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Small Strain Shear Modulus of Sands Grouted with Zeolite-cement Suspension

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ABSTRACT: Cement production is one of the most important sources of CO_2 emission in the world and an energetically demanding process. Therefore, the replacement of a part of it with cheaper and environmentally friendly materials such as zeolite is of great importance. In the present study, a series of bender element tests on loose sandy soils grouted with zeolite and cement was conducted to investigate the effects of cementation on the small strain shear modulus (G_0) of them. The results showed that the G_0 of grouted samples increased with an increase in zeolite content (Z) up to 30% (Z_{30}). After that, a further increase in the amount of zeolite results in a decrease in the G_0. Also, in all Z and W/CM, the G_0 decreased with increase in the sand grain size. The G_0 corresponding to Z_{30} for *D11* sand (the smallest particles) samples grouted with suspension having W/CM of 3, 5 and 7 is, respectively, 21.7, 16.7 and 12.5 times that of pore (unstabilized) sand. The minimum G_0 is observed in samples grouted with Z_{90} and W/CM of 7, which is 2.16, 1.2 and 1.19 times the G_0 of corresponding pore sands for *D11*, *D1* and *D2* sands, respectively.

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1. INTRODUCTION

Permeation grouting with cement is one of the most widely used soil improvement methods in geotechnical engineering. However, the use of cement creates problems. From the environmental point of view, the cement industry is responsible for about 7% of carbon dioxide emissions in the world [1]. A lot of energy is also used to produce cement. Zeolite, as pozzolanic materials, due to their unique and attractive properties, including high cation exchange capacity and specific surface area, are used in many geotechnical engineering aspects [2-6]. Therefore, to reduce cement production cost and also reduce the environmental impacts of Portland cement, part of it can be replaced with zeolite in soil stabilization.

Bender element test is a non-destructive test used for the laboratory determination of small strain shear modulus (G_0). Based on geotechnical studies in the last decades, the bender element test on cement-based stabilized soils has received enormous attains [7-11].

Although in recent years, some studies have been conducted to determine the strength parameters of soils stabilized with cement and zeolite by mixing method [2-6], however, no research has been conducted on soil grouted with zeolite-cement suspension to evaluate different parameters of the grouted soil such as G_0. Accordingly, in this research, by performing a series of bender element tests, the effect of zeolite-cement grouting on the G_0 of loose sand samples is investigated.

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2. MATERIALS AND METHODS

In the present study, Firoozkooh *D11*, *D1* and *D2* poorly-graded (SP) sands are used. The grain size distribution curves of the used sands are presented in Figure 1.

Abyek Portland cement (type II) and clinoptilolite type zeolite are used as cementitious materials. The chemical compositions and specific gravities (G_s) of the cementitious materials are given in Table 1.

A superplasticizer (1% by weight of cementitious materials) is used to improve the characteristics of the grouts. Sand samples are prepared in a loose condition with a relative density of approximately 30% using a dry deposition method in split, acrylic, and cylindrical molds. The internal diameter and height of the molds are 70 and 140 mm, respectively. The two ends of the molds are closed with PVC-type caps having a hole for entering and leaving the grout. Laboratory equipment according to ASTM D4320/D4320M are used for grouting [12]. Depending on the sand particles' size, water to cementitious materials ratio (W/CM) and cement replacement with zeolite content (Z), the grouting pressure is 20-50 *kPa*. When the volume of the injected grout doubles the void volume of the sand samples in the mold, the grouting

Table 1. Cementitious materials properties

Properties	Cement (%)	Zeolite (%)
Calcium oxide (CaO)	61.9	4.2
Silicon dioxide (SiO_2)	20.3	69.12
Magnesium oxide (MgO)	3	0.65
Potassium oxide (K_2O)	0.68	1.09
Sodium oxide (Na_2O)	0.2	0.84
Aluminum oxide (Al_2O_3)	5.4	10.79
Ferric oxide (Fe_2O_3)	3.94	0.73
Sulfur trioxide (SO_3)	1.97	0.04
C_2S	33	-
C_3S	43	-
C_3A	8	-
C_4AF	13	-
G_s	3.1	2.2

