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High-performance cementitious grouts for structural repair

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Abstract

Laboratory investigation was undertaken to develop high-performance cement-based grouts for infiltrating fiber-reinforced cementitious composites that makes them ideally suited for structural repair and seismic retrofit. The rheological and mechanical properties of the proposed grouts are interesting since, from a practical point of view, they exhibit no bleeding or segregation and reach high compressive strength and flowability. This study recommends the use of natural pozzolan in combination with silica fume in the production of high-performance cement-based grouts for providing technical and economical advantages in specific local uses in concrete industry. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Compressive strength; Grout; Silica fume; Natural pozzolan; Superplasticizer

1. Introduction

Recently, there has been a growing interest in the use of high-performance fiber-reinforced concrete (HPFRC) for seismic repair and retrofit of concrete structural elements [1–4]. This is because most of the rheological, mechanical and durability properties of these materials are better than those of conventional FRC. Among the HPFRCs, which have been successfully used in structural rehabilitation, are slurry infiltrated fiber concrete (SIFCON) and slurry infiltrated mat concrete (SIMCON) [1–3]. SIFCON is relatively a new HPFRC in which formwork molds are filled to capacity with fibers and the resulting fiber network is infiltrated by a cement-based slurry (grout). SIMCON is a new HPFRC made by infiltrating nonwoven steel fiber mats with specially designed cement slurry (grout). Numerous researchers [1–4] agree that the performance of the composites mentioned is highly dependent on the behavior of the cement matrix (grout) in which they are embedded. It is a challenge for the materials engineer to design a cementitious grout that possesses high strength and good durability and is capable of infiltrating such composites easily.

A high-performance cementitious grout intended for use in structural repair should meet several performance criteria, including fluidity, impermeability, strength, corrosion protection, sulfate resistance and in some cases frost durability. High performance is made possible by reducing porosity, inhomogeniety and microcracks in the cement grout and the transition zone. This can be achieved by using superplasticizers and supplementary cementing materials such as fly ash, silica fume, granulated blast furnace slag and natural pozzolan. The superior grout properties obtained in systems in which silica fume is added in combination with superplasticizers is well documented [4–9]. Limited data exist in the literature on the use of a combination of pozzolanic products for producing high-performance cementitious grouts [4,10]. The advantages of incorporating natural pozzolan in the grout include reduction in cost, lowering heat of hydration, decrease in bleeding, improved watertightness and sulfate resistance and enhanced longevity of the grout.

The main objective of this study is to develop high-performance cementitious grouts containing a suitable combination of silica fume and a local natural pozzolan for infiltrating relatively new classes of composite systems such as SIFCON and SIMCON. The study evaluated the rheological and mechanical properties of the grout mixes proposed and investigated their durability in terms of resistance to sulfate attack.

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2. Materials used in the study

Locally available ordinary Portland cement (ASTM Type 1) was used. The natural pozzolan was a blend of certain volcanic tuffs from Tal Rimah region of northeastern Jordan [4]. The Silica fume was in powder form with an average of 93% silicon dioxide. The chemical composition and some physical characteristics of these materials are given in Table 1. The superplasticizer used was a naphthalene formaldehyde sulfonated superplasticizer with 41% solids content and a specific gravity of 1.21. The superplasticizer was incorporated in all mixes to maintain the same degree of workability. All of the grouts used in the tests contained natural silica sand (75–600 μm) and had a mixing water/cementitious material ratio of 0.33. The actual w/c, taking the water from the liquid superplasticizer into account, was 0.34.

3. Experimental investigation

The laboratory program investigated the formulation and preparation of the grout mixes along with some of their important properties such as flowability, compressive strength, sulfate resistance, final bleed, setting times and drying shrinkage.

3.1. Mix proportions

The objective was to produce high- to very high-strength flowable grout containing local natural pozzolan and silica fume. Accordingly, a few trial grout mixes using different mix proportions and several combinations of natural pozzolan and silica fume were initially performed [4]. The laboratory program conducted in this investigation focused on four basic mixes in which silica fume and natural pozzolan contents were varied between 0% and 15% (by weight of cement). For comparison purposes, selected tests were also performed on the first mix by varying the proportions of its constituents, including silica fume, natural pozzolan, silica sand and superplasticizer. The details of these mixes are given in Table 2.

