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Laboratory tests for studying the performance of grouted micro-fine cement

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Abstract. In geological engineering, grouting with Portland cement is a common technique for ground improvement, during which micro-fine cement is applied as a slurry, such that it intrudes into soil voids and decreases soil porosity. To determine the utility and behavior of cements with different Blaine values (index of cement particle fineness) for stabilization of fine sand, non-destructive and destructive tests were employed, such as laser-ray determination of grain size distribution, and sedimentation, permeability, and compressive strength tests. The results of the experimental study demonstrated a suitable mix design for the upper and lower regions of the cement-grading curve that are important for grouting and stabilization. Increasing the fineness of the cement decreased the permeability and increased the compressive strength of grouted sand samples considerably after two weeks. Moreover, relative to finer (higher Blaine value) or coarser (lower Blaine value) cements, cement with a Blaine value of 5,100 cm^2/g was optimal for void reduction in a grouted soil mass. Overall, study results indicate that cement with an optimum Blaine value can be used to satisfy the designed geotechnical criteria.

Keywords: non-destructive tests; micro-fine cement; grouting

1. Introduction

Portland cement is one of the most common materials used in grouting to improve soil, that is, to decrease soil hydraulic conductivity and increase soil stiffness and strength. In addition to the rheological properties and the water to cement (W/C) ratio of the grout slurry, the ability of the slurry to penetrate the soil depends upon physical characteristics of the soil under treatment (Eriksson *et al.* 2004). In fine compacted soils, using coarse-grained cement for grouting is virtually impossible. Normal cement contains large (up to 40 m) particles that can clog fine pores in the soil. Therefore, the cement particles would be deposited before reaching the required location in soil voids, resulting in a small grouted area. One practical approach to overcome this difficulty is to use micro-fine cement, with a Blaine value greater than 3,000 cm^2/g. The Blaine value is an index of cement particle fineness, with fineness increasing with increasing Blaine value. Micro-fine cement particles are ground to a very small size and their specific area is relatively high

Permeation grouting involves filling pore spaces in soil with grout, without disturbing the soil structure. Unlike injection of chemical solutions in silt and fine sand soils, which is expensive and can be harmful to the environment, permeation grouting is inexpensive and simple, and therefore is broadly applicable for soil improvement and reclamation. Permeation grouting techniques involving micro-fine cement have been developed and refined during the last two decades. Determination of the effects of various factors on grouted sand particles has been the objective of numerous research studies e.g., (Schwarz and Krizek 1994, Dano *et al.* 2004, Schwarz and Chirumalla 2007, Mollamahmutoglu and Yilmaz 2011, Markou and Droudakis 2013).

However, the effect of certain factors such as the cement type and fineness, the suspension properties, the curing time (>28 days), the sand grading and the degree of saturation of sand prior to grouting, on the strength and permeability of microfine cement grouted sands needs further documentation. Moreover, the available, limited in number, means of estimation of the microfine cement grouting effectiveness include a correlation between the unconfined compressive strength and the permeability coefficient of microfine cement grouted sands as well as an equation relating the grouted sand strength to the cement to water ratio of microfine cement suspension (Dano *et al*. 2004).

The compression strength of grouted sand increases significantly and its permeability coefficient decreases considerably with decreasing W/C ratio of the slurry and also increasing with cement fineness.

The experimental investigation reported herein is part of an extensive research effort aimed towards the development of a relatively fine-grained material, suitable for permeation grouting obtained by an ordinary cement produced in Iran. The objectives of this paper are : 1) to quantify the influence on permeability and strength of Tehran alluvial fine sand samples of grouting with slurries made with micro-fine Portland cement from the Abiek Cement Production Complex, 2) to document the effect of different cement fineness and water to cement ratio, 3) to employ the laser-ray determination of grain size distribution and sedimentation test in order to determine the utility an behavior of grouted sand, and 4) to evaluate the

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stabilization ability of this Portland cement after 28 days of curing time.

The outcome of the experiments will lead to the production of cement with suitable Blaine values for projects requiring grouting, such as constructing a base and/or cover liner on pervious geomaterials to reduce infiltration into and leaching out of the site (Henn *et al*. 2005, Pantazopoulos *et al*. 2012).

2. Experimental materials and methods

2.1 Cement type and fineness

For the purposes of this investigation, Type I Portland cement was produced by inter-grinding with seven different Blain values between 3000 Cm^2/g and 7000 Cm^2/g were selected. For all cases, the percentage of 45-µm residue was determined by Alpine sieving apparatus, and this value was considered as a criterion in categorizing the cements. For instance, the percentage of 45-µm residue for PC with 3000±100 cm^2/g and 4600±100 cm^2/g Blaine fineness were obtained to be 7% and 2.8%, respectively. The grain size distributions of these cements were obtained using the laser-ray technique shown in Fig. 1. All slurries for grouting during this investigation were prepared using potable water since it is considered appropriate for preparing grouted microfine cement. The water-to-cement ratio (W/C) of the slurries was set equal to 1.5 and 1.8 by weight.

2.2 Slurry

In total, 360 kg of Type I Portland cement was used to prepare slurries for grouting. Cements had Blaine values (the specific surface area of the cement particles per gram of cement) of 3000, 3900, 4600, 5100, 6000, 6800 or 7000 cm^2/g. The microfine cement and water are mixed thoroughly in a container by means of high-speed propeller-type mixer at 2800 rpm for about three minutes (Fig. 2(a)). Bentonite is one of the most common additives used in cement-based suspension grouts.

