PROPERTIES OF SUPERPLASTICIZER-AMENDED SUPERFINE CEMENT GROUTED SAND

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The effect of superplasticizer on the grouting performance of superfine cement and the engineering properties of grouted sand were investigated. At first, the bleeding, setting time, and viscosity tests were conducted to determine the rheological characteristics of superfine cement grouts with or without superplasticizer at different water-cement ratios. Thereafter, the groutability of superfine cement grouts into various graded sand specimens with or without superplasticizer were tested. Those specimens grouted successfully were then subjected to unconfined compression tests at different time intervals. The addition of superplasticizer to superfine cement grouts increased their bleeding, initial and final setting times but decreased their viscosities. As the unconfined compressive strength (UCS) of superfine cement grouted sand specimens increased with the addition of superplasticizer. It was shown that the engineering properties of superfine cement grouted sand specimens were better improved with the addition of superplasticizer.

Keywords: *Superplasticizer; Superfine cement; Groutability; Unconfined compressive strength; Permeability*

1. Introduction

Geotechnical engineering uses penetration grouting as a ground improvement technique to decrease the permeability or raise the strength of soil and rocks. Either suspensions or solutions are used in penetration grouting. In the treatment of fine-grained soils, superfine cement grouts have attracted considerable attention over the last decades. The definitions for superfine cement regarding international and United States standards were given below [1]. The International Society for Rock mechanics states that the 95 percent of particles must be less than 16 microns with steep grain size distribution. The ACI declares that all particles must be less than fifteen microns. The cement particles are less than ten μm in diameter with fifty percent of particles less than five mm. The Portland Cement Association explains that all particles are less than ten micron and fifty percent of which must be less than five micron. In addition, the British Standard reports that 95 percent of the particles less than twenty micron must have a specific surface area greater than 800 m^2/kg [2]. Ordinary Portland Cement (OPC) injections fail to permeate medium-to-fine sands where chemical grouting is possible but chemical grouts have severe disadvantages such as low strength, toxicity, and costliness. Therefore, superfine cement grouts have been developed to overcome those drawbacks. The flow and bleed characteristics of superfine cement injections are better than those of OPC injections [3-5]. Zebovitz [6] stated that superfine cement grouts could result in higher strength than those of chemical grouts at a lower cost. Mollamahmutoglu [7] mentioned that superfine cement grouted sands did not lose their strength with time as silicate-based grouts did due to syneresis. The microfine cement was first commercially produced in Japan under the brand name of MC-500 [8]. Various products having much finer cement particles have been manufactured in Europe and in U.S., which have three different fundamental origins and production methods. They are OPC, blast furnace slag cement, and pumice and slag amended Portland cement. These differences can dramatically influence the groutability of superfine cement grouts [5]. The groutability of the same sort of cement products may be advanced by further grinding but it is obvious that the cement products cannot be ground beyond their final fineness. Hence, the goal of this research was to investigate if the groutability of superfine cement was better improved by the addition of superplasticizer. Many researchers have studied the effects of the additives to the superfine cement on strength of injected sands [9-12]. In addition, in this experimental study, the effects of superplasticizer to be added into superfine cement suspension on the strength properties of grouted sands were investigated.

2. Materials and Methods

2.1 Sand

In this study, quartz sand was used for grouting purpose. The specific gravity of which was tested to

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Table 1

Sand speciment

Sample No	Particle size content %		$\gamma_{dry(max)}$ kN/m³	$\gamma_{dry(min)}$ kN/m³	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	70	30	15.70	12.70	1.13	0.72
5	60	40	15.60	12.70	1.12	0.73

Table 2

Physical and chemical properties of superfine cement

	Composition	80%Slag+20%Portland
Physical Properties	D_{50} (μm)	1.7
	D_{95} (μm)	4,0
	Specific Gravity	3.94
	Fineness (cm²/g)	11,800
Chemical Properties	SiO_2	30.0
	Al_2O_3	9.5
	Fe_2O_3	1.25
	CaO	45.0
	MgO	5.6
	SO_3	—

be 2.61 with respect to ASTM D 854-02 [13]. At the beginning, the sand specimen was partitioned into two different subgroups. Each one was formed utilizing two sets of sieves as follows. The specimen was sifted through a set of No 10 and No 40 sieves in the first place and the accumulated portion on No 40 sieve were removed and referred to as medium sand. Afterward, the sand specimen was sifted through a set of No 40 and No 200 sieves. The retained fraction on No 200 sieve was collected and referred to as fine sand [14]. Fine and medium sand specimens were mixed with each other at various percentages (Table 1) by dry mass to obtain different graded sand samples whose grain size distribution curves were displayed in Fig. 1.

