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Fresh and hardened properties of steel fiber-reinforced grouts containing ground granulated blast-furnace slag

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HIGHLIGHTS

- The addition of steel fibers significantly increased the crack resistance of grout.
- GGBS notably enhanced the chloride penetration resistance, flowability of grout.
- SFRCs with GGBS showed suitable work ability for PSC offshore substructures.

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ABSTRACT

Fresh and hardened properties of steel fiber-reinforced grout (SFRG) containing ground granulated blast-furnace slag (GGBS) were investigated for applications to prestressed concrete substructures of offshore wind turbines. The addition of short smooth steel fibers (6 mm in length, 0.2 mm in diameter) generally decreased the flow, bleeding, and time of setting of SFRG, whereas the addition of GGBS for the replacement of 40% of the cement by weight ratio clearly increased its flow and the time of setting. The effect of adding GGBS on bleeding was different according to the type of cement. Despite these outcomes, it was observed that the addition of GGBS notably enhanced the chloride penetration resistance of SFRGs, while the addition of steel fibers significantly increased their flexural strength.

1. Introduction

There is an increasing interest on the development of new and renewable energy owing to the depletion of fossil fuel resources, the instability in oil prices, and climate changes. A tremendous amount of research efforts have focused on the development of wind power energy as one of renewable energy resources, and the amount of wind energy in offshore farms has steeply increased compared to onshore wind farms. In the development of wind power energy, small turbines have been firstly applied; and, accordingly steel towers holding the small turbines have been mostly applied in offshore windmills. However, as the size of the wind turbine has become bigger, the wind tower for the turbine has also become taller and larger. Consequently, prestressed concrete (PSC)[1] is now considered as one of attractive and economically feasible substructures for larger offshore wind turbines. PSC substructures are expected to be suitable for use in the substructures of offshore wind turbines due to the relatively low cost and higher corrosion resistance of concrete. Moreover, prestressed concrete were widely applied to offshore structure for oil and gas production.

However, the prestressing tendon in PSC is vulnerable to corrosion, especially in marine environments: the stress corrosion of the prestressing tendon has been reported previously [27]. Grout injected in the sheath between the prestressing steel and duct is "*the final line of defense against the corrosion of the pre-stressing steel*" [23]. In addition, there is an urgent need in developing ductile grouts for the joints between precast PSC structural members in large offshore structures. Numerous research efforts have been carried out to enhance the material and mechanical resistance (flow, bleeding, setting time, and chloride ion penetration) of grouts by incorporating fly ash, silica fume, and ground-granulated blast furnace slag (GGBS) [15,4] [22]. Current research has mostly focused on reducing the permeability of grouts: chloride ion permeability for prestressed concrete [23] or water permeability for isolating landfill contaminants [5], especially for

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[1] SFRG, Steel fiber reinforced grout; GGBS, Ground granulated blast-furnace slag; PSC, Prestressed concrete; UTM, Universal testing machine; LVDT, linear variable differential transducer.

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enhancing the corrosion resistance of PSC substructures. Despite the fact that migration of chloride ions through the grout could be considerably delayed or prevented by reducing the permeability of noncracked grout, the penetration of chloride ions through the cracks of grouts is much more significant than that through the noncracked part of the grout.

The crack resistance of grouts is also very important for preventing the corrosion of PSC, especially in marine environments. Thus, in this study, fiber-reinforced grouts incorporating GGBS is proposed to be used for the PSC substructures of offshore wind turbines under severe marine environments. The addition of fibers to grouts is highly expected to enhance the crack their resistance [10] while that of GGBS would delay water or chloride ion penetration through noncracked parts of the grouts [5,6,4,17,16]. However, there is very limited information in prior published reports on the performance of steel fiber-reinforced grout (SFRG) with GGBS, with the exception of the publication by [10].

In this study, we aim to develop steel fiber-reinforced grouts, incorporating GGBS with high corrosion resistance. Detailed objectives are: 1) to investigate the effects of replacing GGBS on the fundamental properties of grouts according to the different types of cement, 2) to discover the effects of adding steel fibers on the fresh and hardened properties of SFRG, and 3) to investigate the resistance of SFRG under chloride ion penetration.

2. Grout in prestressed concrete

The role of grout in PSC is to protect the prestressing steel from harmful chloride ion attack. Numerous research efforts have investigated the properties of grouts, including the flow, flow (or efflux) time, bleeding, setting time, and chloride ion penetration. The addition of silica fume was determined to be very effective for reducing the bleeding and permeability of grout [15] although it notably decreased its flow owing to the very fine particle size of silica fume [3]. The addition of GGBS also noticeably densified the microstructure of grout, reduced permeability, and increased the resistance of concrete (or grout) under severe seawater attacks ([32], Gao et al., 2004, [28]). GGBS would be more financially feasible for the grout in PSC substructures of offshore wind turbines compared to silica fume because of its lower price [4], although both silica fume and GGBS are effective for enhancing the resistance of concrete and/or grout under marine environments. The performance of grout was also determined to be sensitive to the type of cement [4] as well as to the size of cement particles [25]. Furthermore, the addition of agents that modify viscosity, air entrainment, and water-reducing agents, also influenced the performance of grouts [22].

