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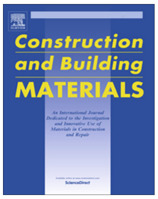

Alignment of hooked-end fibres in matrices with similar rheological behaviour to cementitious composites through homogeneous magnetic fields

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HIGHLIGHTS

- Static yield torque is a main key factor to induce initial rotation on fibres.
- HMF generate a magnetic torque on steel fibres to align them.
- The magnetisation of the fibres indicates a magnetic response to initiate rotation.
- A novel way to measure the yield torque per fibre using a rotational rheometer is shown.
- Fibres with perpendicular angle to the magnetic field direction can be aligned easier.

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ABSTRACT

The following study aim is to analyse the parameters affecting the alignment of hooked-end steel fibres (HSF) in fluid matrices with Yield Stress (τ_o), using homogeneous magnetic fields as a main source to modify their orientation. HSF are commonly used as reinforcement in composites in the construction industry, mainly in cementitious materials which also show τ_o. The parameters studied here are: on one hand those referring to the rheological properties of the matrix, mainly τ_o, and on the other hand those associated to the HSF: aspect ratio, geometry and magnetic dipole moment (μ_f). To do so, a homogenous Magnetic Field (MF) with controlled strength and time pulse was used to induce a torque to the HSF and hence to control their orientation by mean of turning fibres. The source to obtain the MF was designed to reach up to 10 mTeslas, using a Helmholtz coil of 10.5 cm radius.

The results obtained here assess how a MF with intensities adjusted to a known τ_o of a matrix can induce fibres orientation. Some steel fibre parameters such as geometry (specially length) and mass, affect considerably the total induced torque needed to rotate the fibres, and hence to align them in a matrix. Besides, rheological parameters can be also adjusted to achieve the fibre alignment, as well as the magnetic pulse shape and the magnetic field peak intensity.

1. Introduction

Matrices used in composites can show a different rheological behaviour during manufacturing and casting, before the final hardening of the product [6]. The importance of the behaviour of the matrix in fluid state is crucial for the manufacture of a composite, specially when it is reinforced. Many binders used in the industry present an elastic response in the fluid state, showing an opposition to flow before flowing as a liquid [37]. This elastic response is known as yield stress (τ_o), and it can be, for example, caused by a network formed by agglomerated particles in a cementitious material or by a complex network of large chains which form a polymer structure [30]. Some concrete rheological parameters are theoretically previously determined by authors such as Mechtcherine and Shyshko [24] and Chidiac and Mahmoodzadeh [7].

Addition of fibres is commonly used to improve the mechanical performance of a composite material in the hardened state.

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Industrial fibres used in the industry can have different geometries and be manufactured with different materials depending on the desired application [38]. In the cement industry the use of hooked-end fibres (HEF) has become very popular for example in Ultra High Performance Concrete (UHPC) [8,18].

Moreover, in many industrial applications, the directional control of the fibres used as reinforcement can improve the mechanical properties of the cementitious composites, to have stronger non-isotropic construction materials [35,38]. Several aligning methods have been studied as a general framework by Laranjeira de Oliveira [22], and the mechanical enhancement due to preferential orientation of fibres in Self Compacting Fibre Reinforced Concrete (SFRC) has been determined in Gram [12].

Several constructive processes can modify the orientation of fibres. The way concrete is poured into a formwork has a major impact on fibres orientation [22]. Vibration applied in a fresh concrete also can rotate fibres in planar orientations [16]. Moreover, the flow of fresh concrete through pipes has also been identified as a key factor on fibre alignment [13]. The first cases of steel fibre alignment using electric fields in composites was described in 1980's decade by Knoblach [21].

Magnetic fields to align fibres has also been used is composite manufactures. The first innovative contribution to magnetic fibre alignment in composites was done by Shine and Armstrong [31], who studied how nickel cylinders with different aspect ratios (length/diameter) ranging from 5 to 40 rotate in a Newtonian fluid. The feasibility of orientation control, using a short fibre composite radiated with magnetic fields, was carried out with a paramagnetic short fibre coated with ferromagnetic substance (nickel) by [14,35] proved rotating and translating fibres so that they become aligned with the magnetic lines of force.

The first aligning device used in fresh concrete was patented by West et al. [37] as a magnetic device which is placed in a fin dragged through the concrete during screeding operations in slab fabrication (based on [32] US Patent). An experimental approach to prepare aligned steel fibre reinforced cement mortar (ASFRC) by an external uniform magnetic field of 0.15 mT was presented recently by [26]. However, this alignment method was combined with a vibrational device -in this case a shaking table - during a period of time of one minute. These experiments showed that the flexural and splitting tensile strength of aligned steel fibre reinforced cement mortar is higher once the mortar is radiated.

