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Correlating water extraction to viscosity variations of injection grouts

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HIGHLIGHTS

- Development of testing protocol to simultaneously evaluate water extraction and viscosity changes due to vacuuming.
- Use of slotted vanes to enable viscosity measurements over several minutes of time.
- Effect of partial water extraction on viscosity variations of injection grouts.

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ABSTRACT

Cementitious grouts injected by vacuum pressure techniques are expected to loose part of the free mixing water with direct consequences on fluidity and penetrability. A new set-up was developed to enable simultaneous assessment of water extracted due to vacuuming and real-time viscosity changes occurring over several minutes of time. A slotted four-bladed vane was used to prevent migration of cement particles away from the center and enable the vane to remain in contact with new material during motion. Test results have shown that the extraction of water decreases fluidity (i.e., flow time) and increases viscosity, mostly due to increased internal friction within the solid particles. Grouts prepared with low water-to-cement ratio and containing moderate to high concentrations of viscosity-modifying admixtures yielded adequate water retentivity with minor variations in viscosity. “Injectability boxes” are proposed to simplify product development and predict variations in grout viscosity during vacuuming.

1. Introduction

The use of vacuum techniques to inject cementitious grouts during construction of post-tensioning tendons and repair of deteriorated concrete structures has considerably increased in recent years. After reducing the air pressure inside the void using a vacuum pump, the grouting process consists on using the air flowing back into the void to inject the grout [1,2]. The entire void system should be sealed airtight; a comparison of the previously measured void volume and injected grout can be used to confirm the success of procedure. Compared to conventional pumping pressure techniques, numerous benefits have been associated to injection by vacuuming including reduced risks of leaving air voids along the tendons, prevention of pressure build-up with further de-bonding of pieces during the repair work, and elimination of the need for vent tubes [1,3,4]. Typical areas of application include grouting of large voids, long horizontal tendons without defined high points where entrapped air would collect, and external tendons located inside massive diaphragms where the provision of vent tubes is complicated.

Cementitious grouts injected by vacuum techniques should meet stringent fluidity and water retentivity requirements. The high fluidity is needed to facilitate penetrability and ensure proper coating of prestressed steel [5,6]. This can be secured by the incorporation of high-range water reducers (HRWR) without increasing the water-to-cement ratio (w/c). Most importantly, the grouts should possess adequate water retentivity to minimize extraction of free mixing water that can dramatically affect the material’s fresh and hardened properties. The free mixing water can be defined as being the interstitial liquid that is not chemically linked to cementitious hydrating compounds or physically retained within the material [7]. In fact, the extracted water may hinder penetrability due to increased viscosity of the suspension; and if trapped inside the void, it can result in decreased strength, bonding to surrounding media, and protection against corrosion [8]. It is to be noted that the mechanism of water extraction due to porous media is controlled by transfer of water and adsorption properties by capillary suction, and becomes highly pronounced when vacuum pressure is applied [9]. Green et al. [10] found that water

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retentivity (R) can be directly related to the applied pressure (P) following an empirical expression: $R = C\ P^n$, where C and n refer to a constant term and exponent of the relation, respectively.

Viscosity-modifying admixtures (VMA) based on cellulose or microbial polysaccharides such as welan gum are essential components used to improve water retentivity. These molecules function by thickening the liquid phase, as a result of intertwinement and development of attractive forces through hydrogen bonding and polymer entanglement [5,11]. Bülichen et al. [12] reported that the working mechanism of methyl hydroxyethyl cellulose (MHEC) relies on two separate effects including water sorption (binding) and formation of hydro-colloidal associated 3D polymer networks. At concentrations lower than 0.3% of cement weight, water sorption of MHEC presents the main mechanism for water retention; while above this concentration, the formation of associated polymer networks that are highly effective in retaining water becomes predominant within the cementitious matrix [12].

Limited testing methods have been proposed in literature to assess the effect of water extraction due to vacuuming on real-time viscosity changes of flowable grouts. The current standardized methods for evaluating water retentivity of mortars are suitable for testing thin layers of relatively cohesive materials (i.e., masonry renderings and plasters, tile adhesives, and patching mortars) applied over porous substrates [13–15]. Their basic principles consist on desorbing an amount of water through contact with absorbing filter paper sheets or plates, or applying around 6.5% atmospheric vacuum pressure under a portion of mortar placed in a perforated dish. Nevertheless, these methods become inappropriate when testing flowable grouts containing a combination of chemical admixtures and subjected to vacuum pressure that can be as high as 90% of atmospheric pressure [1,3]. Additionally, no information can be deducted from such tests pertaining to the evolution of material's viscosity at any given elapsed time after mixing, as a consequence of water loss. It is to be noted that the elapsed duration required for injection depends on several parameters such as ambient air temperature, type of grout, size of duct, amount of prestressing steel, duct surface profile (smooth vs. corrugated), and level of vacuum pressure applied [8]. Typical durations reported in literature vary from just a few minutes to less than about 15 min, in order to limit the effect of cement hydration on fluidity and penetrability of grouts [3].