The minimum and the maximum dry unit weights of those sand specimens compacted at 40 percent relative density were obtained in accordance with ASTM D 4253-00 [15] and ASTM D 4254-00 [16] standards in return and given in Table 1.

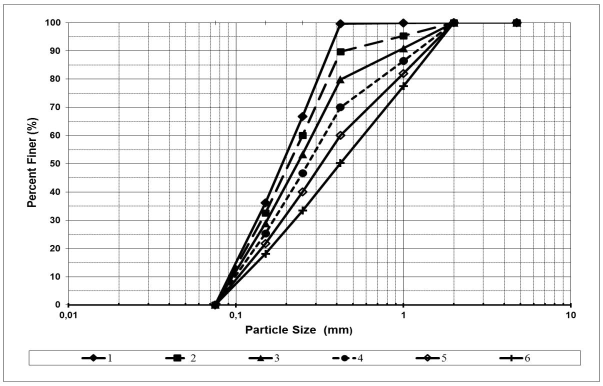

Fig. 1- Grain size distribution of sand specimens.

2.2 Superfine Cement

If the specific surface area of cement is greater than 8000 cm²/g and the corresponding ninety five percent finer (D_{95}) particle diameter is smaller than twenty μm then it is defined as superfine cement [2]. In this regard, the specific surface area of superfine cement (Spinor A6) used in this study is 11,800 cm²/g and 95% finer particle diameter is smaller than 4μm. It is composed of eighty percent slag and twenty percent Portland cement and its grain size distribution was determined by particle sizing instrument which uses the technique of laser diffraction to measure the size of particles.

Particle size distribution of superfine cement were determined with a Laser Particle Size Analyzer (wet method), which measures the intensity of the scattering light when a laser beam passes through a dispersed particulate sample. The data obtained were then analyzed to calculate the size of the particles forming this scattering pattern. The data obtained in this way was then

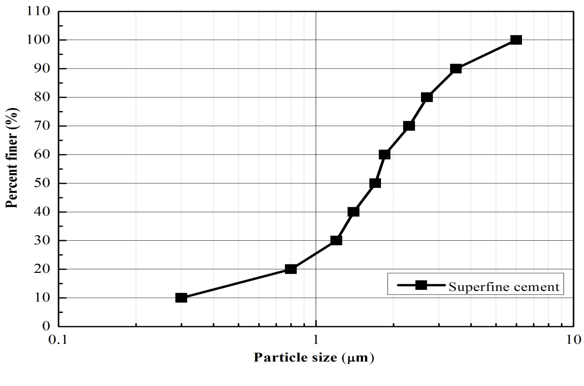

Fig. 2- Particle size distribution of superfine cement.

evaluated to figure out the particles 'size which brought forth the grain size distributions of superfine cement given in Fig. 2. Additionally, Table 2 showed the physical and chemical properties of superfine cement.

2.3 Superplasticizer

Superplasticizers are synthetic water-soluble organic materials that decrease the amount of water required to achieve a certain stability of concrete, the water-cement ratio and the cement content and increase the slump. The superplasticizer is also known as highly water reducing agents. Fine cement particles are liable to flocculate as a result of humidity and electrostatic interaction. No matter how vigorously they are mixed. Cement particles eventually get lumpy when they are blended with water and the viscosity of superfine cement suspensions increase and their groutability decreases after all. To get over this problem, dispersive agents are generally added to the grouts in the range of one and five percent of the dry mass of the cement, which decreases their viscosity [17,18]. The dispersive agent used as a superplasticizer was naphthalene sulphonate based MasterRheobuild 561 (BASF) with a density varying from 1.142 g/cm^3 to 1.202 g/cm^3.

2.4 Stability, Setting Times and Viscosity Tests

Stability, setting time and viscosity characteristics of superfine cement grouts with or without superplasticizer were determined regarding the water-cement (w/c) ratios of 0.8, 1.0, 1.2 and 1.5. The contents of superplasticizer added to the superfine cement suspensions were 1%, 3%, and 5%.

