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ORIGINAL ARTICLE

Investigating the effect of additives' size on the improvement of the tensile and compressive strengths and deformation characteristics of collapsible soils

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Abstract
In the present study, an experimental investigation was conducted to examine the effect of the size of additives on the improvement of collapsible soils. For this purpose, three collapsible soils with severe collapse potential were selected from Varamin Plain, Iran. The selected soils were then treated in the laboratory by the addition of alumina materials in two sizes of 70 nm (nano-alumina) and 685 nm (micro-alumina) and in different contents to improve their mechanical properties. Soil properties including collapse potential, uniaxial compressive strength, compressive modulus of elasticity, direct tensile strength, and tensile modulus of elasticity were selected as the target parameters for the improvement. These parameters were measured and determined before and after the treatment and the behaviors of treated soils were studied in both compression and tension states. The obtained results indicated that the nanometric and micrometric additives have diverse effects on the performance of the treated soil under compression and tension conditions.

Keywords Collapsible soil · Soil treatment · Additive material size · Tensile and compressive behavior

Introduction

Collapsible soils are mainly composed of silt-sized particles with a porous metastable structure prone to collapse upon wetting (Xie et al. 2018). Loess soils are aeolian sediments mainly composed of silt particles with a yellowish color, porous massive structure, and interparticle binding by clays and/or carbonates (Assadi-Langroudi et al. 2018; Peng et al. 2019). From an engineering geology point of view, the most important characteristics of loess include having metastable structure, low initial density, low natural water content, low plasticity, and relatively high strength and stiffness in dry state (Zimbardo et al. 2016; Li et al. 2016). The collapse potential of loess soils, which are the most important collapsible soils in the nature, can be identified through their index properties (e.g., Gavar 2012), in-situ tests (e.g., Mendes and Lorandi 2008; Dusan et al. 2014), and laboratory tests (e.g., Akbari Garakani et al. 2015). The double consolidation test (ASTM D5333 2003) is the most widely used laboratory test to determine the collapse potential of collapsible soils.

The collapse of the soil structure leads to a sudden volume reduction in the soil mass (Assadi-Langroudi et al. 2018) and consequently collapse-associated problems such as sudden foundation settlement, differential settlement, ground fissuring, and landslides. These issues pose serious damages to both infrastructures and the environment (Li et al. 2016; Nikbakhti et al. 2018; Wang et al. 2018; Xie et al. 2018; Xu et al. 2018). There are various approaches to avoid or mitigate the collapse problem of collapsible soils such as replacing them with suitable soils, soil treatment approaches, and using special foundations like piles (Gaaver 2012). The underlying mechanism of soil treatment approaches is mainly densifying or/and solidifying soil structure to mitigate the collapsibility of soils (Evstatiev 1988). Soil compaction is one of the most commonly used approaches for treatment of collapsible soils (Rollins and Jihyoung 2010). This simple and efficient method significantly increases density and, thus, reduces the collapse

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potential of the soil (Feng et al. 2015). Soil stabilization with additives is another commonly used method for the treatment of collapsible soils. In this technique, soil properties are improved using a wide variety of additive stabilizer materials such as cement (Cardoso et al. 2017), lime (Jha and Sivapullaiah 2017), fly ash (Alsafi et al. 2017; Kafodya and Okonta 2018a), rubber (Yadav and Tiwari 2017), glass (Arulrajah et al. 2017), fiber (Cui et al. 2018; Tran et al. 2018a, b), synthetic binders (Correia et al. 2015), and polymers (Estabragh et al. 2012). The additive stabilizer binds the soil particles to each other and thus increases the strength and stiffness of the soil, as well as decreasing its compressibility and collapse potential (Alsafi et al. 2017). In recent years, with the advance in nanotechnology and applying it in geotechnics, nano-sized materials have been used as additives for the treatment of problematic soils including collapsible ones (Ghasabkolaei et al. 2017). In this regard, Iranpour and Haddad (2016) applied four types of nanomaterials including nanoclay, nano-alumina, nanocopper, and nanosilica for the treatment of three collapsible soils. They added different amounts of each nanomaterial to each soil in order to study the effect of type and amount of nano-additives on the reduction of the collapse potential of the soils. They reported that although all added nanomaterials decline the collapse potential of the studied soil, nanoclay showed a more considerable reduction in the collapse potential because of its higher specific surface area. Tabarsa et al. (2018) studied the improvement of collapsible loess soils using nanoclay both in laboratory and in situ. They added nanoclay to loess soil in fractions of 0.2–3% by mass and then examined geotechnical properties and problems such as collapse and dispersion of the improved soils. Moreover, investigating the in-situ effectiveness of nanoclay on the improvement of loess soils, they found a general agreement between laboratory and field results. Based on their results, the addition of 0.5–3% nanoclay to loess significantly improves the behavior of the soil and reduces its collapsibility and dispersivity problems.

In general, a successful soil treatment should result in enhanced soil strength and a decrease in its deformability (Jha and Sivapullaiah 2015). In the case of collapsible soils, targeted properties for improvement, regarding the type of collapse-associated problems and soil application, include strength, stiffness, collapse potential, permeability, and erodibility (Iranpour and Haddad 2016; Nikbakhti et al. 2018; Tabarsa et al. 2018). From the strength point of view, in most previous studies on collapsible soils, the improvement of compressive strength of treated soils has been evaluated (e.g., Tabarsa et al. 2018) but the tensile strength has been neglected. Tensile strength is a significant mechanical property of collapsible soils when they are subjected to tensile stresses including those stresses imposed on the soil during earth fissuring and slope instability in loess plateaus (Sun et al. 2009, 2016; Li 2018; Nikbakhti et al. 2018). In this circumstance, the weak tensile strength of loess facilitates the formation of earth fissures and slope failures (Sun et al. 2016; Li 2018). Therefore, the tensile strength of collapsible soils should also be targeted for soil improvement.

This study was conducted to examine the effects of the additives' size on the improvement of collapsible soils. Soil samples with a severe collapse potential were obtained from Varamin Plain, Iran. In the laboratory, additives including alumina powders were utilized in two different scales of nanometric and micrometric to improve the targeted mechanical properties of the studied soils including tensile strength and stiffness, compressive strength and stiffness, and collapse potential. Finally, the effects of each size of additives on the improvement of each property were evaluated and discussed.

Materials and experimental procedures

Collapsible soils

Collapsible soils used in this study (i.e., S1, S2, and S3) were collected from the peripheral area of the Varamin plain, Iran, which is subjected to earth fissuring. This area consists of collapsible soils experiencing tensile stresses caused by land subsidence of the Varamin plain. Moreover, the construction of a highway with inefficient drainage facilities has caused water accumulation on collapsible soils of this area during rainfalls. Therefore, an association of various factors including imposed tensile stresses, the low tensile strength of the soil, water accumulation, and high collapse potential of loess soils has caused the formation and expansion of earth fissures around the highway. Overall, these factors threaten the safety of this important infrastructure (Nikbakhti et al. 2018). The main characteristics of the studied soils are given in Table 1.

Table 1 Index properties of the studied soils

Soil properties	S1	S2	S3
Sand (%)	26.7	19.8	12.2
Silt and clay (%)	73.3	80.2	87.8
Liquid limit (%)	27.5	24.5	24
Plasticity Index (%)	6	4.5	6.5
Specific gravity of particles	2.65	2.64	2.53
Natural unit weight (kN/m^3)	13.24	14.12	14.53
Maximum dry unit weight (kN/m^3)	17.85	18.57	19.12
Optimum moisture content (%)	16.5	11.5	8.8
Soil classification (USCS)	CL-ML	CL-ML	Cl-ML

Additives

There is a wide variety of additives that can be used for the treatment of collapsible soils. Iranpour and Haddad (2016) showed that nano-alumina significantly improves the collapse potential of collapsible soils. Therefore, in the present study, alumina additives were applied in nanometric and micrometric scales. These materials were purchased at the desired particle size from US Research Nano-materials Inc. The specifications of the additives are given in Table 2. As can be seen from this table, the average particle size of nano-alumina and micro-alumina are about 70 nm and 685 nm, respectively. Therefore, micro-alumina particles are tenfold larger than the nano-alumina particles.

Sample preparation

Preparing a homogenous mixture is crucial for achieving proper results in soil improvement by the addition of additive stabilizer materials, especially when the materials are added in small contents (Taha and Taha 2012). In this study, mixtures containing 0.5%, 1%, and 1.5% additives referred to dry weight were prepared. To obtain homogeneous mixtures, alumina powders were mixed with soils according to the procedure proposed by Cui et al. (2018). For this purpose, the micro- and nano-alumina powders were dispersed in a certain amount of deionized water and then the solution was carefully added to oven-dried soil considering the intended ratios between the soil and additives. Next, the mixture was stirred mechanically until the alumina powders were homogeneously distributed in the soil to produce uniform samples. Finally, the mixtures were dried in an oven at a temperature of 105 °C for 24 h and then were compacted at optimum moisture content. The benefit of this procedure is that the combination of nano- or micro-alumina with soil in the form of colloid solutions reduces the agglomeration of additive particles and results in achieving a uniform and homogenous mixture (Iranpour and Haddad 2016; Cui et al. 2018).

