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Set-on-demand concrete

Sriramya Duddukuri Nair [a], Raissa Douglas Ferron [b,*]

[a] The University of Texas at Austin, United States
[b] The University of Texas at Austin, CAEE-STR, 301 East Dean Keaton Street, C1748, Austin, TX 78712, United States

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ABSTRACT

The ability to control the fresh-state properties of concrete in real-time provides the user greater control over processing and placing of concrete. Based on the principles of magnetorheology, a smart cement-based material system has been developed wherein magnetic particles are added and an external magnetic field is applied to control the fresh-state properties of concrete. Rheological tests were conducted on paste mixtures containing magnetic particles and when a magnetic field was applied, it was determined that the shear resistance of the paste could be altered significantly. The response of the paste was found to be dependent on the magnetic field strength and the concentration of the magnetic particles. Furthermore the magnetic particles used did not have any effect on cement hydration products or on compressive strength results. Such a material can be useful in applications in which controlling the fresh-state behavior of concrete is critical.

1. Introduction

Today's concrete is no longer a simple combination of cement, aggregates and water. With increased use of various types of supplementary cementing materials and chemical admixtures, material incompatibility problems have been observed in concrete construction [1–4]. As a result, some of the greatest problems in concrete manufacturing occur when concrete does not stiffen, set or harden on time [3]. However, what if it were possible to create a concrete in which the contractor is able to control in real-time its stiffening/setting behavior? Cement-based magnetorheological (MR) fluids can potentially be used in civil engineering applications to act as a "set-on-demand" material, allowing the user greater control over the processing (e.g. mixing, pumping, and placing) of concrete. MR fluids undergo large, reversible and fast changes in their rheological properties when subjected to an external magnetic field. Jacob Rabinow first discovered MR fluids in 1948 [5]. MR fluids typically consist of micrometer sized magnetic particles that are suspended in a carrier fluid. As very few elements possess ferromagnetic properties, the particles used are limited to iron and iron based materials. In the presence of a magnetic field, the magnetic dipoles of these particles align along the magnetic field lines and the response time of MR fluids is generally within a few tens of milliseconds [6]. The interaction between the dipoles causes the particles to form columnar structures, parallel to the applied field (see Fig. 1). These chain-like structures restrict the motion of the fluid, thereby increasing the solid-like characteristics of the suspension. The mechanical energy needed to yield these chain-like structures increases as the applied field increases resulting in a field dependent yield stress.

A detailed review of properties and applications of MR fluids has been published elsewhere [7–11]. Although MR fluids are not common in civil engineering applications, they have been used in a variety of areas, such as automotive clutches [5], cancer treatment [12], drilling fluids [13], body armor [14], gun recoil system [15], precision polishing [16], prosthetic knee dampers [17], seat dampers, fluid brakes, vibration damper [18], and seismic vibration control [19]. In such applications, a magnetic field can be generated by passing current through an electric coil or through the use of permanent magnets. The magnetic field generated through an electric coil can be altered in real time by varying the magnitude of applied current. This is beneficial in applications where different levels of magnetic field would be required at different periods of time. However, at high levels of applied current (or in other words, high levels of magnetic field), the electric coils have to be cooled to counteract the heat that is produced. On the contrary permanent magnets generate a constant magnetic field without the use of electricity and also without the generation of any heat. In addition, permanent magnets can be manufactured in any desired shape and size [20–23]. Similar to the set-ups used in the above-mentioned applications [12–19], a set-up consisting of electric coils or permanent magnetics could be used for generation of magnetic fields in-situ for cement-based materials. It is envisioned that cement-based magnetorheological fluids can potentially be used in applications to act as a "set-on-demand" material, allowing the user greater control over the processing (e.g. casting and pumping) of concrete. Such a material can be useful in civil engineering applications such as:

- drilled shaft construction of bridges
- formwork pressure reduction of self-consolidating concrete;

* Corresponding author. Tel.: +1 512 232 2691; fax: +1 512 471 7259.
E-mail addresses: sriramya@utexas.edu (S.D. Nair), rferron@mail.utexas.edu (R.D. Ferron).

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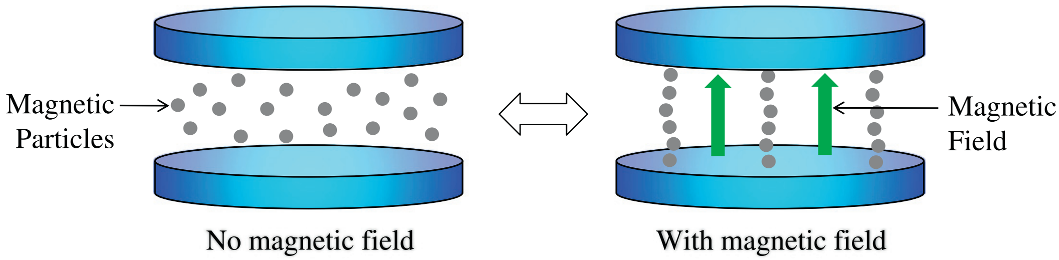

Fig. 1. Schematic showing the response of an MR fluid to an external magnetic field.

- casting of narrow channels or long casting distances;
- improving segregation resistance of aggregates in concrete;
- to avoid sloughing or slumping of shotcrete from its receiving surface.