To evaluate the effect of vacuuming on changes in properties of freshly mixed grouts, Assaad and Daou [16] developed a set-up that consists of a perforated dish having given volume and containing 116 evenly distributed opening holes. The dish filled with flowable grouts rests on a funnel connected to a vacuum graduated cylinder capable of maintaining a constant pressure of 0.9 bar. After subjecting the grout to given vacuum period to extract part of the free mixing water, the adopted approach consisted on stopping the vacuum and recuperating the specimen for homogenization in a mixer and subsequent use for testing grout properties. This approach was found suitable to reflect changes in fresh and hardened properties [16], albeit quite tedious to realize as it requires significant time and materials for testing. Additionally, such approach does not mimic the actual conditions encountered on field including the on-time viscosity variations due to water extraction during vacuuming.

Monitoring viscosity variations of flowable grouts over several minutes requires the use of appropriate impeller geometry and adequate control of flow patterns during shearing. The vane geometry has been popular in yield stress characterization because of its simplicity and, mostly elimination of the serious wall-slip effects [17,18]. Shearing takes place within the material itself along an area assumed to be circumscribed by the vane cylindrical surface. Several researchers extended the use of vanes to other rheological measurements such as viscosity, thixotropy, oscillatory flow paths, low-strain modulus, and steady state flow curves [19–21]. For instance, Barnes and Nguyen [19] found that when a material moves within a four-bladed vane, then a vane-in-cup rheometer should be equivalent to coaxial cylinders rheometer, with the exception that slip is prevented. Barnes and Carnali [22] analyzed the flow of materials using vane-in-cup rheometer and found that, for shear thinning behavior, the material within the periphery of the vane blades is essentially trapped there and turns with the vane as a solid body. Thus, the torque required to turn the vane-in-cup would be equivalent to a spindle and identical flow curves would be predicted.

Assaad et al. [21] used the vane geometry during the assessment of thixotropy of flowable mortars and concrete. Nevertheless, to prevent progressive migration of large particles away from the center during rotation, a slot was cut through each of the four blades of the vane. Such design enabled the impeller to remain in contact with "new" material during motion, as materials displaced from the center of the bowl can be immediately replaced by new ones coming from the outer part. It is to be noted that the slotted devices have also been used by other researchers [23], so as to avoid wall–sample interactions and allow shearing to take place within the material.

The real-time viscosity variation due to water extraction is of particular interest for successful injection of flowable grout by vacuum techniques. The main objective of this paper is to develop a testing protocol that can be used to mimic the viscosity changes as a result of water extraction during vacuuming. The effect of vacuuming on changes in static yield stress was addressed in Ref. [16]. Two four-bladed vanes, slotted or not, connected to a stress-controlled rheometer are used for testing. The grouts were proportioned with different w/c and concentrations of cellulose or welan gum VMA. "Injectability boxes" are proposed to simplify product development and predict viscosity variations during vacuuming. Such data can be of special interest to contractors, engineers, and researchers dealing with vacuum grouting for construction of post-tensioning tendons or repair of deteriorated structures.

2. Experimental program

2.1. Materials

Commercially available portland cement conforming to ASTM C150 Type I was used in this study. The cement had C_3S, C_3A, and $Na_2Oeq.$ characteristics of 60%, 6.2%, and 0.74%, respectively. Its specific gravity, Blaine surface area, and median grain diameter equal to 3.14, 335 m^2/kg, and 44 μm, respectively.

A powder welan gum (WG) and liquid hydroxyethyl cellulose (HEC) were employed as VMA. The WG is a high molecular weight microbial polysaccharide produced by fermentation of carbohydrate substances. It exhibits excellent stability and viscosity retention characteristics up to 150 °C temperature. The WG is water soluble at room temperature, although possesses a slow dissolution rate. Thus, to avoid formation of powder lumps in tested grouts, the WG was vigorously mixed in 5% solution of the mixing water to prehydrate the polymer prior to addition [11,16]. The liquid HEC had a specific gravity and solid content of 1.04 and 15%, respectively. It is produced by substituting number of hydroxyl groups within the cellulose backbone by functional groups to improve water solubility through a decrease in crystallinity of the molecule. The average weight molecular mass and degree of substitution are equal to 310 kDa and 1.8, respectively.

Polycarboxylate ether (PCE) HRWR conforming to ASTM C494 Type F was employed. It had a specific gravity, solid content, pH, and alkali content of 1.07, 30%, 6.3, and 0.32%, respectively. Adequate compatibility, including fluidity retention without abnormal setting, is reported when combining PCE with WG or HEC molecules in cementitious materials [11]. A liquid sodium gluconate-based set-retarder was used to minimize fluidity loss of grouts during testing. Its specific gravity and solid content were equal to 1.15 and 25%, respectively.

2.2. Grout proportioning

Normally, injection grouts should be designed to meet a set of relevant criteria related to fluidity, stability, and long-term performance such as strength and volume change [2,8]. Nevertheless, given the context of this project, the grouts were proportioned to exhibit different stability and water retentivity levels in order to