Finite Element Stress Computations Applied to Images of Damaged Concrete: A Possible New Diagnostic Tool for Concrete Petrography

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FINITE ELEMENT STRESS COMPUTATIONS APPLIED TO IMAGES OF DAMAGED CONCRETE: A POSSIBLE NEW DIAGNOSTIC TOOL FOR CONCRETE PETROGRAPHY

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ABSTRACT

Concrete petrography is used to assess damaged concrete in order to determine the probable mechanism of damage. However, using traditional petrographic analyses, it is often difficult to say what mechanisms caused the crack damage, since many deterioration mechanisms produce cracks. This article describes a hybrid imaging-finite element modelling technique that can be used to help determine the mechanism of damage in such cases. This application is intended to assist concrete petrographers in the assessment of degradation mechanisms.

INTRODUCTION

There is a recurring problem in the field of concrete petrography: What caused the cracks in a piece of deteriorated concrete? This is a difficult question to answer from just a field evaluation and often is a difficult task in petrographic investigations. A typical example is cracked concrete with crystals growing in the cracks. Did the crystal growth cause the cracks, or did the crystals grow in the open space provided by the cracks? Knowledge of the materials and environmental history can help guide the petrographer's approach to the problem. For example, if the temperature of the concrete was always above freezing, then frost attack can be excluded as a possible mechanism, or if there was no source of external sulfate ions anywhere near the concrete during its lifetime, then external sulfate attack can be ruled out. Even with environmental information available, however, the crack-causing mechanism(s) usually cannot be uniquely determined.

Most causes of deterioration involve mechanics, in that some phase grows/shrinks because of chemical or physical attack and induces stresses that produce cracking of various patterns. Examples include frost attack, sulfate attack, and alkali-silica reaction. Using video imaging, stereo microscopy, and back-scattered scanning electron microscopy, we can take images of damaged areas, and identify the different phases, including the cracks. For the SEM, if gray scale alone is not enough to distinguish among phases, then x-ray bitmaps can be produced that give chemical information that can further distinguish phases [1,2]. This article describes a hybrid imaging-finite element modelling technique that can be used with these kinds of images to help determine the mechanism of damage. This is accomplished by qualitatively linking mechanics to the microstructural image via simulations of selected deterioration mechanisms. The details of the technique, as well as its limitations and research needs, will be described in this paper.

TECHNIQUE AND EXAMPLE

This hybrid imaging-finite element modelling technique requires as input a high-resolution image that clearly shows the different concrete phases. After taking an image of the region of interest, gray scale or false color is used to label the pertinent regions. Thresholding is then applied, so that the image becomes an n-phase image, with each phase having its own label for all its pixels. On a larger scale, images captured through a stereo microscope or video camera are equally suitable, providing the constituents and cracks can be distinguished. The following example utilizes all these imaging schemes to examine cracking in a pavement from US 20 in Iowa.

It should go without saying that the process used to prepare the specimen for imaging should not introduce any new damage [3]. The number of phases is usually fewer than 10, though the finite element technique can handle more. A thresholded image is created through processing to remove the cracks and identify selected constituents like coarse and fine aggregate, air voids, paste, or mortar. The selected constituents depend upon the degradation mechanism one wishes to model. If the mineralogy of certain aggregates, or the presence of alkali-silicate reaction (ASR) gel, indicate that ASR was a probable mechanism, then those aggregates are given a different gray scale from the other aggregates and are chosen to be expansive. If frost attack of the cement paste is thought to be the culprit, then the paste is chosen to be expansive. Frost attack of the aggregate creating expansive stresses within the aggregate may be modelled in the same fashion as alkali-aggregate attack. This demonstrates the need for good petrographic work, since the identification of alkali-aggregate reaction products is necessary to distinguish between these two phenomena. The mechanical equivalents of other deterioration mechanisms are found in any good textbook dealing with concrete durability [4].

