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Cementitious grouts with adapted rheological properties for injection by vacuum techniques

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ABSTRACT

The injection of cementitious-based grouts by vacuum pressure techniques is expected to extract part of the mixing water with direct consequences on the fresh and hardened properties. A research program was undertaken to evaluate the effect of vacuuming on the amount of water extracted along with resulting changes in grout properties including flowability, static yield stress, viscosity, unit weight, Wick-induced bleeding, and compressive strength. Tests were conducted using specimens sampled right after mixing as well as after being subjected to vacuum. Test results have shown that the extraction of water decreases fluidity (i.e., flow time and mini-slump cone) and increases the magnitude of yield stress and viscosity, mostly due to increased internal friction and cohesion within the solid particles. Grouts prepared with low water-to-cementitious materials ratio and containing moderate to high concentrations of viscosity-modifying admixtures yielded adequate water retentivity, with minor variations in rheological and hardened properties.

1. Introduction

The injection of cementitious-based grouts by vacuum techniques has considerably increased during the construction of post-tensioning tendons and repair of deteriorated concrete structures. 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]. Such vent tubes often made of plastic can be buried during casting of concrete or crushed/blocked due to congested reinforcement, aggressive construction, or unaware personnel.

Injection by vacuum can broadly be divided into two methods, depending on the location of vacuuming with respect to the injected grout. The first method uses only one access to the void at any location in the tendon duct or repaired structure to perform the injection [1,3]. In general, this could be the borehole that has been made for inspection of the tendon or taking samples to determine presence of chlorides and sulfates [3]. This method consists on reducing the air pressure inside the void to around 90% of atmospheric pressure using a vacuum pump, and the air flowing back after opening the inlet valves is used to inject the grout inside the void. Vacuum and pressure pumps can be used during injection, and the method is refereed to as vacuum-assisted-grouting (VAG). This procedure is feasible only if the entire void system is airtight sealed; a comparison of the previously measured void volume and the injected grout can be used to confirm the success of the grouting. The VAG is mostly recommended for grouting large voids and external tendons where the provision of vents at high points is complicated or not possible [1,3].

The second method of vacuuming utilizes the advantage of a vacuum pump located at the far end of a tendon while the grout is introduced from the other end [2,4]. The vacuum pressure is maintained as the grout advances until complete encapsulation of the wire strands. It is referred herein to as the vacuum grouting (VG) method. To protect the vacuum pump from being contaminated with the grout, a trapping device with protective filters is generally connected between the outlet hose and vacuum pump. The VG method reduces the risks of leaving voids inside the tendons, and can be particularly interesting for grouting long horizontal tendons without defined high-points where entrapped air would collect [1,2,4].

2. Fluidity and stability requirements for injection grouts

Cementitious grouts intended for injection works by vacuum techniques should meet stringent performance criteria related to fluidity and stability. The grouts should be fluid enough during injection to ensure proper deformability and coating of prestressed steel with reduced risks of blockage [1,2,5]. Most importantly, the grouts should possess adequate water retentivity to minimize extraction of mixing water due to vacuuming, which may dramatically decrease fluidity with direct consequences on the rheological properties including yield stress and viscosity [6–8]. For instance, if grouting ceases by

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accidental or deliberate shutdown, flocculation amplified by the extracted mixing water occurs among the cementitious particles, thus causing the development of a gel structure in the tendons that has to be broken down (i.e., exceeding the yield stress) before grouting can resume again [9]. Also, the increase in viscosity due to water extraction may hinder penetrability and proper filling of the void. If injection is realized using the VAG method, the extracted water can be trapped inside the void and result in decreased strength, protection against corrosion, and bonding to surrounding media. The hardened grout properties may be less affected by extraction of water when injection is realized using the VG method, given that this water will most likely be removed by suction during vacuuming.

Following the end of injection, the grouts should be stable enough until onset of hardening to ensure proper homogeneity and avoid bleeding of free water that is often coupled with sedimentation of cement particles [10,11]. Powers reported that bleeding of cement pastes occurs because of the presence of water in excess of what is required for the "base" structure to take as a result of flocculation forces [12]. Khayat et al. defined free water as being the interstitial liquid that is not chemically linked to cementitious hydrating compounds or physically retained within the material [13]. In the case of injection grouts, the high fluidity is often associated with very diluted suspensions of moderately flocculent state and consisting of interconnected channels of various dimensions, potentially leading to bleeding and instability. Bleeding particularly occurs whenever there are variations in elevations between different grouted areas, such as in vertical ducts where water can rise upwards by capillary action around the wire strands (Wick-induced bleeding) [1,5]. The bleed water can be reabsorbed into the grout during the curing period, leaving air voids in the areas where it had accumulated and reducing bond to prestressed steel and durability of the final product.

