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RESEARCH PAPER

An Investigation on the Effects of Adding Nano-SiO_2 Particles and Silica Fume with Different Specific Surface Areas on the Physical and Mechanical Parameters of Soil-Cement Materials

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ABSTRACT: Soil cement is a mixture of Portland cement, soil and water, in which hydration of cement and compaction causes the materials' constituents to bond together makes a dense and durable composition with low permeability and abrasion resistant. Since most of the recent researches are focused on the addition of nano-SiO_2 on concrete, in this paper it has been attempted to use nano-SiO_2 particles in soil-cement and observe the effects. Due to the fact that in concrete there are no particles passing sieve 200 and this restriction does not apply to soil-cements, some tests were carried out on the nano-SiO_2 + soil-cement matrix because of the meaningful difference between concrete and soil-cement. The test procedure consists of moisture-dry density, unconfined compressive test and hydraulic conductivity. In these tests, silica fume (with specific surface area of 21 m^2/g), nano-SiO_2 (with specific surface area of 200 and 380 m^2/g) were added to soil-cement. The results show that adding certain amounts of nano-SiO_2 particles to the soil-cement matrix can improve the compressive strength and reduce permeability and speed hydration reactions in the matrix in presence of nano-SiO_2 particles.

Keywords: Compaction Test, Hydraulic Conductivity, Nano-SiO_2, Soil-ement, Uniaxial Compression Test.

1. Introduction

According to ACI 116R, soil-cement is a mixture of soil and a certain amount of cement and water which is compacted to a high density. International committee of large dams defines soil-cement as a mixture of Portland cement, soil and water, which, as a result of cement hydration and compaction by rollers, its constituents adhere together and produce a durable, strong and dense composition with low permeability and high resistance against. In ACI 230.IR (2005) a more comprehensive definition is provided for soil-cement. It defines soil-cement as a mixture of soil, aggregate, water, cement, chemical additives, and possible supplementary cementing materials such as pozzolans, which after compaction and curing produce a hard material with specific engineering properties such as waterproofing (ACI,

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2006; ICOLD, 1996; Tajdini et al., 2020).

Soil-cement is usually considered as an alternative material to Roller Compacted Concrete (RCC) in construction projects. Soil-cement and RCC both are dense mixtures of cement, water and aggregate. However, the main difference is in the type and size of aggregate particles (ACI, 2006; ICOLD, 1996).

The aggregate used in soil-cement is primarily naturally produced fine-grained soils, while those in RCC contain particles coarser than 19 mm and usually produced by crushers (ACI, 2006; ICOLD, 1996). Nowadays, soil-cement is used for protecting the slopes in earth dams, while, RCC is mainly used in mass concrete sections such as gravity dams. Almost any type of soil, except organic, plastic clays and reactive sands can be used in soil-cement mixture. The most economic are those with 5-35% of fines (finer than 0.075mm), and the soils with more than 2% of organic materials are not acceptable to be used (ACI, 2006; ICOLD, 1996).

Early attainment of target strength is a concern in dam construction projects, which may require using rapid hardening cement type III. However, this type of cement suffers from deficiencies such as lower strength after final setting, higher cost and higher heat generation, which could be problematic in massive structures such as dam, and hence, its use requires caution (ACI, 2006; ICOLD, 1996).

Among the pozzolanic additives, silica fume, which is a byproduct of electric arc furnaces, has been found to be the most efficient in concrete, which is due to the inclusion of more than 90% of amorphous silica. A new pozzolanic material which has recently been considered to be used in concrete is nanosilica, which is available as solid powder or emulsified in water (Choobbasti et al., 2017; Khaloo, 2011; Sanchez and Sobolev, 2010; Jalal et al., 2015; Rai and Tiwari, 2018).

Nanosilica contains higher amorphous silica and its particles are finer than, silica fume, resulting in having better performance than, silica fume. The ratio of the effective surface to the particles volume increases with decreasing particle size, leading to stronger surface effects. Therefore, it can be stated that the reactivity of materials with nano-size dimensions increases considerably, giving specific properties to the nono-size materials compared with the materials in larger dimensions (Choobbasti et al., 2018; Madani et al., 2012; Lia et al., 2018).

The microstructure of cement-based materials such as concrete and soil-cement plays a vital role on their properties. It is expected that using nano-materials affects considerably the microstructure of cement-based materials and their properties. Nano-materials fill the small voids in the mixture and affect the hydration process (Choobbasti et al., 2018; Madani, 2012; Tajdini et al., 2018).

