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Investigation on fundamental properties of microfine cement and cement-slag grouts

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HIGHLIGHTS

- Properties of eight cement grouts with various composition and grains are presented.
- Effects of W/C ratios (1.0–3.0), fineness, SP and composition are studied.
- Rheological parameters, fresh states and mechanical properties are determined.
- Property optimization and grouting effectiveness for MC based grouts are discussed.

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ABSTRACT

To ensure excellent rheological behavior, penetrability and mechanical property of microfine cement (MC) grout in the field work, it is essential to obtain and control its property by laboratory tests. In this study, rheological and mechanical properties of six different MC grouts (three portland-based and three slag-blended) and two ordinary Portland cements (ASTM I and III) are measured. MC suspension was prepared at five W/C ratios (1.0, 1.2, 1.5, 2.0 and 3.0) without or with superplasticizer (SP). The properties investigated in this study were: particle size distribution, rheological properties (apparent viscosity, yield stress and plastic viscosity), fresh states (mini-slump, bleed capacity and final setting time) and mechanical properties (early strength development, compressive strength, flexural strength, elasticity modulus, shrinkage/expansion and sand-consolidation strength). The results showed that rheological behaviors and mechanical properties of MC grouts were affected obviously by the W/C ratio, cement fineness, cement type and the addition of SP, etc. All MC suspensions behaved as the Bingham fluids and were stable for W/C = 1.0, 1.2 and 1.5. The detrimental effect of finer grain size on viscosity can be negated by using SP. To ensure less leaching, sufficient fluidity and enough penetrability in sand voids or micro cracks, the W/C ratio was recommended as 1.0–2.0. The SP dosages should not be excessive to avoid instability, oversaturation or long-setting.

1. Introduction

To ensure the safety of structures under construction or operation, cement-based grouts or chemical grouts are usually used in permeation grouting to enhance the mechanical properties of soils or rocks. The ordinary cement is inexpensive and non-toxic, however, it cannot penetrate into fine-medium sands, finer soils and the micro-cracks ($\leq$0.5 mm) [1,2]. Based on the criteria for good injectability $N = D_{15}/G_{85} > 15$ [3], the average D_{15} of the medium sand is 0.5–0.7 mm, the average G_{85} of microfine cement (MC) is approximately 10 μm, and the average G_{85} of ordinary Portland cement (OPC) is approximately 50 μm. Generally, the N_1 for OPC is approximately 10–14 (<15) and the N_2 for MC is about 50–75 (>15). The chemical grouts (epoxy resins, polyurethanes and silicate gels, etc) and MC grouts can penetrate into the above sands, soils or cracks. Nevertheless, chemical grouts are not only extremely expensive but also pose health and environmental hazards. Moreover, chemical grouts showed poor bonding in moist environments and insufficient durability (chemical stability and creeping) [4]. Due to excellent performance of penetration capacity, environmental friendliness, durability and low cost, chemical grouts are often replaced by MC grouts in grout engineering, especially for fine-medium sands, finer soils and micro-cracks of rocks or concretes [5–7].

Since the beginning of 1980s, MC grout was developed to ensure the injectability and large application ranges of cement suspension [8]. MC grouts can be defined by their fineness and their

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high specific surface area. MC was defined as $d_{max} < 15$ μm and $d_{95} < 16$ μm by ACI Committee 552 (Geotechnical Cement Grouting) and the International Society for Rock Mechanics. In Europe, the MC was defined as $d_{95} < 20$ μm and Blaine fineness ≥ 800 m^2/kg based on EN 12715 [4,9,10]. Because of the high specific surface area of MC, it is necessary to use superplasticizer (SP) to obtain workable suspension with high fluidity and penetration capacity [11,12].

There exists numbers of researches about grouts based on OPC [13–15]. However, the "microfine" effects of cement particles and synergistic effects of chemical composition, W/C ratio and SP on rheological behavior and mechanical performance of MC grouts are not reported systematically. According to grouting practice, the objective of this experimental study was to determine rheological properties (apparent viscosity, yield stress and plastic viscosity), fresh states (mini-slump, bleed capacity and final setting time) and mechanical properties (early strength development, compressive strength, flexural strength, elasticity modulus, shrinkage/expansion and sand-consolidation strength) of MC grouts. Furthermore, the influencing factors were chemical composition (cement type), grain sizes, SP contents and W/C ratios. Suggestions of performance optimization of MC grout for soil voids or micro cracks were provided.

2. Experiments

2.1. Materials

In general, mixtures of granulated blast furnace slag (GBFS) and Portland cement, or merely Portland cements are used to manufacture microfine cements. In this study, eight commercial cements including six MC (three Portland-based MC and three slag-blended MC, marked as A, B, C, D, E and F, respectively) and two OPC (ASTM I and III, marked as G and H) were selected for laboratory tests. The Portland-based MC and three slag-blended MC were obtained by superfine dry grinding in the cooperated factories in China. Table 1 provided the oxide composition of cements obtained from manufacturers. The silica contents and alumina contents of slag-blended MC are higher than those of Portland-based MC, whereas the calcium contents of slag-blended MC are lower. These data in Table 1 can provide explanations or references to choose suitable cements for specific grouting in the field works.

To improve the rheological properties of MC grouts, a polycarboxylate ether-type SP was selected as high-range water reducer (HRWR). Table 2 showed the property of the SP used in this study. The main chain of the selected SP contained a copolymer of methacrylic acid with lateral carboxylate and ether groups, and the ratio of side chain to main chain length was 1 [16]. In this investigation, all grouts were prepared with potable water [17]. The silica sands were used in sand-consolidation strength experiments, the medium sands were sieved as 0.6–1.0 mm with d_{15} size of 0.7 mm. The silica sands were dense and dry before grouting.