Alternating Magnetic Field (AMF) has been also used to enhance the compressive strength of plain concrete, [1]. The AMF had an intensity of 0.5 Tesla (T) and a frequency of 50 Hz, radiating ready mixed and hardened concrete. Its compressive strength improves up to 7.78 %, which implies an increases orientation factor in fibres.

Related also to magnetic alignment, Kloft and Ledderose [20] presented a magnet-controlled rearrangement of steel fibres added to UHPFRC (Ultra-High Performance Fibre-Reinforced Concrete). Reinforcement of composites with magnetic Short-Fe-fibre with different distribution patterns and fibre orientation have been studied [35,36]. Moreover, based on reinforced alignment, some authors such as Martin et al. [23], opened a new concept called *3D magnetic printing* used as bioinspired architecture.

In this work, the use of homogeneous magnetic fields to improve fibre alignment has been studied in matrices with τ_o. Hooked-end fibres with different aspect ratios and immersed in different matrices have been orientated to a magnetic field direction, and the enhancement of the orientation factor has been determined. From the results obtained, an assessment of the fibre orientation has been done, highlighting those factors that were more useful to increase the success of fibre alignment. This study is interesting for many other composites where fibre orientation is a main goal.

2. Theoretical case

The yield stress of a composite matrix which binders is very strong and properly prevents the initial rotation of fibres within the mixture. Once the fibre is rotating, due to an external torque, other viscoplastic effects (e.g. plastic viscosity) must be also overcome [33,7].

Literature agree to assess the rheological behaviour of mortars and pastes under the so called Bingham law [2,4,12]. The law can be formulated in terms of torque units as follows:

$$T_R(\omega) = T_o + S\omega \qquad \textit{if} \quad T_R \geqslant T_o \tag{1}$$

where ω is the angular velocity of the rotating cement/paste. The relationship between the torque and angular velocity is plotted and the intercept at zero-torque rate considered as the dynamic *yield torque* T_o (N·mm), while the slope S (N·mm/min) is the *viscoplastic torque*. Relationship between yield tress and yield torque was studied by Flatt et al. [11].

Rotational rheometers can measure torque (T_R) in binders which following approximately the Bingham expression (see Bingham equation (1)), as other researchers already previously found [3,25]. Calibration procedures for specific rheometers can translate the torque measurements to shear stresses, defining a relation between $\tau_o \simeq T_o$ (See [25] for details).

When a fibre immersed in a binder, it turns and is summited to several forces opposed to its rotation. The steel fibre yield torque (T_o^f) is the macroscopic result of forces caused by the intergranular friction in the matrix before the fluid can be sheared by the fibre, as long as the matrix behaves as a solid. Moreover, plastic viscosity torque S^f is the opposition of the fibre to turn around while it is shearing the matrix which behaves such as a fluid. To check the fibre rotation due to homogenous magnetic fields, the yield torque T_o^f must be overcome to initiate the rotation. Once the fibre is turning, the dynamical behaviour of fibres are held by the viscoplastic torque S^f.

In this research, the steel fibres are exerted to rotate due to the existence of an external homogenous magnetic field; the magnetic torque contribution $\vec{T}_M$ is the driving action able to rotate the steel fibre against the fibre yield torque (T_o^f). The magnetic torque has a formal expression:

$$\|\vec{T}_M\| = \|\vec{\mu}_f \times \vec{B}(t)\| = \|\vec{\mu}_f\|\,\|\vec{B}(t)\|\,\sin\theta \tag{2}$$

where $\vec{\mu}_f$ is the dipole magnetic moment due to the fibre magnetisation, and $\vec{B}(t)$ is the magnetic field intensity. The angle θ is the orientation between the fibre dipole magnetic moment and the external field at this point.

This external driving action is always opposed by the existence of resistive rheological torque (T_R). Finally, the fibre moment of inertia T_I always is opposed to the external turn driving action caused by the magnetic torque. All of these three torques must satisfy the following equilibrium equation:

$$\underbrace{\|\vec{\mu}_f\|\,\|\vec{B}(t)\|\,\sin\theta}_{\text{Magnetic T.}} \approx \underbrace{T_o^f + S^f\,\dot{\theta}}_{\text{Rheological T.}} + \underbrace{I\ddot{\theta}}_{\text{Inertial T.}} \tag{3}$$

The value $\theta(t)$ is the angle obtained between the magnetic torque and the magnetic field in their center of gravity. The moment of force needed to rotate the fibre is considered from its edges to its center of gravity (CG), so the CG is the pivot point [34]. The value of I correspond to the inertial moment respect to the axis of rotation passing by the fibre center of gravity. Other terms in Eq. (3), such as inertial moment ($I\ddot{\theta}$) are neglected form this expression because the order of moment of inertia (I) of one fibre is 10^{-8} kg·m^2.