Table 1
Characteristics of cements, natural pozzolan and silica fume used in this study

Oxide (%)	Natural pozzolan	Silica fume	Cement (Type 1)
SiO_2	40.8	93	20.9
Al_2O_3	12.8	0.4	5.6
Fe_2O_3	10.5	1.2	3.1
CaO	11.8	0.2	62.7
MgO	9.1	1.2	2.2
Na_2O	2.3	0.1	0.2
K_2O	1.1	1.1	0.8
SO_3	0.1	0.3	2.9
Loss on ignition (%)	9.30	0.75	1.30
Specific gravity	2.68	2.10	3.15
Specific surface (m^2/kg)	600	20,000	300

Table 2
Grout mix proportions (by weight of cement)

Mix designation	Cement	Silica sand	Silica fume	Natural pozzolan	Water	Super plasticizer
1	1.00	0.60	0.00	0.00	0.33	0.02
2	1.00	0.60	0.05	0.05	0.33	0.02
3	1.00	0.60	0.10	0.10	0.33	0.02
4	1.00	0.60	0.15	0.15	0.33	0.02

3.2. Mixing and casting

The grout mixes were prepared following a modified ASTM C 305 procedure [11] using a Hobart-type laboratory mixer and extended mixing time to break as much as possible the natural pozzolan and silica fume clumps that tend to occur in the dry material and to obtain a fluid mix. The sequence of mixing was to add 75% of mixing water, 50% of superplasticizer, cement, silica fume, natural pozzolan and the remaining amount of superplasticizer and water. The mortar mixes were poured and compacted in 50-mm cubes in accordance with a modified ASTM C 109 procedure [11].

3.3. Curing and testing

After casting, the specimens were covered with wet burlap and stored in the laboratory at 23 °C and 65% relative humidity for 24 h and then demolded and placed in water. Each specimen was labeled as to the date of casting, mix used and serial number. The specimens were then taken out of water a day before testing and dried in air. A 2000-kN capacity uniaxial compressive testing machine was used to test the specimens. The specimens were loaded at a rate of 45 kN/min.

3.4. Flowability

The flowability is an important parameter relative to grout mix design. The flow of the grout was measured using an ASTM C 939 flow cone [11]. In the flow cone test, 1725 ml of grout flows from the discharge tube of the cone and the time of efflux or flow is recorded. The flow time of 1725 ml of water through the ASTM cone is 8 s.

3.5. Setting time

The initial setting time represents the onset of the solidification phase at which fresh grout can no longer be properly handled or injected and final setting time approximates the time at which hardening begin. The setting times were determined using the vicat apparatus described in ASTM C 191 and C 953 [11].

3.6. Bleeding

Bleeding is the appearance of free water on the surface of the unset grout, as the relatively heavy solid particles settle because of gravity. Bleeding of the freshly mixed grouts was measured following the procedure given in ASTM C 940 [11]. An 800-ml quantity of freshly mixed grout was poured into a 1000-ml glass graduated cylinder and covered. The height of free water was noted after complete sedimentation. This height, expressed as a percent of the original height of the grout, is referred to as the "percent final bleed".

3.7. Compressive strength

Considering the relative importance of compressive strength in cement and concrete technology, this property was investigated in depth during this study. The compressive strength of the grouts was measured on 50-mm cubes that were cast and cured in steel molds, following ASTM C 942 [10] and C 109. Strength measurements for grouts cured in water were conducted at ages of 3, 7, 28 and 56 days. The results are reported as an average of three specimens.