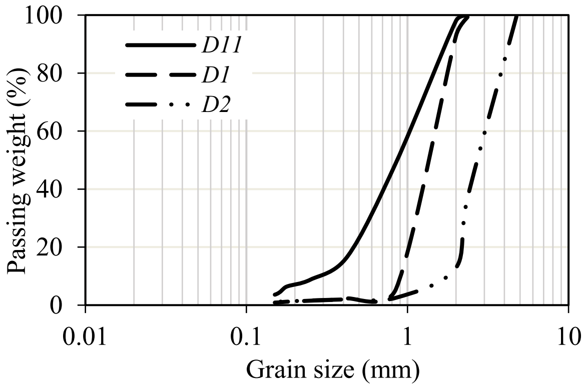

Fig. 1. The grain size distribution of sands

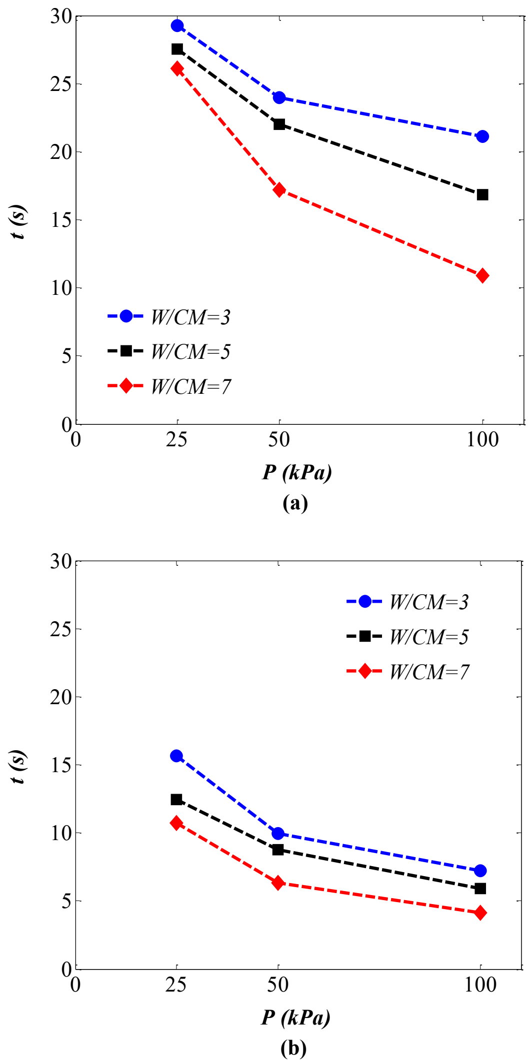

Fig. 2. Grouting time-pressure curves for suspension having Z = 30%, (a): *D11*, (b): *D1*

is stopped. After 48 to 72 hours, the specimens were removed from the mold and placed in a two-layer plastic bag. Then, the samples were kept in a room at a temperature of about 23 °C for curing of 90 days. In the end, the bender element tests are performed on the grouted samples.

3. RESULTS AND DISCUSSION

Groutability is evaluated based on grout penetration potential in sand pores. The groutability are tested on *D11* and *D1* sands by grouts having *Z* of 30% in three grouting pressure of 25, 50 and 100 *kPa*, and three *W/CM* of 3, 5 and 7. Figure 2 shows the variations of pressure time (*t*) against grouting pressure (*P*) for sand samples of 1 *m* length. As expected, with increasing in the grout, due to the reduced viscosity, the pressure-time decreases. Also, in all *W/CM*, the grouting time decrease with an increase in the grouting pressure. According to Figure 2, it can be found that all grouts applied in the present study can be injected into the used sands.

Bender element tests on pore sands show that the G_0 of *D11*, *D1* and *D2* sands are 53.8, 58.3 and 66.5 *MPa*, respectively. The G_0 values against cement replacement with zeolite (*Z*) for the grouted sand samples are presented in Figure 3. As seen, for all *D11*, *D1* and *D2* sands, with increasing *Z* percentage up to 30 (Z_{30}), the G_0 grows. Because the pozzolanic reactions between $Ca(OH)_2$ from cement hydration with SiO_2 and Al_2O_3 in zeolite cause the formation of more *C-S-H* and *C-A-H* gels (in comparison with samples grouted with cement alone) in sand pores. Therefore, stronger cementitious bands are formed between grouted sand particles. After Z_{30}, more increase in *Z* percentage leads to a decrease in G_0. Because with more increase in zeolite content (compared to Z_{30}), the cement content reduces. Reducing cement leads to lower *CaO* levels, resulting in less hydration reactions. The G_0 corresponding to Z_{30} for *D11* sand (the smallest particles) samples grouted with suspension having *W/CM* of 3, 5 and 7 is, respectively, 21.7, 16.7 and 12.5 times that of pore (unstabilized) sand. The minimum G_0 is observed in samples grouted with Z_{90} and *W/CM* of 7, which is 2.16, 1.2 and 1.19 times the G_0 of corresponding pore sands for *D11*, *D1* and *D2* sands, respectively.