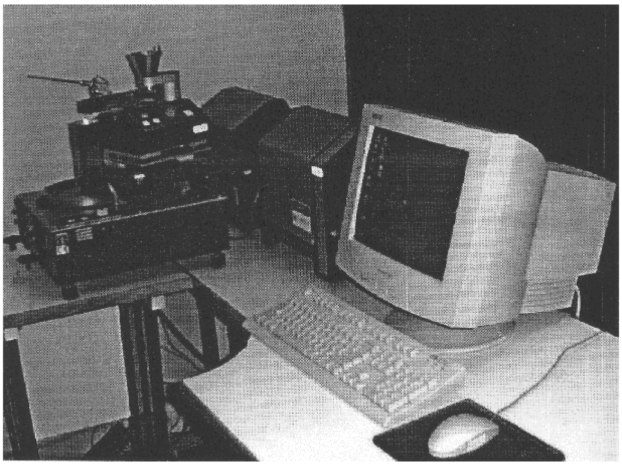
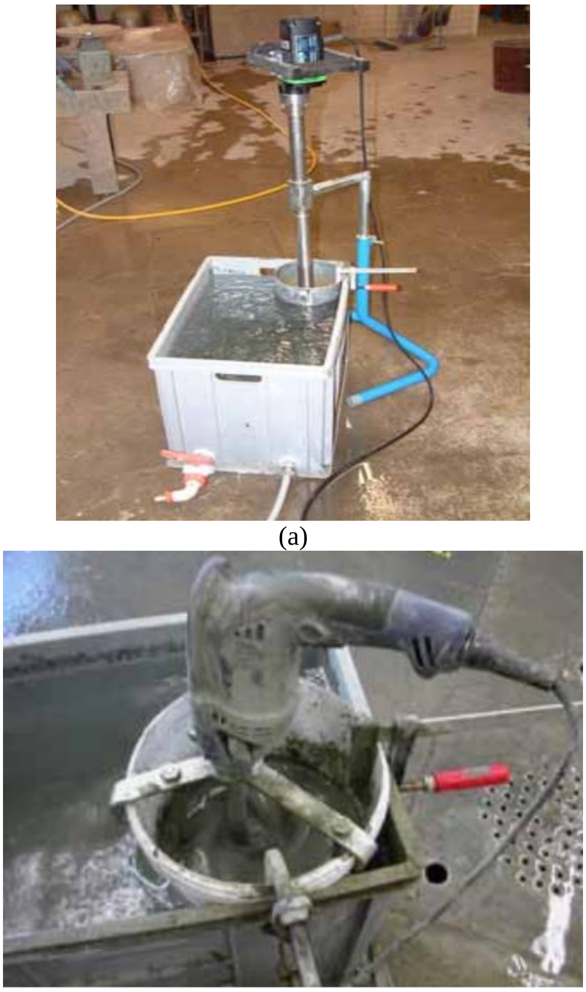


Fig. 1 Laser-ray apparatus for determination of grading of cement particles

It enhances resistance to pressure filtration, reduces bleed, enhances stability and penetrability, and increases the cohesion and viscosity of the grout. The bentonite clay is then added to the slurry and then mixed for two additional minutes to ensure the dispersion of cement particles in the slurry. The grout is then transferred to the grouting tank where it is agitated at a speed of 150 rpm to avoid the sedimentation of cement grout during injection (Fig. 2(b)). The slurry was then injected into the sand samples through two-spaced array of vertical perforated pipes (Mollamahmutoglu 2003, Eriksson *et al.* 2004).

2.3 Soil types A and B

Two soil types were investigated, both of which are fine-grained sands that occur near Tehran City, where they are used for making concrete. Geologically speaking, these soils are representatives of fine-grained alluvium deposited in the south of the Tehran Plain. Sieve analysis on soil samples generated the grading curves shown in Fig. 3. According to the unified soil classification system, soil type A is a fine but poorly graded soil, whereas soil type B is a predominantly well-graded soil.



(a)

(b)

Fig. 2(a) mixing of mass in a container with a high speed mixer and (b) with a medium speed

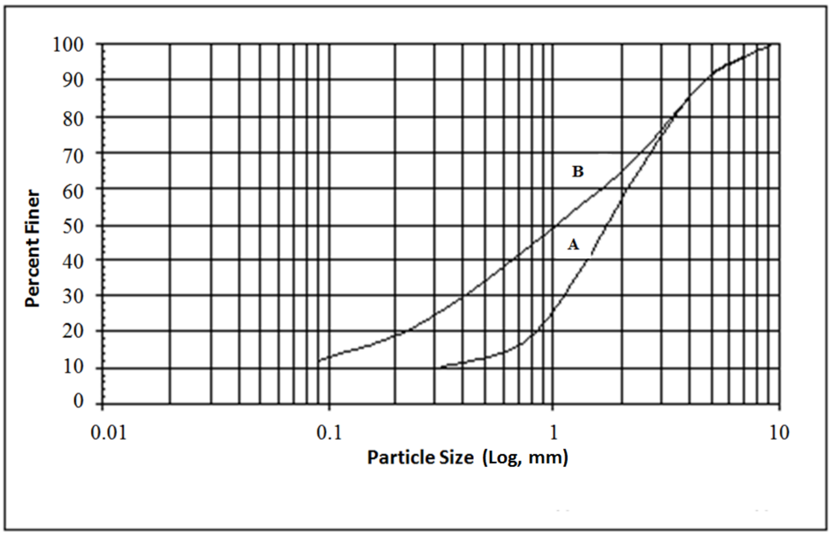


Fig. 3 Grain size distribution curves of two samples of fine grained alluvium from near Tehran

3. Preparation of sand cylinders for permeability and strength tests

Two sets of 120 mm diameter cylindrical molds were made from aluminum: one set was 180 mm long and the other was 240 mm long. The shorter molds made for preparation of specimen for permeability determination and the longer ones for strength determination. The molds could be split into two halves longitudinally. The interiors of the molds were slightly lubricated with grease to eliminate sample disturbance during removal of samples from molds. Grouting apparatus was simply the two-spaced array of vertical perforated pipes driven into the soil sample. The injection process is transferring the grout from the grouting tank into the samples of compacted sand. To prepare the samples, sand was poured into the molds in three equal layers. Each layer was compacted with a wooden tamp to achieve maximum relative density, according to (ASTM D4254 2010). Prepared samples are shown in Fig. 4.

