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Factors affecting the performance characteristics of cementitious grouts for post-tensioning applications

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HIGHLIGHTS

- Commercially available grouts for post-tensioning applications were characterized.
- Flow cone test should not be used as a screening test for post-tensioning applications.
- Increase in fineness can increase the flow retention & bleed resistance of PT grouts.
- Increase in fineness is critical for enhancing the fillability in post tensioned systems.
- Mixing speed and ambient temperature significantly influence the grout performance.

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ABSTRACT

In grouted post-tensioned (PT) systems, cementitious grouts are supposed to completely fill the interstitial spaces between the strands and act as the 'last line defence system' against corrosion. However, use of poor quality grout materials and grouting practices result in voided grout systems, ultimately leading to premature failure of tendons in many bridges around the world. To ensure an intact system, the grout must have excellent fresh properties, in particular the flow properties. Such high-performance grouts are not available in many developing countries, where grouting for post-tensioned structures is still a nascent technology. In this research, a two-stage test program was carried out to evaluate the fresh and hardened properties of seven commercial grouts, which includes three Pre-Packaged Grout mixes (PPG); three Site-Batched Grout mixes (SBG) and one standard Ordinary Portland Cement grout mix (PCG). Further, one PPG mix and SBG mix were chosen and their properties were evaluated for three levels of mixing speed and two ambient temperature conditions. Fresh properties such as wet density, efflux time and its retention, standard bleed, wick-induced bleed and pressure bleed, as well as set/hardened properties such as setting time, compressive strength and volume change were evaluated. Three batches of grout were tested for each grout material, to ensure reliability of results. The influence of binder fineness on the performance of grouts was also evaluated. The study serves as a strong evidence in substantiating that the most commonly used grout materials for PT system in developing countries, fail to meet the standard requirements and even the manufacturer's own specifications. It is also found that the performance of the grout is influenced by mixing speed, ambient temperature, and fineness. The study emphasises that the evaluation of the grout behaviour under simulated field conditions is essential to ensure void free and durable PT systems.

1. Introduction

Prestressing technology, conceived and developed by Freyssinet in the 20th century is considered as one of the most significant breakthrough technologies in construction. Widespread use of this technology, especially post-tensioning (denoted as 'PT', herein), began in the 1950s and 60s with the construction of many long span bridges in Europe and the United States of America (USA).

Abbreviations: % bvog, percentage by volume of grout; ASTM, American Society for Testing and Materials; C, cement; EN, European Norms; F, fly ash; FHWA, Federal Highway Administration US; HRWR, high range water reducer; IBG, interground blended grouts; IMG, in-situ mixed grouts; PB, pressure bleed; PCE, polycarboxylate ether; PCG, plain cement grout; PPG, pre packaged grouts; PT, post-tensioned; RH, relative humidity; SB, standard bleed; SBG, site-batched grouts; U, ultra-fine fly ash; UK, United Kingdom; US, United States of America; VMA, viscosity modifying agent; w/c or w/b, water cement ratio or water binder ratio; WB, wick-induced bleed.

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Over the past 60 years, PT has found wide applications in the construction of long span bridges, marine structures, nuclear pressure vessels, water retaining structures, oil exploration structures, etc. Based on these young structures, PT systems were believed to be inherently maintenance free. But the collapse of a few PT bridges in the Europe [1,2] shed light on the potential long-term risk associated with these systems. Thus, an enhanced focus on the tendon system becomes essential because of its importance in PT structures. This becomes more critical in developing countries, where major infrastructure development is taking place and is being planned for the coming decades.

1.1. Lessons from past failures

Several failures of the tendon systems have been observed in the last 20 years. Following the failure of Bickton Meadows footbridge in 1967 and Ynys-y-Gwas Bridge in 1985, a ban on the construction of PT bridges (1992–1996) was imposed in the United Kingdom (UK). This ban brought to light the potential problems and triggered investigations in other countries like France, Switzerland, Austria, Korea, US etc. [1–3]. Many failures were found to be a result of poor grout materials, poor workmanship or quality control during construction [1,4,5].

1.2. Voids in grouted PT system

The stressed strands in a PT system are provided with various levels of protection systems, as shown in Fig. 1. As evident from the figure, the grout material that is in direct contact with the stressed strand acts as the last line of defence system. The grout creates an alkaline environment, forming a passive layer on the steel surface thereby preventing corrosion [5–7]. Hence, long term protection of PT strands necessitates the complete filling of the ducts with high performance, flowable grout [1,3].