3.8. Resistance to sulfate attack

To evaluate the resistance of the grouts to sulfates and aggressive chemicals, 50-mm cube specimens were prepared following the guidelines of ASTM C 109 and C 942. After 28-day moist curing, the specimens were submerged in 20% magnesium sulfate solution, 20% sodium sulfate solution, seawaters and tap water. Sulfate concentrations were kept relatively high to accelerate deterioration and to compensate for small variations in concentration during the test. The progressive deterioration of the specimens were followed by visual observation, ultrasonic pulse velocity (UPV) measurements and relative strength determinations with respect to strengths of control specimens stored in tap water.

3.9. Drying shrinkage

Drying shrinkage is caused by loss of moisture during curing. Shrinkage can lead to the formation of shrinkage cracks, which may affect the long-term performance of the grout. The linear shrinkage of the grouts was measured following the procedure described in ASTM C 311 [11]. The method involves preparing prismatic specimens, curing them in water for 1 week and storing in air for 28 days in ambient temperature. Length changes of the prisms were determined weekly using a length comparator as described in ASTM C 490 [11].

Table 3
Basic properties of grouts

Mix designation	Flow (s)	Initial setting time (h)	Bleeding (%)	Increase in shrinkage at 28 days (%)
1	39	6	1.25	0.08
2	26	5	none	0.08
3	26	4	none	0.09
4	30	3	none	0.09

Table 4
Compressive strength of the grouts proposed

Mix designation	Compressive strengths (MPa)			
	3 days	7 days	28 days	56 days
1	50.9	62.9	72.0	79.6
2	59.4	70.9	86.9	90.4
3	56.0	65.8	78.5	83.9
4	59.8	68.3	89.8	93.2

4. Results and discussion

The following paragraphs underline the major trends regarding the properties of fresh and hardened grouts proposed in this study.

4.1. Fresh grout properties

Tables 3 and 4 presents some information about the fresh and hardened grouts and makes possible a comparison between the four grout formulations.

4.1.1. Flowability

Good flowability or low viscosity grouts are preferred for injection purposes. ASTM C 939-87 states that the flow cone test is intended for use with grouts having flow times less than 35 s. This value was not exceeded by the grouts containing a combination of natural pozzolan and silica fume as proposed in this study and shown in Table 3. For the grouts containing silica fume and natural pozzolan separately, (Tables 5 and 6), the ASTM flow limit was exceeded. This indicates that the rheological behaviour of the grouts containing a combination of natural pozzolan and silica fume is improved significantly compared to the grouts containing silica fume or natural pozzolan separately. If high flowability

Table 5
Effect of varying silica fume content on compressive strength and flow of Mix 1

Content (% by weight of cement)	Flow time (s)	Compressive strength (MPa)			
		3 days	7 days	28 days	56 days
0	39	50.9	62.8	72	79.6
5	25	61.3	67.5	70.4	76
10	27	55.5	57.4	67.5	72.2
15	55	56	61.0	77.8	83.0

Table 6
Effect of varying natural pozzolan content on compressive strength and flow of Mix 1

Content (% by weight of cement)	Flow time (s)	Compressive strength (MPa)			
		3 days	7 days	28 days	56 days
0	39	50.9	62.9	72.0	79.6
5	33	49.3	60.2	68.9	76.3
10	38	47.2	58.6	66.0	71.2
15	37	45.3	56.5	62.7	69.1

is desired for specific application, (Table 7), extra care should be exercised in increasing the amount of superplasticizer because this may increase the bleeding, cause delays in setting time and thus adversely affect the engineering properties of the hardened grouts.

4.1.2. Bleeding

Excessive bleed of grout mixes may leave numerous uncontrolled open channels within the grouted mass, which leads to weakness, porosity and lack of durability. The percent final bleed for the grouts proposed is presented in Table 3. It is observed that none of the grouts that contains a combination of natural pozzolan and silica fume exhibited bleeding. It is apparent that the addition of silica fume and natural pozzolan to the cement-based grouts decreased the porosity, increased the packing density and thus eliminated or minimized bleeding.