Mechanical properties of collapsible soils depend on various factors including water content, dry density, sample size, etc. (Li 2018). So, to eliminate the influences of unintended factors, the moisture content, dry density, and dimensions of prepared samples of each examined soil (S1, S2, and S3) were kept constant while the size and amount of additives were varied. The maximum dry density and optimum moisture content of each soil (Table 1) were determined by conducting standard Proctor test (ASTM D698 2007) and additive-soil mixtures were compacted at optimum moisture content and maximum dry density. The density of compacted specimens was controlled by measuring their weight and volume and dividing the obtained weight by the volume. To prepare specimens for uniaxial compressive and tensile strength tests, mixed materials were placed in a cylindrical split-mold, with an inner diameter of 38 mm, and two cylindrical plastic pieces of the same diameter were positioned at the top and bottom of the mixture inside the mold. Next, a static pressure with a 1 mm/min rate and a maximum value of 800 kPa was applied to them (Fig. 1a, b) to compact the mixture and achieve the desired density. This method resulted in high-quality soil specimens with a homogenous fabric (Fig. 1c) suitable for mechanical tests (Kafodaya and Okonta 2018a, b). For the quality control of this method, three specimens from each soil were prepared without additives and the UCS test was applied to them. Test results (Fig. 2) show that the UCS value of each tested specimen deviated at a minimum rate from the average UCS values of three specimens of each soil, suggesting that the specimen preparation method minimized the human errors and the effects of unintended factors. The same method was applied to prepare the specimens with a diameter of 50 mm required for the collapse potential test (Fig. 1d).

Table 2 Basic properties of alumina additives

Properties	Nano-alumina	Micro-alumina
Formula	Al_2O_3	Al_2O_3
Purity (%)	99+	99+
Average particle size (nm)	70	685
Density (g/cm^3)	3.9	3.9
Specific surface area (m^2/g)	> 15	6–10
Color	White	White

Experimental tests

To determine the collapse potential of specimens, a double consolidation test was conducted in accordance with ASTM D5333 (2003). Through this procedure, the prepared specimens with a diameter of 50 mm and a diameter-to-height ratio of 2.5 were placed in the loading device and then were loaded incrementally from 25 to 200 kPa. At a pressure of 200 kPa, the soil was saturated by adding distilled water to make it collapse and then the load increments were continued to 800 kPa. During the test, deformations were recorded versus pressure. The collapse potential of tested samples was calculated using Eq. 1 as follows:

$$I_c = (\Delta h/h_0).100, \quad (1)$$

where I_c is collapse potential, Dh is the change in specimen height upon saturation, and h_0 is initial specimen height.

An unconfined compressive strength (UCS) test was performed following the procedure outlined by ASTM D2166 (2007). In this test, cylindrical specimens with a diameter of 38 mm and a height-to-diameter ratio of 2.5 were placed in a strain-control loading device and the load was applied

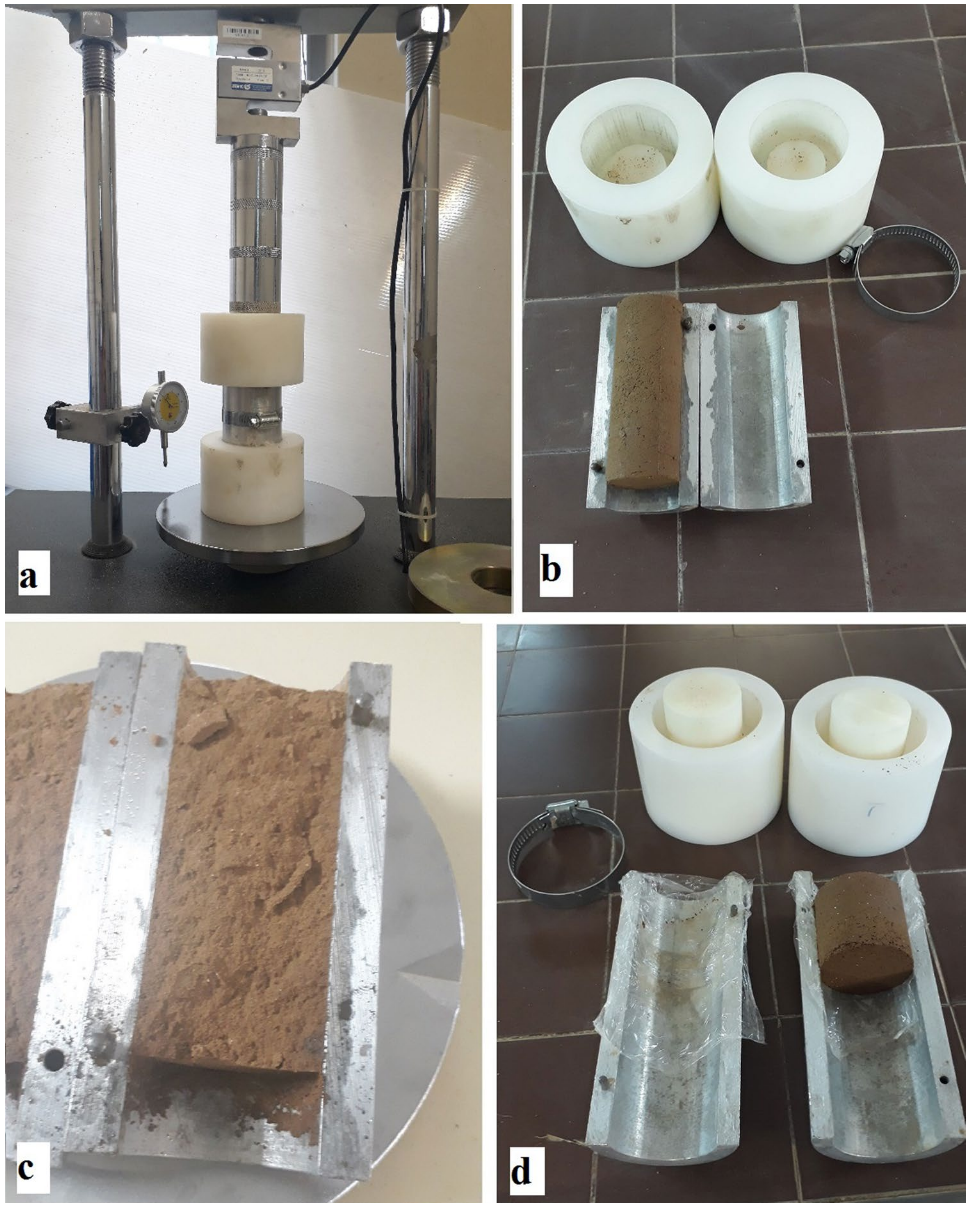

Fig. 1 **a** Specimen fabrication using static load, **b** and **c** Homogenous and uniform specimens prepared for UCS and DTS tests, **d** a specimen prepared for collapse potential test

to produce a constant axial strain at a rate of 1%/min. During the test, the values of load, deformation, and time were recorded at sufficient intervals. Finally, axial deformation and compressive stress values were calculated and the stress–strain curve was plotted using these values. In each test, three specimens were applied and their mean value was obtained as the UCS (Fig. 3).

To perform the direct tensile strength (DTS) test, a tension cell was developed and mounted on a triaxial test apparatus (Fig. 4). The cell included two plates that specimens were bounded between them using glue (Fig. 5). The lower plate was fixed on the force transmission plate of the triaxial apparatus and the upper one was connected to the load cell (Fig. 4). During the test, the force transmission plate was moving down at a rate of 0.24 mm/min, leading to the generation of a tensile load applied to the specimen. At the same time, the values of deformation, load, and time were recorded automatically by the data-logger of the apparatus. Each test continued until the occurrence of the failure of the specimen, which usually occurs perpendicular to the specimen axis (Fig. 5). By calculating the tensile stress and deformation, tensile stress–strain curves were obtained for each soil. Cylindrical specimens of a diameter of 38 mm and a height-to-diameter ratio of about 2 were used for this test. In each test, three specimens were applied and their mean value was recorded as the DTS.

Two major approaches for determining the tensile strength of soil include indirect and direct methods. Direct methods, which give usually lower but more precise values for the tensile strength (Li 2018), can be performed vertically or

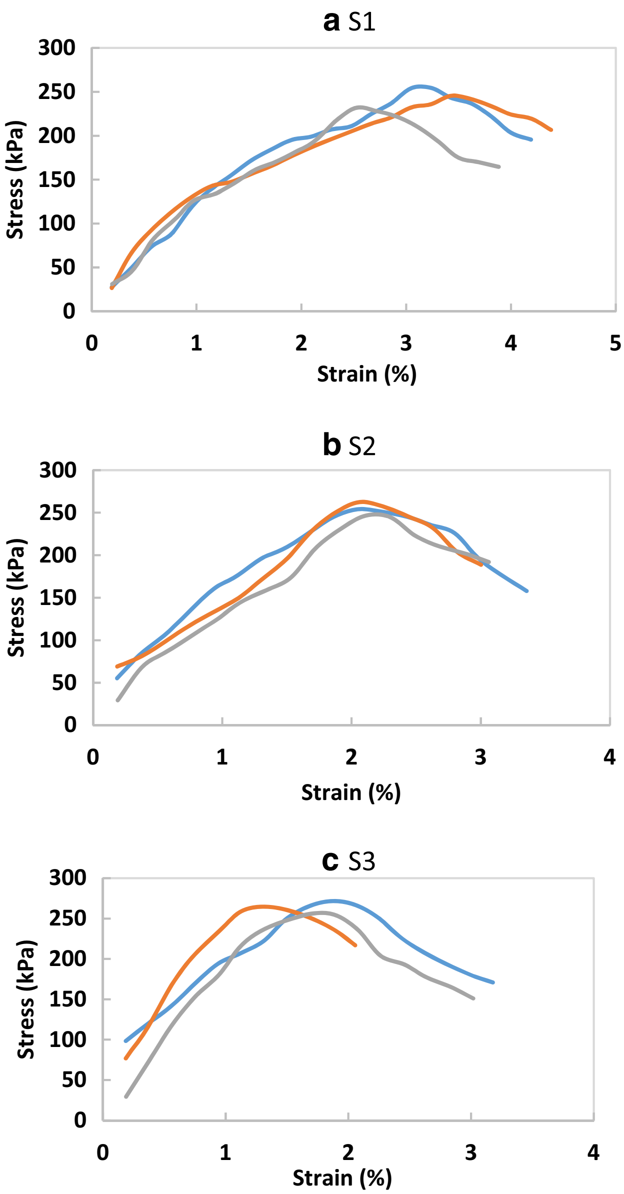

Fig. 2 The results of UCS tests on three un-treated fabricated specimens of **a** S1 Soil, **b** S2 Soil, and **c** S3 Soil

Fig. 3 Three un-treated specimens of S1 Soil after UCS test

Fig. 4 Setup used for direct tensile strength test

horizontally and via stress-controlled or strain-controlled modes (Sun et al. 2016; He et al. 2018). In the horizontal stress-controlled tensile apparatus, the specimen is placed and loaded horizontally and the failure plane occurs perpendicular to the tensile load. The horizontal apparatus prevents fracturing the sample under the action of gravity (Sun et al. 2009, 2016). As mentioned above, in the present study, a vertical strain-controlled apparatus was used in which the specimens were placed and loaded vertically and failure plain occurred perpendicular to the tensile load. The apparatus was strain-controlled type and the force was measured continuously with a digital load cell (Fig. 4). In this way, all forces affecting the specimen including gravity force were measured and considered. As the soil specimens were subjected to pure tensile load and the failure plane occurred perpendicular to the tensile load, the measured tensile strength should correlate well to the fissuring tensile stresses.