Many investigations have reported that the presence of unwanted air voids in the PT system is an important cause of strand corrosion [2,3,5,8–10]. In voided tendons, the presence of moisture or standing water creates a GAS (Grout-Air-Strand) interface. The location and orientation of this interface, especially in the anchorage zone of tendons plays an important role in strand corrosion, thereby affecting the structural and service reliability of the bridge systems [9]. The major reasons for the formation of these unwanted voids include poor fluidity, significant bleeding and evaporation of bleed-water, poor grouting, poor construction practices, or a combination of these [11–13]. Fig. 2 shows the typical cross-section of ducts with strands and voids along the length of a PT bridge girder.

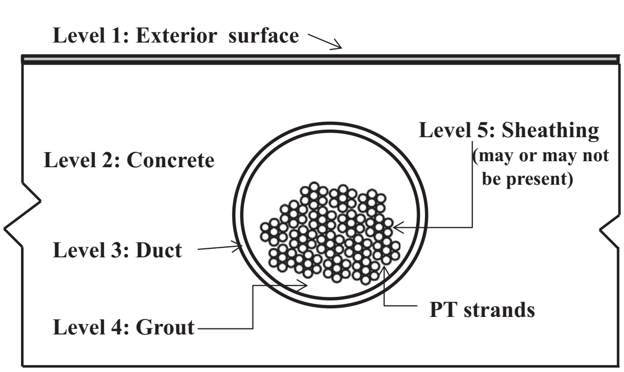

Fig. 1. Levels of protection in typical PT systems (adapted from [5]).

1.3. Fluidity and bleed resistance of PT grouts

Significant work on the performance of masonry grouts are available in literature. For example, the performance of masonry grouts made using superplasticizers, fly ash, and silica fume under different temperature conditions have been reported [14,15]. Later, similar effects on masonry grouts and how these can influence the injectability has been reported [16]. However, limited information is available on the performance of highly flowable post-tensioning (PT) grouts. Following is a discussion on some of these fresh properties (say, fluidity and bleed resistance).

The ability of grout to penetrate the interstitial spaces between the strands and the duct, as shown in Fig. 1, to ensure complete filling is controlled mostly by its fluidity and fluidity retention. For enhanced pumpability, fresh grouts should have low viscosity (an indicator of fluidity) and adequate fluidity retention. Fluidity can be enhanced by the addition of superplasticizer [17]. However, uncontrolled enhancement of flow will lead to bleeding, sedimentation and segregation. Fluidity of PT grouts can be determined using flow cone or Marsh funnel test [17,18].

If excess water is added to the grout, the cement particles can flocculate and settle under gravity; and the water moves up and gets collected at the top. This water is called as 'bleed water'. It results in anisotropic behaviour of the grout, causing segregation [10]. This excess water gets collected at high points of tendon profiles (say, at anchorage zones) and later evaporates or gets reabsorbed into the grout, leaving large voids and exposed strands [19]. Bleed is quantified by standard bleed and wick-induced bleed ("SB" and 'WB', respectively) tests based on ASTM C 940-2010 and EN445 Part-3 (2007), respectively [20,21]. WB is usually higher than SB due to the capillary movement of water through the space between the wires in a strand in the former (see Fig. 3(a) and (b)). The third bleed test is the Schupack Pressure Bleed Test (see Fig. 3 (c)), which can be carried out when the tendons have significant slope or are vertical in profile leading to considerable static water pressure [11,22].

1.4. Factors affecting the properties of grout

1.4.1. Ambient temperature

Temperature of the ambient environment, water and the grout materials can significantly influence the fresh properties [8,18,23,24]. Grout mixes subjected to elevated temperature show rapid reduction in viscosity due to accelerated reactions between cement particles leading to workability loss. Plastic viscosity can decrease with increase in temperature until about 35 °C [8]. At more than 35 °C, there can be a significant workability loss (increase in viscosity) [8].

Similar is the case with setting time, which is prolonged at low ambient temperature; at higher temperatures it is shortened, due to accelerated hydration [23]. Expansion of grout at about 10 °C (i.e., low temperature) can be very slow [25]. Achieving acceptable range for mechanical properties like compressive strength and modulus of elasticity can be difficult when the ambient temperature is less than 10 °C [25].

1.4.2. Fineness of grout

The particle size distribution of all the cementitious materials or binders in the grout is an important factor that controls the rheological and mechanical behaviour of grouts and the complete grout filling [5,26]. Efforts have been made to extend the injectability range of suspension grouts by developing materials with very fine gradation, resulting in "micro-fine" ($D_{95} < 20\ \mu m$ and Blaine fineness over 800 m^2/kg according to EN 12715) and "ultrafine" (D_{95}