Effect of silica fume on the ultrasonic pulse velocity of cemented sand

I Shooshpasha¹, A Hasanzadeh¹ and M Kharun²,³*,

¹Babol Noshirvani University of Technology, Babol, Iran
²Peoples’ Friendship University of Russia (RUDN University), Moscow, Russia
³Moscow State University of Civil Engineering, Moscow, Russia

E-mail: miharun@yandex.ru

Abstract. One of the geotechnical engineering strategies for dealing with weak soils in a construction site is to modify their mechanical properties with the aid of soil improvement techniques. Chemical stabilization of soil using cement is one of these effective approaches that can considerably enhance workability and shear strength parameters of soil. However, very limited investigations have been carried out to reveal the effect of silica fume on the ultrasonic pulse velocity (UPV) and the ultrasonic stiffness (E_u) of cement-treated sandy soil. For this purpose, in the present research, a series of UPV tests were performed on sand-cement-silica fume specimens. The cement percentages were 3, 5 and 7% and silica fume contents were 0, 0.25, 0.5 and 1% by weight of dry sand. The cylindrical samples were prepared and cured for 3, 7, 14, 28, 42 and 56 days and tested. The results show that inclusion of silica fume to the cemented sand increases UPV and E_u which this enhancement is more pronounced at longer ages.

Keywords: sand, cement, silica fume, ultrasonic pulse velocity.

1. Introduction

A natural soil may be widely available on a construction site, but sometimes its properties are such that it does not meet the engineering specifications required for a particular project. For example, shallow footings, when built on these soils, have low bearing capacity and can undergo excessive settlements [1]. In such a case, soil improvement techniques in order to enhance its mechanical characteristics may become an attractive alternative, from the environmental, technical and economic points of views. According to the literature, there are different methods which can be selected for soil improvement such as mechanical, hydraulic, dynamical, physical and chemical methods. Chemical soil stabilization using additives has been employed for many years in order to render the problematic soils capable of meeting the requirements of engineering projects [2].

The chemical stabilization of soils with cement is a desirable technique because of economic and environmental considerations such as avoiding the use of borrow materials from elsewhere. In highways and other shallow constructions, cement is commonly used to strengthen local soils, for example to make them suitable as subgrades, formations and foundation backfill [3]. Cementation plays an important role in the behavior of soils under applied loads. Many investigators have made considerable contributions to the understanding of cemented soil behavior. Their findings have illustrated that several factors such as porosity, physical and chemical properties of soil and type and percentage of cement impact soil-cement behavior [4–8].

On the other hand, silica fume is a by-product from the manufacture of ferrosilicon alloys. It is made up of very fine amorphous SiO₂ particles with a diameter of 1 – 2 μm [9]. Silica fume is very reactive owing to its high surface area and belongs to the category of highly pozzolanic materials. Thus, it is usually considered as one of the best pozzolans utilized for concrete. The results of previous studies have depicted that the use of silica fume as a concrete admixture has many advantages such as...
improvement of the resistance versus abrasion [10] and chemical attack [11] and also increase of tensile and flexural strengths [12].

While numerous studies have been carried out on the impact of silica fume on the concrete behavior, the influence and effectiveness of silica fume on the properties of soil particularly ultrasonic pulse velocity (UPV) of cemented sand have not been completely explored. Therefore, in the present research, based on an experimental program, it has been attempted to investigate this issue. The experimental platform covers characteristics of materials and a program of UPV tests.

2. Materials

2.1. Sand

The sand utilized in this study was achieved from Babolsar city, north of Iran. The sand was categorized as poorly-graded sand (SP) according to Unified Soil Classification System (USCS) [13] with specific gravity (Gs) of 2.73 [14]. The average diameter of the sand particles at D_{50} is 0.23 mm. Based on the gradation curve, shown in Figure 1, the coefficient of uniformity is 1.67, and the coefficient of curvature is approximately 0.86.

