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Quantitative evaluation technique of Polyvinyl Alcohol (PVA) fiber dispersion in engineered cementitious composites

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ABSTRACT

The fiber dispersion in fiber-reinforced cementitious composites is a crucial factor with respect to achieving desired mechanical performance. However, evaluation of the fiber dispersion in the composite Polyvinyl Alcohol-Engineered Cementitious Composite (PVA-ECC) is extremely challenging because of the low contrast of PVA fibers with the cement-based matrix. In the present work, a new evaluation technique is developed and demonstrated. Using a fluorescence technique on PVA-ECC, PVA fibers are observed as green dots in the cutting plane of the composite. After capturing the fluorescence image with a Charged Couple Device (CCD) camera through a microscope, the fiber dispersion is evaluated using image processing and statistical tools. In the image processing step, the fibers are more accurately detected by employing a series of processes based on categorization, watershed segmentation, and morphological reconstruction. Test results showed that the dispersion coefficient α_f was calculated reasonably and the fiber-detection performance was enhanced.

1. Introduction

Synthetic fibers have been used to improve the toughness of quasi-brittle cement-based materials such as concrete and mortar [1]. Recently developed ultra-ductile Engineered Cementitious Composite (ECC) is an example of application of this approach [2–4]. ECC is a micromechanically designed cementitious composite that is able to exhibit extreme tensile strain capacity (typically more than 2%) while requiring only a moderate amount of fibers (typically less than 2% in a volume fraction). Since the fibers can bridge micro-cracks, the dispersion of fibers strongly influences the resulting mechanical performance of the composite [5].

Several techniques, including image analysis and transmission X-ray photography [6–10], are available for evaluating the fiber dispersion in a composite, i.e., determining the degree to which the fibers are homogeneously dispersed in the composite. These are mostly applicable to non-organic fibers such as steel or glass fibers. Recently, Ozyurt et al. [11,12] proposed a nondestructive technique using AC-impedance spectroscopy and correlated the fiber dispersion, rheology and mechanical performance of FRCs; however, this approach is useful only for conductive fibers including steel and carbon fibers.

To date, the evaluation of organic/non-conducting fiber dispersions has seen little attention. The key step in evaluating an organic fiber dispersion is the fiber detection, since the contrast of organic fibers with cementitious materials is too low to allow detection in the composite by X-ray imaging. To overcome this obstacle, a fluorescence technique has been employed to specifically detect (Polyvinyl Alcohol) PVA fibers using their fluorescent characteristics.

Torigoe et al. [5] suggested a new evaluation technique for PVA fiber dispersions. After capturing a fluorescence image with a Charged Couple Device (CCD) camera through a microscope, the image is divided into small units of appropriate pixel size. The degree of fiber dispersion is then calculated based on the deviation from the average number of fibers in a unit, which is obtained by a rigorous process of directly counting the fibers point by point. In addition, the distribution coefficient, which represents the degree of fiber dispersion, significantly depends on the size of the unit.

In the present work, the authors describe a new image processing technique to eliminate the undesirable impact of the unit size on the distribution coefficient. In the development of the proposed technique, the fiber-detection performance is enhanced by employing categorization, a watershed algorithm, and morphological reconstruction. To categorize the types of fibers, features based on the shape of the fiber image are extracted and a classifier is constructed using an artificial neural network. Then, aggregate fibers are correctly detected using a watershed segmentation algorithm and morphological reconstruction algorithm.

2. Fiber dispersion evaluation technique

The proposed technique is essentially composed of stepwise tasks. First, the specimen is prepared and treated, followed by

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acquisition of a fluorescence image. Based on the proposed image processing algorithm, the fiber images are then automatically detected in a binary image, which is originally converted from the fluorescence image. Next, a mathematical treatment is performed on the data obtained from the previous task, which finally provides the calculated fiber dispersion coefficient of the composite.

2.1. Specimen preparation and image acquisition

The PVA-ECC specimen was produced and then cured in water at 20 ± 3 °C for 28 days. The specimen was cut with a diamond saw to obtain samples for fiber dispersion evaluation. Each sample, a rectangular block with a size of 13 × 36 × 20 mm in Fig. 1, was polished to create a smooth surface on the exposed cross-section, i.e., the cutting plane. The polished surface was then photographed using image acquisition equipment, i.e., a fluorescence microscope (Olympus, BX51), a CCD camera, and image processing software (Fig. 2). To obtain a digital image, the sample surface was first illuminated by a mercury lamp, followed by capture of a fluorescent image using a CCD digital camera through a Green Fluorescent Protein (GFP) filter under 40× magnification. Fig. 3 shows a fluorescence image of the cutting plane, where greenish points represent PVA fibers.

