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Ultrafine Portland Cement Grouting Performance with or without Additives

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Abstract

The aim of this experimental study was to investigate the penetrability of ultrafine Portland cement suspensions with or without additives into sand specimens and the strength and permeability of grouted sand samples. It was shown that ultrafine Portland cement grouts with dispersive agent could be used to treat not only medium to fine sand but also 100% fine sand where chemical grouts can only penetrate The basic rheological properties of ultrafine Portland cement suspensions with or without additives were studied. The penetration performance of suspensions into various graded medium to fine sand specimens prepared at different relative densities was examined. The unconfined compressive strength and the permeability characteristics of sand specimens permeated with ultrafine Portland cement suspensions with or without additives were searched at different time intervals.

Keywords: *microsilica, ultrafine Portland cement, permeability, rheology, strength*

1. Introduction

Permeation grouting is widely used in geotechnical engineering as a ground improvement technique which involves the injection of suitable suspension and/or solution into soil and rock to either reduce the permeability or improve the mechanical properties. The properties and behavior of ultrafine cement, also referred as superfine cement or microfine cement, grouts have been a major research subject in recent years.

One of the main challenges in the utilization of ultrafine cement is their grain size distributions, which are quite finer than that of Ordinary Portland Cement (OPC). Henn and Soule (2010) compared three international and U.S. standards definitions for ultrafine cement: The International Society for Rock Mechanics (ISRM) defines it as: superfine cement is made of the same materials as ordinary cement. It is characterized by greater fineness (d_{95} < 16 μm) and an even, steep particle size distribution. Committee 552 of the American Concrete Institute (ACI) states that the particles must be less than 15 microns. The definition of Portland Cement Association is that the cement particles are less than 10 micrometer in diameter with 50 percent of particles less than 5 mm. Furthermore, British Standart characterizes cement as a ultrafine cement if the specific surface area is greater than 800 m^2/kg and the corresponding 95% finer (D_{95}) particle size is smaller than 20 μm (BS EN 12715, 2000). Ultrafine cement grouts are primarily used for grouting medium-to-fine sands where grouting is almost impossible using OPC grout. Ultrafine cement grouts have also better flow properties and bleed characteristics than OPC grout (De Paoli *et al*., 1992; Schwarz and Krizek, 1994; Warner, 2003). Although the cost of ultrafine cement is typically three to four times higher than that of OPC, this higher cost is often more than offset by the advantages and overall superior performance of ultrafine cement grouts. In addition, ultrafine cement grouts have substantial advantages over the more traditionally used chemical grouts in that toxicity is not of concern, and significantly higher strengths can be obtained at a lesser cost (Zebovitz *et al*., 1989). Furthermore, ultrafine cement grouts do not suffer strength reduction with time, as some chemical grouts do (Mollamahmutoglu, 2003). The first ultrafine cement available commercially was MC-500, manufactured by Onoda Cement Corporation in Japan (Clarke, 1984). Later, much finer cement products such as Sipinor A16, Rheocem 900, MC 300, MC 500 and MC 100 were produced in Europe as well as in U.S. Ultrafine cements of three different fundamental origins and methods of manufacture are commonly available. These include products based on OPC, granulated blast furnace slag cement and blended cement which is a combination of Portland cement and a pozzolanic material such as pumice and slag. There are fundamental differences in the chemistry of final products derived from this different basic ingredient however, and this can have a dramatic effect upon the penetrability of any resulting grout (Warner, 2003). It should be noted that even the same kind of cement products may not be compatible and/or comparable since some ultrafine cements are made by further grinding of OPC in which the gypsum has previously been combined, whereas others are ground to their final fineness, after which the gypsum is added. In the former case, setting time is less predictable, as the gypsum, which is

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softer than the other constituents, grinds more readily and thus provides excessive surface area for reaction (Taylor, 1990). For this reason, the properties of each ultrafine cement products such as grain size distribution, rheology, hydration and setting time must be very carefully investigated before use in any particular application.

The main purpose of this experimental study was to evaluate the grouting performance of ultrafine cement which is a Portland cement based product and has higher specific surface area than those of the same kind products such as MC 300, Onada MC 500 and Rheocem 900. In addition, the rheological properties of ultrafine Portland cement grouts with or without additives, their penetrability into various graded medium to fine sand specimens prepared at different relative densities were investigated. Finally, strength and permeability characteristics of successfully permeated sand samples at different time intervals were also examined.

2. Materials and Methods

2.1 Properties of the Sand

Quartz sand was used in this experimental study (Fig. 1). The specific gravity of the sand was determined to be 2.61 (ASTM D 854-02, 2002). The sand used was first divided into two different subgroups. Each subgroup was obtained using two sets of sieves in such a way that the coarser fraction of sand particles was first passed through a set of upper sieves (No.10-No.40) and those retained on No 40 sieve were collected and named as medium sand. Then the other subgroup was passed through a set of lower sieves (No.40-No.200). The amount of sand particles retained on No 200 sieve was collected and named as fine sand (ASTM D 2487-11, 2011). To broaden the range of various graded sand samples, the subgroups were mechanically mixed with each other at different percentages by dry mass. In this way, 15 different graded sand samples were formed (Table 1) and their particle size distribution curves were given in Fig. 2.