Highly flowable grouts are often proportioned with high-range water reducers (HRWR) in order to ensure high fluidity without increasing the water-to-cementitious materials ratio (w/cm). The partial substitution of cement by supplementary cementitious materials and/or addition of viscosity-modifying admixtures (VMA) are necessary to secure adequate stability during and after injection. For example, the partial substitution of cement by silica fume was found to reduce bleeding and enhance stability as well as decrease temperature rise and improve long-term strength and impermeability [10,14]. This can be of particular interest to improve service life of post-tensioned concrete structures exposed to adverse conditions. From the other hand, the use of fly ash having spherical shape particles was reported to reduce inter-particle friction and enhance flow properties [10]. Strong water retaining characteristics were achieved with the addition of lime in mortars used as renders or plasters [15]. For example, water retentivity was improved by around two-folds with the use of (1:1:6) cement:lime:sand mixtures, as compared to (1:5) cement:sand mixtures incorporating air entraining admixtures. Improvements in grout stability were reported when ordinary cement was substituted by micro-fine cement having higher fineness [16].

Cellulose-based VMA and microbial polysaccharides such as welan gum function by occupying and thickening the liquid phase, as a result of intertwinement of molecules in adjacent polymer chains and development of attractive forces through hydrogen bond and polymer entanglement [17]. This could directly affect bleeding and water retentivity of freshly mixed mortars. For example, Patural et al. found that consistency and water retention of cementitious materials could be improved with the use of cellulose ethers, particularly those possessing high molecular weights [18]. Bülichen et al. 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 [19]. 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 [19]. Izaguirre et al. found that water retentivity of lime-mortar mixtures containing cellulose ethers is less pronounced as compared to similar mixtures made with guar ethers [20]. This was attributed to the adsorption of cellulose molecules onto the lime particles.

The importance of mixing procedure on fluidity and stability of injection grouts was already studied [21–23]. For given water content, Papadakis found that increasing the mixing intensity results in considerably lower level of bleeding [21]. However, during continuous mixing, the in-time viscosity may increase due to the abrasion of cement particles, whereas hydration may be accelerated due to temperature elevation [21]. Reduced bleeding was also noted by Markestad when using high turbulence mixing with external cooling [22]. Toumbakari et al. compared the effect of mechanical and ultrasonic mixing on injectability and penetrability of grouts in very fine voids [23]. For similar penetrability, ultrasonic mixing was found to improve dispersion, especially when silica fume is added to the grout, and permit the use of lower water content as compared to that added when high turbulence mixing is applied.

3. Objectives and significance of this project

Various international standards propose quantifying water retentivity of mortars by desorbing an amount of water through contact with absorbing filter paper sheets or plates, or by applying around 6.5% atmospheric vacuum pressure under a portion of mortar placed in a perforated dish [24–26]. These methods have proved quite suitable for testing relatively thin layers of materials applied over porous substrates such as masonry renderings, tile adhesives, and plastering and patching mortars [8,27–29]. Nevertheless, these become inappropriate when testing highly flowable grouts containing a combination of chemical admixtures and subjected to vacuum pressure as high as 90% atmospheric. In fact, the mechanism of water extraction due to porous media is mostly controlled by transfer of water and absorption properties by capillary suction [28,30]. At increased levels of vacuum, Groot reported the existence of a "funicular" state where both liquid and air (including vapor) transport become possible [31]. The limit between "capillarity" and "funicular" states is a so-called "air entry value" of the mortar that corresponds to the suction pressure needed for an external amount of air to break through the liquid-air interface and penetrate the porous system. For given wet mix, Green et al. reported that water 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 [15].

Limited data exists in literature pertaining to the effect of cyclic carbonate compounds such as propylene carbonate (PC) on water retentivity and corresponding variations in rheological properties of flowable grouts injected by vacuum techniques. The use of PC was reported to yield potential benefits for the concrete construction industry such as increased set acceleration of hydraulic cement [32], enhanced resistance to bleeding and surface settlement [33], and reduced lateral pressure developed on formworks [34]. Cementitious composites containing PC exhibit high thixotropic properties whereby the material begins to gel and stiffen in a relatively short time while at rest after mixing, yet when mechanically agitated, returns to a fluid state with lower viscosity. Maeder et al. reported that the addition of PC at relatively high dosage (greater than 0.5% by mass of water) can lead to the formation of a gel structure within 10 min from the first contact of cement with water [35]. The fluidity of the suspension could, however, be re-established following rigorous mixing. Unlike most cellulose-based VMA and polysaccharide polymers, PC undergoes chemical reactions in the aqueous alkaline environment and rapidly reacts to form propylene glycol and carbonate anions [36,37]. While hydrogen bonding is one possible source of the increase in viscosity of cementitious materials, Khayat et al. reported that the actual mechanism of PC may be related to a combination of several effects including physical interactions of the