The stability tests of superfine cement suspensions with different w/c ratios were carried out in a 1,000 ml graduated cylinders in accordance with ASTM C 940-98a [19]. The bleed liquid volume accumulated on the surface of suspension were noted at the end of two hours and the bleeding percent was defined as the ratio between the bleed liquid volume and the total volume of the suspension. Fig. 3 showed the stability test results of suspensions with and without superplasticizer.

The setting times (initial and final) of superfine cement suspensions with and without superplasticizer were obtained with regard to ASTM C 191-04b [20] and the results were presented in Fig. 4.

The viscosities of superfine cement suspensions with or without superplasticizer were measured by Brookfield DV-III Rheometer with reference to ASTM D 2196-15 [21] and the test results were given in Fig. 5.

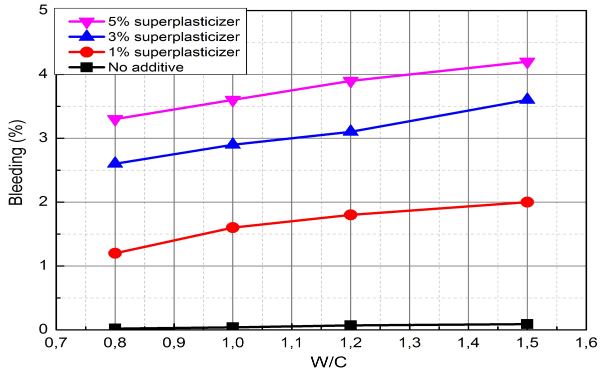

Fig. 3- Variation of superfine cement suspensions' stabilities with w/c ratio.

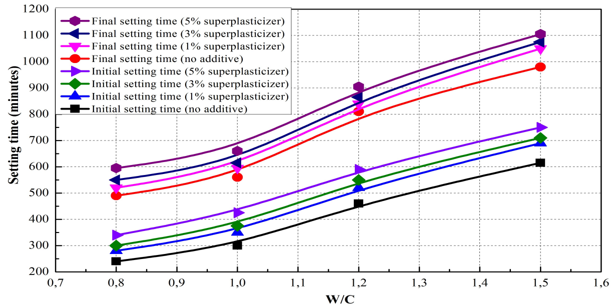

Fig. 4- Variation of setting times with w/c ratio.

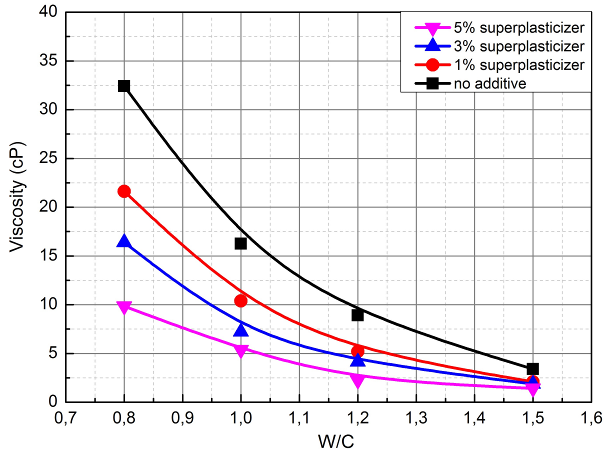

Fig. 5- Variation of viscosities with w/c ratio.

2.5 Grouting test

The grouting apparatus comprised a grout tank with propeller, a manometer, specimen molds 52 mm in diameter and 120 mm in length and fittings, the details of which were given in Fig. 6.

Before grouting process, the inside surface of the specimen molds was slightly greased to avoid the grouted sample disturbance during removal. The specimens for grouting were prepared as follows: an about eight mm fine gravel layer was positioned at the bottom of the specimen molds to permeate the superfine cement suspension uniformly within the specimen and then the molds were filled with sand in almost three equal layers. Each of which was compacted by means of a vibratory hammer to have the

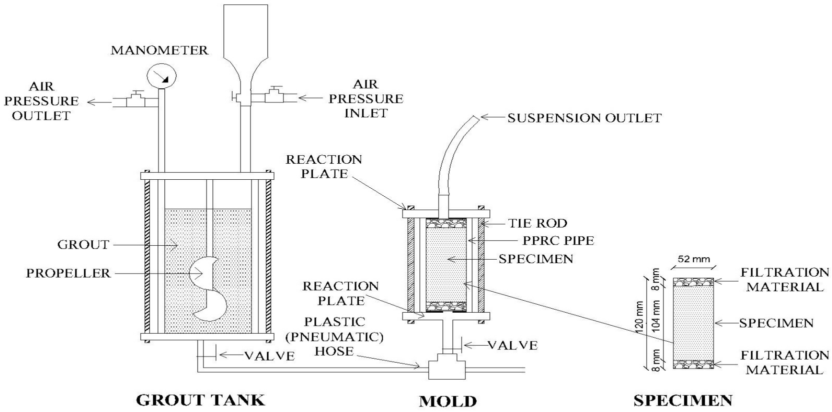

Fig. 6- Grouting test set-up.