Fig. 1. Fine and Medium Sand Specimens

Table 1. Sand Samples

Sample Name	Particle size content (%)		$\gamma_{dry\ (max)}$ kN/m^3	$\gamma_{dry\ (min)}$ kN/m^3	e_{max}	e_{min}
	Fine	Medium				
1	100	0	15.80	12.60	1.14	0.71
2	90	10	15.70	12.60	1.14	0.71
3	80	20	15.70	12.70	1.13	0.72
4	75	25	15.70	12.70	1.13	0.72
5	70	30	15.70	12.70	1.13	0.72
6	60	40	15.60	12.70	1.12	0.73
7	55	45	15.60	12.70	1.12	0.73
8	50	50	15.60	12.80	1.11	0.73
9	45	55	15.60	12.80	1.11	0.73
10	40	60	15.60	12.80	1.11	0.73
11	35	65	15.50	12.80	1.11	0.73
12	30	70	15.50	12.80	1.10	0.74
13	20	80	15.50	12.90	1.10	0.74
14	10	90	15.50	12.90	1.09	0.74
15	0	100	15.40	13.00	1.08	0.75

2.2 Properties of Ultrafine Cement

The specific surface area of Ultrafin 12 (Fig. 3) is 2200 m²/kg and 95 percent of its particles is finer than 12 µm. Ultrafin 12 is a further grinding of Portland cement in ball mill. Moreover, it is sulphate resistant, chromate reduced and low alkaline injection cement. Chemical and physical properties of Ultrafin 12 together with those of ultrafine Portland cement products commonly cited in literature were given in Tables 2 and 3. Moreover, the grain

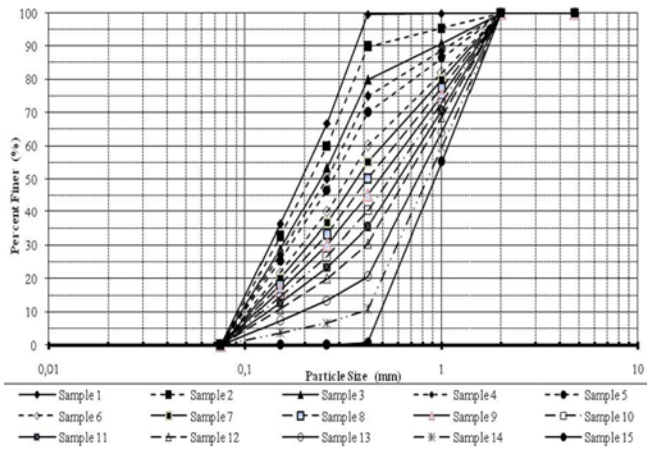

Fig. 2. Particle Size Distribution of Sand Specimens

Fig. 3. Ultrafin 12

Table 2. Physical Properties of some Commonly-used Ultrafine Cements

Types of Ultrafine cement	Ultrafin 12	MC 300	Rheocem 900	MC 500
Composition	Portland	Portland	Portland	Portland
Manufacturer	Heidelberg Cement AG	Onoda Cement Corporation	BASF The chemical company	Onoda Cement Corporation
D_{50} (μm)	3.1	2.8	3.7	4.1
D_{95} (μm)	10	11.2	11.1	9.9
Specific Gravity	3.1	3.15	-	3.1
Fineness (m^2/kg)	2,200	1,000	900	900

Table 3. Chemical Composition of some Commonly-used Ultrafine Cements and OPC

	*Ultrafin 12	*MC 300	*Rheocem 900	*MC 500	*OPC
SiO_2	22.5	17.9	19.6	30.6	21.3-25.0
Al_2O_3	3.8	4.9	4.2	12.4	3.4-6.0
Fe_2O_3	4.7	3.5	4.1	1.1	2.7-4.3
CaO	64.3	61.6	62.5	48.4	62.2-64.3
MgO	0.9	2.6	2.8	5.8	1.8-2.9
SO_3	2.3	2.4	2.1	0.8	1.6-2.3

Note: *obtained from manufacturer

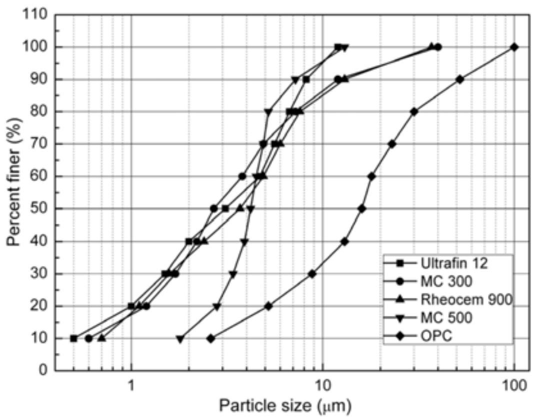

Fig. 4. Particle Size Distributions of various Ultrafine Cements and OPC

size distributions of Ultrafin 12 and others were also shown in Fig. 4. As seen, Ultrafin 12 has finer particles and higher specific surface area than others. The particle size distribution of ultrafine cement was determined by particle sizing instrument called Mastersizer. It uses the technique of laser diffraction to measure the size of particles. It does this by measuring the intensity of light scattered as a laser beam passes through a dispersed particulate sample. This data was then analyzed to calculate the size of the particles which created the scattering pattern.