Figure 1 shows an image of a damaged specimen with the cracks highlighted to enhance visibility. The coarse aggregates are comprised of dolomitic limestone and are lighter-colored than the cement paste and fine aggregates. Shale in the coarse sand was deemed to be alkali-reactive and potentially a source of cracking and, being dark, was easily distinguished from the other concrete constituents. Figure 2 shows the image after choosing the phases and removing the cracks. For this example, the coarse aggregates will be assumed to be expansive due to frost attack on the aggregates. The border and boundary regions will be described below.

Finite element elastic programs specialized to work on digital images have been developed over the past few years [5]. The program that was used for this analysis is a 2-D thermoelastic program, called `thermal2d.f` [6], where each phase has its own elastic moduli tensor and thermal strain or eigenstrain matrix. Other similar programs are also available [7]. If a phase is desired to expand, then it is given a positive eigenstrain. This phase then expands, but not freely, as the phases around it act as elastic restraints. In the concrete studied so far, individual phases have been given elastic moduli that are roughly correct for the cement paste and the aggregates, though only the relative magnitudes are important, not the absolute magnitudes. The phase that is desired to expand or shrink is given an eigenstrain of ± 0.1. We are interested in the qualitative question of where the stresses are greatest and where cracks could occur, not in the quantitative question of the value of absolute stress magnitudes.

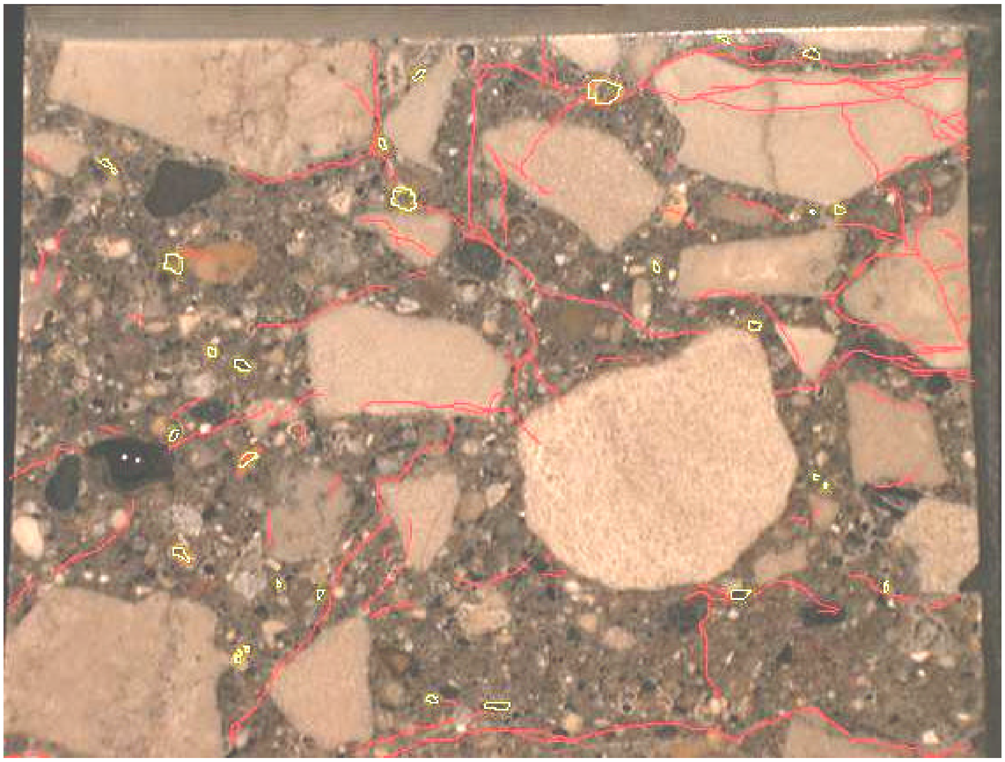

Figure 1: Video image of a polished cross-section of pavement concrete. Back-scattered SEM imaging allowed identification of cracks and potentially alkali-silica reactive shale, and mapping their locations on the video image. Image field width: 10 cm

The original digital image of the microstructure must be converted to a form that can be used in `thermal2d.f`. A variety of convenient programs are available via the WEB to easily convert images. The necessary image format is `.pbm`, which is an ascii graphics format that can easily be interpreted by the elastic program [5].