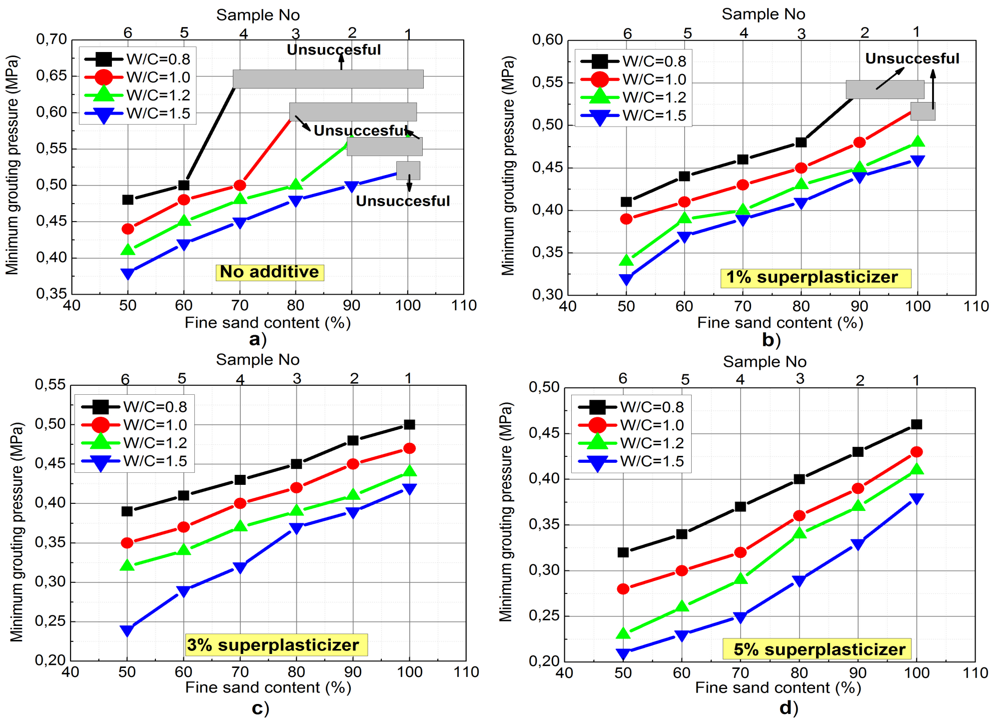

Fig. 7- Variation of grouting pressure with w/c ratio and fine sand content.

desired relative density before positioning the next one. The relative density chosen for the sand specimens to be grouted was 40 percent which represented the medium dense sand. The empirical equation of relative density was used to calculate the initial void ratio based on the minimum and maximum void ratios determined experimentally as stated before. Taking into account specific gravity, the initial void ratio and the related unit weight, the amount of sand needed was figured out. So the relative density for each layer of sand specimen was controlled by way of these quantities.

After forming the final layer at the required relative density, an about eight mm fine gravel layer was also positioned at the top of the sand specimen in order to prevent the drag of fine particles along with grout. Thereafter, the end-plates of molds were fixed through tie rods (Fig. 6) and the molds were filled with water. The in and out ends of molds were then sealed off and put aside by the time of grouting. Prior to grouting, the sand specimens in molds were fully saturated with water under 0.020 MPa pressure. The saturation was ensured in such a way that water continued to permeate the specimens till no air bubbles were released from the outlets of the molds.

The superfine cement, water, and superplasticizer were properly blended in a bucket nearly 3 minutes using high-speed propeller-type mixer at three thousand rpm. The suspension was then poured into the grouting tank and the grouting operation was initiated. The grouting pressure was supplied with an air compressor and monitored by a manometer fixed on it. During grouting of sand specimens, the agitation of suspension in the tank was carried on by means of propeller (Fig. 6) at a speed of one hundred and fifty one hundred and fifty rpm to prevent the sedimentation of cement particles. The grouting operations were run at two stages. The first stage was without superplasticizer and the second one was with superplasticizer at the afore-mentioned ratios of w/c and the contents of superplasticizer. The minimum permeation grouting pressures for the sand specimens to be grouted were obtained by way of trial. The variation of grouting pressure with both fine sand, w/c ratio and the superplasticizer contents was presented in Fig.7.

