The influence of micro silica on the compaction properties of cemented sand

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Abstract. In this experimental research, a series of standard Proctor compaction tests have been performed to explore the effect of micro silica on the compaction properties of cemented sand. The cement contents were 3, 5 and 7% and micro silica contents were 0, 0.25, 0.5 and 1% by weight of dry sand. The results showed that micro silica particles increase maximum dry unit weight of sand-cement mixtures and decrease their optimum moisture content. The results of Scanning Electron Microscope (SEM) images confirmed the results of compaction tests and indicated that micro silica can effectively fill the pores of sand-cement mixtures which can lead to creation of a cement-treated sand mixture with compact microstructure.

Keywords: sand, cement, micro silica, standard Proctor compaction test, SEM.

1. Introduction

Due to economic and social development of the populations and lack of suitable areas, construction of structures on problematic soils which are taken into account as inappropriate soils has been increased [1]. In geotechnical engineering, stabilization is considered as one of the popular methods for improving characteristics of undesirable soils. Different stabilization techniques can be employed for enhancement of soil properties, one of which is chemical stabilization using additives. Cement is known as a suitable additive for stabilization and modification of a wide variety of soils, particularly problematic soils such as loose sand. Stabilization of soil with cement has been widely accepted as an attractive method for ground improvement in many countries because of economic and environmental issues. Besides, using cement for soil stabilization can provide great advantages including increasing shear strength parameters of soil and avoiding the use of borrow materials from elsewhere. This reliable and simple technique has been utilized for various applications such as construction of stabilized bases under pavements, canal lining, backfill materials of retaining walls, embankments and engineered fills. The results of recent investigations about the effect of cement on the sand properties have shown that mechanical behavior of cemented sand can be influenced by several factors such as content and type of cement and also porosity, density and grain size of the sand [2-6].

On the other hand, micro silica (also known as silica fume) is a by-product of the smelting process in the production of metallic silicon or ferrosilicon in the alloys industry. Micro silica is usually a grey colored powder with very high content of amorphous silicon dioxide and is categorized as one of the most effective Supplementary Cementitious Materials (SCM). This term refers to materials that are utilized in concrete in addition to Portland cement. Micro silica consists of very fine smooth spherical particles with sizes less than 1 μm, which are approximately 100 times smaller than particles of cement [7]. Many studies have been carried out on the effect of micro silica on the performance of concrete [8-12]. However, very few studies are available about the impact of micro silica as an additive material on the behavior of cemented sand. Thus, in the present research, it has been attempted to investigate the effect of micro silica on the geotechnical characteristics of cemented sand. The experimental platform covers properties of materials and a program of tests including standard Proctor compaction and microstructure analysis using Scanning Electron Microscope (SEM).
2. Materials

2.1. Sand
The sand used in this study was obtained from Babolsar city, north of Iran. The sand was classified as poorly-graded sand (SP) based on Unified Soil Classification System [13] with specific gravity (Gs) of 2.73 [14]. The mean grain size (D$_{50}$), uniformity and curvature coefficients of this sand are 0.23 mm, 1.67 and 0.86, respectively. Figures 1 and 2 show the particle size distribution curve and SEM image of Babolsar sand, respectively.

![Figure 1. Gradation of Babolsar sand.](image1)

![Figure 2. SEM image of Babolsar sand.](image2)

2.2. Cement
Type II Portland cement produced by Mazandaran cement factory (Neka, Iran) was used 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. Table 1 and Figure 3 indicate the chemical properties and SEM image of cement, respectively. As observed in Figure 3, cement particles have generally an irregular polygonal shape.
Table 1. Chemical compositions of cement used in this study.

| 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   |

Figure 3. SEM image of cement.

2.3. Micro silica

In this study, amorphous micro silica in powder form with particle size diameter, specific gravity and surface area of <1 μm, 2.2 and 13000-30000 m$^2$/kg, respectively, was employed. Table 2 and Figure 4 show chemical components and SEM image of this micro silica, respectively.

Table 2. Chemical compositions of micro silica.

| Chemical name | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | K$_2$O | CaO | MgO | SO$_3$ | Na$_2$O |
|---------------|---------|-------------|-------------|--------|-----|-----|--------|--------|
| Percent (%)   | 96.65   | 0.23        | 0.07        | 0.56   | 0.31 | 0.04 | 0.17   | 0.15   |

Figure 4. SEM image of micro silica.
3. Sample preparation and test program

3.1. Standard Proctor compaction test
In order to investigate the compaction properties of sand-cement-micro silica mixtures, standard Proctor compaction tests based on ASTM D 698 [15] were considered in the present research. Thus, sand, cement (3, 5 and 7% by the dry weight of the sand) and micro silica (0, 0.25, 0.5 and 1% by the dry weight of the sand) were thoroughly mixed until a uniform color was obtained. Then, water was added to facilitate the mixing and compaction process. The standard Proctor compaction tests were conducted using energy derived from a rammer of 2.5 kg mass falling through a height of 30 cm in a 943 cm$^3$ mold. The mixture was compacted in three layers, each receiving 25 blows. After performing compaction, weight and moisture of samples were measured. For each combination of variables, standard Proctor compaction tests were carried out on three identical samples and the average value of achieved results was then reported.