2.3 Dispersive Agent

Due to the humidity and electrostatic interaction, fine cement particles tend to flocculate. When mixed with water, lumping of

Fig. 5. Microsilica

cement particles is inevitable although they are mixed vigorously. As a result, the viscosity of ultrafine cement suspension increases and the groutability decreases. To overcome this limitation, it is common practice to add dispersive agent to the suspension to increase fluidity (Bremen, 1997; Eriksson *et al*., 2004; Perret *et al*., 2000) in amounts that vary between 1 and 5% of the dry mass of the cement. In this study, Addiment Injektionshilfe 1 was used as a dispersive agent. Addiment Injektionshilfe 1 is a melamine-based dispersive agent and used to decrease interparticle attractive forces and enhance full wetting of the cement particles during mixing. According to the information given by the Addiment Injektionshilfe 1 supplier (HeidelbergCement AG, Germany), its density varies from 1.180 g/cm^3 to 1.220 g/cm^3.

2.4 Microsilica

Microsilica, also known as silica fume or condensed silica, produced by German company was used in this experimental study. The average particle size of microsilica was around 3.21 μm. It is usually added into cementations' suspensions by about 10% of the dry mass of cement (Fig. 5).

2.5 Dispersive Agent and Microsilica mixtures

The percentages of Dispersive agent and Microsilica in grouts were 2% and 10% of dry mass of ultrafine cement respectively.

2.6 Injection Test Apparatus

The injection test apparatus consisted of a manometer, 5 molds for compressive strength tests, 3 molds for permeability, a grout tank with propeller and relevant connections (Fig. 6). Molds had an inside diameter of 53.60 mm and 150 mm height. They were designed in a way that the height to diameter ratio of 2.0 could be obtained for compressive strength tests. The details of test apparatus were shown in Fig. 7.

2.7 Specimen Preparation for Injection

The inner surface of the molds was lightly lubricated to eliminate sample disturbance upon removal from molds after injection. To prepare the specimens, a coarse sand layer of about 20 mm in thickness was first placed at the bottom of the molds to

Fig. 6. Grouting Test Apparatus

distribute the suspension evenly into the sample. Sand samples were then poured into molds in three equal layers. Each layer was compacted using a wooden tamp to achieve the desired relative density before placing the next layer. In order to produce sand specimens at a desired relative density, the maximum and the minimum dry unit weights of the samples were determined (ASTM D 4253-00, 2002; ASTM D 4254-00, 2002) (Table 1). After placing the specimen at the achievable relative density, a coarse sand layer of about 20 mm in thickness was also placed at the top of the molds. Then the top and bottom end-plates of the molds were clamped using tie rods (Fig. 7). Finally, samples were saturated by applying upward flow of water before injection. After grouting, the specimens were kept in molds until the grout sets. Then the specimens were removed from the molds and preserved in a humid room at a temperature of 20°C until testing time.

2.8 Preparation of Suspension

The ultrafine cement and water were mixed thoroughly in a container by means of high-speed propeller-type mixer at 3000 rpm for about three minutes. Then, 10% microsilica and 2% dispersive agent by dry mass of ultrafine cement were added to the suspensions and the suspensions were mixed for two additional minutes to ensure the dispersion of solid particles in the suspension. The grout was then transferred to the grouting tank where it was agitated at a speed of 150 rpm to avoid the sedimentation of grout during injection and was finally injected into the sand specimen in molds as agitation went on. The injection pressure was ranged from 0.25 and 0.50 MPa.

2.9 Rheological Properties of Suspension

2.9.1 Stability

The stability (bleed capacity and bleeding rate) of a grout is very important such that the lack of stability of a grout results in the particles dropping from suspension and clogging the lines. Also the voids of soil mass may not be adequately filled from the bleeding of unstable grout.

Suspensions with applicable range of Water/Cement (w/c) ratios were placed in a 1000 ml graduated cylinder and the volume of bleed liquid on top of grout to the total volume of the suspension at the end of two hours were recorded (ASTM C 940-98a, 2002) and given in Table 4. The results indicated that pure ultrafine Portland cement grouts with w/c ratios of 0.8, 1.0, 1.2 and 1.5 were stable. While the addition of dispersive agent reduced the bleedings of pure ultrafine cement grouts, the