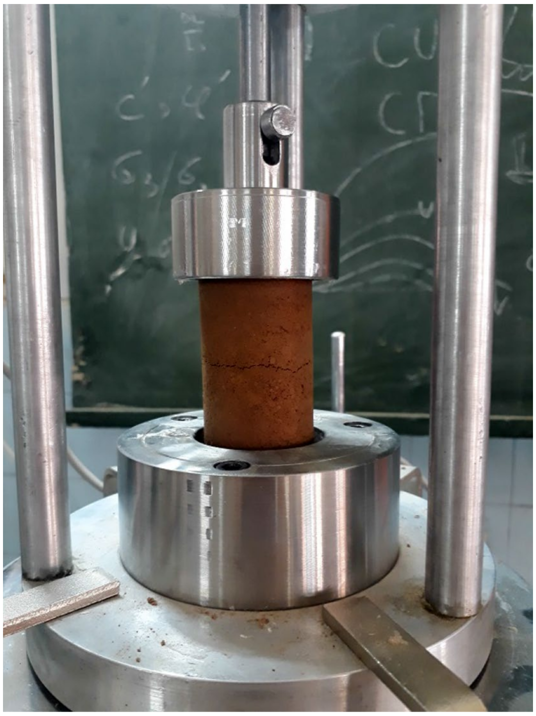

Fig. 5 A specimen fixed between upper and lower plates of tension cell

Experimental results

Collapse potential

Collapse potential (Eq. 1) is an important characteristic of the collapsible soils that indicates the severity of collapse-associated problems. Therefore, in most soil improvement projects, this parameter is determined before and after soil improvement to examine the success of the applied methods and materials. The collapse potential values of the studied soils in a natural state are more than 10% (Nikbakhti et al. 2018), suggesting that these soils have the potential for a severe collapse and the associated problems. In this study, examined specimens contained 0%, 0.5%, 1%, and 1.5% additives referred to dry weight. Specimens of 0% additive were those treated only with the compaction and no additive was used to decline their collapse potential. The results of the collapse potential tests conducted on the studied soils are presented in Figs. 6, 7. The collapse potential values of soils S1, S2, and S3 with no additive are 3.05%, 2.75%, and 2.50%, respectively. According to these values, the soils have a moderate degree of collapse potential. In these specimens, compaction of natural soils decreases the collapse potential from a severe degree to a moderate degree. Compaction reduces porosity and increases the density of soils. As a result, it minimizes the collapse potential to a moderate degree. However, the soils still have the potential to collapse. Using additives in addition to the compaction causes further reduction of the collapse potential of soils to the degree of slight- or non-collapsible soils. Results indicate that the addition of materials to the soils significantly decreases the collapse potential (Fig. 7). However, the rate at which the collapse potential decreases is dependent on the amount and size of additives. The collapse potential shows a drop-down trend when 0.5% and 1% of materials are added to soils. In comparison, the addition of 1.5% of materials adversely increases the collapse potential. The lowest collapse potential corresponds to 1% additives in which the studied soils have a slight degree of collapse potential. Based on the obtained results, the addition of additives to more than the optimum value leads to negative side effects on the collapse potential of the soil due to the agglomeration of additive particles (Iranpour and Haddad 2016), which consequently decreases the point contacts between the soil particles.

The collapse potential of specimens prepared using soil S1 without additive is about 3.05% that reduces to 1.6%, 0.5%, and 1% with addition of 0.5%, 1%, and 1.5% nano-alumina, respectively (Figs. 6a, 7a), whereas these contents of micro-alumina reduce the collapse potential (Cp) of soil S1 specimens to 1%, 0.7%, and 0.8%, respectively (Figs. 6b, 7a). The optimum content (1%) of nano-alumina and micro-alumina reduces the collapse potential of soil S1 about 6 and 4 times, respectively. On the other hand, the addition of 0.5%, 1%, and 1.5% nano-alumina to soil S2 reduces collapse potential from 2.5 to 1.75%, 0.55%, and 1.15%, respectively (Figs. 6c, 7b). Micro-alumina in contents of 0.5%, 1%, and 1.5% reduce the collapse potential of this soil from 2.5 to 1.55%, 0.75%, and 1.35%, respectively (Figs. 6d, 7b). Therefore, nano-alumina and micro-alumina reduce the collapse potential of soil S2 maximum 4 and 3 times, respectively. Based on the obtained results, soil S3 specimens have a collapse potential of about 2.75% that addition of 0.5%, 1%, and 1.5% nano-alumina reduces it to 1.95%, 1%, and 1.7%, respectively (Figs. 6e, 7c). The addition of these amounts of micro-alumina to this soil decreases collapse potential to 2.25%, 1.25%, and 1.75%, respectively (Figs. 6f, 7c). Therefore, nano-alumina and micro-alumina reduce the collapse potential of soil S3 2.75 and 2.2 times, respectively. According to the results of the collapse potential tests on improved specimens, nano-alumina compared to micro-alumina results in a lower Cp at the optimum content of additives (1%).

Uniaxial compressive strength and stiffness

Results of UCS tests on the specimens improved by the addition of alumina materials are presented in Figs. 8, 9. As can be seen from these figures, the addition of additives significantly increases the UCS and compressive modulus of elasticity (CME) of the improved specimens.

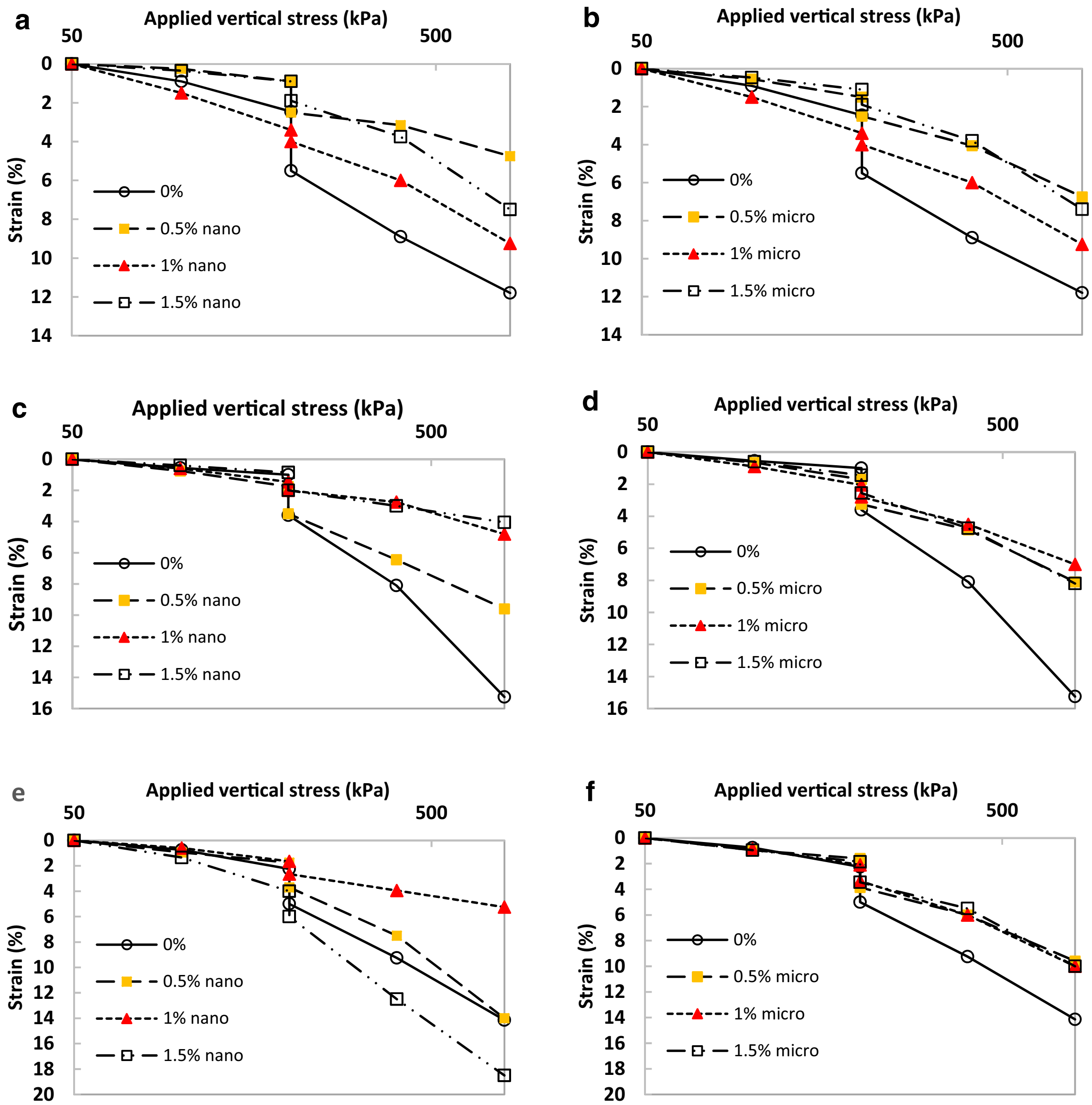

Fig. 6 The results of collapse potential test on **a** and **b** S1 Specimens, **c** and **d** S2 Specimens, and **e** and **f** S3 Specimens

