfield number of aggregates inside the core, possibly because of adsorption. Also the CT numbers obtained from crushed aggregate could not be deemed apriori reliable, because of the possibility of air entrained in the fines-column during packing. We performed a systematic series of imaging studies with large aggregate particles in a water bath to determine the CT numbers and the standard deviation; the latter is smaller than before and it appears possible –in some cases– to identify the aggregate type by its CT number.

We have not yet run extensive studies to determine the CT number of different concrete mixes. Based on our preliminary results we expect that we should be able to identify high strength concrete or light–weight mixes directly form the CT number; however, we don't have definitive results as yet.

5 Determination of the Beam Hardening Correction Function

Commercial x–ray tubes produce beams which are not of single energy; even when propagating through a homogeneous material, the different energies in the beam attenuate at different rates and the resulting image appears slightly inhomogeneous. When imaging a uniform core with a truly monochromatic x–ray source, one would obtain an image with uniform grey–level intensity everywhere. With a commercial tube one obtains an image which is progressively darker towards the center. This is a standard image processing artifact and appropriate reconstruction algorithms exist to remove it; however, again, they are tuned towards removing artifacts from human imaging studies.

We followed the standard procedure for obtaining a beam hardening correction image appropriate for building materials. We scanned a uniform core with crushed aggregate and then averaged the data over the entire cross–sectional area. Then we obtained a transfer function which related the deviation of the CT value of any given pixel from the average CT number with the pixel location. Then we applied this transfer function back to the image and the beam hardening artifacts were effectively removed.

In the this phase of our project we were not able to determine whether a single beam hardening correction image can be used to correct the images of cores of different densities. This will allow the routine imaging of concrete cores without having to construct a special uniform core to determine a specific transfer function for each density.

6 Histogram Equalization and Edge Detection

Histogram equalization is a means for enhancing the contrast of CT images obtained when the inhomogeneities of an object have CT numbers which are very similar. The method works by first taking the histogram of frequencies of CT numbers within a CT image. The materials of interest such as aggregates, concrete and air will appear on the histogram as peaks. New grey–level values are reassigned to these peaks and then the image is reconstructed and displayed again. This procedures makes the "dark" areas of the image darker and the light areas of the images lighter. An example of the results of histogram equalization are shown is shown in figure 2. We would like to emphasize that this procedure is done only when the visual enhancement of the image is necessary for display purposes. Histogram equalization is not performed when calculating mass fraction or density data.

Histogram equalization is also useful when performing edge detection studies. In edge detection, the perimeter of the aggregate areas is determined and displayed, as shown in figure 3. This type of data could be very useful in relating aggregate type to performance during loading and in providing input data for the validation of finite element codes.

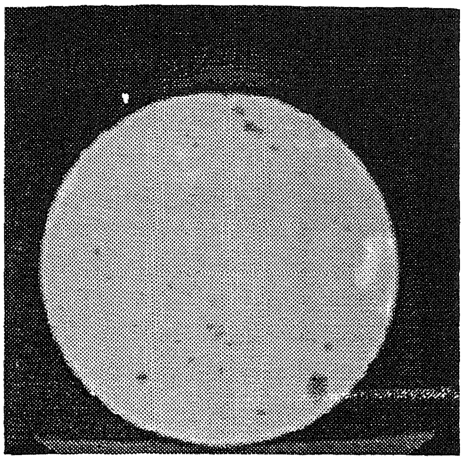

Figure 2a. A tomogram of a cross–section of a concrete core after the beam hardening correction function has been applied along with the histogram of grey–scale intensities.

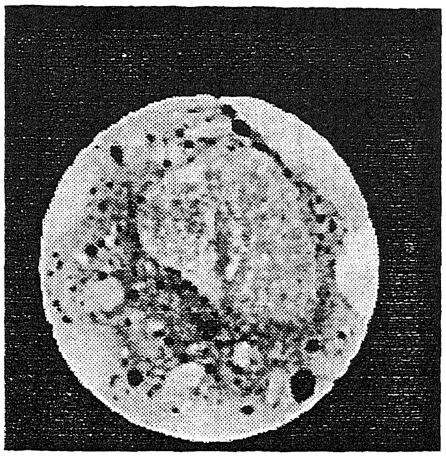

Figure 2b. A tomogram of a cross–section of the same concrete core after histogran equalization, along with the equalized histogram of grey–scale intensities.