2.6 Unconfined Compressive Strength (UCS) Test

The grouted sand samples in molds were kept in a vertical position for five days and then extracted. They were then submerged underwater in a tank with 20°C temperature and kept there for a given period. Just before testing, the fine gravel layers at both ends of grouted specimens were cut off by a diamond blade saw and the both ends were capped with Paris plaster. The UCS tests were conducted on the specimens cured at 7, 14,

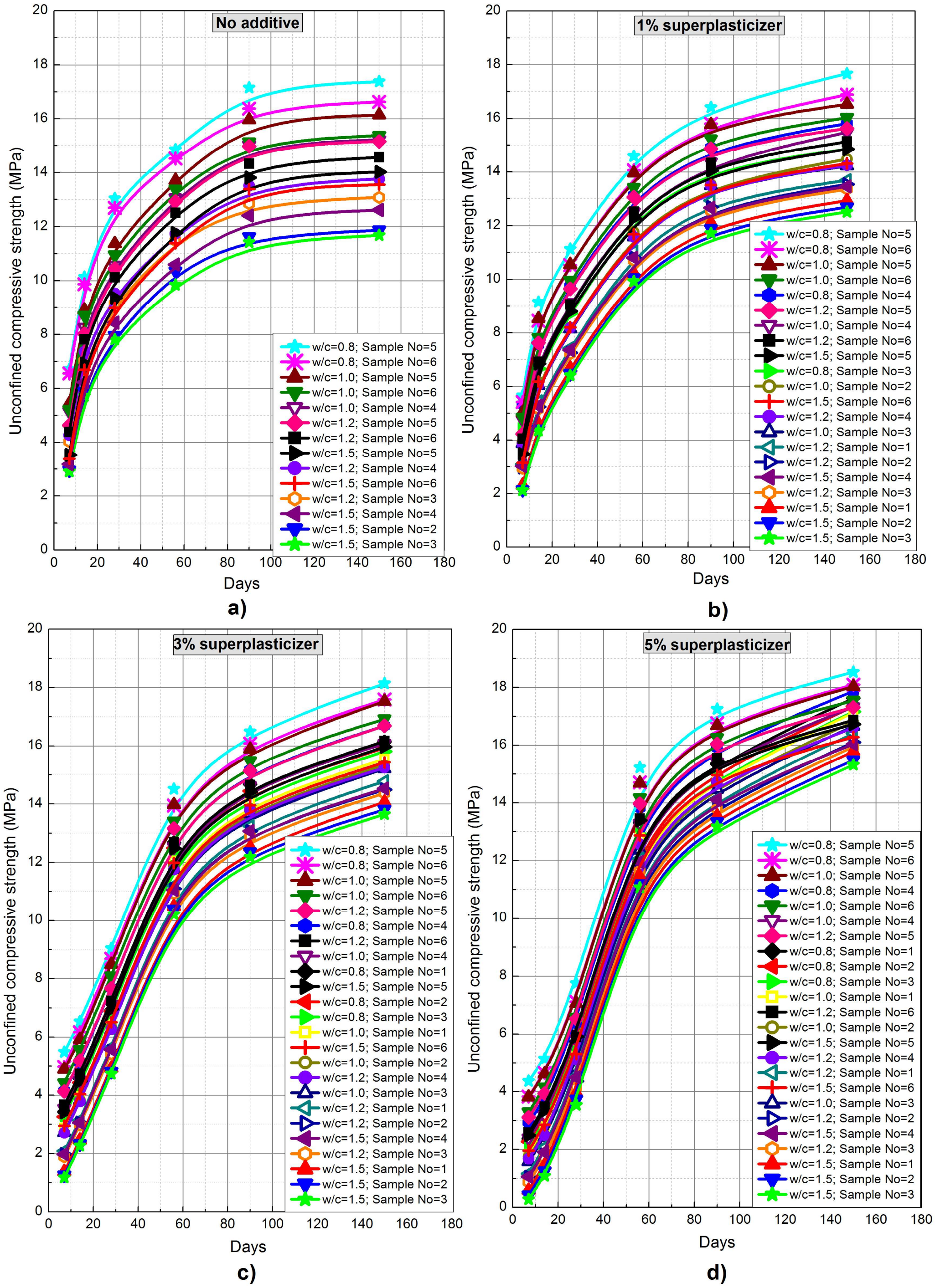

Fig. 8- Effect of curing time and superplasticizer content on the UCS of grouted sand specimens.