4. Experimental design: Sand type and grouting parameters

Four sets of samples were prepared:

1. Soil type A: 21 samples grouted with 200, 300 or 500 g of slurry were used for permeability tests with W/C ratio of 1.
2. Soil type B: 13 samples grouted to saturation (slurry refusal took place on the surface of the samples) with slurry were used for permeability tests with W/C ratio of 1.
3. Soil type B: 14 samples grouted to saturation with slurries with W/C ratios of either 1.5 or 1.8 were used for permeability and unconfined compressive strength tests.

Mortar: 10 samples grouted with slurries with W/C ratios of either 0.7 or 0.9.

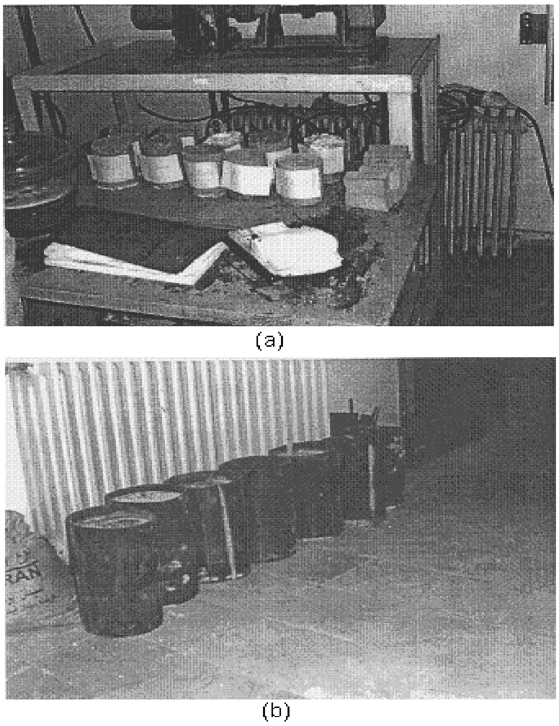


Fig. 4 Samples for the determination of permeability and strength of grouted sands

4.1 Laser-ray grading

Unexpected results of permeability and sedimentation tests and uncertainties about the fineness of the cements led to the application of a specialized laser-ray technique to accurately determine the grading and fineness of cement particles. One cement sample for each of the seven Blaine values was analyzed with the laser device in the Research and Development Center of the Abiek Cement Production Complex (Fig. 1).

4.2 Sedimentation tests

One of the objective of this research is to examine the sedimentation versus time of cement slurries with seven Blain values from the end of mixing to the complete setting. Slurries were placed in a 500 mL cylinder with 10 mm diameter. Sedimentation height was measured to the centimeter level at 15, 30, 45, 60, 90 and 120 min. Sedimentation was calculated as a percentage of the total height of the slurry. Due to the humidity and electrostatic interactions, fine cement particles are susceptible to flocculation. To decrease the amount of sedimentation and consequently increase the groutability of the water-cement mixture, bentonite clay was used as a stabilizing material (dispersing agent) at a concentration 1 or 4% by weight of cement (Naudts 2003, Rosquoet *et al*. 2003, Pantazopoulos *et al.* 2012). Sedimentation decreased from 20% to 10% at a bentonite concentration of 1% and from 20% to 5% at a bentonite concentration of 4%. Based on these results, a bentonite concentration of 4% was used in all grout slurries to control viscosity.

4.3 Permeability tests

A review of the available results indicates that the compression strength and permeability coefficient of sand grouted with cement slurry is affected by the W/C ratio as well as cement type and fineness. The falling-head permeability test, (ASTM C5856 2010) was performed on one set of grouted type A sand samples and one set of type B sand samples two weeks after grouting. This method does not disturb samples. Sample set 1 received either 200, 300 and 500 g of slurry, such that 10%, 15%, or 25% of the pores were filled with slurry, respectively. Sample set 2 received slurry until slurry refusal took place on the surface of the samples (Akbulut and Saglamer 2002). Test conditions simulated field conditions (De Paoli 1992).
In these tests, grout was injected into the soil through perforated pipes in volumes based on estimates of the volume of voids to be treated. Equation 1 was used to calculate the volume of grout to be used each time of grouting of sample and L is equal to of the perforated pipe (Saada 2003, Henn *et al*. 2005).

$$V_g = V_z(n \times F)(1 + L) \tag{1}$$

where:

V_g = volume of grout
V_z = volume of grouted soil
n = soil porosity
F = coefficient of filling voids
L = effective length of grout hole

4.4 Unconfined compressive strength tests

The effect of cement fineness, expressed as Blain specific surface, on the strength and permeability of sand grouted with cement slurry is well documented. It is known that the use of microfine cement can lead to higher unconfined compression strength values of grouted soil in comparison with ordinary Portland cements. The unconfined compression strength of the grouted sand increased with increasing curing time, increasing cement fineness and decreasing W/C ratio.

The third and fourth sets of samples were selected for strength measurements. After grouting and sample setting, samples were removed from molds and cured at 20°C for 28 days. The unconfined compressive strength of these samples was then measured (ASTM C4219 2010).