The boundary conditions used to simulate the elastic behavior are important to the results obtained. The sample shown in Fig. 1 was taken near the top of a pavement surface, so that the top surface should be a free boundary in any finite element analysis. For the bottom of the pavement, a fixed, zero-displacement boundary condition is more reasonable. The pavement thickness was 300 millimeters, and the edges of the pavement were away from the location where the sample was taken. The sample can then be surrounded by an effective material, that is, material having the same elastic modulus and eigenstrain as the total sample. These parameters come from separate calculations, computing both the effective moduli and eigenstrain of the material [5]. Figure 2 shows how the boundary conditions were approximated in the finite element analysis. Since only the bottom of this image has fixed boundary conditions, the total stress after equilibration will be close to zero. This small value, however, is made up of positive and negative contributions from different phases, so that any given region in the image could be under large stress.

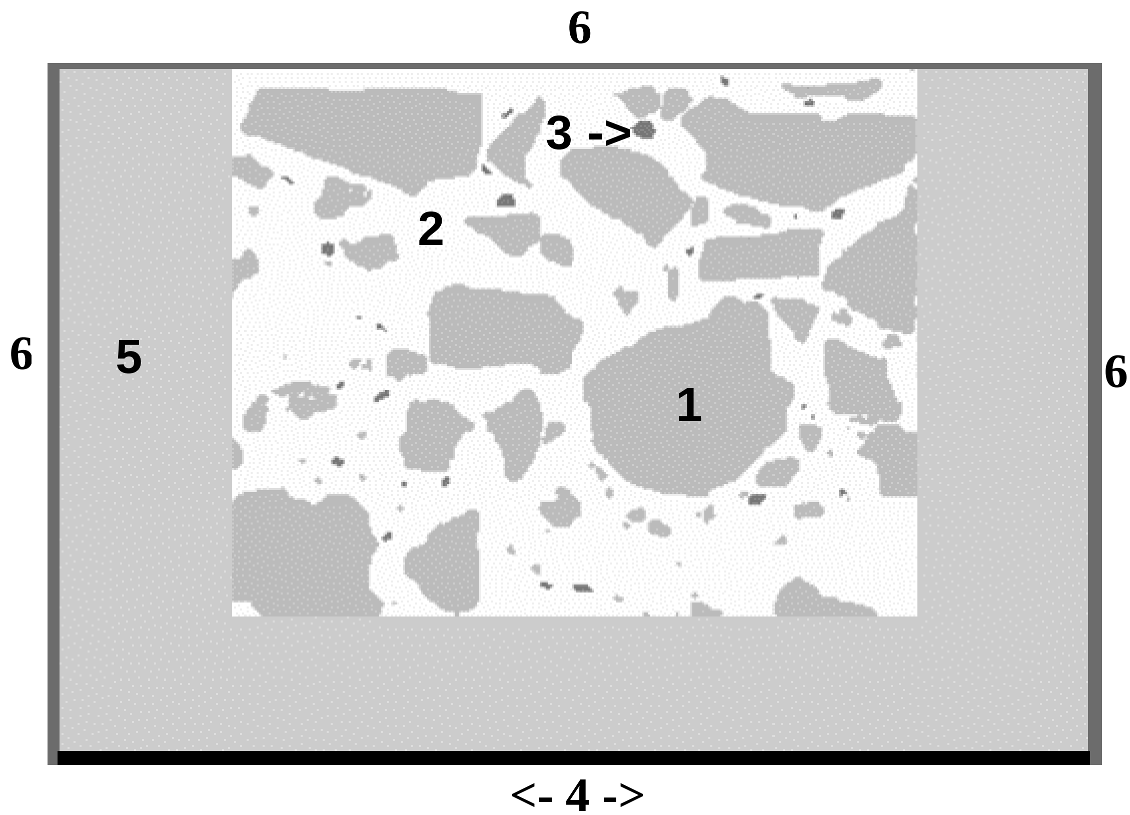

Figure 2: Image analyzed microstructure from Fig. 1. The phases are: (1) coarse aggregates, (2) cement paste/fine aggregates, and (3) shale fragments. The phases that define the boundary conditions are: (4) fixed zero-displacement boundary, (5) effective material, and (6) air or free boundary.