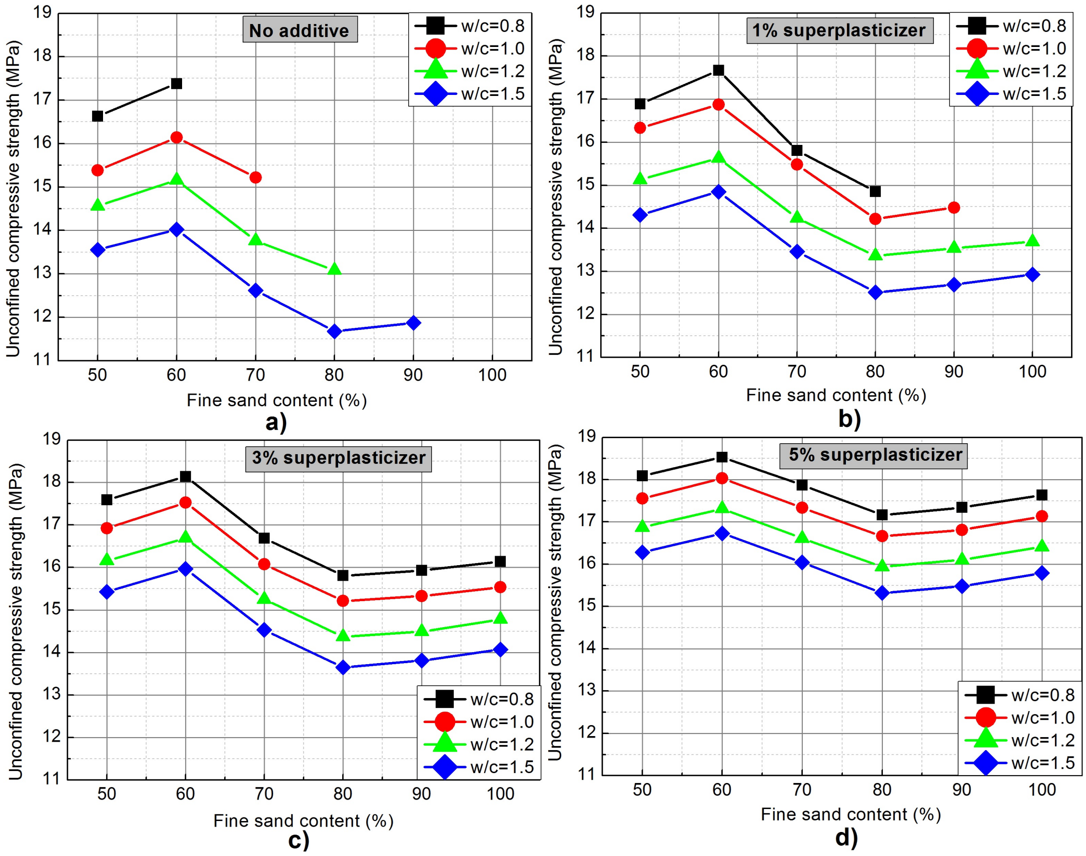

Fig. 9- Effect of fine content on the UCS of grouted sand specimens.

28, 56, 90 and 120 days according to ASTM D4219-02 [22]. The UCS values of grouted sand specimens with and without superplasticizer at different time intervals were given in Fig. 8. Furthermore, the effect of fine content on the UCS of grouted sand samples were also presented in Fig. 9.

3. Results and Discussion

3.1 Suspensions

Fig. 3 showed that superfine cement grouts with and without superplasticizer at 0.8, 1.0, 1.2 and 1.5 w/c ratios bled less than 5% at the end of two hours and thus they were regarded as stable grouts. The bleeding percentage of grouts increased with the increase of both w/c ratio and superplasticizer content.

The initial and final setting times of superfine cement suspensions without superplasticizer ranged from 240 to 615 minutes and 490 to 980 minutes respectively. The initial setting times of superfine cement suspensions with 1%, 3% and 5% superplasticizer contents varied from 280 to 690 minutes, from 300 to 710 minutes and from 340 to 750 minutes respectively. Furthermore, the final setting times of superfine cement suspensions with 1%, 3% and 5% superplasticizer contents ranged from 520 to 1050 minutes, from 550 to 1075 minutes and from 595 to 1105 minutes respectively. The setting times (initial and final) of superfine cement solutions were extended as w/c ratio and superplasticizer content increased (Fig. 4).

