EARLY MEASUREMENT OF CONCRETE DETERIORATION
BY THE DEFORMATION MAPPING TECHNIQUE

D. Rothstein, J. J. Chen, J. J. Thomas, and H. M. Jennings
Northwestern University, USA

Abstract
In the advanced stages of concrete deterioration, macroscopic features such as focused
 crack networks and surface spalls may indicate damage to a structural element. In such
cases, compressive strength measurements provide a quantitative criterion for evaluating
the engineering serviceability of the construction. Although microstructures may record
degradation before it is apparent at the macroscale, there are currently no generally
accepted forensic techniques to quantify the degradation—materials are classified as
either intact or damaged. Early detection and quantification of microstructural indicia of
concrete deterioration could assist in identifying structures where early repair or
isolation may provide cost-efficient solutions before the progression of damage requires
more costly methods, such as removal and replacement. The Deformation Mapping
Technique (DMT) has a microscale resolution that may quantify deterioration in the
microstructures of cement-based materials. One application of DMT compares
deformations measured in the laboratory after loading deteriorated samples and their
controls. Measuring the deformation in the deteriorated and control samples allows the
calculation of a relative deformation variable, $\Omega_r$. To illustrate the efficacy of the DMT,
the $\Omega_r$ of a set of ordinary Portland cement pastes and mortars exposed to sodium sulfate
solutions were compared with their respective controls. Preliminary results suggest that
with refinement, there is great potential for using DMT as a quantitative forensic tool.

1. Introduction
Measuring and understanding the mechanisms of concrete degradation is central to
maintaining modern infrastructures around the world. This contribution describes the
Deformation Mapping Technique (DMT), which provides a means of quantifying the
extent of degradation in the microstructure of cement-based materials. Developing an
ability to monitor degradation before significant loss of performance occurs may
maximize the cost-efficiency of maintaining concrete infrastructures in a wide variety of
aggressive environments.
The paper begins with a review of the need for developing quantitative microstructural forensic methods. A description of the basic elements of the DMT and strategy for using the DMT as a forensic tool follows. We then summarize the results of experiments that take the initial steps toward investigating the efficacy of the DMT as a forensic tool. We conclude with a discussion of these results work and a critical appraisal of the successes and needs for additional research in using the DMT.

2. The Need for Quantitative Microstructural Forensics

The progression of damage in concrete involves complex relationships between the chemical and/or physical alteration of the microstructure of concrete and its macroscopic properties such as strength. Nearly all damage processes (with the notable exception of mechanical agents such as impact and abrasion) involve the transport of fluids through the pore network of the material. Because this alteration depends upon the percolation of fluids, it progresses over time from the exposed concrete surfaces toward the core of the structure. This allows the reconstruction of the time-integrated effects of concrete alteration by comparative analysis of different portions of a construction element.

There is clearly a link between the microstructure and engineering properties of cement-based materials. However, no forensic techniques are available that quantify, from microstructural observations, the degradation of cement-based materials under severe conditions. The paucity of such techniques has significant implications for the maintenance of structures in aggressive environments for both the public and private sector. For example, claims of damage from sulfate attack in southern California [1, 2] hinge on the use of strictly qualitative observations made via scanning electron microscopy (SEM) on concrete from residential foundations as prima facie evidence of material failure [3, 4]. However, macroscopic strength tests performed in accordance with ASTM standards indicate no loss of compressive or splitting tensile strength in concrete from the same locations [5]. The disparity of such observations exemplifies the need to develop quantitative, reproducible, and unbiased techniques if microstructural observations, particularly those made solely at the micron-scale and below, as with the SEM, are to take their place as performance indicators alongside well-established macroscopic criteria such as strength measurements.

3. Introduction to Deformation Mapping Technique (DMT)

3.1 Background
The DMT is an image intensity matching technique that computes the displacements between two images for each pixel in a microstructure through a finite element algorithm [6]. Because detailed descriptions of the DMT are found elsewhere [7, 8] this contribution summarizes only the relevant conceptual framework.
There are several steps in the DMT. The first involves the acquisition of a reference image of a specific region within the sample microstructure. A stress is then imposed on the sample in the laboratory, most often by drying or mechanical loading. An image of the same area comprised within the reference image, but now recording the effects of the stress, is then acquired. Both the images are digitized with grayscale values ranging between 0 and 255 assigned to each pixel. Measuring the displacement of each pixel after the application of the stress provides an opportunity to calculate the deformation recorded by each pixel within the region of interest. Neubauer et al. [8] give the details of these calculations. The DMT calculates an average linear deformation for each pixel that represents the degree of compaction or rarefaction recorded by each pixel. Two-dimensional maps of the distribution of compressive and tensile deformations and histograms that represent the statistical distribution of deformation intensities provide convenient venues for summarizing the output of the DMT. Before showing examples of the results in these forms, we outline the general strategy for using DMT as a forensic tool.