Figure 8a presents the stress–strain curves for soil S1 specimens stabilized with nano-alumina. As can be seen from this figure, the specimens made of soil S1 without nano-alumina have a UCS of about 245 kPa. Addition of 0.5%, 1%, and 1.5% nano-alumina to this soil increases the UCS up to 433, 692, and 462 kPa, respectively (Fig. 9a). These results indicate that the addition of nano-alumina to soil S1 up to 1% content leads to a three-fold increase in UCS, whereas the nano-alumina content of more than 1% has a negative effect and causes a decrease of the strength. Therefore, the nano-alumina content of 1% is optimum in the achievement of the highest UCS in the soil S1. Results also show that the addition of nano-alumina causes an increase in the CME of the improved specimens. The CME of soil S1 is about 6.6 MPa that increases to 13, 19.3, and 9.3 MPa by the addition of nano-alumina contents of 0.5%, 1%, and 1.5%, respectively (Fig. 9b). Therefore, increasing the nano-alumina content up to 1% results in a 2.9-fold increase in CME and when the nano-alumina content increases beyond 1%, a decline in CME is noticed. Residual strength also increases by increasing the nano-alumina content up to 1% and then significantly decreases when nano-alumina content increases to 1.5% (Fig. 8a). In the case of adding micro-alumina to the soil S1, the UCS increases from 245 kPa to 367, 517, and 390 kPa by addition of 0.5%, 1%, and 1.5% additives, respectively (Figs. 8b, 9a). As can be seen from these results, the optimum content of micro-alumina is

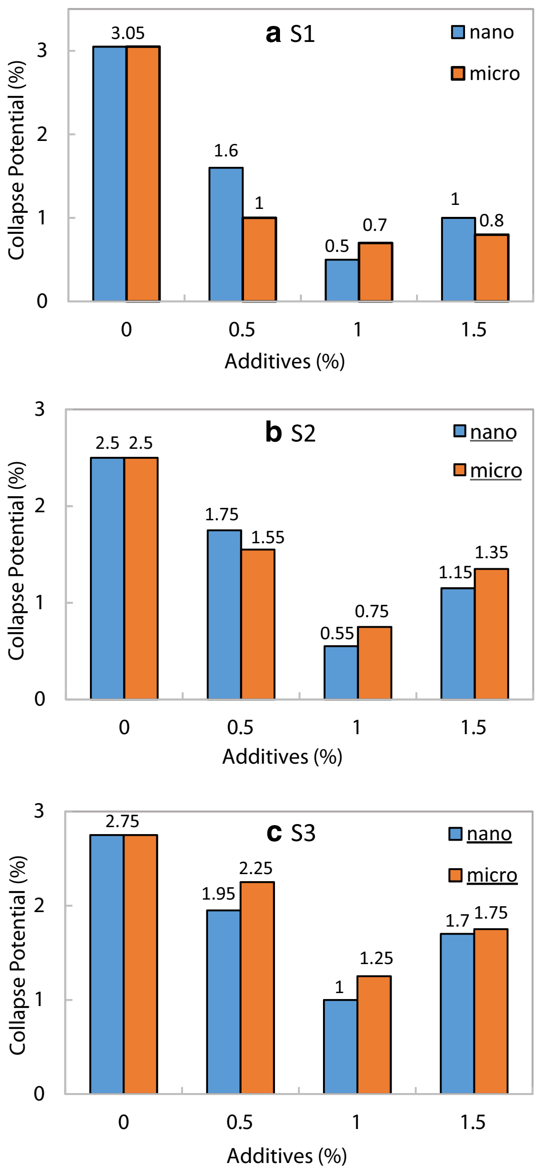

Fig. 7 The effect of alumina additives on the collapse potential of **a** S1 Specimens, **b** S2 Specimens, and **c** S3 Specimens

1%, which leads to a twofold increase in UCS compared with non-stabilized specimens of soil S1. Micro-alumina content of more than 1% has a negative effect and leads to a decrease in the UCS. The addition of micro-alumina causes also an increase in the CME of soil S1 such that 0.5%, 1%, and 1.5% contents of micro-alumina resulted in an increase in the CME from 6.6 MPa to 8.8, 12.1, and 7.9 MPa, respectively (Fig. 9b). Based on the obtained results, the addition of micro-alumina does not result in an increase in the residual strength of the soil. As presented in Fig. 8b, the residual strength of stabilized specimens is close to that of non-stabilized specimens. Comparing the effects of nano-alumina with those of micro-alumina on the soil properties indicates that nano-alumina has better effects on soil S1 properties and causes more increase in UCS and CME of this soil.

The results of adding nano-alumina to soil S2 specimens are presented in Fig. 8c. As this figure shows, the non-improved soil S2 has a UCS about 263 kPa that increases with the addition of nano-alumina. The addition of 0.5%, 1%, 1.5%, and 2% nano-alumina causes the corresponding increase in UCS to 329, 417, 557, and 294 kPa, respectively (Fig. 9c). According to these results, the increase ratios of UCS are 1.25, 1.58, 2.11, and 1.12 for nano-alumina contents of 0.5%, 1%, 1.5%, and 2%, respectively. As these results represent, the maximum increase ratio of UCS occurs at 1.5% content of nano-alumina; therefore, this content is the optimum content for improvement of UCS of soil S2. The CME of soil S2 specimens is about 8.6 MPa, which increases to 13.6, 31.1, 38.9, and 19.2 MPa when adding nano-alumina contents of 0.5%, 1%, 1.5%, and 2%, respectively (Fig. 9d). At the optimum content of nano-alumina, the increase in the ratio of CME in soil S2 is about 4.5. Also, the addition of 0.5%, 1%, 1.5%, and 2% of micro-alumina to soil S2 specimens causes the increase in UCS from 263 to 352, 406, 542, and 293 kPa, respectively (Fig. 9c). The CME of the specimens also increases from 8.6 to 25.4, 20.7, 31.8, and 18.2 MPa when micro-alumina contents of 0.5%, 1%, 1.5%, and 2% are added, respectively (Fig. 9d). As these results indicate, the maximum increase ratios of UCS and CME are 2.1 and 3.7, respectively. Comparing the increase in these ratios with those for the addition of nano-alumina suggest that nano-alumina results in higher increase ratios of UCS and CME. Therefore, the addition of nano-alumina leads to the better improvement of UCS and CME of soil S2.

Soil S3, without additives, has a UCS of about 271 kPa that increases to 385, 444, and 318 kPa with the addition of nano-alumina in 0.5, 1, and 1.5 wt.%, respectively (Figs. 8e, 9e). These nano-alumina contents cause also the CME to increase from 8.9 to 15.7, 17.5, and 13.6 MPa, respectively (Fig. 9f). According to these results, the addition of 1% nano-alumina results in the maximum 1.64-times and 1.96-times increase of UCS and CME of the improved soils, respectively. Besides, the addition of 0.5%, 1%, and 1.5% micro-alumina to S3 specimens causes the increase in UCS from 271 to 324, 507, and 348 kPa (Figs. 8f, 9e) and the increase in CME from 8.9 to 16.9, 29.3, and 22.9 MPa, respectively (Fig. 9f). According to these results, the UCS and CME of the soil S2 specimens improved with micro-alumina are 1.87 times and 3.2 times greater than those of non-improved specimens.

Direct tensile strength and stiffness

As mentioned earlier, the studied soils are under tensile stresses induced by the subsidence of the Varamin plain.