5. Results and discussions

5.1 Cement grading curve by the laser-ray

Generally, fine-grained soils cannot be grouted effectively with slurries of normal cement. For this reason, accurate determination of the grading curve was necessary. As expected, the grading curves increased with Blaine value among the seven cements: the curve was lowest for the cement with a Blaine value of 3000 cm^2/g and highest for the cement with a Blaine value of 7000 cm^2/g (Fig. 5). However, at a particle size of approximately 20 micrometer, the curve for the 7000 cm^2/g line plateaued and then increased gradually. It is possible that a part of coarse-grains is the cause of the enhanced hydration of fine-grains compared with that expected from the grinding of coarse-grains (Perret *et al*. 2000, Henn *et al.* 2005).

5.2 Sedimentation results

For all cements, sedimentation increased sharply until 60 min., then plateaued (Fig. 6). Sedimentation increased with increasing fineness when Blaine values were between 6000 and 7000 cm^2/g, possibly due to flocculation. However, sedimentation decreased with increasing fineness at Blaine values from 3000 to 5100 cm^2/g. Cement with a Blaine value of 5,100 cm^2/g had the lowest sedimentation at each time interval (Fig. 6). This Blaine value is optimal, given that sedimentation is positively related to the cement bleeding rate, that is, the movement of water to cement surface (Rosquoet *et al.* 2003, Dano *et al*. 2004). Cement bleeding is associated with several problems, including:

- Rheological properties of the grout
- Physical characteristics of the soil
- W/C ratio and mixing equipment
- Pressure injection

Therefore, the grout properties do vary and should not be regarded as uniform.

5.3 Permeability results

In order to have a proper understanding of the permeability of cement grouted sand which is essential in the study of permeation grouting, investigation of the cement grouted sands characteristics including factors influencing the permeability is considered necessary and is therefore incorporated in the present study.

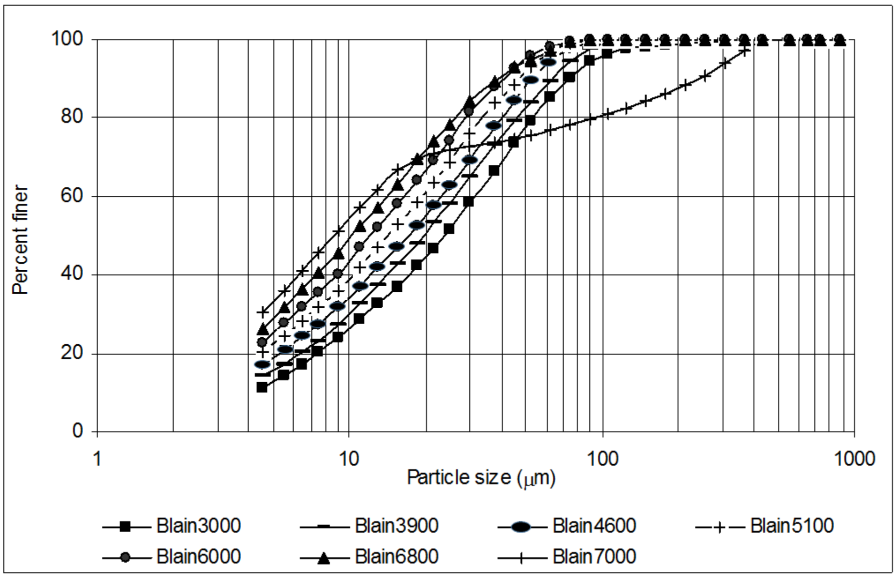


Fig. 5 Grain size distribution of cements with differing Blaine values, measured with the laser-ray technique

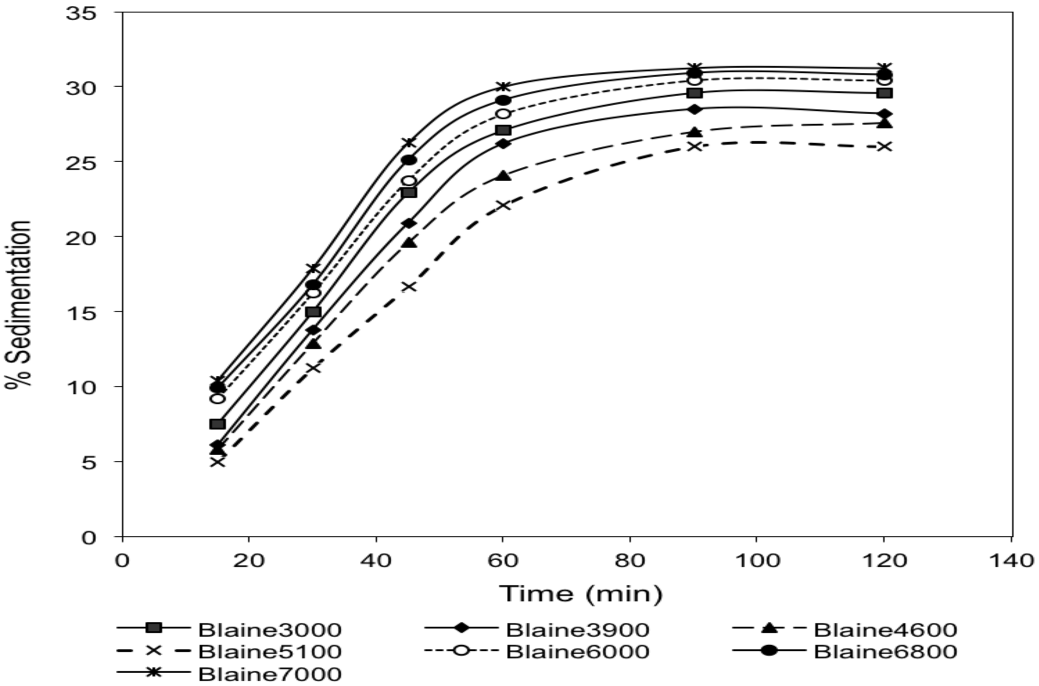


Fig. 6 Sedimentation versus time of cement slurries with seven Blain values

Nevertheless, differences in cement fineness and also W/C ratio appear to have a significant effect on the permeability coefficient but increasing of Blain specific surface does not always lead to strength increase and permeability decrease of grouted sands because cement grains with very high fineness provide more surfaces that need more water to be wet.