7 Nominal System Resolution

It is customary in CT investigations to determine the system resolution by calculating what is referred to as the point spread function. This test was done by imaging a 0.4 mm platinum wire in an air phantom. If the system had infinite resolution then the image of the wire would occupy exactly 0.4mm worth of pixels on the CT display; since there are 2 pixels/mm, then the wire should occupy exactly one pixel.

To determine the nominal resolution, we plotted what is referred to as the point spread function (PSF). In this plot the centerline of the wire was at approximately 12.5 pixels. Under ideal conditions, one would expect to see a single line at that distance. Instead, we observed that the distribution "spilled" over adjacent pixels. The nominal CT resolution is determined by measuring the width in pixels of the distribution at an elevation exactly half of the maximum CT number. In our case the the half–width was at $CT = 160$ corresponding to 4.63 pixels; this implies a nominal system resolution of 2.3 mm. Note that the system detectability may be higher than the nominal system resolution; small particle images may "bleed" into adjacent pixels making them visible.

Another useful system performance parameter is the system detectability. This parameter refers to a typical physical dimension of the smallest particle which can be identified in the tomograms. We would like to note that the detectability of the imaging protocol is much higher than the nominal system resolution. Even though our results with concrete are not available yet, based on our results in asphalt tomography, we expect the system detectability to be about $0.5mm$. (See Agbabian et al, 1990 for details.)

8 Software Development

A significant part of our effort has been in developing software specifically for analyzing concrete cores. Our software package can run on MacintoshII and on Sun 330 (or better or newer) workstations. The software is menu driven and it can be used once the CT raw data is transferred on the particular system. We will briefly summarize what our software can now do.

1) Perform automated beam hardening corrections on any concrete core using a standard correction image.

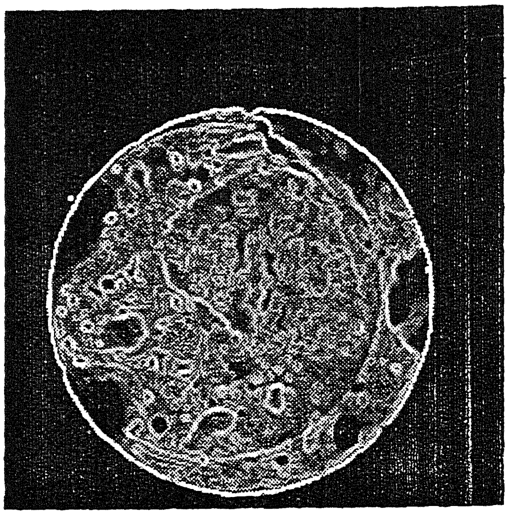

Figure 3 The figure shows is a tomogram of the same cross–section as in figure 2 after edge detection analysis.

2) Perform automated edge detection analysis.

3) Perform automated mass fraction analysis.

4) Perform image flow calculations.

This latter part has been developed in conjunction with our work with optical flow calculations is asphalt rheology. Here, given a set of image data from a core before and after loading, our software can actually determine the motion of aggregate particles within the core, and it can determine the velocity field of the entire deformation. The results are impressive, but can they can only be reproduced in full–color. (See Synolakis et al, 1990).

9 Summary and Conclusions In summary, our results suggest that computerized axial tomography can be used effectively in evaluating the interior structure of concrete/aggregate mixes. (Unfortunately, the quality and the resolution of the images which we have obtained cannot be readily reproduced in this proceedings volume.) We conjecture that our work will provide –for the first time data– quantitative data to calibrate and validate finite-element codes used in mix design. We are hopeful that further advances in concrete core tomography will result in predictive methods for concrete performance and applications in concrete forensic engineering.

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