The viscosities of superfine cement suspensions without superplasticizer were in between 3.4 and 32.41 cP. The viscosities of superfine cement suspensions with 1%, 3% and 5% superplasticizer contents ranged from 2.1 to 21.62 cP, from 1.86 to 16.39 cP and from 1.42 to 9.85 respectively (Fig. 5). The viscosities of superfine cement suspensions were decreased with the increase of w/c ratio and the superplasticizer content.

3.2 Groutability

The groutability of suspensions with w/c ratios of 0.8, 1.0, 1.2 and 1.5 and without superplasticizer was unsuccessful for specimens 1, 2, 3 and 4, for specimens 1, 2 and 3, for specimens 1 and 2, and for specimen 1 respectively. The grouting pressures for the sand specimens successfully grouted with non-additive superfine cement suspensions varied from 0.38 to 0.63 MPa (Fig. 7).

The penetrability of superfine cement suspensions with w/c ratios of 0.8 and 1.0 and with 1% superplasticizer content was unsuccessful for specimens 1 and 2 and for specimens 1 respectively. In addition, the penetrability of

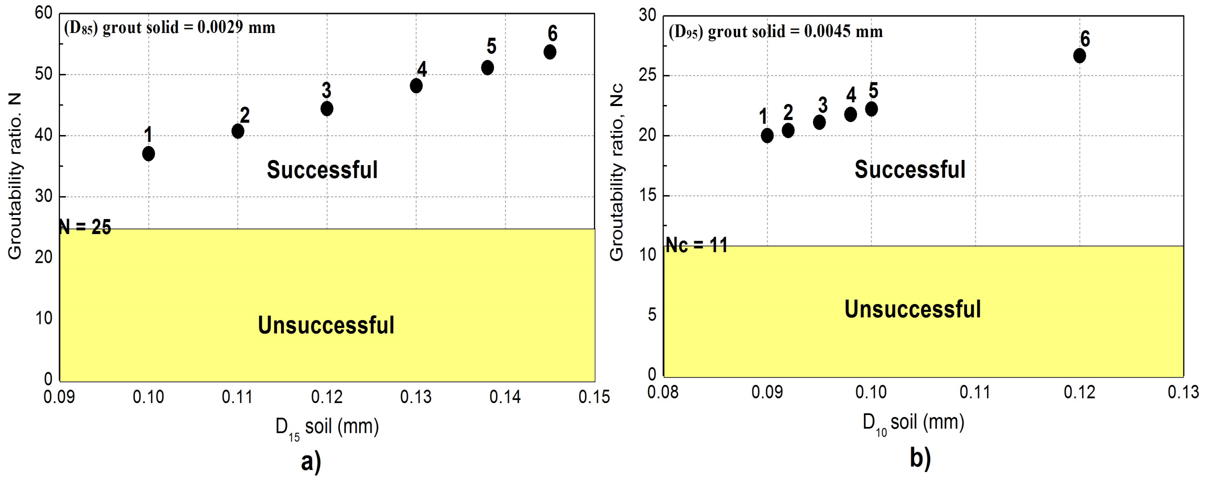

Fig. 10- Assessment of groutability with reference to Burwell criteria.

superfine cement suspensions with w/c ratios of 1.2 and 1.5 and with 1% superplasticizer was successful for all specimens. The grouting pressures for the sand specimens successfully grouted with 1% superplasticizer content varied from 0.32 to 0.53 MPa (Fig. 7).

Besides, all sand specimens were successfully grouted with the superfine cement suspensions mixed with 3% and %5 superplasticizer contents. While the grouting pressures of the superfine cement suspensions with 3% superplasticizer content varied from 0.24 to 0.50 MPa, the grouting pressures of the suspensions with 5% superplasticizer content ranged from 0.21 to 0.46 MPa (Fig. 7).

Groutability of superfine cement suspensions prepared at different w/c ratios increased with the addition and the content of superplasticizer and the grouting pressures for sand specimens were also reduced accordingly (Fig. 7).