![Figure 1. Particle size distribution curve of Babolsar sand.](image)

2.2. Cement

Portland cement is the most frequently used cement agent for soil treatment. Portland cement type II was applied in the present research. Blaine, initial setting time and specific gravity of this cement are 3050 cm$^2$/gr, 115 min and 3.15, respectively. The chemical characteristics of the cement are presented in Table 1.

| Chemical name | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | K$_2$O | CaO | MgO | SO$_3$ | Na$_2$O |
|---------------|--------|-------------|-------------|-------|-----|-----|-------|--------|
| Percent (%)   | 21.90  | 4.86        | 3.30        | 0.56  | 63.32 | 1.15 | 2.10  | 0.36   |

Table 1. Chemical properties of Portland cement.
2.3. Silica fume

The amorphous silica fume in powder form with particle size diameter, specific gravity and surface area of <1 μm, 2.2 and 13000–30000m²/kg, respectively, was applied. Table 2 displays the chemical properties of the silica fume.

| Chemical name | SiO₂ | Al₂O₃ | Fe₂O₃ | K₂O | CaO | MgO | SO₃ | Na₂O |
|---------------|------|-------|-------|-----|-----|-----|-----|------|
| Percent (%)   | 96.65| 0.23  | 0.07  | 0.56| 0.31| 0.04| 0.17| 0.15 |

3. Specimen preparation

To prepare samples for UPV tests, first, oven dried sand, cement (3, 5 and 7% by the dry weight of the sand) and silica fume (0, 0.25, 0.5 and 1% by the dry weight of the sand) were mixed and then, based on the results of standard Proctor compaction tests [15], optimum water amount was added to the mixture and blended. The mixture was then compacted into five layers using a metal hammer in the lubricated cylindrical split mold (diameter = 51 mm, height= 104 mm) until the desired height was reached for each layer. In this research, 95% of maximum dry unit weight was selected as the required dry unit weight of the specimens used. After the molding process, the specimens were removed from the mold and covered in plastic wraps to avoid variations of moisture content. Then, the specimens were stored in a room with controlled temperature under different curing times of 3, 7, 14, 28, 42 and 56 days.

4. Testing program

Ultrasonic waves are stress waves with frequencies greater than 20 kHz that propagate in mass media. The characteristics and conditions of the material influence the propagation of ultrasonic waves in a material [16]. The UPV test is a valuable non-destructive method using relatively inexpensive equipment which is applied for various purposes. This test is commonly utilized for characterization of cement-based materials and particularly for comparative studies. For example, to evaluate the effectiveness of various additives for improving the mechanical properties of treated samples without carrying out any strength test. In UPV test, a pulse travels inside the sample and is received by the similar transducer coupled on the opposed surface. The pulse transmission time is recorded by a digital screen. To determine the UPV, the distance between the transducers (L) is divided by the transmission time (T):

\[ \text{UPV} = \frac{L}{T} \]  

The accuracy of the measurement depends upon the ability of the operator to determine accurately the distance between the transducers and of the equipment to measure precisely the pulse transmit time. Moreover, the following equation provides the ultrasonic stiffness (\( E_u \)):

\[ E_u = \rho \cdot (\text{UPV})^2 \]  

where \( \rho \) is the sample density. In the present investigation, a commercially available device called PUNDIT7 (Portable Ultrasonic Non-destructive Digital Indicating Tester) with an excitation voltage of 500 V and a resolution of 0.1 μs was used for UPV tests, consisting of:

1. A pair of axially aligned piezoelectric broadband transducers, with a nominal frequency of 54 kHz and 50 mm in diameter.
2. A waveform generator; an amplifier and an interval timer with a direct reading digital display.