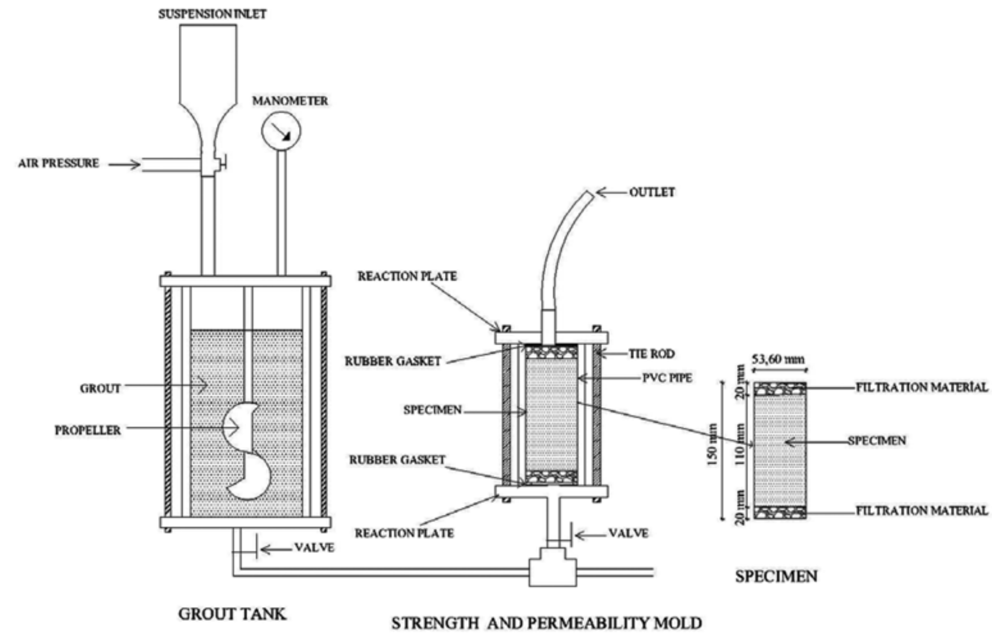

Fig. 7. Technical Details of the Grouting Test Apparatus

Table 4. Results of Stability, Setting Time and Viscosity

	W/C	Microfine cement		Microfine cement + Dispersive agent		Microfine cement + Microsilica		Microfine cement + Dispersive agent + Microsilica	
		Bleeding (%)	Explanation	Bleeding (%)	Explanation	Bleeding (%)	Explanation	Bleeding (%)	Explanation
Stability	0.8	0.00	Stable	0.00	Stable	0.00	Stable	0.00	Stable
	1.0	0.00	Stable	0.00	Stable	0.90	Stable	0.60	Stable
	1.2	1.33	Stable	1.32	Stable	1.40	Stable	1.30	Stable
	1.5	2.67	Stable	1.50	Stable	3.00	Stable	2.00	Stable
	2.0	8.15	Unstable	5.50	Unstable	5.30	Unstable	5.45	Unstable
	2.5	23.15	Unstable	20.20	Unstable	25.15	Unstable	24.30	Unstable
Setting Time	W/C	Initial Setting Time (min.)	Final Setting Time (min.)	Initial Setting Time (min.)	Final Setting Time (min.)	Initial Setting Time (min.)	Final Setting Time (min.)	Initial Setting Time (min.)	Final Setting Time (min.)
	0.8	360	440	410	790	380	490	550	740
	1.0	370	467	420	880	450	615	625	825
	1.2	433	693	470	1320	505	780	697	1252
	1.5	455	930	480	2680	615	1220	550	2520
	2.0	680	4058	-	-	-	-	-	-
	2.5	1625	22290	-	-	-	-	-	-
Viscosity	W/C	Flow time (sec.)	Viscosity (cP)	Flow time (sec.)	Viscosity (cP)	Flow time (sec.)	Viscosity (cP)	Flow time (sec.)	Viscosity (cP)
	0.8	52	45.05	51	43.74	-	-	84	85.86
	1.0	41	24.50	40	23.15	44	36.02	43	34.03
	1.2	37	15.99	35	10.97	39	19.83	38	17.81
	1.5	34	8.33	33	3.50	35	12.67	35	9.65
	2.0	33	2.61	31	1.22	33	4.03	33	5.19
	2.5	33	2.26	31	1.20	32	2.40	31	1.24

addition of microsilica increased them. However, the bleedings of the mixtures of ultrafine Portland cement and microsilica suspensions remained within the range of stability. Furthermore, the addition of dispersive agent to the mixture of ultrafine cement and microsilica suspensions reduced their bleedings. In summary, the bleedings of all grouts with w/c ratios of 0.8, 1.0, 1.2 and 1.5 were less than five percent and they were stable in general.

2.9.2 Setting Time

The initial and final setting times of ultrafine cement suspensions given in Table 4 were determined (ASTM C 191-04b, 2002). It was seen that as the w/c ratio of pure ultrafine cement suspensions increased, the setting time increased too. The addition of dispersive agent and microsilica to ultrafine cement suspensions increased the setting times. Moreover, the combining effect of microsilica and dispersive agent on the setting times of ultrafine cement suspensions was much higher than the individual effect of dispersive agent and microsilica.

2.9.3 Viscosity

Flow times from Marsh cone (ASTM C 939-02, 2002) and the viscosities from Lombardi's (1985) approach were obtained respectively and given in Table 4. Lombardi (1985) devised a cohesion meter that can be used in conjunction with the Marsh viscosity to determine the viscosity of the grout. When the w/c ratio increased, the viscosities of pure ultrafine cement suspensions decreased. While the addition of dispersive agent to ultrafine cement suspensions decreased their viscosity, the viscosities of ultrafine cement suspensions increased with the addition of microsilica. Similar results for viscosity regarding dispersive agent effect were also reported in literature (Hakansson *et al*., 1992).