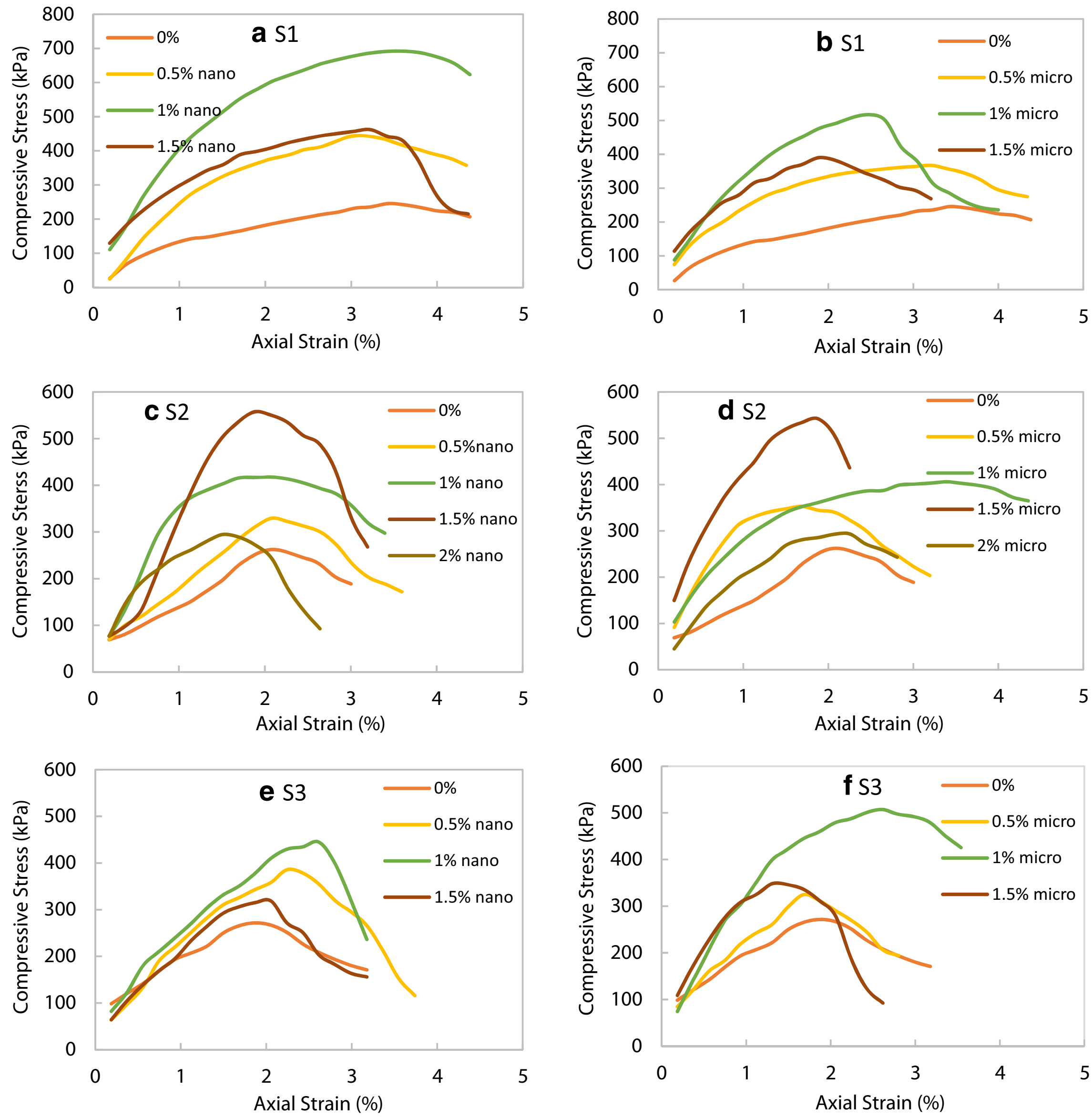

Fig. 8 The stress–strain curves of UCS test on **a** and **b** S1 Specimens, **c** and **d** S2 Specimens, and **e** and **f** S3 Specimens

This subsidence, along with other factors including the collapsibility of soil, causes the formation and expansion of earth fissures in the loess area (Nikbakhti et al. 2018). Therefore, the tensile strength of these soils and their improvement can significantly prevent the formation of earth fissures in this area. The results of direct tensile strength (DTS) tests on the studied soils are presented in Figs. 10, 11. Results of tensile strength tests on specimens fabricated without additives indicate that these soils have a DTS varying between 14.6 and 17.1 kPa, a tensile modulus varying between 1.8 and 6.7 MPa, and a tensile failure strain ranges between 0.3 and 0.8%. As presented in Fig. 11a, DTS of specimens prepared using soil S1 is about 14.6 kPa that increases to 24.7, 29.1, and 25.3 kPa by addition of nano-alumina in contents of 0.5%, 1%, and 1.5%, respectively. The increase ratios of the DTS are 1.69, 1.99, and 1.73, respectively (Fig. 11a). The tensile modulus of elasticity (TME) of soil S1 is about 1.8 MPa that increases to 4.2, 7.3, and 5.9 MPa by addition of 0.5%, 1%, and 1.5% nano-alumina, respectively (Fig. 11b). The increase ratios of TME are 2.3, 4, and 3.2, respectively. Based on the obtained results, the addition of nano-alumina does not significantly increase the tensile failure strain. On the other hand, the addition of micro-alumina in contents of 0.5%, 1%, and 1.5% increases DTS from 14.6 to 27.1, 42.3, and 29.8 kPa (Figs. 10b, 11a) and increases TME from 1.8 to 4, 6, and 4.4 MPa, respectively (Fig. 11b). The failure strain also increases from 0.6% to about 1% (Fig. 10b). The maximum increase ratios for DTS

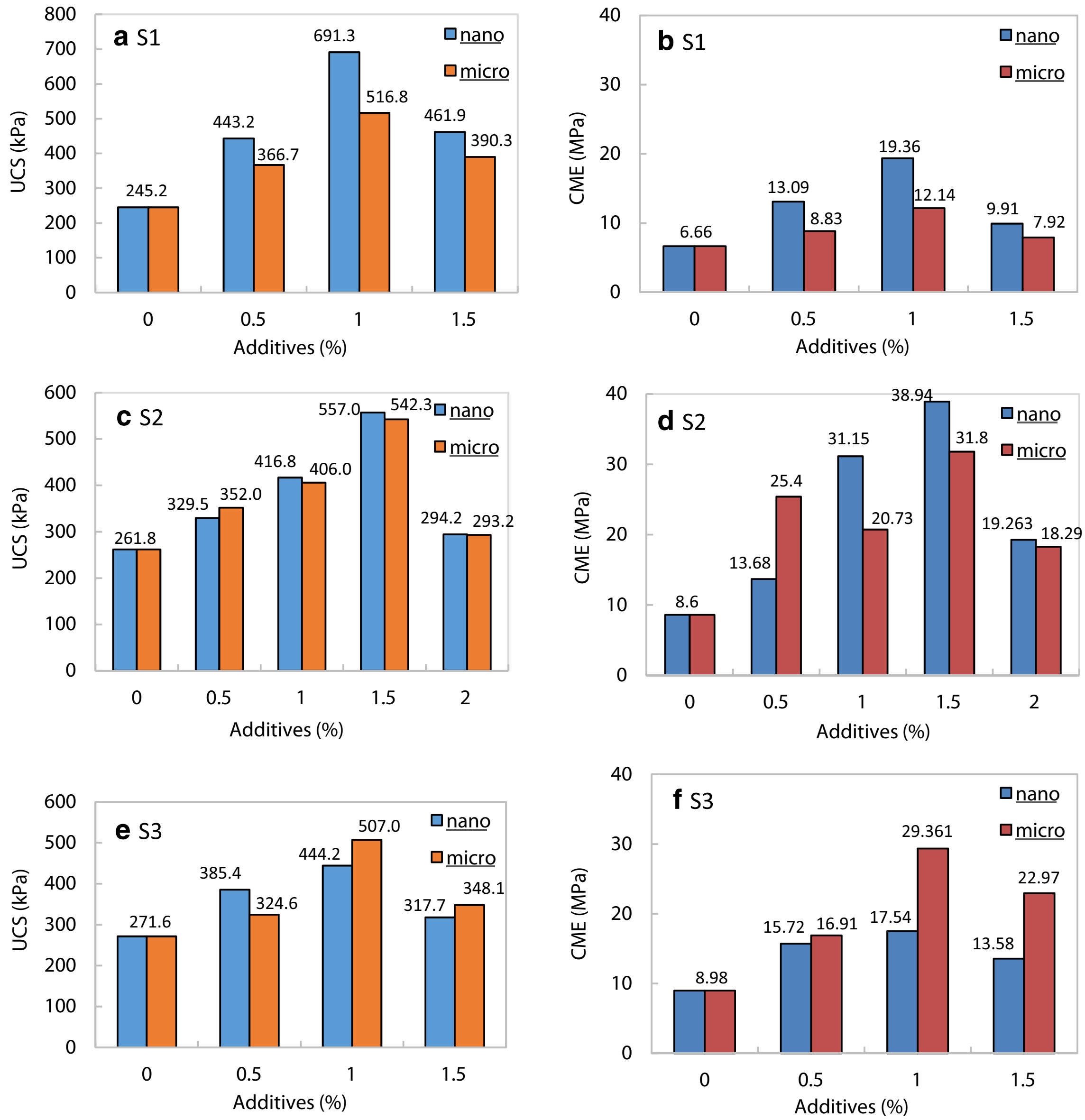

Fig. 9 The effects of alumina additives on UCS and CME of **a** and **b** S1 Specimens, **c** and **d** S2 Specimens, and **e** and **f** S3 Specimens

and TME are 2.89 and 3.3, respectively. A comparison of these increase ratios with those caused by nano-alumina indicates that micro-alumina increases DTS more than nano-alumina, whereas nano-alumina increases TME more than micro-alumina.

Soil S2 has the DTS, TME, and failure strain of 15.8 kPa, 2.4 MPa, and 0.7%, respectively. Addition of 0.5%, 1%, and 1.5% nano-alumina to this soil increases DTS from 15.8 to 22.7, 27.5, and 26.2 kPa (Figs. 10c, 11c) while it increases TME from 2.4 to 4.6, 6.1, and 5.8 MPa, respectively (Fig. 11d). Nano-alumina in 1% content decreases also the tensile failure strain of this soil to about 0.5% (Fig. 10c). The maximum increase ratios of DTS and TME after improvement are 1.74 and 2.5, respectively, suggesting that nano-alumina significantly increases the tensile stiffness of soil specimens. When micro-alumina contents of 0.5%, 1%, and 1.5% are added to soil S2, its DTS increases from 15.8 to 25.3, 33.5, and 25.9 kPa (Figs. 10d, 11c); and its TME increases from 2.4 to 3.4, 5.2, and 3.8 MPa, respectively (Fig. 11d). As presented in Fig. 10d, the addition of micro-alumina to soil S2 leads to an increase in the tensile failure strain from 0.7% to about 0.9%. Results indicate that the maximum increase ratios of DTS and TME after improvement by micro-alumina are 2.12 and 2.1, respectively. Comparison of the maximum increase ratios resulted from nano-alumina with those ratios resulted from micro-alumina indicates