3.2. Scanning Electron Microscope (SEM)
To study the microstructure of the mixtures, samples of cemented sand and cemented sand including micro silica were prepared for inspection under the Scanning Electron Microscope (SEM). The Zeiss-Sigma VP scanning electron microscope was used for morphological investigations of the micro silica treated and untreated cemented sand. Before imaging, the SEM specimens mounted on aluminum stubs were coated with gold for better conductivity.

4. Results and discussion

4.1. The results of standard Proctor compaction tests
The results of standard Proctor compaction tests for sand, sand mixed with cement, and sand mixed with cement and micro silica are presented in Figures 5 to 8 in which $s=$ sand, $c=$ cement and $m=$ micro silica. It can be observed in Figure 5 that the maximum dry unit weight of the cement-treated sand increases with increasing cement content. This is related to higher specific gravity of cement (3.15) in comparison with sand (2.73). In addition, the pores within sand are occupied by fine grains of cement which makes a coherent and dense structure with higher maximum dry unit weight. The reduction in optimum moisture content in the cement-treated sand may be attributed to self-desiccation of the water. When no water movement to or from the cement paste is allowed, the water is used up in the hydration reaction until too little is left to saturate the solid surfaces; and hence, the relative humidity within the paste decreases. As shown in Figure 5, variations in compaction properties are noticeable at lower percentages of cement. However, at higher cement contents, these changes in cement-stabilized sand are minimal.

Figures 6 to 8 indicate that there is an increase in the maximum dry unit weight of cemented sand with increasing content of micro silica. It is worth remarking that cement paste matrix is fundamentally a porous material consisted of calcium hydroxide (CH), aluminates and unhydrated cement (clinker) embedded into an amorphous nanostructured hydration product, the so-called CSH (calcium silicate hydrate) gel [16]. The extremely fine micro silica particles, in addition to being a high pozzolanic material, fill the gap between cement grains, leading to micro-filling or particle packing which contributes towards an increase of density. In other words, micro silica occupies pores between sand-cement particles which results in reduction of void ratio of the specimens, contributing to the increase of the maximum dry unit weight. Therefore, micro silica particles decrease the porosity of the blended cement paste and improve the interfacial microstructure properties. Figures 6 to 8 also show that there is a decreasing trend in the optimum moisture content of the samples with the increase in the micro silica content. It would be ascribed to the fact that when a material with high specific surface such as micro silica is added to cement, it acts as the micro-filler of the cement particles, which can decrease the amount of water that filled in the void of the blending materials.
Figure 5. Influence of cement on compaction curves.

Figure 6. Compaction curves of sand with 3% cement and various micro silica contents.

Figure 7. Compaction curves of sand with 5% cement and various micro silica contents.
4.2. The microstructure analysis

Figures 9 and 10 depict the morphological characteristics of the cemented sand microstructure without and with micro silica, respectively. It should be mentioned that the magnification of the SEM photos is 20000 times and the SEM instrument was operated at 10 kV. As seen in Figure 9, the structure of cement-sand mixture is loose and porous. The SEM image of the cemented sand with micro silica (Figure 10) shows the compact and dense microstructure without considerable pores which confirms the results of standard Proctor compaction tests. Figure 11 indicates the microstructure of the sand-cement-micro silica mixture which is dense and uniform. It can be found that micro silica acts as filler due to its fineness and because of which it fits into spaces between sand and cement particles. This phenomenon is frequently referred to as particle packing or micro-filling. The small micro silica particles fill the interstitial spaces inside the skeleton of hardened microstructure of cement paste that can lead to an increase in the density. The presence of micro silica in the sand-cement mixes leads to a considerable reduction in the volume of large pores.
5. Conclusions
In this study, the effect of micro silica on the compaction properties of cemented sand was assessed. The results showed that due to filling effect of micro silica particles, the porosity of the mixtures decreased and their density increased. Based on the results from the present research, the following conclusions can be drawn:

1. The increase of maximum dry unit weight and the reduction of optimum moisture content of sandy soil were observed with the increase in the cement content. Furthermore, maximum dry density of the sand–cement mixtures increases and their optimum moisture content decreases with increasing micro silica content.

2. The SEM examinations were conducted to verify the behavior measured by compaction tests. The SEM images demonstrated that adding micro silica particles creates a cement-treated sand mixture with compact microstructure. This shows that micro silica particles with extremely fine sizes can efficiently fill the gap between cement grains and the pores of the cement paste which results in reduction of void ratio and increase of maximum dry unit weight.

6. References
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