For investigation of some parameters affecting permeability such as cement fineness, slurry volume, grouting to saturation and W/C ratio, masses of the three sets of samples used for permeability tests are shown in Fig. 7.

5.3.1 Effect of altering slurry volume

The permeability of Type A sand samples grouted with 200 g of slurry had the highest permeability, whereas those grouted with 500 g of slurry had the lowest permeability across all cement Blaine values (Fig. 8). For a given slurry volume, cements with Blaine values of 4600, 5100 and 6000 cm^2/g had the best grouting efficiency and the lowest permeability. For all slurry levels, increasing the fineness of the cement from 3000 to 5100 cm^2/g resulted in a decrease in permeability of approximately 80%. However, increasing the fineness from 5100 to 7000 cm^2/g increased permeability. This leads to the conclusion that the

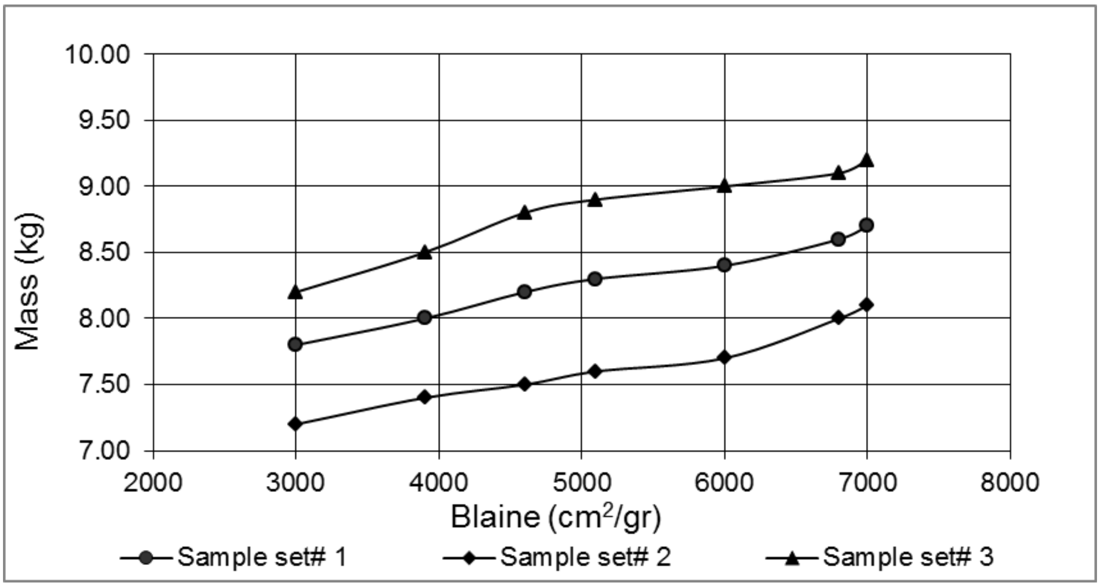


Fig. 7 Mass of the three sets of sand samples grouted with slurries prepared with cement at seven levels of fineness

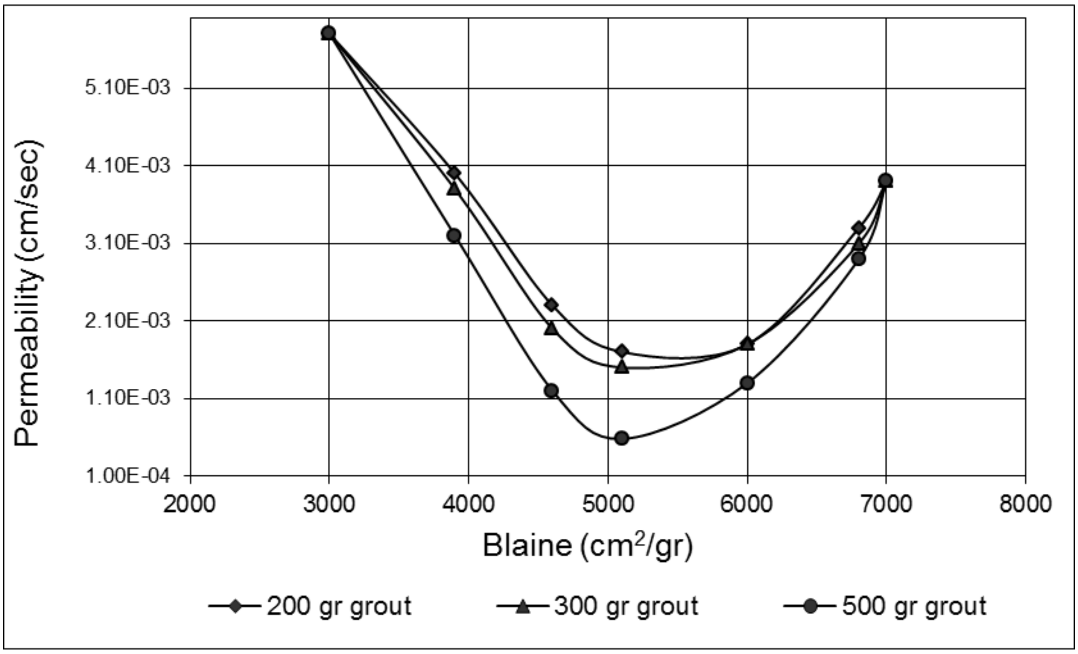


Fig. 8 Permeability of Type A sand samples grouted with slurries prepared with cement at seven levels of fineness and grouted at three levels

permeability is governed by the minimum pores of the sand. Since the pores dimension are larger than the maximum grain size of the grout especially for cement finer than 6000 cm^2/g to 7000 cm^2/g and for the 500 g slurry treatment, the excess slurry can pass through the sand resulted in an increase in permeability.