Fig. 10 showed that the superfine cement grouting was possible for all sand specimens according to Burwell criteria [23]. However, the grouting tests displayed that the non-additive superfine cement suspensions with different w/c ratios did not satisfy Burwell criteria. In addition, the superfine cement suspensions with the contents of 3% and 5% superplasticizer merely met Burwell criteria. It appeared that grouting of soils was not only related to soil and cement particle sizes as suggested by Burwell but also it was pertaining to w/c ratio and the content of superplasticizer as revealed by this experimental study (Fig. 10).

3.3 UCS

The UCS values of sand specimens grouted with non-additive superfine cement suspensions at the end of 150th day curing period ranged from 11.68 MPa to 17.38 MPa. The UCS of grouted sand specimens increased swiftly with time up to 28th day and then the rate of UCS increase slowed down (Fig. 8).

The UCS values of sand specimens grouted with superfine cement suspensions mixed with 1% superplasticizer content at the end of 150th day curing time ranged from 12.51 MPa to 17.67 MPa] and then the rate of UCS increase slowed down (Fig. 8).

The UCS values of sand specimens grouted with superfine cement suspensions mixed with 3% superplasticizer content at the end of 150th day curing time ranged from 13.65 MPa to 18.14 MPa. The UCS of grouted sand specimens increased swiftly with time up to 60th day and then the rate of UCS increase slowed down (Fig. 8).

The UCS values of sand specimens grouted with superfine cement suspensions mixed with 5% superplasticizer content at the end of 150th day curing period varied from 15.32 MPa to 18.53 MPa. The UCS of grouted sand specimens increased swiftly with time up to 70th day and then the rate of UCS increase slowed down (Fig. 8).

The addition of 1%, 3% and 5% of superplasticizer contents to superfine cement suspensions brought about 4%, 11% and 18% increases in the UCS of grouted sand specimens respectively. The increase appeared to result from two reasons: the first one was due to the improvement of the permeation of superfine cement solutions enhanced by superplasticizer. The second one was that the superplasticizer used had a property of increasing the UCS of superfine cement owing to its chemical nature.

The sand specimens grouted with superfine cement suspensions without superplasticizer reached 98% of their ultimate UCS at the end of 90th day. Similarly, those sand specimens grouted with superfine cement suspensions having 1%, 3% and %5 contents of superplasticizer gained 94%, 90% and 88% of their ultimate UCS at the end of 90th day respectively. As the content of superplasticizer added to superfine cement solutions was increased the time needed for the strength gaining of grouted sand specimens was prolonged (Fig. 8).[1]

The UCS of grouted sand samples reduced with the increase of w/c ratio of superfine cement suspension with or without superplasticizer. While the highest UCS of grouted sand samples was obtained by the superfine cement suspension with w/c ratio of 0.8, the lowest UCS of grouted sand samples resulted from the superfine cement suspension with w/c ratio of 1.5 (Fig. 8).

The grain size distribution of sand specimens also affected the UCS of injected sand samples. As the highest UCS was obtained from the sample 5 grouted with superfine cement suspensions with or without superplasticizer, the specimen 3 resulted in the lowest UCS (Figs. 8 and 9). It seemed that the permeation of superfine cement suspensions into the voids formed by coarse particles of sand specimens were filled by fine particles thus interrupting the sufficient and uniform penetration of superfine cement suspensions. As a result, the UCS of grouted sand decreased (Fig. 9).

4. Conclusions

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- Bleeding percentages have decreased with the addition of silica fume into the superfine Although the bleeding percentages, initial and final setting times of superfine cement grouts having w/c ratios of 0.8, 1.0, 1.2 and 1.5 were increased with the addition and the increase of superplasticizer content as well as the w/c ratio, they all remained stable and had a good bleeding properties.
- The groutability of superfine cement grouts was increased with the increase of w/c ratio and bettered more by the addition and the content of superplasticizer. Accordingly the grouting pressures were reduced.
- Burwell criteria were only satisfied with superfine cement grouts blended with 3% and 5% superplasticizer contents. Therefore, they could not be used as a sole and exclusive criteria for the prediction of the groutability of soils based on grout and soil particles' sizes.
- The strength of grouted sand specimens was decreased with the increase of water-cement ratio. Although the addition of superplasticizer to the superfine cement grouts prolonged the setting time of grouted sand it increased the strength of grouted sand. The strength of superfine cement grouted sand continued to increase with time at a decreasing rate.
- In general, the engineering properties of superplasticizer-amended superfine cement grouted sand were found to be better than those of non-additive superfine cement grouted sand.

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