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Review

# Different testing methods for assessing the synthetic fiber distribution in cement-based composites

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## HIGHLIGHTS

- Fiber distribution testing methods in cement-based composites are considered.
- The Optical Microscope, Scanning Electron Microscope, Fluorescence Microscopy and X-ray computed tomography are explained.
- The relationship between fiber distribution and properties of fiber reinforced cement-based composites (FRCs) are discussed.
- Fluorescence microscopy is more widely used for studying fiber dispersion in FRCs.

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## ABSTRACT

Fiber distribution is an important factor which affects the fresh and hardened properties of composites. A variety of methods are available for studying the fiber distribution but image analysis is more widely used for fiber reinforced cement-based composites (FRCs). In this paper, different fiber distribution methods are discussed in detail including optical microscope, scanning electron microscopy, fluorescence microscopy and X-ray computed tomography. It is found that fluorescence microscopy is more widely used for studying fiber dispersion in FRCs and can be applicable to the synthetic fibers.



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## 1. Introduction

The distribution of fibers in cement-based composites is closely related to their properties in fresh state and hardened state [1–4], which directly affects the reinforcement and toughening effect of fibers as well as the development of cracking [5–13]. However, the performance of fiber reinforced cement-based composites (FRCs) has an important impact on fiber dispersion [5,14–16]. The accurate characterization and evaluation of fiber dispersion in FRCs are of great significance for the development of FRCs. Up until now, a variety of methods had been studied for fiber dispersion in FRCs i.e. the electromagnetic induction method [17], X-ray imaging technology [18], C-type ferromagnetic probe method [19], the open coaxial probe method [20], AC impedance spectroscopy [21] and four electrode resistivity [22]. However, these methods are based on the conductivity of the fibers, such as steel fiber and carbon fiber. Image analysis is more widely used for studying fiber dispersion and can be used for both organic fibers and inorganic fibers in FRCs [23,24]. It is a more intuitive and easy method to achieve quantitative analysis. The evaluation of fibers in FRCs is mainly for fibers of one scale, but the dispersion of fibers at different scales is rare. A large number of studies have used image analysis to evaluate the dispersion of fibers. The advantages of fiber dispersion are obvious in image analysis. Firstly, the image analysis method is able to directly reflect the distribution of fibers, the orientation of fibers and the position of fibers. Secondly, the image analysis method can quantitatively describe the dispersion of fiber, so that there is a clear contrast between the fiber dispersion performance, different kinds of fibers and different contents of fibers. Moreover, it facilitates the qualitative or quantitative study of the dispersion of fibers in FRC and other properties of FRC. Based on the image analysis method, it is necessary to make a comprehensive review of image analysis method for FRCs. In this paper, different methods and parameters of FRCs are discussed. The evaluations of different methods were emphasized in order to better understand the fiber distribution in FRCs. The relationship between the fiber dispersion and properties of FRCs is also explained.

## 2. Parameters for fiber distribution

The image analysis is a visual method of cutting a specimen at the desired location to obtain a cross section where there are many fibers [25]. It quantitatively evaluates the degree of fiber distribution i.e. the uniformity of fiber distribution by using computer software to process the cross-sectional images obtained by the image forming apparatus. The different parameters of fiber distribution are fiber distribution coefficient, orientation of the fiber, the number of fibers per unit in the cross-sectional area and the distribution of fiber number and the fiber area fraction.

The fiber distribution coefficient is one of the most intuitive parameters used to describe fiber dispersion [24–30]. It considers the deviation between the actual number of fibers and the average number of fibers per unit. It is an excellent parameter to characterize the homogeneity of fibers in FRCs. The fiber distribution coefficient has the following three equations, i.e. Eq. (1) [24–27], Eq. (2) [24,29,30] and Eq. (3) [31] as shown below. The basic idea of the three expressions tends to be consistent.

$$\phi_{(X)} = \sqrt{\frac{\sum \left(x_i - \bar{x}\right)^2}{n}} / \bar{X} \qquad \alpha = \exp\left[-\phi_{(X)}\right] \tag{1}$$

$X_i$ is the number of fibers in the unit area $i$, $\bar{X}$ is the average number of fibers in all unit areas, $n$ is the number of unit areas.

$$\phi_{(x)} = \sqrt{\frac{\sum (x_i - 1)^2}{n}} \qquad \alpha = \exp\left[-\phi_{(x)}\right] \tag{2}$$

$n$ is the total number of fibers on the image, $x_i$ is the number of fibers on the $i$th cell.

$$\alpha = \exp\left[-\sqrt{\frac{\sum \left(X_i / X_{average} - 1\right)^2}{n}}\right] \tag{3}$$

$X_i$ is the number of fibers in the $i$th image, $X_{average}$ is the average number of fibers in all images, and $n$ is the number of images.

In all of the three expressions, the fiber distribution is more homogeneous when the fiber distribution coefficient is closer to 1. When the fiber distribution coefficient is close to 0, the fiber dispersion becomes more inhomogeneous. Among these three equations, Eq. (1) [24–27]and Eq. (3) are divided according to the processed images. The greater number of images can result in more accurate analysis but the workload will also increase significantly. Therefore, selection of an appropriate number of images for analysis should be done according to the actual situation need. According to Torigoe et al. [25] based on the correlation and trend of the obtained fiber distribution coefficients, it was determined that 270 cell divisions was ideal. The dispersion result of different units of 13 mm × 30 mm section was investigated and it can be found that the tendency in the distribution coefficient between the specimens with a number of units between 56 and 270 are the same. Despite the 5 times difference in the number of units, the distribution coefficient trends between the specimens were identical. Therefore, the preferable number of units is between 56 and 270. Keeping all other conditions constant, the 56 division unit is the most sensitive. However, a large deviations in the number of fibers will occurred by considering edges or boundaries in the cross sectional images. Therefore, the 270 division unit is more suitable. In addition, such deviation would seriously affect the distribution coefficient in the case of a smaller number of units. The Eq. (2) deals with the images based on the total number of fibers in the image. When the fiber distribution is absolutely uniform, each individual unit has a fiber. Theoretically, a large number of cells can make the value of the resulting fiber distribution coefficient more effective. Therefore, when the number of divided units is small, the influence of the wall of the mould and other factors on the fiber dispersion effect may be neglected.

The orientation of the fiber in FRCs has a great effect on the mechanical properties [28,32]. The fiber orientation coefficient indicates the fiber and specimen axis between the cosine of the angle and is shown in Fig. 1 and Eq. (4) [30].

$$\cos\theta = \frac{d}{l} \tag{4}$$