3. Results and Discussion

3.1 Penetrability

The ability of a grout to penetrate porous material is a function of the rheological properties of grout suspension and the physical characteristics of the cement, as well as the physical characteristics of the soil (Mollamahmutoglu *et al*., 2012; Eklund and Stille, 2008; Mollamahmutoglu *et al*., 2007; Schwarz and Krizek, 1994).

The penetrability of the ultrafine cement suspensions, with or without additives, into various graded fine-to-medium sand specimens at different relative densities was investigated. For grouting of sand specimens, w/c ratio of 1.0 of ultrafine cement suspensions was chosen because its sedimentation percentage was zero and setting times were short by comparison with others. Moreover, the w/c ratio of 1.0 for practical applications is widely adopted in practice.

The penetration of ultrafine cement suspensions became unsuccessful for the specimens of 1, 2, 3 and 4 at the relative density of 30%, for the specimens of 1, 2, 3, 5 and 6 at the relative density of 50%, and for the specimens of 1, 2, 3, 5, 6, 8 and 10 at the relative density of 70% as the percentage of fine

Table 5. Permeation Test Results of Ultrafine Cement Grouts with or without Additives

Sample Name	Particle size (%)		D_r (%)	W/C	Grouting performance			
	Fine	Medium			Ultrafine cement	Ultrafine cement + Dispersive agent	Ultrafine cement + Microsilica	Ultrafine cement + Dispersive agent + Microsilica
15	0	100	30	1	Successful	Successful	Successful	Successful
12	30	70		1	Successful	Successful	Successful	Successful
11	35	65		1	Successful	Successful	Successful	Successful
10	40	60		1	Successful	Successful	Successful	Successful
9	45	55		1	Successful	Successful	Successful	Successful
8	50	50		1	Successful	Successful	Successful	Successful
7	55	45		1	Successful	Successful	Successful	Successful
6	60	40		1	Successful	Successful	Successful	Successful
5	70	30		1	Successful	Successful	Successful	Successful
4	75	25		1	Unsuccessful	Successful	Unsuccessful	Successful
3	80	20		1	Unsuccessful	Successful	Unsuccessful	Successful
2	90	10		1	Unsuccessful	Successful	Unsuccessful	Successful
1	100	0		1	Unsuccessful	Successful	Unsuccessful	Successful
15	0	100	50	1	Successful	Successful	Successful	Successful
12	30	70		1	Successful	Successful	Successful	Successful
10	40	60		1	Successful	Successful	Successful	Successful
8	50	50		1	Successful	Successful	Successful	Successful
6	60	40		1	Unsuccessful	Successful	Unsuccessful	Successful
5	70	30		1	Unsuccessful	Successful	Unsuccessful	Successful
3	80	20		1	Unsuccessful	Successful	Unsuccessful	Successful
2	90	10		1	Unsuccessful	Successful	Unsuccessful	Successful
1	100	0		1	Unsuccessful	Successful	Unsuccessful	Successful
13	20	80	70	1	Successful	Successful	Successful	Successful
12	30	70		1	Successful	Successful	Successful	Successful
10	40	60		1	Unsuccessful	Successful	Unsuccessful	Successful
8	50	50		1	Unsuccessful	Successful	Unsuccessful	Successful
6	60	40		1	Unsuccessful	Successful	Unsuccessful	Successful
5	70	30		1	Unsuccessful	Successful	Unsuccessful	Successful
3	80	20		1	Unsuccessful	Successful	Unsuccessful	Successful
2	90	10		1	Unsuccessful	Successful	Unsuccessful	Successful
1	100	0		1	Unsuccessful	Successful	Unsuccessful	Successful

particles and relative density increased (Table 5). The effect of relative density was more pronounced. However, with the addition of dispersive agent to ultrafine cement suspensions, all specimens including 100% fine sand were successfully permeated. The results of the penetration were characterized as “successful” when the predetermined quantity of grout (two void volumes of the sand specimen) were injected, as “unsuccessful” when the grout penetration was less than the length of the sand specimens (150 cm) or particles are filtered from the grout (Schwarz, 1997).

Ultrafine cement suspensions mixed with microsilica had the same penetration performance as pure ultrafine cement suspensions. With the addition of dispersive agent to ultrafine cement plus microsilica suspensions, all samples were successfully injected. It was proved that the addition of dispersive agent to ultrafine Portland cement and/or mixture of ultrafine Portland cement and microsilica suspensions, the penetrability of all suspensions was enhanced and even 100% find sand specimen at a relative density of 70 percent was able to be grouted.