Traditionally in MR fluids, Newtonian carrier liquids, such as mineral oil, synthetic oil, water or ethylene glycol, are used to suspend the magnetic particles. The viscosities of these carrier liquids generally range from 0.2 to 0.3 Pa s at 25 °C [11]. As such, when a magnetic field is applied the transformation in the material from a liquid-like to a solid-like material is amplified. However, the lack of yield stress and the low viscosity of these Newtonian carrier liquids, as well as the differences in density between the magnetic particles and the carrier fluids, typically make particle sedimentation a major concern in MR fluids. While reducing the size of the magnetic particles has been shown to reduce sedimentation, using smaller particles usually leads to a reduction in the yield stress of the field-induced fluid [24,25]. Other approaches to increasing sedimentation resistance in MR fluids are to use additives, such as stabilizing additives, thixotropic additives [26] and nano-scale particles [27–29], or by choosing a carrier fluid with a yield stress [30]. Cement paste, mortar and concrete have been characterized as being yield stress fluids [31–33], and they are typically modeled as a Bingham fluid [34]. This inherent yield stress of cement-based suspensions can be beneficial in minimizing sedimentation of the magnetic particles.

The research presented in this paper presents an innovative approach to control the fresh state performance of cementing operations. Through better control of fresh state properties the quality and durability of the cementing operations can be improved [35]. The aim of the current research was (a) to investigate the viscoelastic behavior of cement-based MR fluids over time and (b) to evaluate the influence of magnetic particles and magnetic field on cement hydration. In a traditional MR fluid, the dosage of magnetic particles generally varies from 40% to 50% of the fluid volume [36]. A unique aspect of this work is the use of small dosages of magnetic particles (less than 5% of paste volume) to investigate the changes in rheological properties with application of magnetic field. The dosages were kept to a minimum to maximize cementitious content and to minimize increase in cost.

2. Materials and methods

2.1. Materials

2.1.1. Material composition

An American Petroleum Institute (API) class A oil well cement [37] (comparable to a ASTM Type I Portland cement [38]) was used in this study. The Blaine fineness of the cement was 307 m^2/kg and details regarding the chemical composition of the cement can be found in Table 1. All pastes were prepared using deionized water. The water to cement ratio of all the samples was 0.4 (by mass). Two grades of carbonyl iron powder (CIP), CM and SM were obtained from BASF. CM contains a minimum of 99.5% iron and SM contains a minimum of 99% iron. Hereupon the CM grade of the CIP will be referred to as *CIP*, and the SM grade of the CIP will be referred to as *CIP*(*sm*). Carbonyl iron powder is the most commonly used magnetic particles for MR applications because of its high saturation magnetization. The carbonyl iron powder was added on an addition basis, based on the mass of cement. Glenium 3400 NV (supplied by BASF) polycarboxylate-based high-range water reducer (HRWR) was used in three samples to evaluate the effect of yield stress of the cement paste on the MR properties after application of magnetic field. The smallest recommended dosage (130 ml/100 kg of cement) of HRWR was used. The mix proportions of all the samples are shown in Table 2.

2.1.2. Size and shape of particles

A Mastersizer 2000 particle size analyzer with a Hydro MU 2000 (Malvern, Worcestershire, United Kingdom) wet dispersion unit was used to measure the particle size distributions of *cement*, *CIP* and *CIP*(*sm*) magnetic particles (see Fig. 2). The data shown in Fig. 2 is based on the average of five measurements for each sample. A refractive index of 1.7 and absorption of 1.0 were used for cement based on the values found in literature [40]. In order to prevent hydration of the cement particles, the cement particles were dispersed in isopropyl alcohol (IPA). A refractive index of 1.39 was used for the IPA [41]. For the *CIP* magnetic particles, a refractive index of 1.51 [40] and absorption of 0.1 were used. Using an absorption value of 0.1, the residual weighted particle size distribution calculated by the Mastersizer software was less than 1, indicating the proper choice of the value. The *CIP* and *CIP*(*sm*) magnetic particles were dispersed in water; and a refractive index of 1.33 was used for water [41]. Prior to measuring the particle size distribution, the particles were recirculated at a pump speed of 2000 rpm and sonicated with an ultrasonic probe (at 10 μm of tip displacement) for 30 s. During testing the sample was recirculated in the particle size analyzer at a pump speed of 2000 rpm with no ultrasonication. From Fig. 2, it can be seen that for *cement* particles the d_{50} (where 50% of the total powder volume consists of particles with effective diameter less than that diameter) was found to be 23.3 μm. For *CIP* magnetic particles, the d_{50} was determined as 8.7 μm and for *CIP*(*sm*), the d_{50} was determined as 3.3 μm.

JSM 6490-LV Scanning Electron Microscope (JEOL Ltd., USA) was used to image the shape of the particles. The accelerating voltage was kept at 20 kV while the working distance was held constant at 9–11 mm at various magnifications. From Fig. 3 it can be seen that the *CIP* and *CIP*(*sm*) magnetic particles were mostly spherical in shape.

Table 1
Composition of cement [39].

Chemical composition	Percentage by mass
Calcium oxide (CaO)	64.8
Silica dioxide (SiO_2)	20.2
Aluminum oxide (Al_2O_3)	5.3
Ferric oxide (Fe_2O_3)	2.7
Magnesium oxide (MgO)	1.1
Sulfur trioxide (SO_3)	3.3
Na_2O_{eq}	0.75
Loss on Ignition (LOI)	2.6
Insoluble Residue (IR)	0.6
Tricalcium silicate (C_3S)	58
Dicalcium silicate (C_2S)	13
Tricalcium aluminate (C_3A)	9