**3.2 DMT as a Forensic Tool**

The central hypothesis to the development of DMT as a forensic tool is that the alteration of concrete by deleterious environmental agents changes the ability of the microstructure to resist deformation when subjected to external stress. In other words, a deteriorated sample will partition deformation differently than a control sample, with a more heterogeneous deformation distribution in the deteriorated samples [9]. Therefore, obtaining a control sample that provides a window toward the mechanical behavior of concrete unaffected by deleterious environmental agents is central to the DMT. In the experimental investigation outlined below, sequestering a set of samples from the materials prepared for accelerated exposure tests provides such control. In testing field concrete control samples are available from the structures of interest. Because the ingress of fluids into the concrete drive the relevant damage mechanisms, the intensity of damage decreases from the exposed surfaces toward the core of a structural element.

The approach to quantifying damage in cementitious microstructures via DMT is based in part on the principles of damage mechanics [10]. Damage mechanics models typically attempt to correlate damage to an applied stress or deformation through a damage evolution law that relates the damage of a material, $\Omega$, to a macroscopic material property, such as elasticity. Rather than develop such phenomenological or empirical relationships to estimate $\Omega$, DMT affords the potential opportunity to measure directly this previously elusive variable. Comparing the area percentage of a microstructure that records a given level of deformation can provide insights toward the relative deformation, $\Omega_r$, of a concrete microstructure. The output of the DMT facilitates the retrieval of such data (see Figure 3 below). A relative deformation variable that compares the net deformation calculated via DMT in a control sample ($D_c$) and a deteriorated sample ($D_d$), is given by the relation:
\[ \Omega_t = \left| \frac{D_d - D_c}{D_c} \right| = \left| \frac{D_d}{D_c} - 1 \right| \] (1).

In the following sections we apply the DMT to mortar samples exposed to sodium sulfate solutions in the laboratory.

4. Experimental Procedure

4.1 Sample Preparation

Mortars composed of La Farge Type I cement were prepared in accordance with ASTM C 109 at a w/c = 0.485 and a cement/sand ratio of 0.36. Mixing was in accordance with ASTM C 305 under ambient conditions of \(\sim 22^\circ C\). The mortars were cast into 1 x 1 x 11\(\frac{1}{4}\) inch molds prepared in accordance with ASTM C 490. The samples were cured at 100\% relative humidity for 24 hours, demolded, and placed in a saturated lime bath. After 96 days the samples were removed from the bath, sliced into 2-4 mm thick coupons and replaced in the lime bath. After 141 days, a set of coupons were removed from the lime baths, weighed (surface dry-saturated), and submerged in a saturated sodium sulfate solution for one week. The approximate volumetric ratio of the samples to the sulfate solution was \(~ 125:1\). After one week the samples were removed. There was no significant weight loss in the samples and no visual deterioration detectable to the naked eye. A sulfate exposure sample and its corresponding control were then tested by the DMT protocol as described below.

One of the requirements for the input images into the DMT is a variation in grayscale patterns at a very fine scale. Although digital image correlation techniques often require painting an artificial speckle pattern on the material of interest, the heterogeneous microstructure of a cement paste or mortar naturally provides the requisite variation in grayscale. Achieving an acceptable level of precision in resolving fine scale microstructural features via optical microscopy required the development of a consistent sample preparation procedure. Following guidelines outlined by Stutzman [11], the mortars were processed through dry grinding on 320 and 600 SiC papers. Polishing with 6\(\mu m\), 3\(\mu m\), 1\(\mu m\), 0.25\(\mu m\) Buehler Metadil® oil based diamond suspensions on Buehler Textmet® cloths for 2, 3, 4 and 8 minutes, respectively, at 230 rpm. This selection of polishing times minimized surface damage. Further precautionary steps included use of lint-free cloths, compressed air and 200 proof ethanol for removing debris between grinding and polishing steps.

