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Aligning steel fibers in cement mortar using electro-magnetic field

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HIGHLIGHTS

- A detailed approach of aligning steel fibers in cement mortar using magnetic field was presented.
- Necessary magnetic induction of magnetic field and workability of fresh mortar for aligning steel fiber were suggested.
- X-ray CT test results showed that the steel fibers in hardened mortar was highly aligned.
- Aligned steel fibers significantly increase the efficiency of reinforcement on mortar.

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ABSTRACT

An approach of aligning steel fibers in cement mortar using external uniform electromagnetic field is presented, which is the rotating process of steel fiber driven by magnetic force to overcome the viscous impeding of the mortar. Using the approach, the aligned steel fiber reinforced cement mortar (ASFRC) is prepared. Then the orientation distribution of the steel fibers in ASFRC is measured by X-CT image analysis. The results show that the orientation efficiency factor of the steel fibers in ASFRC reaches around 0.90, while that of ordinary steel fiber reinforced cement mortar (SFRC) is around 0.50. Also, the splitting tensile strength, flexural strength and toughness of the ASFRC are tested. The test results show that, compared with SFRC, the splitting tensile strength and flexural strength of ASFRC increase up to more than 100%, which is attributed to the increase in reinforcing efficiency of aligned steel fibers.

1. Introduction

Concrete, known as a brittle composite, has high compressive strength but low tensile strength. Therefore, concrete is vulnerable to crack once subjected to tension, which often leads to the deterioration or even damage of concrete structures. To overcome these problems, incorporation of fibers into concrete is an effective approach to increase its performance in tension and prevent cracking [1–4]. Various fibers can be used to strengthen the concrete, such as asbestos, steel, glass, carbon, Kevlar, polypropylene, nylon, cellulose, sisal, etc. [5–8]. Steel fiber is still one of the commonly used fibers to improve the tensile properties of hardened concrete. In ordinary steel fiber reinforced concrete, short steel fibers are randomly dispersed, which means that the fibers have random location and orientation. The previous theoretical and experimental studies in the literature [9–12] demonstrated that fiber orientation has significant influence on the efficiency of reinforcement of the steel fibers. The orientation efficiency factor, η_θ, defined as the ratio between the reinforcement of short inclined fibers and the reinforcement of continuous fibers aligned to the load, is used to indicate the efficiency of reinforcement of fibers. According to the definition, the orientation efficiency factor of the fibers aligned to the load is 1.0, and that perpendicular to the load is 0. The inclined fibers have the orientation efficiency factor between 1.0 and 0. The theoretic analysis results show that the orientation efficiency factor of the randomly distributed steel fibers in concrete is 0.405 [13], while that from the tests of ordinary steel fiber reinforced concrete is in the range of 1/6 to ½ [14–16]. Obviously, if the orientation of short steel fibers in concrete elements can be aligned to parallel to the tensile stress of the elements, the orientation efficiency factor will increase significantly and the tensile performance of the concrete will be improved greatly. Several attempts have been made to control the steel fibers with orientation in a certain range in concrete. Bayer [17] and Arman [18] have proposed aligning steel fibers in concrete magnetically. Yamamoto et al. [19] have tried to disperse steel fibers with regular orientation in concrete by keeping the fresh concrete flowing into formwork from

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a fixed direction. Xu [20] has reported a steel fiber reinforced shotcrete with all steel fibers aligned to the axis of the structural element prepared by spraying steel fibers using a special machine. Rotondo and Wiener [21] have manufactured the aligned long steel fiber reinforced concrete poles by centrifugally casting.

From these attempts, it is seen that though the aligned steel fiber reinforced concrete has been successfully prepared, the approach and mechanism of aligning short steel fibers in concrete should be clarified, which is important for the regular application of aligned steel fiber reinforced concrete. In this investigation, the process of aligning steel fibers in fresh cement-based materials using electromagnetic field was analyzed and tested. For the sake of simplification, aligned steel fiber reinforced cement mortar (ASFRC) without coarse aggregate was concerned in this investigation. The methodology can also be extended to concrete with coarse aggregate.

2. Aligning steel fibers in cement mortar

2.1. Working principles

The orientation of steel fibers in fresh cement mortar can be changed and controlled if an external electromagnetic field is applied, based on the principle of magnetism. In a uniform magnetic field, a steel fiber always tends to rotate to have the same direction as the magnetic field due to the driving of magnetic force. Therefore, if the direction of the magnetic field is the same as that of the tensile stress in concrete, the steel fibers in the concrete can be aligned to the direction of the tensile stress and the maximum reinforcing efficiency can be achieved. The results of trial tests confirmed that the steel fibers can be effectively aligned in either fresh mortar or concrete. In the aligning process, the steel fibers, made of ferromagnetic material, are magnetized by the external magnetic field. The two ends of each magnetized fiber are the north and south poles, respectively. In a magnetic field, the fiber magnet is subjected to the action of a pair of forces on its two poles. The magnetic forces of the pair are the same in magnitude but opposite in direction, and drive the magnet (steel fibers in this study), which behaves just like a compass, rotating to the direction of the external magnetic field.