The measurements were taken based on ASTM D2845 [17] along the longitudinal axis of the specimens, with the specimen vertically aligned and the transducers installed on opposite faces, therefore with a path length (L) of about 104 mm. The acoustic coupling between the transducers and the specimen was obtained using ultrasound gel, while tightly pressing the transducers against the top surfaces of the specimen.
5. Results and discussion

5.1. Effect of silica fume on UPV

Figures 2 to 4 show the effect of silica fume on the UPV of cemented sand. As seen, the propagation velocity of ultrasonic pulse increases with the silica fume content. A higher silica fume percentage in the samples contributes to higher heat growth, accelerating the hydration processes and increasing the UPV. To express with more details, it can be stated that silica fume particles, due to their high specific surface area, react with calcium hydroxide (CH) and form dense phase of calcium silicate hydrate (CSH). CSH gel fills the pores, makes the structure denser and strengthens the binding of the matrix. It should be noticed that the contact surface between cement and sand particles, one of the weakest sections of the samples, is also improved because of the silica fume micro-filling property.

![Figure 2 Variation of UPV with silica fume content for sand with 3% cement.](image)

![Figure 3 Variation of UPV with silica fume content for sand with 5% cement.](image)
Silica fume will also facilitate the acceleration of cement hydration by supplying a large number of nucleation sites for the precipitation of cementitious hydration products. In other words, the blending of cement with silica fume can accelerate the hydration reaction of the cement clinkers due to the filler effect as silica fume provides additional surfaces where the hydrates can nucleate \cite{18,19}. The addition of high silica fume content (1% in this study) to cemented sand may lead to the agglomeration of silica fume particles, mainly because of their high specific surface area and van der Waals force \cite{20}. Consequently, weak spots develop throughout the microstructure of the cementitious composite and UPV will not rise substantially.

Moreover, it can be observed that since pozzolanic reactions are time dependent, UPV increases with the increase of curing time. The superfineness of silica fume (higher specific surface area than cement) and its high content of silica dioxide promote pozzolanic reaction. The rate of pozzolanic reaction is proportional to the amount of surface available for reaction and chemical and mineralogical composition of silica fume. Pozzolanic reactions occur until the soil contains both silicate and aluminate.

5.2. Effect of silica fume on $E_u$
As observed in Figures 5 to 7, the $E_u$ increases with the inclusion of silica fume to the cemented sand. The reasons that might explain the increase of the $E_u$ with the addition of silica fume to cemented sand are the increase in effective contact area, decrease in the void ratio, and the creation of a stronger matrix induced by the development of cementitious products.
Figure 5. Variation of $E_u$ with silica fume content for sand with 3% cement.

Figure 6. Variation of $E_u$ with silica fume content for sand with 5% cement.
Figure 7. Variation of $E_u$ with silica fume content for sand with 7% cement.

It can be stated that the cement particles are obviously the primary bonding agent in the mixture, where hydration of cement formed a stiff soil matrix in the treated samples. The addition of silica fume to cemented sand contributes to the improved interfacial bond strength, a better interlock between cement paste and sand and as a result, a stiffer soil matrix. This improved bond is attributed to the conversion of the CH into CSH, formation of a less porous and more compact microstructure in the transition zone due to the presence of reactive silica [21]. Small particle size of silica fume results in a filler effect in which the silica fume particles bridge the spaces between cement grains and sand. In other words, the voids of cemented sand are filled with very small silica fume particles (micro filler effect) which leads to the increase in density, the formation of a much denser structure and as a result, the growth of $E_u$.

6. Conclusions
In general, wave-based measurements are a practical, mostly non-invasive, and cost-effective means of evaluating the small-strain stiffness of soils. In this regard, the UPV test can be employed as a non-destructive technique for monitoring the quality and success of stabilization process. The results of UPV tests indicated that silica fume particles promote the cement hydration, fill the pores and make the microstructure of cemented sand denser, leading to an increase of UPV and $E_u$. These particles are able to react with CH to form more CSH. In addition, the pores of the soil skeleton created by cement are efficiently filled by silica fume particles as they are smaller than the cement grains and thus, the interface bond strength between cement paste and sand improves.