After obtaining a suitable polish the samples were placed in a compressive loading stage operated by a computer-driven stepper motor. After obtaining a reference image, the sample was subjected to uniaxial compression and images of the deformed microstructure were obtained. Care was taken to ensure the images were captured at the same focus and with minimal rotation. The work shown here was performed at magnifications of 50x using a standard ausJena (Zeiss) Jenavert petrographic microscope in reflected light mode.
5. Results

5.1 DMT Maps
The ability to map deformations directly onto the real microstructure is a unique feature of the DMT. Figures 1 and 2 are maps of the compressive and tensile linear deformations (in grayscale) for the control and sodium sulfate exposed mortars superimposed over the outlines of the original sand particles (in solid black lines). The grayscale intensity of the linear deformations is proportional to the deformation magnitude. As expected, the more elastic cement paste is predominantly in compression while the stiff sand particles are in tension. Comparing the sulfate exposed to its control at 0.7 MPa, deformation is more localized in the sulfate exposed specimen, particularly at the sand/paste interface.

Figure 1. The DMT compression maps for the control (a) and sulfate exposed (b) mortars, superimposed over the outlines of the original sand particles (shown in solid black outlines). The stress on both samples is 0.7 MPa. Length of bar = 100μm.

Figure 2. The DMT tension maps for the control (a) and sulfate exposed (b) mortars. Same conditions as above, solid black lines = outlines of original sand particles.
5.2 Deformation Distribution Curves
Statistical information found in the deformation distribution curves of Figure 3 compliment the spatial information shown in the DMT deformation maps of Figure 1 and Figure 2. The deformation distribution for the sulfate exposed sample is broader than the control sample, indicating that a larger fraction of pixels record higher deformations. Computing the net linear deformations by integration under the deformation distribution curves yields a net linear compression of $-0.045\%$ for the sulfate exposed sample while the control has a value of $-0.028\%$, consistent with greater deformation in the sulfate exposed sample.

![Figure 3](image)

Figure 3. Linear distribution curves for the control (solid) and sulfate exposed (dashed) mortar specimens. The sulfate specimen shows a broader distribution and a higher net linear compression from integration under the curve.

5.3 Relative Deformation Variable
Using the net linear compressive deformations calculated from the deformation distributions above, Equation (1) takes the form of

$$\Omega_r = \frac{D_d - D_c}{D_c} = \frac{(-0.045)}{(-0.028) - 1} = 0.607$$

The calculation of $\Omega_r$ provides a convenient parameter that quantifies the relative deformation of the sulfate-exposed sample against its control. Understanding the relationship between deformation measurements and the extent of damage that reduces
the engineering properties of the material still involves considerable research, as discussed below.

6. Summary and Discussion

Use of the DMT to detect and quantify differences in the deformation response of a sulfate exposed sample from its control confirms the potential for developing this method as a quantitative forensic tool. In the experiment described here, there was no visible damage apparent in a sulfate exposed sample. However, the DMT provided a quantitative measure of the difference in the deformation of samples subjected to identical mechanical loads. Rather than rely on subjective opinions of individual observers, such measurements represent a critical step toward using microstructures to evaluate the performance of cement-based materials in quantitative, rather than qualitative terms.

At this point DMT provides a method for determining the relative deterioration of different sets of samples in comparison with their controls. This is an important step and research can now turn to the challenge of understanding how such differences in deformation response affect the engineering properties of the material. Future applications of the DMT could involve calculating $\Omega_r$ for several samples extracted from a concrete core taken from a structural element. By monitoring changes in $\Omega_r$ over distance from the exposed surface of the element, it may be possible to quantify better the microstructural alteration of the material. Such information may also provide an important source of information for gaining insights toward the material properties of specific phases in cement pastes, for example.

The development of DMT as a forensic tool requires additional work. Quantifying the possible diminution of engineering properties from microstructural studies of materials from aggressive environments requires a normalization procedure for $\Omega_r$. Such procedures will not be possible until the link between the deformation response and real damage are understood better. This is a formidable challenge. Another topic of ongoing research involves the refinement of precision calibrations in a variety of different cement-based materials. An improved understanding of the relationships between sample size and the type of the loading device, loading geometry, deformation rates, and other variables that affect such tests are also needed. Despite such challenges, the ability of the DMT to quantify differences in the deformation response of cement-based materials constitutes an initial, but important step toward developing quantitative, reproducible, and unbiased techniques to monitor the deterioration of cement-based materials.
7. References