4.1.3. Setting time

The time required for grout to achieve its initial set and finally harden is important, relative to its practical use in the field. A commonly accepted problem encountered when using superplasticizers is excessive retardation of setting times. Thus, it is important to choose an appropriate amount of superplasticizer for a particular grout without encountering unacceptable delays in setting time. The initial setting time for the grouts investigated varied between 3 and 6 h as shown in Table 3. The initial setting time, however, for mixes with superplasticizer contents as high as 2% is still within the range of acceptable values for practical application. For all mixes studied, final set was achieved in 10–15 h after the initial setting.

4.2. Properties of hardened grouts

4.2.1. Compressive strength

The compressive strength of the grout is a property that relates directly to the structure of the cement paste and provides a good indicator of its quality. As expected, the hardened grouts developed high early compressive strength. After 28 days, it is around 90 MPa. The highest compressive strengths were observed for the grout formulations incorporating silica fume and natural pozzolan as shown in Table 4. It is interesting to see that the strength results shown in Tables 5 and 6 for the grout mix containing varying amounts of silica fume and natural pozzolan separately were relatively lower than those presented in Table 4 for the grouts containing similar combinations of silica fume and natural pozzolan. The increase in strength of the grouts containing pozzolan and silica fume is probably the result of a combined filler and pozzolanic effect. The filler effect leads to reduction in porosity of the transition zone and provides a dense microstructure and thus increases the strength of the grout. The pozzolanic effect helps in the formation of bonds between the densely packed particles in the transition zone through the pozzolanic reaction with the calcium hydroxide liberated during the hydration of Portland cement to form extra binding calcium silicates hydrates, which leads to further increase in strength [10].

It is worth mentioning that increasing the amount of silica sand beyond the limit specified for the proposed grouts (i.e. 60%; Table 8) would not affect the strength development but would cause a sharp reduction in flow values and thus create difficulties in handling and injecting the grout. However, the flow of the grouts containing larger amount of silica sand can be improved by incorporating larger amount of superplasticizer. This has to be done carefully, because it may lead to unacceptable delays in setting time and increases bleeding and segregation.

4.2.2. Resistance to sulfate attack

The progressive deterioration of the specimens submerged in sulfate solutions, seawater and tap water was monitored periodically by observing the visual changes in the cubes such as cracking, abrasions and spallings. UPV measurements were also taken at the beginning of the test and periodically afterwards. These measurements did not correlate well with the condition of the test. Some reduction

Table 7
Effect of varying superplasticizer content on compressive strength and flow of Mix 1

Content (% by weight of cement)	Flow time (s)	Compressive strength (MPa)			
		3 days	7 days	28 days	56 days
1	150	58.0	74.3	81	85.1
2	26	56.0	65.7	78.5	83.9
3	24	53.5	63.3	74.1	80.6
4	20	48.9	55.6	60.7	70.4

Table 8
Effect of varying silica sand content on compressive strength and flow of Mix 1

Content (% by weight of cement)	Flow time (s)	Compressive strength (MPa)			
		3 days	7 days	28 days	56 days
60	26.0	59.3	68.4	80.5	83.9
80	41	54.3	67.3	77.3	80.9
100	52	48.7	66.8	75.6	79.5
120	71	47.2	62.4	74.0	76.6

Table 9
Compressive strength of grouts submerged in sulfate solutions and sea waters

	Compressive strengths at 360 days (MPa)					
Mix designation	28-day strength	20% Na_2SO_4 solution	20% $MgSO_4$ solution	Red Sea water	Dead Sea water	Tap water
1	72	50.2 (0.60)	48.5 (0.58)	72.7 (0.87)	52 (0.62)	83.6 (1.00)
2	86.9	83.5 (0.84)	75.3 (0.76)	88.5 (0.89)	80.5 (0.81)	99.4 (1.00)
3	78.5	68 (0.77)	56.4 (0.64)	75.6 (0.86)	78.2 (0.75)	87.9 (1.00)
4	89.8	93.4 (0.92)	75.1 (0.70)	76.1 (0.75)	70 (0.69)	101.5 (1.00)

Numbers in parentheses represent relative strengths as fractions of control specimens values stored in tap water.

in UPV values was noticed only after the specimens were considerably deteriorated. Therefore, this method was not used for comparative studies. Relative strength determination with respect to strengths of control specimens stored in tap water was also conducted at final stages of the test. Since the strength tests meant the termination of the experiment, they were delayed as much as possible in this investigation. The compressive strength of the cubes was determined after 1 year of submersion in sulfate solutions and seawaters. The results are presented in Table 9. For comparison, relative strengths as fractions of control specimen values stored in tap water are also calculated and indicated inside parentheses below the strength figures.

