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Vibration of fresh concrete understood through the paradigm of granular physics

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ABSTRACT

Fresh concrete is often cited as an example of a yield-stress fluid, typically being modeled as a Bingham material. We describe how this is an incomplete understanding to rationalize simple but important flow behaviors. As a motivating phenomenon, we consider the practice of vibrating fresh concrete during placement to induce flow and remove air voids. It is demonstrated that a simple yield-stress fluid (an aqueous polymer microgel particle suspension, Carbopol) cannot recreate the phenomenon, falsifying the hypothesis that traditional yield-stress fluid models embody the key physics. However, a granular hard-particle suspension (millimetric glass beads in silicone oil) does recreate the phenomenon. We use shear rheology to further show that concrete displays noticeable granular physics as indicated by vibration-induced loss of the yield stress, consistent with the granular constitutive model of Hanotin et al. (2015). These results have implications for understanding the unseen phenomenon of air bubbles rising in concrete.

1. Introduction

Fresh concrete is commonly vibrated when placed to remove entrapped air voids. However, entrained air bubbles are often purposely introduced to improve the resistance of concrete to damage from freeze-thaw cycles [1]. Standard practice for air entrainment has established the necessary air volume and spacing to avoid damage [2], but the physics underlying bubble motion, especially during vibration, is presently not well-understood. Importantly, the vibration applied to consolidate concrete and remove large air voids may also be removing the small air bubbles that provide freeze-thaw resistance.

Due to the opacity of concrete, direct observation of air bubble motion is impossible. Instead, the freeze-thaw durability, as it relates to the distribution of air bubbles in concrete, is typically quantified via observation of hardened, polished samples in accordance with ASTM C457/C457M-12, or via a recently proposed two-dimensional scanning technique [3]. These standard visualization approaches require preparation of numerous samples – one for each set of vibration parameters – and bubble motion phenomena cannot be directly observed, only inferred. A potentially useful approach to understanding bubble motion in fresh concrete is to find a surrogate material that replicates the relevant physics of concrete during vibration while being transparent. A surrogate-material approach has been used to understand other phenomenon, for example the reorientation of fiber-reinforcement during the flow of concrete [4]. Should a suitable surrogate material be identified, air motion could be observed in real time, and it would allow us to test the effects of material parameters, vibration amplitude and frequency, probe and form geometry, and distance from the vibration source.

The Bingham model permeates the literature of modeling the rheology of fresh concrete, mortar, and cement paste [5-8]. The one-dimensional version of the constitutive model,

$$\tau = \tau_y + \mu_p \dot{\gamma} \tag{1}$$

relates the shear stress (τ) to the shear rate ($\dot{\gamma}$) with two material parameters: the yield stress (τ_y) and the plastic viscosity (μ_p). If the applied stresses are less than the yield stress ($\tau \leq \tau_y$) the material maintains solid-like behavior; if the yield stress is exceeded ($\tau > \tau_y$) the material will flow. An important consequence of this behavior is that a density-mismatched particle (e.g., an air bubble) can be suspended indefinitely in a yield-stress fluid if the stress induced by buoyancy is smaller than the yield stress.

While the categorization of concrete as a yield-stress fluid is uncontroversial, there is not a widely accepted fundamental understanding of the effect of vibration on fresh concrete. L'Hermite did early work in this area, noting that vibration reduced "internal friction" from

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0.02 MPa to 0.001 MPa [9]. Tattersall and Baker [7] and Pichler et al. [10] characterized the rheology of vibrated concrete more thoroughly, noting that the stress/shear-rate relationship of concrete adopted power law-like behavior during vibration. Notably, this implies the yield stress is eliminated when vibration of sufficient strength is applied. Conversely, Hu and de Larrard [6] made rheological measurements of concrete during vibration and noted that it keeps a yield stress during vibration, though it is about half the yield stress measured without vibration. An explanation of the physical mechanism that causes the reduction/elimination in yield stress is absent, but dilatancy, a granular phenomenon, was noted. Banfill et al. [8] developed a two-dimensional (cylindrical) theory to describe the response of concrete to probe vibration, with particular attention to the radius of action: the horizontal distance to which a vibrating probe influences the concrete. The radius of action is modeled based on the imposed stress at the vibrating probe and the yield stress of the concrete, and implicit is the assumption that the effect of the probe is uniform with depth.

The objective of this work is to develop a fundamental understanding of how vibration affects the rheology of fresh concrete. The present understanding of concrete rheology, using the Bingham model, has provided an adequate means of discussing and comparing the rheology of different concrete designs. However, it will be shown that it fails to explain how concrete responds to vibration. We will propose an understanding of the mechanism that relies on granular physics. Concrete has been acknowledged to be a granular material in the literature [11-13], including in flow applications [14-20]. However, these works universally refer to "the" yield stress of the concrete, ignoring important features/phenomena of granular materials, such as a yield stress that increases with depth [21-23] and fluidization [24-26]. It will be shown that concrete cannot be considered a simple yield-stress fluid and instead should be modeled as a granular material.