3.2 Groutability with Reference to Burwell Criteria

The injection test results of groutability were also compared with groutability estimations, empirical relations, developed by Burwell (1958). According to Burwell criteria, if $D_{15\ soil} / D_{85\ grout\ solid} > 25$, the injection is possible where $D_{15\ soil}$ is the diameter through which 15% of the total soil mass passes and $D_{85\ grout\ solid}$ is the diameter through which 85% of the total grout mass passes. If $D_{15\ soil} / D85_{grout\ solid} < 11$, then the injection is not possible. Furthermore, if $D_{10\ soil} / D_{95\ grout\ solid} > 11$, the injection is possible where $D_{10\ soil}$ is the diameter through which 10% of the total soil

Table 6. Comparison of the Test Results with Burwell's Criteria

(D_{85}) grout solid = 0,0072 mm				(D_{95}) grout solid = 0,0100 mm							
Sample No	Grain size percent Fine	Grain size percent Medium	(D_{10}) soil (mm)	(D_{15}) soil (mm)	N = (D_{15}) soil / (D_{85}) grout solid N > 25	N_c = (D_{10}) soil / (D_{95}) grout solid N > 11	Burwell's criteria	Ultrafine cement	Ultrafine cement + Dispersive agent	Ultrafine cement + Microsilica	Ultrafine cement + Dispersive agent + Microsilica
15	0	100	0.50	0.52	72	50	Successful	Successful	Successful	Successful	Successful
14	10	90	0.46	0.48	66	46	Successful	Successful	Successful	Successful	Successful
13	20	80	0.42	0.44	61	42	Successful	Successful	Successful	Successful	Successful
12	30	70	0.38	0.39	55	38	Successful	Successful	Successful	Successful	Successful
11	35	65	0.36	0.37	52	36	Successful	Successful	Successful	Successful	Successful
10	40	60	0.34	0.35	49	34	Successful	Successful	Successful	Successful	Successful
9	45	55	0.32	0.33	46	32	Successful	Successful	Successful	Successful	Successful
8	50	50	0.30	0.31	43	30	Successful	Successful	Successful	Successful	Successful
7	55	45	0.27	0.29	40	27	Successful	Successful	Successful	Successful	Successful
6	60	40	0.25	0.27	37	25	Successful	Successful	Successful	Successful	Successful
5	70	30	0.21	0.23	31	21	Successful	Successful	Successful	Successful	Successful
4	75	25	0.19	0.21	28	19	Successful	Unsuccessful	Successful	Unsuccessful	Successful
3	80	20	0.17	0.18	26	17	Successful	Unsuccessful	Successful	Unsuccessful	Successful
2	90	10	0.13	0.14	20	13	Successful	Unsuccessful	Successful	Unsuccessful	Successful
1	100	0	0.09	0.10	14	9	Successful	Unsuccessful	Successful	Unsuccessful	Successful

Table 7. Unconfined Compressive Test Results

Sample No	Particle size content (%)		D_r (%)	W / C	Ultrafine cement						Ultrafine cement + Dispersive agent					
					Unconfined compressive strength, MPa						Unconfined compressive strength, MPa					
	Fine	Medium			1 st day	3 rd day	7 th day	14 th day	28 th day	56 th day	1 st day	3 rd day	7 th day	14 th day	28 th day	56 th day
15	0	100		1	0.58	1.16	2.90	5.08	10.30	11.80	0.62	1.32	2.99	6.04	10.90	12.56
12	30	70		1	0.52	1.12	2.79	4.98	10.00	11.60	0.54	1.15	2.79	5.75	10.33	11.96
11	35	65		1	0.49	1.00	2.51	4.29	8.72	10.20	0.50	1.02	2.76	5.06	9.18	10.52
10	40	60		1	0.47	0.95	2.38	4.21	8.55	9.80	0.48	0.97	2.61	4.79	8.74	10.11
9	45	55		1	0.45	0.91	2.27	4.02	8.22	9.50	0.46	0.92	2.48	4.59	8.40	9.80
8	50	50		1	0.43	0.86	2.16	3.85	7.89	9.20	0.45	0.89	2.42	4.46	8.11	9.49
7	55	45	30	1	0.41	0.81	2.03	3.61	7.35	8.60	0.40	0.83	2.24	4.22	7.59	8.87
6	60	40		1	0.37	0.77	1.92	3.48	7.02	8.20	0.36	0.75	2.03	3.91	7.24	8.46
5	70	30		1	0.33	0.69	1.73	3.22	6.08	7.20	0.32	0.61	1.51	3.41	6.32	7.37
4	75	25		1	---	---	---	---	---	---	0.28	0.57	1.53	2.81	5.13	5.93
3	80	20		1	---	---	---	---	---	---	0.24	0.49	1.33	2.44	4.42	5.06
2	90	10		1	---	---	---	---	---	---	0.14	0.28	0.76	1.43	2.58	3.02
1	100	0		1	---	---	---	---	---	---	0.10	0.22	0.59	1.13	2.09	2.44
15	0	100		1	0.40	0.52	1.17	1.83	4.01	4.66	0.48	0.77	1.53	3.19	6.11	7.21
12	30	70		1	0.25	0.49	0.93	1.66	3.32	4.91	0.37	0.61	1.21	2.67	5.03	6.14
10	40	60		1	0.19	0.45	0.87	1.56	3.18	4.30	0.26	0.52	1.07	2.01	4.33	5.55
8	50	50		1	0.16	0.33	0.81	1.51	2.99	3.70	0.21	0.37	0.93	1.79	3.60	4.45
6	60	40	50	1	---	---	---	---	---	---	0.18	0.38	0.92	1.68	3.28	4.12
5	70	30		1	---	---	---	---	---	---	0.15	0.32	0.78	1.42	2.78	3.49
3	80	20		1	---	---	---	---	---	---	0.13	0.27	0.66	1.21	2.36	2.96
2	90	10		1	---	---	---	---	---	---	0.11	0.23	0.56	1.02	2.00	2.51
1	100	0		1	---	---	---	---	---	---	0.08	0.18	0.43	0.79	1.54	1.93
12	30	70		1	0.21	0.41	1.02	1.76	3.63	4.21	0.27	0.56	1.38	2.50	4.89	5.67
10	40	60		1	---	---	---	---	---	---	0.23	0.48	1.17	2.12	4.15	4.81
8	50	50		1	---	---	---	---	---	---	0.19	0.40	0.99	1.80	3.51	4.07
6	60	40	70	1	---	---	---	---	---	---	0.16	0.34	0.84	1.52	2.98	3.45
5	70	30		1	---	---	---	---	---	---	0.14	0.29	0.71	1.29	2.52	2.93
3	80	20		1	---	---	---	---	---	---	0.12	0.25	0.60	1.09	2.14	2.48
2	90	10		1	---	---	---	---	---	---	0.10	0.21	0.51	0.93	1.81	2.10
1	100	0		1	---	---	---	---	---	---	0.08	0.16	0.39	0.71	1.39	1.62

