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Mitigating shrinkage cracking in posttensioning grout using shrinkage-reducing admixture

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ABSTRACT

This study aims to reduce the cracking potential of posttensioning high-performance grout (HG) through use of shrinkage-reducing admixture (SRA). With this regard, an HG mixture was initially developed to possess appropriate fluidity with low bleeding and settling. Various amounts of SRA were subsequently incorporated into the developed HG mixture at 1% and 2% by weight to the cementitious components. A widely used ordinary grout (OG) mixture was also considered for comparison. Test results indicated that the HG mixture exhibited similar flowability to the OG mixture, while imparting much better performance with regard to strength, bleeding, and settling. The addition of SRA to the HG mixture led to higher compressive and tensile strength values after 28 days, lower shrinkage strain, lower maximum internal temperature due to hydration heat, and delayed shrinkage cracking. On the other hand, the degree of restraint due to an uneven surface of duct and the filling capacity of the HG were insignificantly affected by the inclusion of the SRA. Complete filling of ducts was observed for the HG samples. The OG mixture exhibited the smallest shrinkage strain and the best performance with regard to shrinkage cracking resistance; however, the OG mixture resulted in insufficiently filled ducts, leading to atmospheric exposure of prestressing strands. Consequently, the HG mixture with 2% SRA was proposed to be most appropriate for posttensioning grout with regard to the several properties denoted above.

1. Introduction

In recent years, many civil and architectural structures have been built with prestressed concrete (PSC) products because PSC structures can lead to less weight, causing increased span lengths, and greater durability, compared to conventional reinforced concrete (RC) elements. In particular, higher durability of PSC structures can be achieved since compressive forces applied to concrete elements via prestressed strands can effectively control cracking due to external loads, serving to effectively prevent permeation of harmful substances and corrosion of steel reinforcements. Additionally, with regard to post-tensioned (PC) concrete structures, the steel strands are covered with grout to fully protect the material from corrosion. However, it has been verified by several researchers [1–3] that the actual service life of PC structures is dramatically reduced due to the corrosion of strands; as a result, partial post-tensioned bridges in Europe collapsed suddenly due to corrosion and deterioration of prestressed strands [4].

The corrosion of prestressing strands in PC structures can be primarily attributed to the insufficient filling of ducts due to grout bleeding [1], which results in the exposure of strands to the atmosphere, allowing chloride ion penetration without generation of cracks in the concrete structure. For this reason, several international standards [5–7] have suggested requirements for bleeding and volumetric changes (expansion or settling) of grout in order to prevent such strand exposure. However, according to the test results performed by Yoo et al. [8], the ordinary grout most widely used for PC structures in Korea exhibited significant bleeding (6.35% as per the wick-induced bleed test) and did not satisfy international standards with regard to bleeding. Therefore, to avoid sudden collapse of PC structures due to corrosion of prestressing strands, the development of a high-performance grout with almost zero bleeding and settling (or expansion) is highly desired.

Although the exposure of strands is a major factor for corrosion,

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cracks occurring in grout can be a source of strand corrosion, due to the permeation of harmful ingredients that reach the strands through cracks. The grout is composed of Portland cement, sand, and water and is hardened by hydration of cement. It is well known that the hydration of cement can result in chemical shrinkage at a very early age. Due to the restraint of chemical shrinkage by hardening of cement pastes, small pores are formed in the hardened cement pastes, and as a result, drying shrinkage is generated from the desiccation of pore water. If the shrinkage of cement-based materials, i.e., mortar, concrete, and grout, is restrained by internal reinforcements or surrounding structures, cracks can be generated perpendicular to the direction of principle tensile stress [9,10]. Shrinkage cracks are closely related to shrinkage behavior under restrained conditions and are affected by a variety of factors including shrinkage rate and potential, strength development, creep or stress relaxation, and degree of restraint. For this reason, free shrinkage measurements are insufficient for evaluating shrinkage cracking behavior, and restrained shrinkage needs to be measured. However, only a few studies [8] have investigated the shrinkage and cracking behavior of posttensioning grout under restrained conditions. Also, to the best of the author's knowledge, there has been no published study on the development of a high-performance grout with improved shrinkage cracking resistance.

Accordingly, in this study, a high-performance grout (HG) exhibiting low amounts of bleeding and settling was preferentially developed. Its shrinkage properties under both free and restrained conditions were evaluated along with an ordinary grout (OG). In order to improve the shrinkage performance of HG, various amounts (1% and 2% by weight of cementitious materials) of a shrinkage-reducing admixture (SRA) were considered, and their implications with regard to the fresh and hardened properties of HG were comprehensively investigated. Lastly, the filling capacity of HG within a duct was evaluated and compared to that of OG.