The induction intensity of the magnetic field to align the steel fibers should be uniform in the region of the fresh cement mortar. Otherwise, the steel fibers may be attracted and concentrated at the place where the induction of the magnetic field is higher.

2.2. Experiment setup

A series of electromagnetic setup with different size was developed to providing uniform magnetic field. The largest setup provides a uniform magnetic chamber with size 300 mm × 300 mm × 1000 mm and is suitable to prepare prisms with maximum size 250 mm × 250 mm × 1000 mm while the smallest one can be used to prepare prisms 20 mm × 20 mm × 80 mm. The setup is mainly composed of a square solenoid coil looped around with empty interior chamber, which is mounted on a vibrating table (see Fig. 1). The vibrating table is used to compact fresh mortar during sample preparation. When the power is turned on, a current in the solenoid creates a uniform magnetic field that controls the orientation of steel fibers in fresh mortar. The magnetic field with the direction same as the axis of the solenoid loop forces the steel fibers to be re-oriented and align with the axis of the coil loop. At the outside of the solenoid loop an insulating layer is applied to protect the coil and avoid the direct touch of the coil in working.

2.3. Aligning steel fibers

The steel fibers in fresh mortar are subjected to the following forces: magnetic force, gravity, buoyancy, and viscous resistance during the aligning rotating. The gravity and buoyancy are in vertical direction and have no influence on the rotating of the steel fibers. To align the steel fibers in cement mortar, the magnetic force must be large enough to overcome the viscous resistance.

The action of all the forces on a single fiber is shown in Fig. 2 [22]. All these forces are distributed forces. However, the gravity and buoyancy are simplified as concentrated forces acted on the center of gravity of the fiber in the figure. Both the magnetic force and viscous resistance on the steel fiber are torque couples, which drives and impedes the rotating of the steel fiber, respectively. Regardless of the vertical movement of the steel fiber that is mainly influenced by gravity and buoyancy, the aligning of the steel fiber can be analyzed as below.

According to the electromagnetism [23], the distributed magnetic force acting on a steel fiber can be calculated using Eq. (1).

$$f_m = \frac{\mu - 1}{2\mu_0 \mu l_f} B^2 A_f \tag{1}$$

where f_m is the distributed magnetic force acting on a steel fiber (N/m), A_f is the cross-section area of the fiber (m^2), B is the magnetic induction (N/A·m), l_f is the length of the fiber (m), μ is the relative permeability (–) and μ_0 is the vacuum permeability (N/A^2). Usually, $\mu_0 = 1.256 \times 10^{-6}\ N/A^2$.

According to Eq. (1), when the geometry of the fiber is fixed, the distributed magnetic force depends on the induction of the magnetic field.

Then the moment of magnetic force, M_m, can be computed using Eq. (2).

$$M_m = \int_0^l \frac{(\mu - 1) B^2 A_f \ \cos\varphi(t)}{\mu \mu_0} \cdot \ dx \tag{2}$$

where M_m is moment of magnetic force (N·m), $\varphi(t)$ is rotation angle of the fiber at time t (rad) and x is distance of an arbitrary point on the fiber to the fiber end (m).

The viscous force acting on the steel fiber is also a distributed force and can be calculated using Eq. (3).

$$f_r = C_D \rho \frac{v^2}{2} \quad A_f = C_D \rho \frac{(\omega(t) r_f)^2}{2} A_f \tag{3}$$

where f_r is the viscous force (N/m), ρ is the density of cement matrix (kg/m^3), r_f is rotating radius (half length) of the fiber (m), v is the relative speed between fiber and matrix (m/s), $\omega(t)$ is the angular velocity of the fiber rotating (rad/s) and C_D is the resistance coefficient (–).

From Eq. (3), it can be seen that if the coefficients of the steel fiber (length, diameter and initial velocity) and the density of cement matrix are known, the viscous force is mainly influenced by the viscosity of the mortar. The viscosity of mortar mainly depends on its workability.

Then the moment of viscous force, M_R, can be computed using Eq. (4).

$$M_R = 2 \int_0^{1/2} C_D \frac{A_f \rho (\omega(t) \cdot r_f)}{2} \cdot x dx \tag{4}$$

If the driving moment from magnetic force, M_m, is greater than the impeding moment from viscous force, M_R, the steel fiber will be able to rotate and get aligned. The greater the magnetic force moment M_m and the less the viscous force moment M_R, the easier the aligning of steel fibers in fresh mortar. Substituting the parameters of the steel fiber (will be given in next section in detail) used in this investigation into Eqs. (2) and (4), the induction of the