5.3.2 Effect of grouting to saturation

Type B sand samples grouted until slurry refusal took place on the surface of the samples (Akbulut and Saglamer 2002) resulted in filling 45% of the soil voids with slurry. Compared to the Type A samples above, the permeability of these Type B samples was lower across all cement Blaine values (Fig. 9), even though the mass was lower (Fig. 7). Similar to the Type A samples, the Type B sand samples grouted with cement slurry with a Blaine value of 5100 cm^2/g had the lowest permeability. This could be attributed to the rapid radial spreading of the grout, which clogged pores at the top of the sample and prevented penetration (Akbulut and Saglamer 2002).

5.3.3 Effect of altering W/C ratio

As observed in the permeability tests above, Type B sand samples grouted with slurry made of cement with a

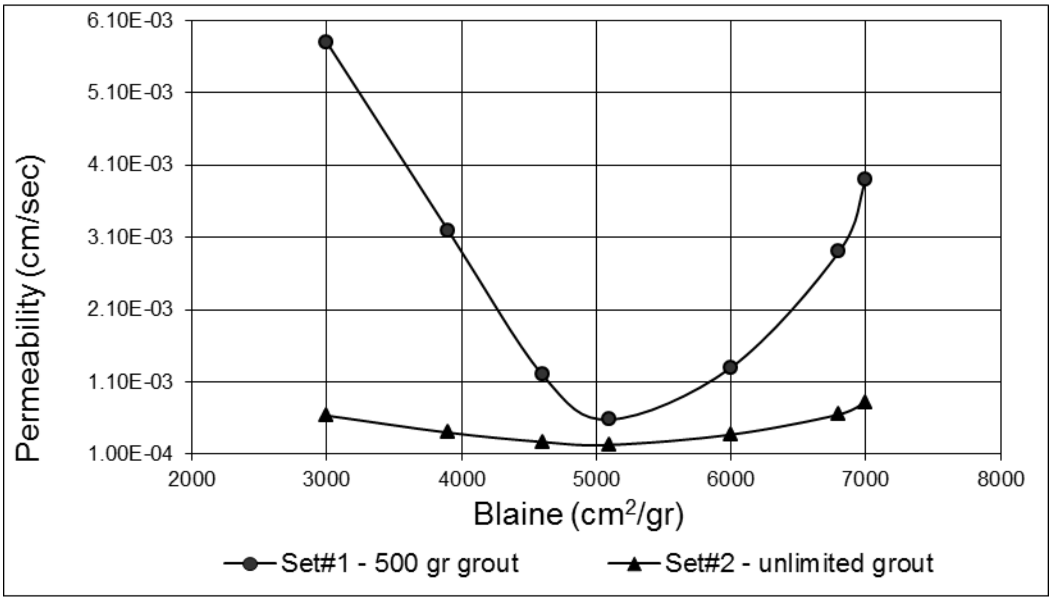


Fig. 9 Permeability of Type B sand samples grouted to saturation with slurries prepared with cement at seven levels of fineness. The Type A sand sample grouted with 500 g slurry is re-plotted for comparison

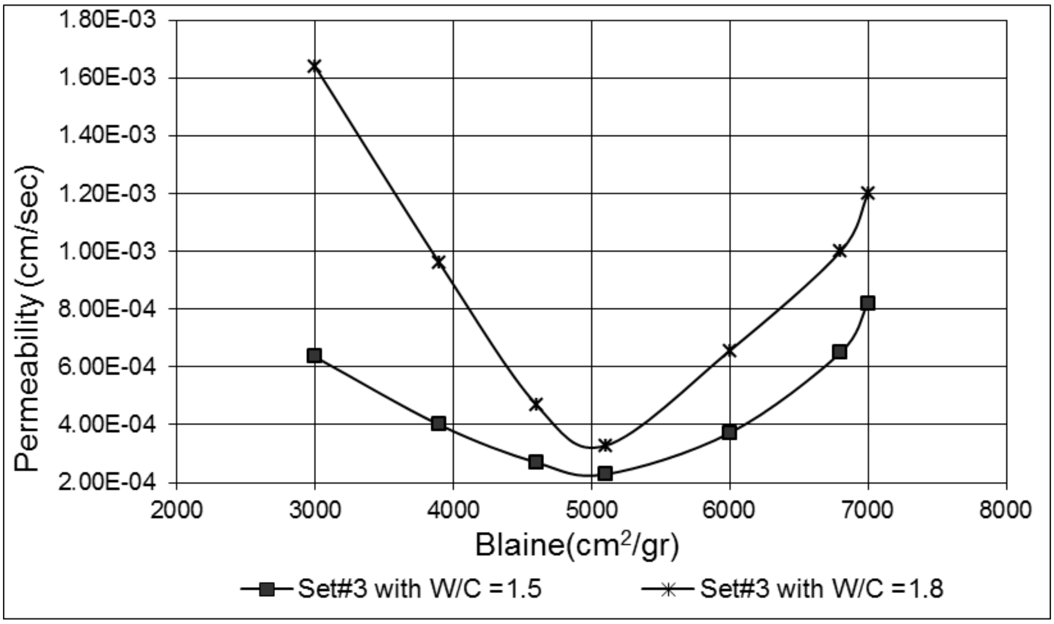


Fig. 10 Permeability of Type B sand samples grouted to saturation with slurries prepared with cement at seven levels of fineness and two W/C ratios

Blaine value of 5100 cm^2/g had the lowest permeability (Fig. 10). A W/C ratio of 1.5 yielded lower permeability than a W/C ratio of 1.8, particularly for cements with low Blaine values. In an overall conclusion it has to be stated that the grout with lower W/C ratio will penetrate the larger sand pores (set#3) reducing the permeability, weight up the mass (Fig. 7) and increases the sealing efficiency.