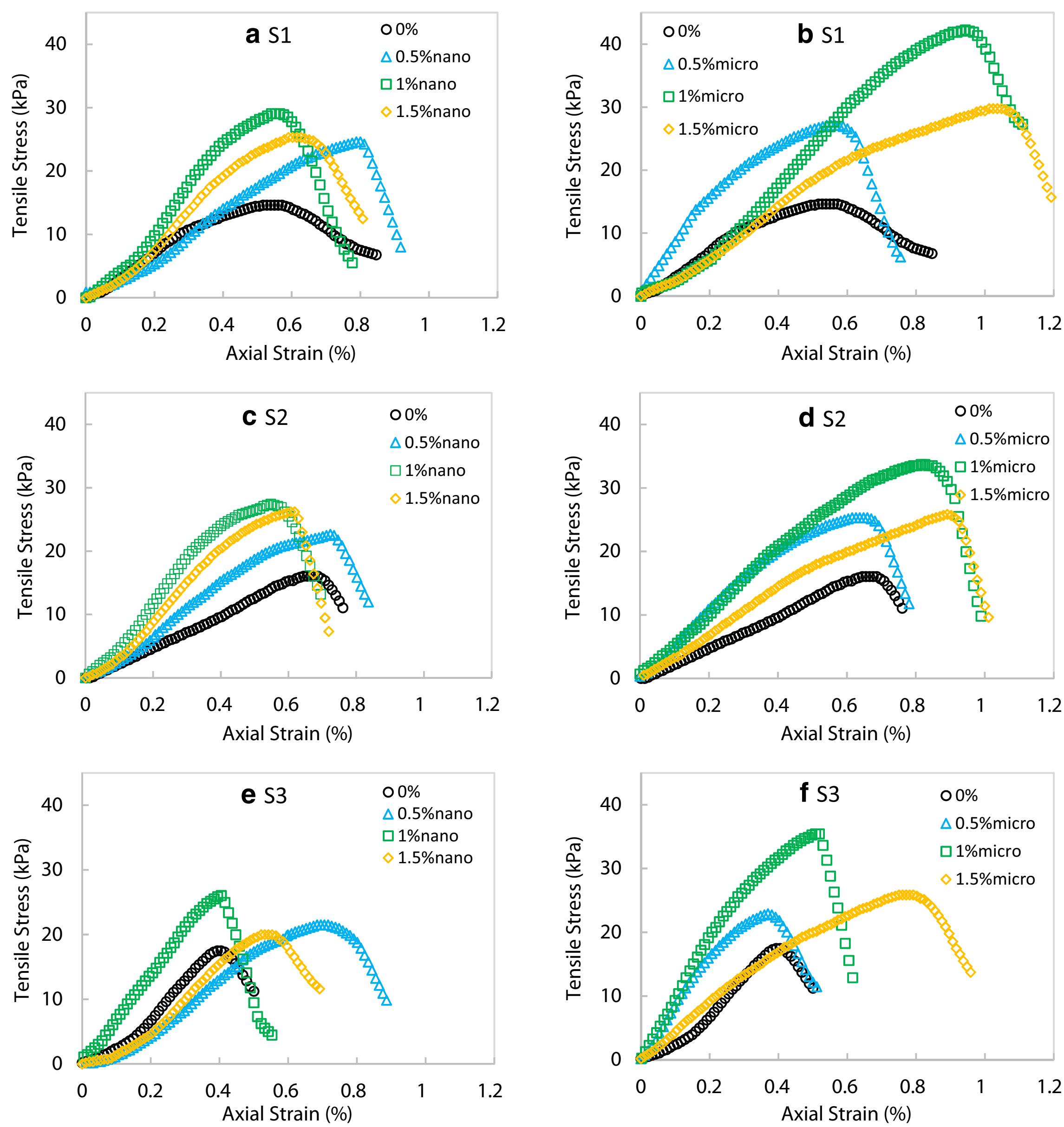

Fig. 10 The stress–strain curves of DTS test on **a** and **b** S1 Specimens, **c** and **d** S2 Specimens, and **e** and **f** S3 Specimens

that nano-alumina increases TME more than micro-alumina and micro-alumina increases DTS more than nano-alumina.

Soil S3 specimens have a DTS, TME, and failure strain of about 17.5 kPa, 6.7 MPa, and 0.4%, respectively. The soil S3 has higher DTS and TME and a lower failure strain compared with soils S1 and S2. Addition of nano-alumina contents of 0.5%, 1%, and 1.5% causes the increase in DTS from 17.5 to 21.5, 26.1, and 19.9 kPa, respectively (Figs. 10e, 11e); the increase in TME from 6.7 to 4.4, 7.1, and 5.5 MPa, respectively (Fig. 11f). According to these results, the maximum increase ratios of DTS and TME are 1.49 and 1.06, respectively. With micro-alumina contents of 0.5%, 1%, and 1.5%, the DTS of soil S3 increases from 17.5 to 22.9, 35.4, and 25.9 kPa, respectively (Figs. 10f, 11e); the TME increases from 6.7 to 5.9, 8.23, and 3.74 MPa, respectively (Fig. 11f); and the tensile failure strain also increases to about 0.55% for 1% micro-alumina content. The maximum increase ratios for DTS and TME are 2 and 1.2 after the improvement by micro-alumina, respectively. Therefore, micro-alumina has greater effects on both DTS and TME of soil S3, compared with nano-alumina.

Results of tensile strength tests on the studied soils indicate that soil specimens improved by micro-alumina have a lower TME (except soil S3) and higher DTS and tensile failure strain in comparison with those improved by

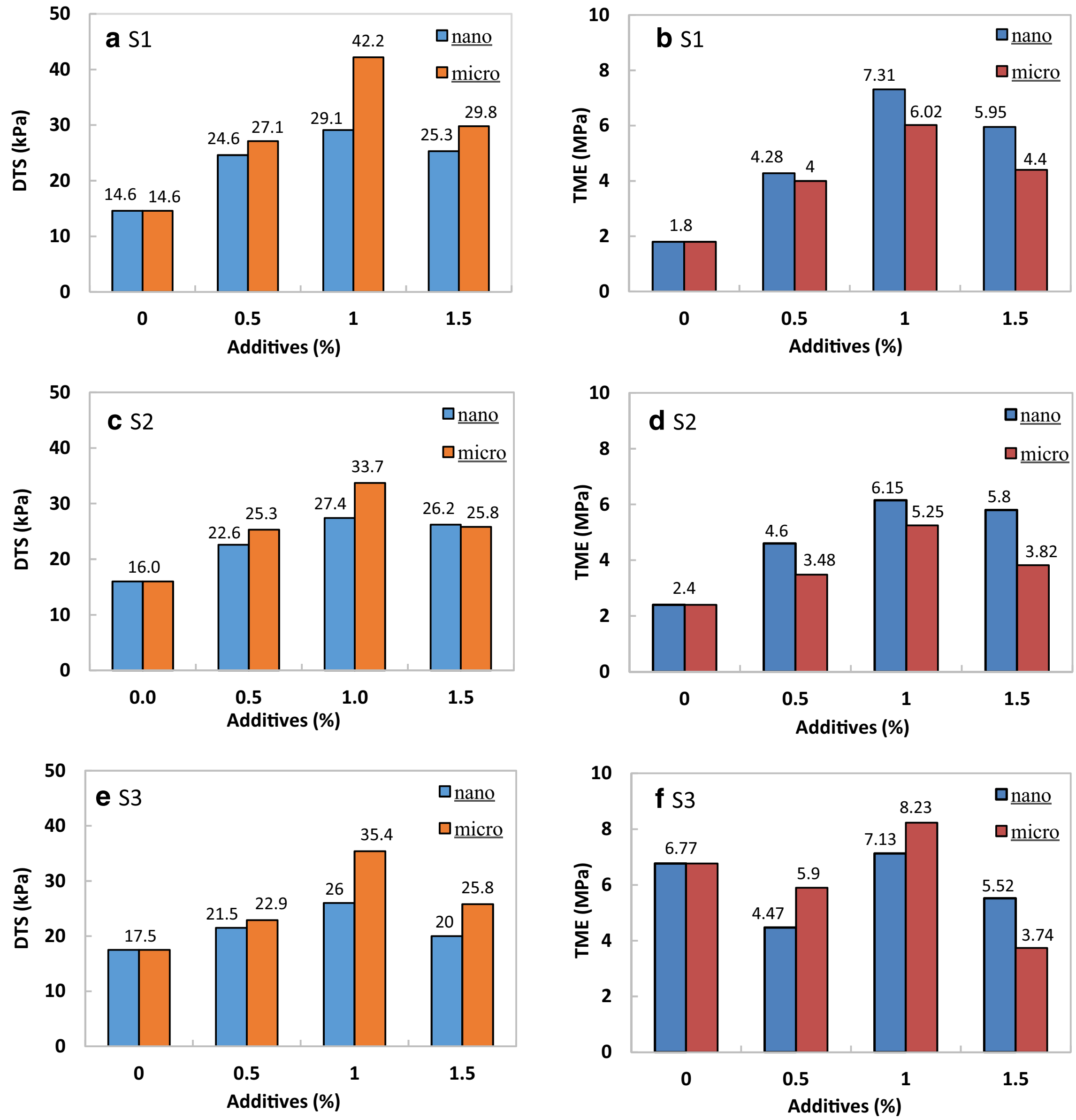

Fig. 11 The effects of alumina additives on DTS and TME of **a** and **b** S1 Specimens, **c** and **d** S2 Specimens, and **e** and **f** S3 Specimens

nano-alumina. Therefore, specimens improved by micro-alumina deform more and easier before failure and bear a higher value of tensile stress compared with specimens improved by nano-alumina.