2.2. Preparation of cement-based suspensions

The water, cements (A–H) and SP in this study were placed at room temperature (25 ± 2 °C). For fresh suspensions with polycarboxylate ether-type SP, the 1.4% SP (relative to the mass of cement) was initially mixed with the required water by a high turbulence mixer at 1000 rpm for 2 min. Then MC (A–F) and OPC (G–H) were added and the fresh suspensions were mechanically mixed by a high turbulence mixer at 1000 rpm for 8 min. For the fresh grouts prepared by water and cements without SP, the mixing speed was also 1000 rpm and the total mixing time was 10 min to ensure the uniformity. It was noted that the mass of SP was considered for calculating the amount of required water. The suspension with W/C larger than 3.0 is forbidden because of its large bleed capacity, long time of setting or hardening and low strength, meanwhile, the viscosity of MC grout is prohibitively high when W/C ratio is less than 1.0. Therefore, the initial W/C ratios of MC grouts were set as 1.0, 1.2, 1.5, 2.0, 2.5 and 3.0 by weight.

2.3. Experimental approaches

Immediately after the preparation of fresh grout at 25 °C and humidity of 50%, the apparent viscosity of suspension (0% SP or 1.4% SP, different W/C ratio and various fineness) were measured by a rotational viscometer NDJ-8S (1–2 × 10^6 mPa s), and its common shear speeds are 60, 30, 12, 6 and 3, 1.5, 0.6 and 0.3 rpm, respectively. Combined with the grouting applications, the rotation speeds of 60, 30, 12, 6 and 3 rpm have been applied to determine rheological parameters more accurately. The fresh grouts were placed in a standard 500 mL beaker and the rheological measurements were performed. At each rotation speed, the initial viscosity values (0 min after preparation) were measured and the time internals were 15, 30, 60, 90 and 120 min, respectively. To ensure stability or uniformity, the stirring was continuous and the stirring rate was low with 3 rpm. Furthermore, initial viscosity value, yield stress and plastic viscosity were investigated. In mini-slump tests, the mini-slump cone is similar to the cone for evaluating concrete consistency (ASTM C-143) [18,19]. The mini slump tests can be defined as the spreading diameter (mm) of fresh grout on a Plexiglas, more specifically, their dimensions are 60 mm of height, 36 mm of bottom diameters and 60 mm of top diameters. Bleeding capacity is defined as the final value of $\Delta V/V_0$, where V_0 is the initial volume and ΔV is the volume of bleeding water. The fresh grout was placed in a graded cylinder (1 L) for 24 h, then the volume of excess water was recorded at every 30 min interval until the completion of sedimentation. According to ASTM Standard C191 [20], the initial setting time is recorded when the penetration height of Vicat needle is 25 mm, and the final setting time is recorded until the height of Vicat needle was less than 1 mm. It was noted that the Vicat mould was filled with the hardened sediment after the completion of bleeding.

The early strength development was tested and evaluated by a pocket penetrometer (maximum value of 0.45 MPa). The fresh grouts were placed in beakers and the bleeding water was removed by the dropper tools. To avoid water loss through evaporation, a plastic membrane was used to seal the grouts. In flexural strength tests, the bleeding water was removed at every 30 min interval in cuboid moldings, and the dimension of grout was 40 × 40 × 160 mm after the completion of bleeding. On the bases of ASTM Standards C942 [21] and D2938 [22], cylindrical specimens (50 mm × 100 mm) were used in compressive tests. The specimens were cured in a moist chamber (25 ± 3 °C and 100% R.H.) for 28 days. The specimens were loaded uniaxially, the loading rate for UCS is 1.0 mm/min. The failure conditions were determined when force reached peak values and the loading was stopped after 3%–5% strain have proceeded. According to ASTM D3148-96 [23], the slopes of axial stress-strain curves (50% of final strength) were regarded as elasticity modulus of hardened MC grouts. To obtain the elasticity modulus of hardened grouts,

Table 1
Typical chemical composition of grouts in this study.

Oxides (%)	Portland-based MC			Slag-blended MC			Portland cements	
	A	B	C	D	E	F	G	H
SiO_2	19.90	20.2	22.40	30.50	30.60	30.8	21.20	20.10
Al_2O_3	3.60	5.5	4.20	9.60	12.40	10.2	4.30	4.80
Fe_2O_3	5.20	2.2	4.90	1.50	1.10	1.5	3.10	2.40
CaO total	64.50	65.3	64.00	45.80	48.40	45.70	62.80	62.60
MgO	2.00	0.9	*	6.60	5.80	6.40	2.50	2.50
SO_3	3.30	3.1	1.90	2.00	0.80	3.20	3.20	4.20
TiO_2	*	*	*	0.50	*	0.5	0.22	0.18
P_2O_5	*	*	0.25	0.00	*	0.00	0.23	0.14
SrO	*	*	*	*	*	*	*	0.44
Na_2O	0.18	0.23	*	0.50	*	0.5	0.32	0.33
K_2O	0.35	0.57	*	0.30	*	0.3	0.83	0.56
Mn_2O_3	*	*	*	*	*	*	*	0.05
MnO	*	*	*	0.20	*	0.2	*	*
Total (%)	99.03	98.00	97.65	97.50	99.10	99.30	98.7	98.30

* =not obtained.