Despite the fact that both set of samples grouted to saturation with slurry but, sample set number 2 had a lower W/C ratio (W/C=1) therefore, the minimum permeability at a Blaine value of 5100 cm^2/g was the lowest for this set see (Fig. 11). In addition, it can be stated that the slurry made of cement with Blaine of 5100 cm^2/g has dispersed steadily, displacing air and water outwards in a radial path homogeneously, but the cement with Blaine of 7000 cm^2/g did not (Dupla *et al.* 2004).

5.4 Unconfined compressive strength tests

As soon as the compacted Type B sand samples were removed from molds, it was evident that samples grouted with cement with Blaine values of 5100 and 6000 cm^2/g and W/C ratio of 1.5 had more integrity than the other samples; they were the only ones that formed a perfect cylinder. The compressive strength was highest for the sample grouted with cement with a Blaine value of 5100 cm^2/g (Fig. 12).

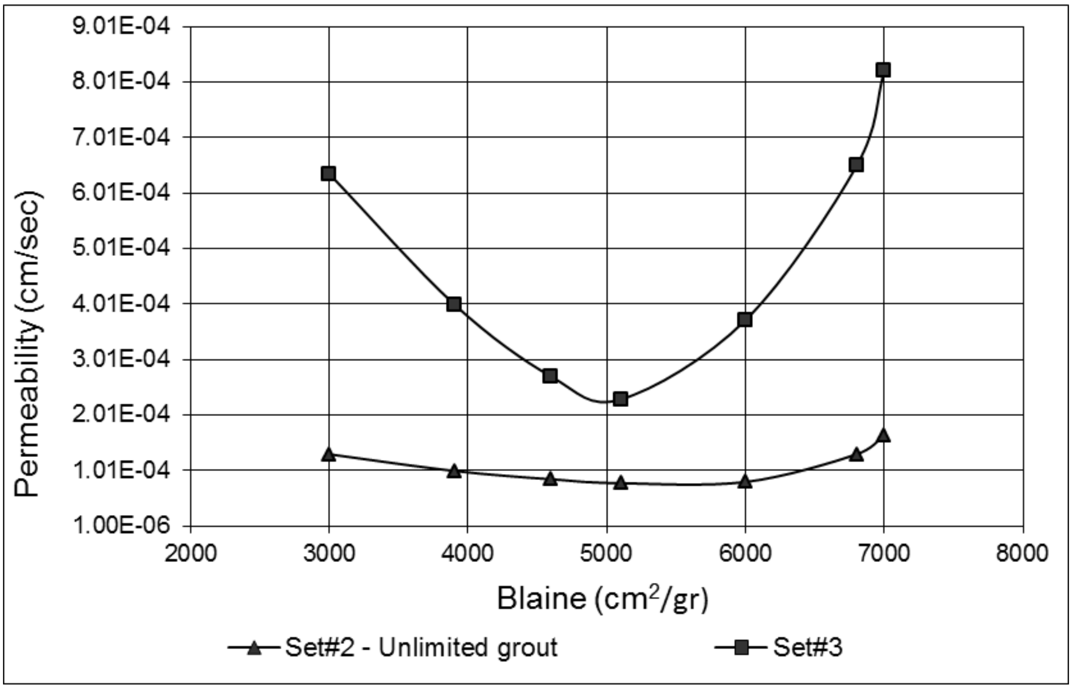


Fig. 11 Permeability of Type B sand samples grouted to saturation with slurries prepared with cement at seven levels of fineness and a W/C ratio of 1.5. The Type B sand sample grouted with an unlimited volume of slurry is re-plotted for comparison