As seen from Table 9, after 1 year of storage in 20% $MgSO_4$ solution, 20% Na_2SO_4 solution and Dead Sea water, the grout containing ordinary Portland cement only (Mix 1) showed a sharp reduction in compressive strength compared to those stored in tap water. The periodic visual observation indicates that severe signs of deterioration due to sulfate attack occurred near the corners of the cubes submerged in the previous solutions. The corners were the first to spall off because near the corners the intrusion will be from the two adjacent faces of the cube. It is well established that sodium and magnesium sulfates are harmful to concrete as they react with hydrated cement forming expansive compound, which cause expansion and loss of strength [12]. Dead Sea water has unusual composition as shown in Table 10, with a total salinity around 27%, about half of it being magnesium chloride followed by sodium and calcium chlorides [13].

As expected, the grout mixes containing various combinations of natural pozzolan and silica fume (Mixes 2–4) exhibited good resistance to sulfates and seawaters. Even though the relative strength of these mixes were reduced significantly, particularly in $MgSO_4$ solution and Dead Sea water, still they remained within the strength range of high-performance concretes reported in the literature [3,14]. The periodic observation indicated that all the cubes of the pozzolanic grouts performed well in sulfate solutions and seawaters. None of the cubes has shown significant deterioration or spalling even at the corners.

Table 10
Composition of sea waters

	Principal ions (g/l)								
	Na	K	Mg	Ca	Cl	Br	SO_4	HCO_3	pH
Dead Sea	33.5	6.3	34.5	13	180.0	4.1	0.9	0.25	6.3
Red Sea	12.2	0.44	1.88	0.51	22.7	0.07	3.16	0.15	8.2

The superior resistance of the mixtures containing pozzolanic products against sulfate attack is attributed to the pore refinement process occurring due to the conversion of lime forming from the hydration of cement into additional binding material through lime–pozzolan reaction. In addition to the pozzolanic reaction, the filler action due to the finer particle size of silica fume (0.1–0.2 μm) further densifies the pore structure to enhance the resistance to sulfate attack [15].

4.2.3. Drying shrinkage

The percent increase in 28-day drying shrinkage of 285-mm long bars containing silica fume and natural pozzolan was calculated by following the procedure prescribed in ASTM C 311. The drying shrinkage of the grouts proposed was very similar with a maximum increase of 0.09%, as shown in Table 3. Although the results were not conclusive, the values were close to each other and slightly exceeded the maximum percent increase of 0.08% as specified by most specifications for high-performance concrete [14].

5. Practical application

Some of the grouts proposed in this investigation were successfully used for repairing large-scale reinforced concrete beams that failed in diagonal shear. Grout Mix 4 was injected through a 25-mm thick jacket that was filled to capacity with hooked steel fibers (0.5-mm diameter, 30-mm long and 1172-MPa tensile strength) and then wrapped around the shear span where the diagonal shear crack has occurred. The repaired beams were tested to failure using third-point loading arrangement. The test results indicated that the use of HPFRC jacket eliminated brittle shear failure and allowed the repaired beams to reach their full flexural capacity resulting in a ductile flexural response.

6. Conclusions

A high-performance cement-based grout containing certain combinations of silica fume and natural pozzolan can provide a good balance between flowability, strength and durability. From a practical point of view, the fresh grouts exhibit no bleeding or segregation, high flowability and reasonable setting times that may be improved to satisfy more specific field requirements. The hardened grouts show high compressive strength, good resistance to sulfate attack and acceptable shrinkage performance.

At this time, there appears to be no hindrance to the use of the grouts proposed in a wide variety of HPFRC field applications to provide technical and economical advantages.

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