2. Materials and methods

2.1. Description of concrete and surrogate materials

The mix designs for the two concretes used in this work are detailed in Table 1. The first was "conventional," batched using Type I Portland cement, potable city water, crushed limestone aggregate, and river sand. The coarse aggregate met a CA07 gradation pursuant to the Illinois Department of Transportation (nominal max size 25 mm, specific gravity 2.75), while the sand met an FA02 gradation (nominal max size 4.75 mm, specific gravity 2.63). The water-to-cementitious (w/cm) ratio (by mass) of the mixture was 0.40, and a nominal 2.7 mL of Sika Viscocrete 2100 high-range water reducing (HRWR) chemical admixture was added per kg of cement to achieve adequate workability. Lastly, a small dosage of Sika 14 air-entraining admixture (AEA) was added in order to increase the number of 10-micron-sized air bubbles. This concrete mixture (Fig. 1 (a)) has slump of 4–6 in (10–15 cm) pursuant to ASTM C143. An image of a polished cross-section with highlighted air content, as per the treatment of [3], can be found in the Appendix, Fig. A.11.

The second concrete mix was a "high-flow" concrete, notably with water-to-cementitious ratio of 0.30 and 5.2 mL of high-range water reducing chemical admixture added per kg of cement. The slump flow of this concrete has a nominal spread of 20 in (51 cm) or greater pursuant to ASTM C1611. The target air content for both concretes is 8%.

Solutions of Carbopol 980 in water (hereafter referred to as "Carbopol") at concentrations from 0.15 wt% to 1.0 wt%, neutralized by aqueous NaOH, were chosen as surrogates for simple yield-stress materials. Carbopol is often used as a model yield-stress fluid [27-29] with precedence as a model material in studying yield-stress flow phenomena [30-32], including some studies of concrete [4]. It has the benefit of being transparent, allowing for observation of air void/bubble motion as the fluid is vibrated (Fig. 1 (b)).

A surrogate wet granular material was created by mixing 100 cSt silicone oil (a Newtonian fluid with dynamic viscosity of 0.096 Pa·s) with approximately monodisperse spherical glass beads of 1.20 ± 0.07 mm diameter. Because the beads are denser than the silicone oil they sink to form a bed of spheres with direct grain-to-grain contact. The system, when backlit, is translucent (Fig. 1 (c)).

Table 1
Mix design for conventional and high-flow concrete.

	Conventional concrete	High-flow concrete
Type III Portland Cement (SG = 3.15)	400 kg/m^3	426 kg/m^3
#7 aggregate (SG = 2.75)	1160 kg/m^3	1237 kg/m^3
#2 sand (SG = 2.63)	700 kg/m^3	746 kg/m^3
Water	160 kg/m^3	128 kg/m^3
Sika AEA-14	0.98 mL/kg cement	0.98 mL/kg cement
Sika Viscocrete 2100 HRWR	2.7 mL/kg cement	5.2 mL/kg cement
Water-to-cement ratio	0.40	0.30

2.2. Rheological measurements and vibration environments

Experiments on air void removal were performed in concrete using an industry-standard DeWalt vibration probe: a cylinder with a diameter of 2.9 cm and a rotation speed of 14,000 rpm. For the surrogate materials, a lab-scale probe was built (Fig. 2 (a), additional details in the Appendix) which replicates the kinematics of a concrete vibration probe, though the exact working mechanism is not the same. The lab-scale probe was a 1.9 cm-diameter PVC cylinder with a channel cut along the center of its length. A metal bar was inserted into the channel and connected to a Dayton 150 W, maximum 10,000 rpm motor via a 0.13 cm offset coupling, ostensibly creating a vibrating motion with 0.13 cm amplitude. The motor rested on a square frame, and its output was not rigidly connected to the probe. Instead, the probe was attached via an elastomer to the frame, and it was guided by the offset interior bar as the motor rotated. Such a connection prevents drill-like motion, which is not a feature of most industrial probes. Rather, the probe translates along a circular path, i.e., in a wobbling or orbital motion. The motor frequency was controlled with a voltage controller – a spectrum of speeds up to approximately 4000 rpm was tested. The associated containing vessel was a transparent acrylic box, with inner dimensions 13 cm tall, 13 cm wide, and 3.2 cm thick.

Rheological measurements of the concretes were made using an ICAR (International Center for Aggregate Research) concrete rheometer [33] (Fig. 2 (b)). The probe geometry was a vane 12.7 cm long with a 12.7 cm diameter, and the containing vessel was a scalloped bucket with 28.6 cm diameter. The vibrating environment for concrete was created using a concrete shaker table with a measured oscillation frequency of 60 Hz and amplitude of approximately 1 mm. The rheometer bucket was placed on the shaker, and the measurement geometry and motor were isolated slightly above the bucket on supporting beams to eliminate direct propagation of vibration into the rheometer.

Data was collected from high to low rotation speeds in twenty linearly spaced steps between $\Omega = 0.5$ rev/s and $\Omega = 0.05$ rev/s, followed immediately by measurements at twenty speeds between $\Omega = 0.15$ rev/s and $\Omega = 0.01$ rev/s to achieve a finer resolution at low shear rates. The duration of each step was 5 s (data sampled 25 times per second) and the torque M was averaged over the last 3 s of each step, thus avoiding transient data attributable to motor ramp time and/or thixotropy. The rotational speed and torque data were processed into shear rate and stress measurements using the narrow-gap Couette flow equations [34]

$$\dot{\gamma} = \frac{\Omega}{2}\left(\frac{R_o + R_i}{R_o - R_i}\right) \tag{2}$$