Once boundary conditions have been set and individual phase elastic and eigenstrain parameters have been chosen, the program `thermal2d.f` is used to calculate the displacement and average stresses in each pixel of the microstructure. The principal stresses in each pixel, and their orientation, are calculated from the average stresses in each pixel using simple elasticity theory [8]. There are two pieces of information that then must be displayed--the relative magnitude of the largest tensile stress in each pixel, and its direction. Only tensile stresses cause cracks in cementitious materials, so the compressive stresses are ignored. Cracks generally propagate perpendicularly to the direction of tensile stress, so that is why the direction of the stresses are important as well. It is difficult in an image to display both direction and magnitude of a vector-valued quantity like the stress. This problem has been solved by using line segments to represent the stress field [9]. The length of the line segments indicate magnitude, and their direction indicates the direction of the maximum tensile stress in the pixel. Since we are mainly interested in what directions the computed stresses would cause cracks to propagate, relative to where the real cracks did occur, we have found that a slightly different procedure gives us a more useful image. Each line segment in the direction of the maximum tensile stress is shifted by 90 degrees, to show the direction that a crack caused by the stress would propagate. The probable crack pattern that would be caused by this mechanism is then readily seen, and can be compared easily to the true crack pattern in the original image.

Figure 3 shows the line segment array indicating the probable crack patterns caused by the aggregates expanding. In this condition, the aggregates are in compression, as they tried to expand but were restrained by the cement paste/fine aggregates matrix. Comparison with Fig. 1 shows a reasonable agreement with the true crack patterns, which would show that this mechanism, the expansion of the aggregates due to frost attack, could have caused at least some of the crack patterns seen.