2. Development of a high-performance grout

At the Korea Institute of Civil Engineering and Building Technology (KICT), research has been carried out since 2013 toward to develop a high-performance grout with low bleeding and settling. Based on numerous fundamental test results, they [11] proposed the HG consisting of cementitious materials (80% cement, 10% zirconium silica fume [Zr SF], 10% fly ash [FA]), water, and a high-range water-reducing admixture (superplasticizer, SP) with a water-to-binder (W/B) ratio of 0.3. It is well known that, to decrease grout bleeding, the viscosity of the grout needs to be increased by increasing the quantity of cementitious materials. However, with an increase in viscosity, grout fluidity is decreased. Accordingly, in order to overcome this drawback, the SP was incorporated into the HG mixture. A comparison of fundamental properties of the developed HG and OG are summarized in Table 1. The OG consists of cement, an expansive agent (EA), and water, yielding a W/B ratio of 0.45. Grout fluidity was evaluated by measuring the duration of flow (from the cone method of KS F 4044 [12]) and the average flow value (from the grout spread method of BS EN 445 [5] and flow table test of ASTM C1437 [13]). The flow duration was found to be 28 s and 22 s for the OG and HG samples, respectively. In accordance with KS F 4044 [12], the flow duration should be less than 60 s for the grout of PC structures. Thus, both the OG and HG samples satisfied the flow duration requirements as per the KS F 4044 standard. The British Standard (BS EN 445 [5]) described two test methods, 1) cone method and 2) grout spread method. Based on the BS EN 445 [5], fluidity of grout can be measured through only one of the two methods, and then, the appropriateness of grout type selected can be evaluated. From the flow duration measurements, both the OG and HG samples were already considered as proper grout materials for PC structures. In addition, the average flow values were measured via two different methods and were found to be 150 and 145 mm (by the grout spread method) and 255 and 250 mm (by the flow table test) for the OG and HG samples, respectively. Although the OG sample exhibited slightly higher flow values than the HG sample, the differences were insignificant. Consequently, it was noted that the fresh properties of the HG sample were similar to those of the OG sample, which is the most widely used grout type for PC structures in Korea.

Grout bleeding and expansion were also measured with two different test methods, according to the ASTM C940 [14] standard with 15.2-mm-diameter strands (wick-induced bleed test) and without strands. A 1000 mL capacity plastic cylinder was used, and the grout volume was approximately 800 ± 10 mL. It has recently been reported that a large degree of grout bleeding occurred when the prestressed strand was contained within a mold, due to a wick effect [8]. Analogous to the previous observations, specimens containing strands exhibited higher grout bleeding values of 6.35% and 0.25% at 3 h for the OG and HG samples, respectively, compared to those without strands, as summarized in Table 1. This was also verified by the illustration in Fig. 1, which presents a comparison of OG sample bleeding with and without strands. In Fig. 1, it is obvious that, although identical grout mixtures were applied, a higher degree of bleeding was generated due to the wick effect. The HG mixture, developed by KICT, yielded much smaller bleeding values than the OG mixture. For instance, minor bleeding (0.03%) was obtained for the HG sample without strands at 3 h, while a higher degree of bleeding (0.79%) was yielded for the OG sample without strands at 3 h. Relatively insignificant settling of cementitious materials was also observed for the HG sample compared to the OG sample, when the strands were contained (Table 1). Synthetically, it was concluded that the developed HG mixture was effective with regard to reducing bleeding and settling, resulting in exposure of prestressing strands, without any significant deterioration in fresh properties. Thus, the HG mixture was considered to be the primary variable in this study along with the OG mixture being adopted for comparison.

Table 1
Properties of fresh grout (OG and HG samples).

		Flow time (s)	Flow (mm)		Bleeding (%)[b]	Expansion (%)[c]
			1)[a]	2)[a]		
OG	w/o strand	28	150	255	0.79	+4.80
	w/ strand				6.35	−0.40
HG	w/o strand	22	145	250	0.03	−0.12
	w/ strand				0.25	−0.25

[a] 1) is based on BS EN 445 and 2) is based on ASTM C1437.
[b] Bleeding is measured after 3 h.
[c] Expansion is measured after 3 h.

3. Experimental program

3.1. Materials and mixture proportions

Detailed mixture proportions are listed in Table 2. With regard to the OG mixture, the W/B ratio was 0.45, and only Type 1 Portland cement was used as the cementitious material. In order to compensate for grout early age shrinkage, 1% (by cement weight) aluminum powder was incorporated as the EA. The chemical composition and physical properties of the cement and aluminum powder are summarized in Table 3. A W/B ratio of 0.3 was adopted for the HG mixture. Three different cementitious materials, namely Type 1 Portland cement, Zr SF, and FA, were employed in an 8:1:1