Discussion

In unsaturated and uncemented clean granular soils, matric suction is responsible for tensile forces between soil grains and the consequent tensile strength of soil (Lu et al. 2007). However, in soil–cement mixtures, cement makes artificial bonds between soil particles which results in a considerable increase in the tensile strength of soil (Cardoso et al. 2017). Since the soil-additive mixtures were investigated in the present study, it was assumed that the additives (as cement) were responsible for the tensile strength of samples, and matric suction was ignored. The results of the present study indicate that both the compressive and tensile strengths of treated soils increase with the addition of the additives up to optimum content. Additives act as cement that create physical connections (bonds) between soil grains. These bonds are responsible for the increment of the compressive strength and stiffness and they also provide tensile strength to cohesionless granular soils (Cardoso et al. 2017). Therefore, there is a straight proportionality between compressive

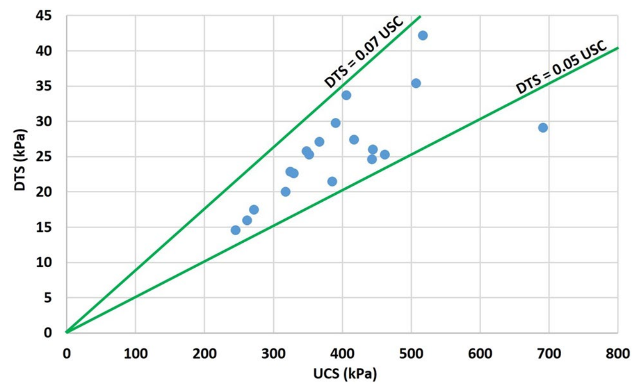

Fig. 12 The relationship between UCS and DTS of the studied soils

and tensile strengths of artificially cemented soils (Consoli et al. 2010; Festugato et al. 2017) such as treated soils in the present study. Previous studies have indicated that both compressive and tensile strengths are controlled by the cement volume and porosity of the compacted soil–cement mixture. Although the voids/cement ratio determines the strengths, the proportion between the compressive and tensile strengths is independent of porosity, cement content, or voids/cement ratio (Consoli et al. 2010; Cardoso et al. 2017; Festugato et al. 2017).

The proportion between the compressive and tensile strengths of the studied soils is presented in Fig. 12. As can be seen from this figure, the proportion between UCS and DTS of the studied soils (the ratio of DTS/UCS) varies between two limits of 0.05 and 0.07 (i.e., DTS = 0.05–0.07 UCS). Consoli et al. (2010) found a proportion of 0.15 between compressive and tensile strengths for an artificially cemented sand. In the investigation carried out by Tran et al. (2018a) on the improvement of the mechanical behavior of a silty soil, the relationship coefficients of splitting tensile strength to compressive strength were 0.162 for cemented soil and 0.145 for fiber-cement stabilized soil. Xiao and Liu (2018) found this proportion in a range of 0.09–0.15 for cemented clay soil and a value of 0.14 for fiber-cement stabilized clay soil. As these results indicate, the value of proportion between the compressive and tensile strengths in the present study is similar to those values observed in previous studies.

The effects of nanomaterials on the compression behavior of treated soils are related to the soil matrix properties and interparticle forces (Zommorodian et al. 2017; Cui et al. 2018; Tabarsa et al. 2018). The studied soils are composed mainly of silt particles with about 10–20% sand and less than 10% clay. Therefore, this soil has a composite matrix composed of coarse and fine particles. In such soils, a combination of chemical–physical forces between particles and the type of inert-particles contacts control and determine the compressive deformation and strength of the soil (Cabalar

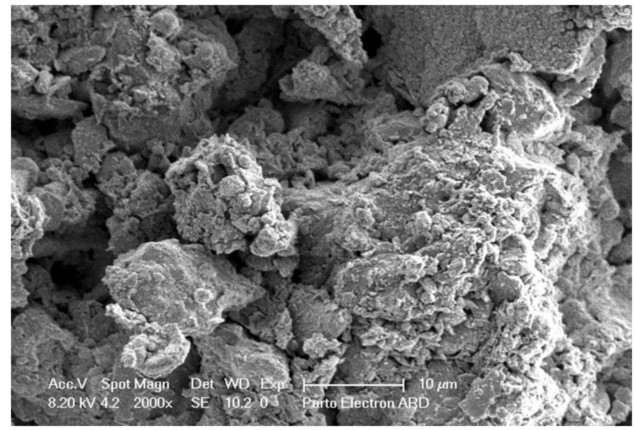

Fig. 13 A SEM image of the matrix of S1 soil treated with 1% micro-alumina

2011; Shipton and Coop 2012). Figure 13 illustrates an SEM image from the matrix of soil S1 treated with 1% micro-alumina. As can be seen, sand and silt particles are in direct contact with each other. Besides, clay content—in addition to additives—bonds them together and fills the pores between the particles. Therefore, additives increase cohesion and decrease the porosity of treated soils effectively, leading to an increase in the UCS and a decrease in the compressibility of soil in compression. In addition to additives, compaction has an important role in the increase in the UCS and the decrease in the compressibility of treated soils. Compaction mainly increases the friction by increasing the contact between particles and decreases the porosity by reducing the volume of interparticle pores (Cabalar 2011). A combination of compaction and additives results in an increase in the friction and cohesion and a decrease in the porosity. However, there is an optimum content of additives to achieve the highest improvement of targeted parameters. In the present study, the optimum content of additives was obtained equal to 1%. The soils treated with an additive content less or more than this value have lower strength and higher deformation in comparison with those treated with 1% content of additives. This observation can be interpreted based on the transition fine content (FC_t) theory. According to this theory, in a soil with a composite matrix of coarse and fine particles, up to a certain fraction of fines (FC_t), compression behavior of the soil is mainly governed by coarse particles, whereas in a situation that fine contents exceed FC_t, finer particles govern the compression (Monkul and Ozden 2005, 2007; Cabalar 2011; Zuo and Baudet 2015). There is also a close relationship between FC_t and shear strength of mixtures as the shear strength tends to increase up to FC_t and exceeding FC_t, the shear strength tends to decline (Monkul and Ozden 2007). As described earlier, in the present study specimens of soil-additive mixtures were prepared by compaction under a constant static load. When additive content is less than 1%, compaction compresses the mixture and causes a direct point contact between coarser particles, leading to the maximum friction between particles under an applied load. Besides, nanomaterials bond the coarser particles and lead to an increase in cohesion between particles. In this situation, the maximum friction is achieved because of the point contacts between grains but the maximum cohesion is not achieved due to the low content of additives and unfilled voids between grins. When the additive material is about 1%, the friction between grains is the maximum and the cohesion is also maximum because additives and clay contents bond the particles and fill the voids between them. Additive contents more than 1% prevent the direct point contacts between coarser particles and result in a decrease in the friction and strength of fabricated specimens. Therefore, specimens prepared using 1% additives have the maximum friction and strength and therefore behave stronger than the specimens fabricated with additive contents more or less than 1%. Because of using the same method for the preparation of fabricated specimens for both tensile and compressive tests, specimens with 1% of additives had the highest strength in both tension and compression states.

Micro-alumina acts like nano-alumina in soil treatment as the addition of optimum content of micro-alumina (1%) to the soil also results in the improvement of UCS and CME of the treated soil, although with a lower increase rate compared with nano-alumina. In other words, nano-alumina improves the UCS and CME of the treated soils more efficiently than micro-alumina. This phenomenon is related to the special characteristics of nano-sized materials namely the high specific surface area of these materials. The large specific surface area of nanoparticles causes active interactions between nano-additives with other soil matrix particles that significantly affect the engineering properties of improved soils (Iranpour and Hddad 2016; Zommorodian et al. 2017; Cui et al. 2018; Tabarsa et al. 2018). Therefore, nano-alumina improves the compressive strength and deformation characteristic of the studied soil more efficiently compared with micro-alumina.

Results obtained from tensile tests show that the additives with larger sizes improve the soil tensile strength more efficiently compared with additives with smaller sizes. This result may be attributed to the basic differences between the processes of tensile and compressive deformations. In compression state, soil particles and additives between them are subjected to a state of compression that makes them closer to each other. Eventually, they fail along the critical planes (Fig. 3) when the compressive stress exceeds the compressive strength. Meanwhile, in a tension state, tensile stress separates the particles of specimens from each other. Tran et al. (2018b) studied the effect of waste cornsilk fiber reinforcement on the UCS and TS of soft soils. They used cornsilk fibers of different lengths for soil reinforcement and found that fiber length has a significant effect on the TS as fibers of the largest length cause the highest enhancement. They found also that unlike TS, the fiber length has a negative effect on the UCS, as fibers of smaller length result in higher improvement of the UCS.

The finding of the present study about the higher effect of micro-alumina on the tensile strength in comparison with nano-alumina can be interpreted considering the sizes and dimensions of these two additives. Results of DTS tests indicate that tensile failure occurs at a low tensile strain, which in most cases is less than 0.5% (Fig. 10). In other words, the studied soils have a very low tensile ductility and fail after a very small tensile deformation. When a tensile load is applied to a specimen without additives, soil particles are forced to separate from each other following a small deformation. As a result, the soil matrix cannot bear the tensile load and fail along a plane perpendicular to the tensile load direction (Fig. 5). The addition of nano-alumina to the soil increases the bonding forces between soil particles and increases the soil strength. When a tensile load is applied to soil specimens treated with nano-alumina, additives help the soil matrix to bear the tensile load and prevent the separation of particles from each other and tensile deformation. However, by increasing the tensile load, the strain increases and reaches the failure strain and the soil fails. The addition of nano-alumina causes more resistance against tensile deformation, leading to an increase in the TME. Although micro-alumina also results in an increase in the DTS and TME like nano-alumina, considering the sizes of these two additives, the increase ratios of DTS and TME are different for nano-alumina and micro-alumina. Micro-alumina particles have a size tenfold larger than the size of nano-alumina particles. These particles with larger sizes can interact with soil particles along a larger contact length compared with nano-alumina particles. A larger contact length between additives and soil particles leads to a more sharing of the tensile stress within the soil matrix (Li et al. 2014; Tran et al. 2018b) and results in higher tensile strength. Moreover, larger contact lengths between additives and soil particles allow a larger tensile deformation before failure and a higher strength at the failure point. Therefore, specimens treated with micro-alumina can bear higher tensile deformation and tensile stress before failure compared with specimens treated with nano-alumina. The higher specific surface area and the smaller contact length of nano-alumina particles cause, respectively, the higher TME and lower DTS of soils treated with these materials compared with the soils treated with micro-alumina.