However, there is limited published information on the performance of SFRGs although a few researchers reported the effects of addition of polypropylene fibers on the flow, permeability, and flexural tensile strength of grouts [5,6,17,16]. Berndt [10] recently reported that the addition of steel fibers could successfully enhance the splitting tensile strength without deteriorating the pumping capacity of SFRGs with steel fibers that were 13 mm in length. However, the performance of SFRGs needs further investigation, especially in regards to the tensile cracking resistance of grouts when steel fibers are added to cementitious matrices incorporating GGBS because the addition of GGBS in grouts possibly affects the interfacial bond strength between the steel fiber and grouts containing GGBS.

3. Experiments

An experimental program was designed to investigate the effects of adding GGBS as the partial replacement of cement and steel fibers on the fresh and hardened properties of SFRG for the application to PSC substructures of offshore wind turbines. The amount of GGBS, as the partial replacement ratio of cement, varied between 0 and 40% of cement by weight in the composition of grouts, and two types of cement (Types 1 and 3) according ASTM standard were used, as summarized in Table 1. The flow, flow (or efflux) time, bleeding, and setting times of six types of grout were investigated according to the different amounts of GGBS and cement type. The notation of C1G0.2 in Table 1 represents the grout containing 80% of Type 1 cement and 20% GGBS, while C3G0.4 represents the grout containing 60% of Type 3 cement and 40% GGBS. In this experiment, Type 3 GGBS was used. As summarized in Table 1, naphthalene type superplasticizer was used in the grouts with Type 1 cement, whereas the polycarboxylate type superplasticizer was applied owing to the different particle sizes of the two types of cements used. Additionally, one type of steel fibers with a length of 6 mm and a diameter of 0.2 mm was added to C3G0.4 (containing 60% of type 3 cement and 40% of type 3 GGBS) to increase the crack resistance of grout, as shown in Table 2. The amount of superplasticizer polycarboxylate used ranged from 0.2 to 0.3% to control the flow value of grout, and was measured using mini cones that ranged from 260 to 270 mm in order to satisfy both the uniform fiber distribution and good workability.

3.1. Material and specimen preparation

The composition and compressive strength of grouts in this experimental program are summarized in Table 1, while the compositions of SFRGs at different fiber volume contents are listed in Table 2. The physical and chemical property of cementitious materials (cement types 1 and 3, and GGBS) are presented in Table 3. Type 1 cement is ordinary Portland cement while Type 3 cement is high early strength cement. The different grain size distributions of the two cement types and GGBS are plotted in Fig. 1. The grain size of GGBS used in this experiment had values between the size values of Type 1 and 3 cement. Furthermore, the fineness of Types

Table 2
Composition of steel fiber reinforced grouts (SFRGs) by weight ratio.

Cement (Type 3)	GGBS[a]	Silica sand	Water	Fiber volume content (%)	Polycarboxylate based super-plasticizer[c]	Flow[b] (mm)
0.6	0.4	1.0	0.45	0.5	0.002–0.003	270
0.6	0.4	1.0	0.45	1.0	0.002–0.003	260
0.6	0.4	1.0	0.45	1.5	0.002–0.003	270
0.6	0.4	1.0	0.45	2.0	0.002–0.003	270

[a] Ground granulated blast-furnace slag (Type 3).
[b] Measured from mini cone test.
[c] 22% solid and 78% water.

Table 1
Composition of grouts by weight ratio and compressive strength.

Notation	Cement		GGBS[a]	Silica sand	Water	Superplasticizer		f_c'[b] (MPa)
	Type 1	Type 3				Naphthalene	Poly-carboxylate[c]	
C1G0.0	1.0		0.0	1.0	0.45	0.001		62.91
C1G0.2	0.8		0.2	1.0	0.45	0.001		63.20
C1G0.4	0.6		0.4	1.0	0.45	0.001		60.80
C3G0.0		1.0	0.0	1.0	0.45		0.001	92.99
C3G0.2		0.8	0.2	1.0	0.45		0.001	94.49
C3G0.4		0.6	0.4	1.0	0.45		0.001	90.50

[a] Ground granulated blast-furnace slag (Type 3).
[b] Measured from 50 mm cube specimen.
[c] 100% solid component.