2.2. Image processing for evaluation of fiber dispersion (proto-type process)

As described in the previous section, the greenish points represent PVA fibers in the fluorescence image. The PVA fibers, therefore, should be easily detected by segmentation from the background image. The degree of fiber dispersion is then quantitatively evaluated based on calculation of a distribution coefficient α_f, referred to as the fiber dispersion coefficient, as expressed by Eq. (1) as follows [13]:

$$\alpha_f = \exp\left[-\sqrt{\frac{\sum (x_i - 1)^2}{n}}\right] \quad (1)$$

where n is the total number of fibers on the image and x_i denotes the number of fibers in the ith unit, which is a square portion allocated to the ith fiber on the assumption that the fiber dispersion is perfectly homogeneous. The fiber dispersion coefficient α_f is automatically calculated via the following steps:

(1) Convert the RGB image to a grayscale image.
(2) Convert the grayscale image to a binary image based on a set threshold – object detection based on a thresholding algorithm [14].
(3) Divide the binary image into units, i.e., equivalent squares, of which the total number equals the number of fibers (n).
(4) Obtain the coordinate data for the centroid of each fiber image.
(5) Count the number of fibers (x) located in each unit.

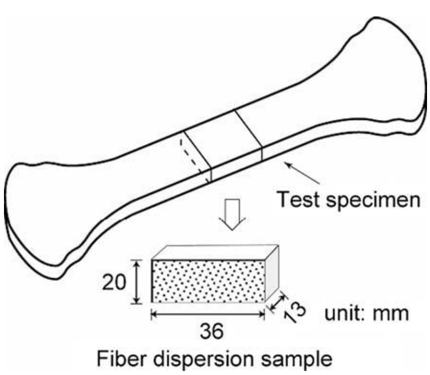

Fig. 1. Sample for the evaluation of fiber dispersion.

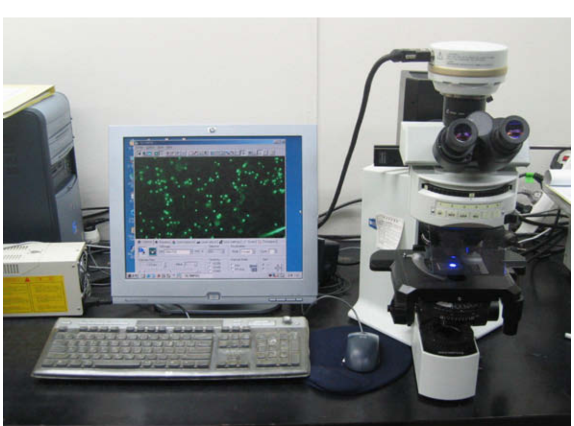

Fig. 2. Fluorescence microscope employed for obtaining fluorescence image (Olympus, BX51).

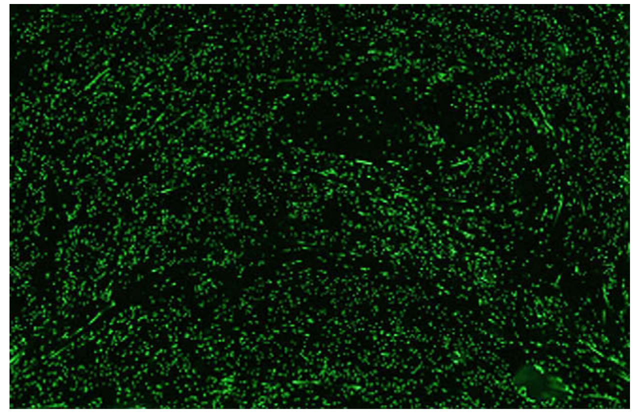

Fig. 3. Fluorescence image.

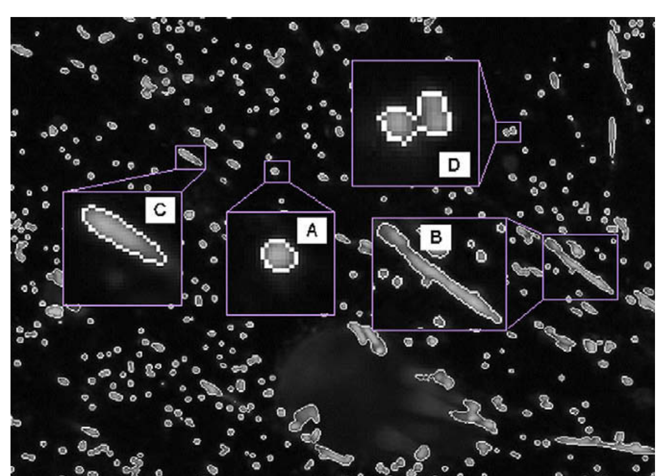

Fig. 4. Composite image obtained by combining original grayscale image with detected binary image (the white line surrounding gray particles).