mass passes and $D_{95grout\ solid}$ is the diameter through which 95% of the total grout mass passes. If $D_{10\ soil} / D_{95grout\ solid} < 5$, then the injection is not possible. A comparison between the results from this experimental study and those from the Burwell's criteria for the sand samples at different relative densities was made and a typical comparison for the sand samples at 30% relative density was given in Table 6.

The test results and the Burwell (1958) criteria were consistent with each other for some cases regarding pure ultrafine and ultrafine plus microsilica cement grouts for the sand samples at relative densities of 30, 50 and 70 percentages. It was previously stated that Burwell approach could not be considered as a universal criteria (De Paoli *et al*., 1992; Zebovitz *et al*., 1989). However, they were in harmony with each other when the ultrafine cement suspensions were agitated with dispersive agent. This might be attributed to the fact that Burwell criteria are based solely on grain sizes of grout and soil and do not take into consideration such factors as w/c ratio, viscosity, dispersive agent and relative density which have a considerable effect on the penetrability of grouts as observed in this experimental study.

3.3 Strength of Grouted Samples

The unconfined compression strength (ASTM D 4219-02) of grouted sand samples were determined at different relative densities, curing periods and particle size distributions. The test results were given in Tables 7 and 8. The results showed that the compressive strength of sand specimens injected with ultrafine cement with or without additives increased with curing period.

The rate of strength increase was high up to 28 day but decreased sharply after that. The fineness to which the cement is ground will evidently affect the rate at which the cement hydrates; grinding the cement more finely will result in a faster reaction. In addition, most of the strength of grouted specimens was gained at the end of 28th day. While the unconfined compressive strength of grouted sand samples were slightly increased by the addition of dispersive agent to ultrafine Portland cement suspen-

Table 8. Unconfined Compressive Test Results

Sample No	Particle size content (%)		D_r (%)	W / C	Ultrafine cement + Microsilica						Ultrafine cement + Dispersive agent + Microsilica					
					Unconfined compressive strength, MPa						Unconfined compressive strength, MPa					
	Fine	Medium			1st day	3rd day	7th day	14th day	28th day	56th day	1st day	3rd day	7th day	14th day	28th day	56th day
15	0	100		1	0.70	1.57	3.93	8.28	15.05	17.35	1.11	2.41	5.37	10.87	19.61	22.55
12	30	70		1	0.66	1.45	3.81	7.79	13.97	16.03	0.91	2.00	4.74	9.78	17.57	20.34
11	35	65		1	0.64	1.33	3.72	7.61	13.00	15.17	0.85	1.74	4.63	8.50	15.42	17.67
10	40	60		1	0.63	1.02	3.33	7.13	12.01	14.13	0.79	1.64	4.33	7.95	14.52	16.78
9	45	55		1	0.61	0.97	3.01	6.96	11.31	13.03	0.75	1.53	4.07	7.53	13.78	16.07
8	50	50		1	0.59	0.90	2.88	6.63	10.07	12.14	0.73	1.47	3.92	7.23	13.14	15.37
7	55	45	30	1	0.54	0.85	2.80	6.03	9.03	11.05	0.64	1.37	3.61	6.79	12.22	14.28
6	60	40		1	0.50	0.80	2.47	5.77	8.01	10.37	0.57	1.22	3.24	6.26	11.59	13.53
5	70	30		1	0.43	0.72	2.01	5.03	7.50	8.99	0.51	0.98	2.41	5.42	10.04	11.73
4	75	25		1	---	---	---	---	---	---	0.44	0.91	2.42	4.44	8.10	9.36
3	80	20		1	---	---	---	---	---	---	0.38	0.79	2.08	3.82	6.94	7.95
2	90	10		1	---	---	---	---	---	---	0.21	0.45	1.19	2.24	4.03	4.71
1	100	0		1	---	---	---	---	---	---	0.16	0.34	0.91	1.75	3.24	3.79
15	0	100		1	0.45	0.94	2.32	4.20	8.22	10.32	0.64	1.34	3.29	5.97	11.67	14.65
12	30	70		1	0.30	0.62	1.52	2.76	5.40	6.77	0.42	0.88	2.16	3.92	7.66	9.62
10	40	60		1	0.25	0.52	1.29	2.34	4.57	5.74	0.36	0.74	1.83	3.32	6.49	8.15
8	50	50		1	0.21	0.31	0.99	1.85	3.65	4.66	0.29	0.44	1.41	2.63	5.18	6.62
6	60	40	50	1	---	---	---	---	---	---	0.26	0.53	1.31	2.38	4.66	5.85
5	70	30		1	---	---	---	---	---	---	0.22	0.45	1.11	2.02	3.95	4.96
3	80	20		1	---	---	---	---	---	---	0.18	0.38	0.94	1.71	3.35	4.20
2	90	10		1	---	---	---	---	---	---	0.16	0.33	0.80	1.45	2.84	3.56
1	100	0		1	---	---	---	---	---	---	0.12	0.25	0.62	1.12	2.18	2.74
13	20	80		1	0.28	0.55	1.37	2.55	5.03	6.11	0.42	0.81	2.00	3.77	7.99	8.71
12	30	70		1	---	---	---	---	---	---	0.36	0.76	1.86	3.38	6.60	7.66
10	40	60		1	---	---	---	---	---	---	0.31	0.64	1.58	2.86	5.60	6.49
8	50	50		1	---	---	---	---	---	---	0.26	0.54	1.34	2.42	4.74	5.50
6	60	40	70	1	---	---	---	---	---	---	0.22	0.46	1.13	2.05	4.02	4.66
5	70	30		1	---	---	---	---	---	---	0.19	0.39	0.96	1.74	3.41	3.95
3	80	20		1	---	---	---	---	---	---	0.16	0.33	0.81	1.48	2.89	3.35
2	90	10		1	---	---	---	---	---	---	0.13	0.28	0.69	1.25	2.45	2.84
1	100	0		1	---	---	---	---	---	---	0.10	0.22	0.53	0.96	1.88	2.18