7. References
[1] Hasanzadeh A and Choobbasti AJ 2016 Estimation of bearing capacity of circular footings on clay stabilized with granular soil: case study Int. J. Civ. Eng. Geo-Environ. (IJCEG) 6 47-54
[2] Kolas S, Kasselouri-Rigopoulou V and Karahalios A 2005 Stabilization of clayey soils with high calcium fly ash and cement Cem. Concr. Compos. 27(2) 301–13
[3] Consoli N C, Da Fonseca A V, Silva S R, Cruz R C and Fonini A 2012 Parameters controlling stiffness and strength of artificially cemented soils Geotechnique 62(2) 177–83
[4] Rasouli H, Takhtfiroozeh H, Taghavi Ghalesari A and Hemati R 2017 Bearing capacity improvement of shallow foundations using cement-stabilized sand Key Eng. Mater. 723 795-800
[5] Ghadakpour M, Choobbasti A J and Kutanæi S S 2019 Investigation of the deformability properties of fiber reinforced cemented sand J. Adhes. Sci. Technol. 33 1913–38
[6] Ghadakpour M, Choobbasti A J and Kutanæi S S 2020 Investigation of the Kenaf fiber hybrid length on the properties of the cement-treated sandy soil Transport. Geotech. 22 100301. https://doi.org/10.1016/j.trgeo.2019.100301
[7] Shooshpasha I and Shirvani R A 2015 Effect of cement stabilization on geotechnical properties of sandy soils Geomech. Eng. 8 17–31
[8] Hasanzadeh A 2019 Numerical analysis of the response of pile-raft systems considering the application of cement and polypropylene fiber treatment Archit. Civ. Eng. Environ. (ACEE) J. 12(3) 81–92
[9] Heikal M, El-Didamony H, Sokkary T M and Ahmed I A 2013 Behavior of composite cement pastes containing microsilica and fly ash at elevated temperature Constr. Build. Mater. 38 1180–90
[10] Wang L, Zhou S H, Shi Y, Tang S W and Chen E 2017 Effect of silica fume and PVA fiber on the abrasion resistance and volume stability of concrete Compos. Part B 130 28–37
[11] Estokova A, Kovalcikova M, Luptakova A and Prascakova M 2016 Testing silica fume-based concrete composites under chemical and microbiological sulfate attacks Mater. 9 324–38
[12] Kumar A, Iqbal F, Memon R and Habib AF 2018 Tensile and flexural strength of cement silica fume concrete Int. J. Civ. Eng. Technol. 9 390-402
[13] ASTM D2487 2017 Standard practice for classification of soils for engineering purposes (unified soil classification system) (Philadelphia: ASTM)
[14] ASTM D854 2014 Standard test methods for specific gravity of soil solids by water pycnometer (Philadelphia: ASTM)
[15] Shooshpasha I, Hasanzadeh A and Kharun M 2019 The influence of micro silica on the compaction properties of cemented sand IOP Conf. Ser.: Mater. Sci. Eng. 675 1-8
[16] Yesiller N, Inci G and Miller CJ 2000 Ultrasonic testing for compacted clayey soils Geo-Denver 2000 Denver, Colorado, United States
[17] ASTM D2845 2008 Standard test method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock (Philadelphia: ASTM)
[18] Poulsen S L, Jakobsen H J and Skibsted J 2009 Methodologies for measuring the degree of reaction in Portland cement blends with supplementary cementitious materials by 27Al and 29Si MAS NMR spectroscopy Internationale Baustofftagung (ibaustil), Weimar, Germany, 17 177–88
[19] Muller A C A, Scrivener K L, Skibsted J, Gajewicz A M and McDonald P J 2015 Influence of silica fume on the microstructure of cement pastes: new insights from 1H NMR relaxometry. Cem. Concr. Res. 74 116–25
[20] Hasanzadeh A and Shooshpasha I 2020 Influence of silica fume on the geotechnical characteristics of cemented sand Geotech. Geol. Eng. https://doi.org/10.1007/s10706-020-01436-w
[21] Hewayde E, Nehdi M L, Allouche E and Nakha G 2007 Using concrete admixtures for sulphuric acid resistance Proc. Inst. Civ. Eng. – Constr. Mater. 160 25–35