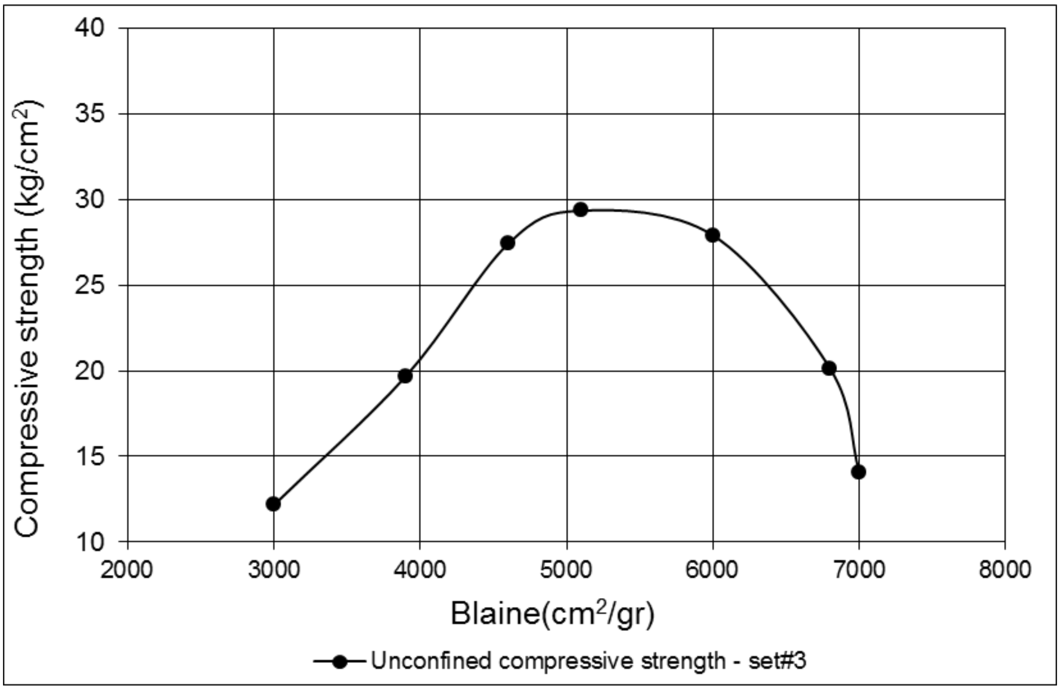


Fig. 12 Compressive strength of Type B sand samples grouted to saturation with slurries prepared with cement at seven levels of fineness and a W/C ratio of 1.5

This agrees well with the results from the permeability tests. In general, the lower the permeability, the higher the compressive strength of the soil. This could be attributed to more cohesion and bonding of the soil particles, which results in an increase in the shear strength of the soil (Shibata 1996, Schwarz and Chirumalla 2007).

Similarly, the compressive strength of mortar samples was the highest when they were grouted with slurries with a Blaine value of 5100 g/cm^2 (Fig. 13). Further, the maximum compressive strength was three times higher at a W/C ratio of 0.7 than 0.9. These test results showed that the effect of ageing, even over relatively short periods, was to move the state inside the state boundary surface (Schwarz and Krizek 1994, Matsui *et al.* 1996, Perret *et al*. 2000).

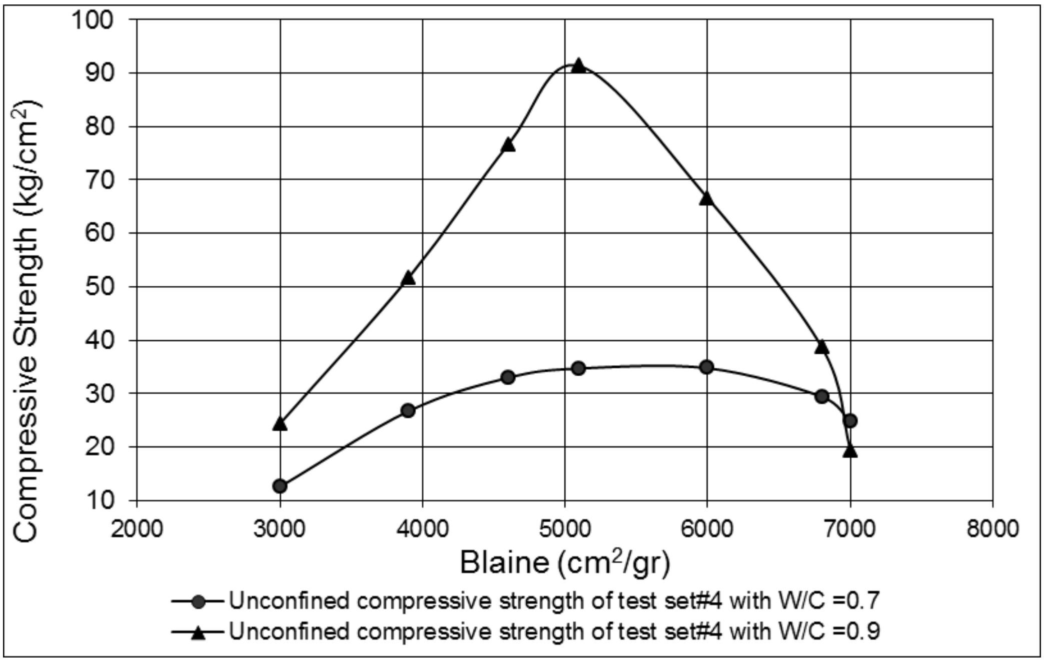


Fig. 13 Compressive strength of mortar samples grouted to saturation with slurries prepared with cement at seven levels of fineness and W/C ratios of 0.7 and 0.9

This also demonstrates that the homogeneous dispersion of slurry with the cement with Blaine of 5100 cm^2/g in a cohesionless soil had the effect of increasing cohesion and bonding over time whilst the angle of internal friction remained essentially the same.

6. Conclusions

The physical and mechanical behavior of micro-fine cement with different Blaine values was studied when applied as grouting material in two types of compacted fine sand. The conclusions from this study are limited permeability and compressive strength, considering the aging effect.

Grouting with a micro-fine cement slurry ground from normal cement was used to assess the performance of stabilized geomaterials. The laser-ray method was used to obtain an accurate particle size distribution and the data obtained highlighted the importance to the mix design of cement for grouting and stabilization of the coarse-grained and fine grained portion of the grading curve. The most satisfactory results have been achieved when fewer coarse-grains existed in fine cement. Coarse-grains are sometimes present in fine cement due to the hydration phenomenon, which can be avoided. It is also shown that grain size distribution of soil (uniformity) is of great importance to filtration tendency.

The permeability data allowed for assessment of how the grouting advanced steadily in the soil voids. A given sample type had a similar permeability if grouted with cements with Blaine values of 3000 and 7000 cm^2/g, and the lowest permeability was achieved using a cement with a Blaine value of 5100 cm^2/g. This level of fineness also yielded the highest compressive strength, probably due to the presence of inter-particle bonding. Bonding between the slurry and solid surfaces resists internal shrinkage stresses and thereby reduces the grout volume change. Therefore, grouts that may not be suitable for gravels and coarse sands may be entirely appropriate for fine sands.

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