sions (Table 7), the addition of microsilica increased them considerably (Table 8). The increasing effect of microsilica on unconfined compressive strength of grouted specimen was also reported by Aitcin *et al*. (1984) and Domone and Tank (1986). The strength of grouted specimens obtained by the combination of ultrafine cement, microsilica and dispersive agent were higher than others. Finally, the unconfined compressive strength of the grouted sand samples decreased with the increase of fine particle percentage and the relative density of sand specimens (Tables 7 and 8). The reason might be twofold: on one hand, increase in relative density reduced the voids of the sand specimens and on the other hand, finer particles filling the voids formed by coarser particles of sand specimens prevented adequate penetration of grouts into sand specimens. The insufficient penetration of ultrafine cement suspensions due to the increasing percentage of fine particles in sands were also stated by Zebovitz *et al*. (1989), Markou *et al*. (2012) and Eklund and Stille (2008).

3.4 Permeability of Grouted Samples

The permeability of grouted sand specimens was investigated by performing falling head permeability tests (ASTM D 5856-95, 2002) under the gradient of 19. No flow of water was observed through specimens for the period of two months. Although some permeability values of microfine cement grouted sand samples such as 10^{-4} m/s (Zebovitz *et al*., 1989) and 10^{-6} m/s (Schwarz and Chirumalla, 2007) were reported, their test conditions were not comparable. There were some differences arising from such factors as w/c ratio of grout used, fineness of cement and therefore efficiency of grout penetration into sand specimens and the time and pressures under which the permeability tests were carried out.

4. Conclusions

The main conclusions drawn from this study were as follows:

1. The ultrafine cement grouts with applicable range of *w/c* ratios of 0.8, 1.0, 1.2 and 1.5 had a good bleeding and flow characteristics with or without additives, namely dispersive agent and/or microsilica.
2. The penetrability of ultrafine Portland cement suspensions decreased with the increase of relative density as well as the percentage of fine particles of sand specimens. However, addition of dispersive agent into ultrafine Portland cement suspensions greatly improved their penetrability. Additionally, the penetrability of ultrafine Portland cement plus microsilica suspensions was also improved by the addition of dispersive agent and all samples having various gradation and relative density were able to be successfully injected.
3. The unconfined compressive strength of sand specimens permeated with ultrafine Portland cement suspensions increased with curing period. Though adding additives to the cement suspensions increased the unconfined compressive strength of grouted sand specimens in general, microsilica addition increased their strength considerably. However, the unconfined compressive strength decreased with the increase of fine particle percentage and the relative density of sand specimens.
4. Specimens permeated with ultrafine Portland cement suspensions with or without additives were subjected to falling head permeability tests and found to be impermeable after two months of testing period.
5. Burwell's criteria were shown to provide a good estimate of groutability of ultrafine Portland cement grouts provided that they were agitated with dispersive agent.
6. It was shown that ultrafine Portland cement grouts having dispersive agent could be used to treat not only medium to fine sand but also % 100 fine sand where chemical grouts can only penetrate. Furthermore, cementations' grouts do not deteriorate with time as most chemical grouts do. They are nontoxic, less expensive and environmentally friendly.

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