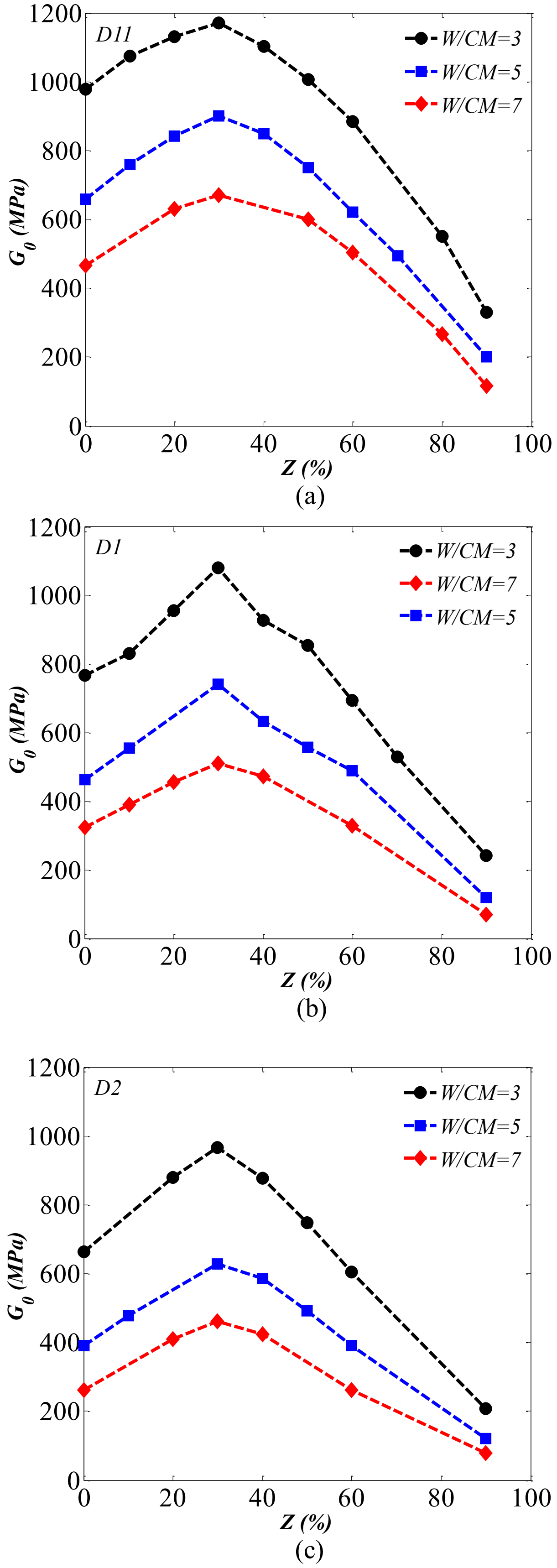

Fig. 3. Effect of the *Z* on the G_0 of grouted sand specimens: (a): *D11*; (b): *D1*; (c): *D2*

The G_0 of the grouted sands reduce constantly with increasing *W/CM* of the grout. This is due to the fact that by increasing the *W/CM*, fewer pores of the grouted sands are occupied by cementitious materials (zeolite and cement), and subsequently, weaker bands are created.

Also, in all *Z* and *W/CM*, the G_0 decreased with increase in the sand grain size. As the sand particles' size decreases, the surface area of the sand particles increases and more surface is available to the grout to form cementitious bands.

4. CONCLUSIONS

The main results of the present research includes:

- The small strain shear modulus (G_0) of the grouted sand samples increased with an increase in zeolite content (*Z*) up to 30% (Z_{30}). After that, a further increase in zeolite content results in a decrease in the G_0.
- The G_0 of the grouted sands reduce with increasing *W/CM* of the grout.
- The G_0 of the grouted sands decreased with increase in the sand grain size.

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