Conclusion

In this study, collapsible soils were treated with alumina additives in two nanometric and micrometric scales in order to investigate the influence of additives' size on the improvement of the tensile and compressive strength and deformation characteristics. Results indicate that the addition of optimum contents of both nano- and micro-sized alumina materials significantly improved the strength and deformation characteristics of the studied soils. These materials cause an increase in the tensile and compressive strength and a decrease in the soil deformation in both compression and tension states. The optimum content of additives for the studied soils is about 1%. Nano-alumina improved more efficiently the collapse potential, compressive strength, and stiffness, and tensile stiffness of the studied soils compared with micro-alumina, whereas micro-alumina improved more efficiently the tensile strength and ductility of the studied soil compared with nano-alumina. Therefore, the size of additives has diverse effects on the performance of the treated soil under compression and tension conditions.

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References

Akbari Garakani A, Haeri SM, Khosravi A, Habibagahi G (2015) Hydro-mechanical behavior of undisturbed collapsible loessial soils under different stress state conditions. Eng Geol 195:28–41

Alsafi S, Farzadnia N, Asadi A, Huat BK (2017) Collapsibility potential of gypseous soil stabilized with fly ash geopolymer; characterization and assessment. Constr Build Mater 137:390–409

Arulrajah A, Kua TA, Horpibulsuk S, Mirzababaei M, Chinkulkijniwat A (2017) Recycled glass as a supplementary filler material in spent coffee grounds geopolymers. Constr Build Mater 151:18–27

Assadi-Langroudi A, Ng'ambi S, Smalley I (2018) Loess as a collapsible soil: some basic particle packing aspects. Quatern Int 469:20–29

ASTM D5333–03 (2003) Standard test method for measurement of collapse potential of soils. ASTM International, West Conshohocken

ASTM D698 (2007) Standard test methods for laboratory compaction characteristics of soil using standard effort. ASTM International, West Conshohocken

ASTM D2166 (2007) Standard test method for unconfined compressive strength of cohesive soil. ASTM International, West Conshohocken

Cabalar AF (2011) The effects of fines on the behaviour of a sand mixture. Geotech Geol Eng 29:91–100

Cardoso R, Ribeiro D, Neri R (2017) Bonding effect on the evolution with curing time of compressive and tensile strength of sand-cement mixtures. Soils Found 57:655–668

Consoli NC, Caberlon Cruz R, Floss MF, Festugato L (2010) Parameters controlling tensile and compressive strength of artificially cemented sand. J Geotech Geoenviron Eng 136(5):759–763

Correia A, Venda Oliveira PJ, Custodio DG (2015) Effect of polypropylene fibres on the compressive and tensile strength of a soft soil, artificially stabilised with binders. Geotext Geomembr 43:97–106

Cui H, Jin Z, Bao X, Tang W, Dong B (2018) Effect of carbon fiber and nanosilica on shear properties of silty soil and the mechanisms. Constr Build Mater 189:286–295

Dušan B, Zoran B, Čebašek V, Šušić N (2014) Characterisation of collapsing loess by seismic dilatometer. Eng Geol 181:180–189

Estabragh AR, Namdar P, Javadi AA (2012) Behavior of cement-stabilized clay reinforced with nylon fiber. Geosynth Int 19:85–92

Evstatiev D (1988) Loess improvement methods. Eng Geol 25:341–366

Feng SJ, Du FL, Shi ZM, Shui WH, Tan K (2015) Field study on the reinforcement of collapsible loess using dynamic compaction. Eng Geol 185:105–115

Festugato L, Menger E, Benezra F, Kipper EA, Consoli NC (2017) Fibre-reinforced cemented soils compressive and tensile strength assessment as a function of filament length. Geotext Geomembr 45:77–82

Gavver EK (2012) Geotechnical properties of Egyptian collapsible soils. Alex Eng J 51:205–210

Ghasabkolaei N, Choobbasti AJ, Roshan N, Ghasemi SE (2017) Geotechnical properties of the soils modified with nanomaterials: a comprehensive review. Arch Civil Mech Eng 17:639–650

He S, Bai H, Xu Z (2018) Evaluation on tensile behavior characteristics of undisturbed loess. Energies 11(8):1974

Iranpour B, Haddad A (2016) The influence of nanomaterials on collapsible soil treatment. Eng Geol 205:40–53

Jha AK, Sivapullaiah PV (2015) Mechanismof improvement in the strength and volume change behavior of lime stabilized soil. Eng Geol 198:53–64

Jha AK, Sivapullaiah PV (2017) Physical and strength development in lime treated gypseous soil with fly ash—micro-analyses. Appl Clay Sci 145:17–27

Kafodya I, Okonta F (2018a) Effects of natural fiber inclusions and pre-compression on the strength properties of lime-fly ash stabilised soil. Constr Build Mater 170:737–746

Kafodya I, Okonta F (2018b) Density control method for compression test of compacted lime-flyash stabilised fiber-soil mixtures. MethodsX 5:848–856

Li Y (2018) A review of shear and tensile strengths of the Malan Loess in China. Eng Geol 236:4–10

Li J, Tang C, Wang D, Pei X, Shi B (2014) Effect of discrete fiber reinforcement on soil tensile strength. J Rock Mech Geotech Eng 6:133–137

Li P, Vanapalli S, Li T (2016) Review of collapse triggering mechanism of collapsible soils due to wetting. J Rock Mech Geotech Eng 8:256–274

Lu N, Wu B, Tan CP (2007) Tensile strength characteristics of unsaturated sands. J Geotech Geoenviron Eng 133(2):144–154

Mendes RM, Lorandi R (2008) Analysis of spatial variability of SPT penetration resistance in collapsible soils considering water table depth. Eng Geol 101:218–225

Monkul MM, Ozden G (2005) Effect of intergranular void ratio on one-dimensional compression behavior. Proceedings of international conference on problematic soils, international society of soil mechanics and geotechnical engineering, Famagusta, Turkish Republic of Northern Cyprus, 3, pp. 1203–1209

Monkul MM, Ozden G (2007) Compressional behavior of clayey sand and transition fines content. Eng Geol 89:195–205

Nikbakhti O, Hashemi M, Banikheir M, Khabbazi Basmenj M (2018) Geoenvironmental assessment of the formation and expansion of earth fissures as geological hazards along the route of the Haram-to-Haram Highway. Iran Bull Eng Geol Environ 77:1421–1438

Peng J, Wang S, Wang Q, Zhuang J, Huang W, Zhu X, Leng Y, Ma P (2019) Distribution and genetic types of loess landslides in China. J Asian Earth Sci 170:329–350

Rollins KM, Jihyoung Kim PE (2010) Dynamic compaction of collapsible soils based on US case histories. J Geotech Geoenviron Eng 136(9):1178–1186
Shipton B, Coop MR (2012) On the compression behaviour of reconstituted soils. Soils Found 52(4):668–681
Sun P, Peng J, Chen L, Yin Y, Wu S (2009) Weak tensile characteristics of loess in China—an important reason for ground fissures. Eng Geol 108:153–159
Sun P, Peng J, Chen L, Lu Q, Igwe O (2016) An experimental study of the mechanical characteristics of fractured loess in western China. Bull Eng Geol Environ 75(4):1639–1647
Tabarsa A, Latifi N, Meehan CL, Manahiloh KN (2018) Laboratory investigation and field evaluation of loess improvement using nanoclay—a sustainable material for construction. Constr Build Mater 158:454–463
Taha MR, Taha OME (2012) Influence of nano-material on the expansive and shrinkage soil behavior. J Nanoparticle Res 14(10):1–13
Tran KQ, Satomi T, Takahashi H (2018a) Improvement of mechanical behavior of cemented soil reinforced with waste cornsilk fibers. Constr Build Mater 178:204–210
Tran KQ, Satomi T, Takahashi H (2018b) Effect of waste cornsilk fiber reinforcement on mechanical properties of soft soils. Transp Geotech 16:76–84
Wang J, Xu Y, Ma Y, Qiao S, Feng K (2018) Study on the deformation and failure modes of filling slope in loess filling engineering: a case study at a loess mountain airport. Landslides. https://doi.org/10.1007/s10346-018-1046-5
Xiao H, Liu Y (2018) A prediction model for the tensile strength of cement-admixed clay with randomly orientated fibres. Eur J Environ Civ En 22(9):1131–1145
Xie WL, Li P, Vanapalli SK, Wang JD (2018) Prediction of the wetting-induced collapse behaviour using the soil-water characteristic curve. J Asian Earth Sci 151:259–268
Xu L, Coop MR, Zhang M, Wang G (2018) The mechanics of a saturated silty loess and implications for landslides. Eng Geol 236:29–42
Yadav JS, Tiwari SK (2017) Effect of waste rubber fibres on the geotechical properties of clay stabilised with cement. Appl Clay Sci 149:97–110
Zimbardo M, Ercoli L, Megna B (2016) The open metastable structure of a collapsible sand: fabric and bonding. Bull Eng Geol Environ 75:125–139
Zomorodian SMA, Moghispour S, Soleymani A, O'Kelly BC (2017) Strength enhancement of clean and kerosene-contaminated sandy lean clay using nanoclay and nanosilica as additives. Appl Clay Sci 140:140–147
Zuo L, Baudet BA (2015) Determination of the transitional fines content of sand-non plastic fines mixtures. Soils Found 55(1):213–219