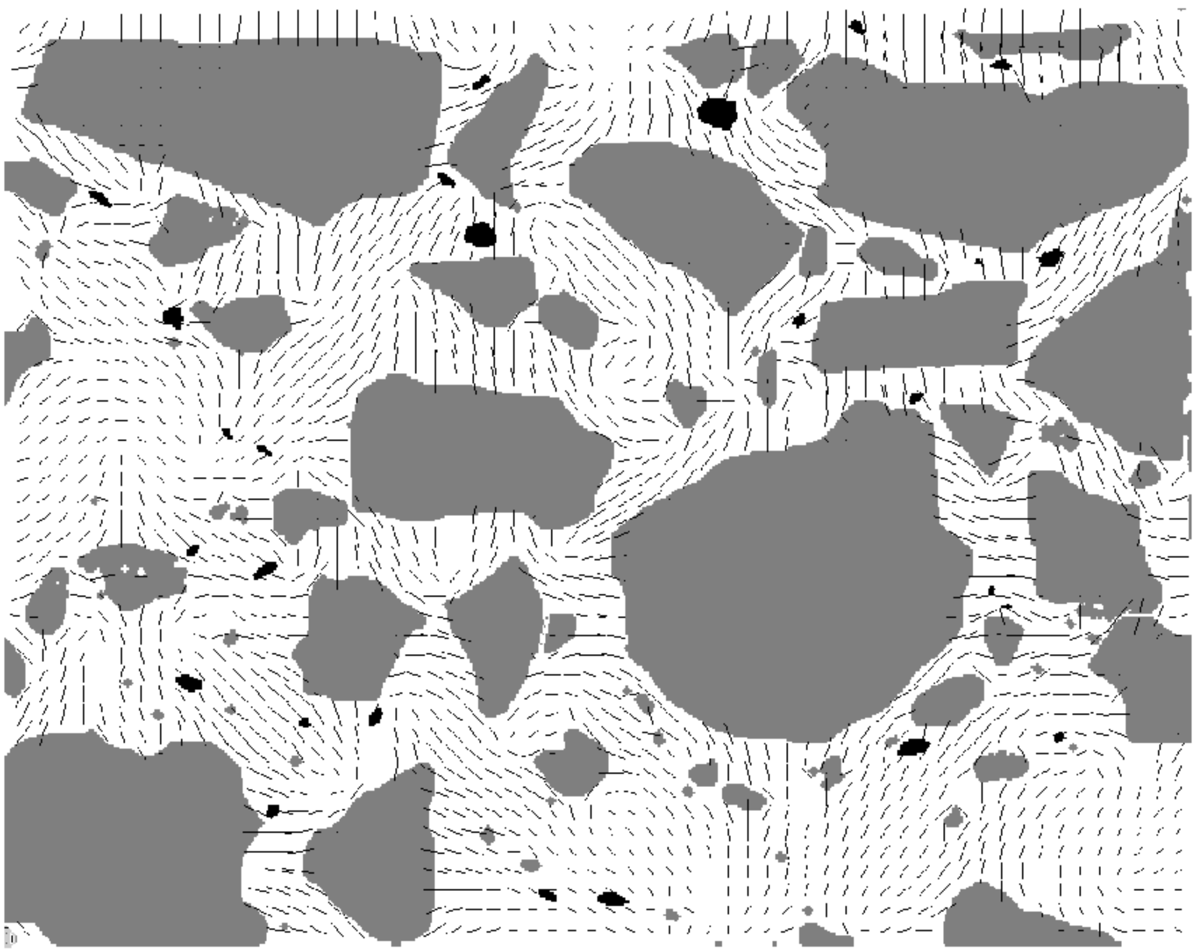

Figure 3: Line segment array superimposed on the microstructure indicating the probable crack patterns caused by the aggregates expanding.

DISCUSSION

There are several limitations to this technique. The first is that the finite element algorithm is linear elastic, while the cement paste should be treated as a viscoelastic material. However, at later ages, where durability questions are important, the cement paste is well-hydrated and not nearly as viscoelastic as at early ages [4], so that linear elasticity certainly becomes a better approximation. The second limitation is that the technique only considers stress analysis, and does not consider fracture mechanics, which is the correct theory of how cracks propagate [10]. The regions of maximum tensile stress will certainly tell where cracks will be important, but will not precisely define crack propagation.

A third limitation is the finite size of the samples, which is only partly overcome by using effective material boundary conditions. However, our electron microscope can image fairly large regions, so that this is only a limitation for crack patterns that are correlated over length scales longer than we can image at one time. Also, we could, if necessary, take carefully correlated mosaic images. Related to this are questions of boundary conditions, for example: How good is the approximation of zero displacement boundary conditions at the bottom of a pavement?

A fourth limitation is that while the cracks were formed in 3-D, we are studying them in 2-D. This limitation can only be overcome by developing 3-D images of damaged concretes, and applying the same technique in 3-D. The program `thermal3d.f` [5] exists, which handles 3-D images, and 3-D images of damaged concrete can be acquired using x-ray microtomography at resolutions that are sufficient to see the damage, though perhaps not all the cracks [11]. Acquisition of such images at the resolutions needed (several micrometers per pixel) are not routine, at present.

Even with all of these limitations, however, this technique should at least still give some qualitative insight into how different deterioration mechanisms can cause different crack patterns. The analytic stress patterns around simple isolated shapes can be used to predict crack patterns under different mechanical conditions [12]. When many randomly-shaped aggregates are present, however, a numerical method like that described herein becomes necessary. The finite element programs are documented and available [5,7], and the image analysis methods necessary are standard tools included in most image analysis packages. This technique represents a first step beyond the usual empirical guessing at deterioration mechanisms from crack patterns, and as such, is a possible new diagnostic tool for concrete petrography.

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