Many studies have been conducted on the use of nanosilica in conventional concrete and cement treated soils such as expansive and problematic soils (Choobbasti et al., 2017, 2018; Madani et al., 2012; Mohammed, 2020). However, the knowledge on nanosilica and its effects is still limited. Most of the papers in literature have investigated the effects of nanosilica on cement paste in early ages of curing. The following are a selection of the studies on the effects of nanosilica on concrete (Choobbasti et al., 2017, 2018; Madani et al., 2012; Taherkhani and Tajdini, 2019).

Some researchers investigated the nanosilica reaction in cement paste (Qing et al., 2007; Mohammed, 2020). They found that, when nanosilica is added to cement as neutral chemical filler, it improves the physical structure and provides the suitable conditions for beginning hydration, and, also, as a pozzolanic material reacts with the calcium hydroxide produced from hydration, which improves the bond between aggregate particles and cement paste. They also found that, the addition of nanosilica in the mixture, results in a reduction of particles size, which, accelerates the chemical reaction, due to the higher surface energy of nanosilica and activity of microstructure. Therefore, nanosilica materials accelerate hydration reaction, leading to the increase of the bond between aggregate particles and cement paste and is much more effective than microsilica in improving the interaction.

Another researchers compared the compressive strength of conventional concrete containing only fly ash and that of concrete in which both fly ash and nanosilica had been added (Li, 2004; Cui et al., 2018). They resulted that the strength of the concrete containing nanosilica during the early days is higher than that of the concrete without nanosilica. They described these results by stating that the nanosilica particles settle between the materials produced by hydration, preventing growth of inferior crystals of ettringite and calcium hydroxide, and also, fill the voids of cement, leading to the increase of concrete compressive strength.

Some researchers measured the permeability of concrete mixtures containing nanosilica (Ji, 2004; Madani et al., 2012, Bahmani et al., 2014). They resulted that calcium silicate hydrate (CSH) gel comprises, approximately, 70% of hydration silica with an average diameter of 10 nanometer. Therefore, nanosilica particles can fill the voids in the CSH resulting in denser matrix with lower permeability.

As mentioned, the majority of previous studies have focused on conventional concrete and cemented treated soils (Choobbasti et al., 2017, 2018; Madani et al., 2012; Mohammed, 2020; Taherkhani and Afroozi, 2017). However, soil-cement is different from conventional concrete in terms of composition and behavior. It has more fines than conventional concrete, in which particles finer than 0.075 mm are not allowed, and also less cement content (150 kg/m^3, approximately). Due to having more fines than conventional concrete, the specific surface area of the soil in soil-cement is high and shows different behavior in interaction with nanosilica. This issue has not been fully investigated and many aspects still remain unknown. The behavior of soil-cement-nanosilica matrix is highly complex, which the complexity mainly comes from unknown effective factors of the material and, thus needs to be investigated by experiments. Therefore, in this study, it has been attempted to investigate the effective factors of soil-cement mixtures containing nanosilica and silica fume, including type of fines, type and content of silica materials, on their compaction, compressive strength and permeability.

Nanosilica in concrete is not yet commonly applied, but silica fume, which is considered a microsilica, has already been used in concrete for several decades to produce high-performance concrete (Choobbasti et al., 2017, 2018; Madani et al., 2012). Nanosilica has been observed to accelerate the hydration process at early ages, refine the pore structure, and enhance the mechanical properties even at small levels of replacement. Moreover, nanosilica also exhibits ideal pozzolanic activity owing to its amorphous nature and high specific surface area (Choobbasti et al., 2017; Khaloo, 2011; Sanchez and Sobolev, 2010).

All the past studies focused on the concrete which has many essential differences with soil cement such as grading, W/C ratio, etc. In this study soil cement is been tested with nanosilica.

2. Materials and Testing Method

2.1. Materials

2.1.1. Soil

The materials used in this research include soil, cement, water and silica products. A type of soil with a gradation conforming the standard specified for soil-cement (ACI, 2006; ICOLD, 1996) has been used. Figure 1 shows the artificial gradation of the soil, which contains 20% of particles finer than 0.075 mm. Three different types of materials finer than 0.075

mm have been used to investigate the effects of type of fines (i.e. specific surface area) on the properties of soil-cement mixture. These include nonplastic silt, Kaolinite and Bentonite having different plasticity and specific surface areas. Table 1 shows the gradation properties and Table 2 shows the results of surface absorption test using BET (Brunauer, Emmett and Telle) method for determining the specific surface area of fines.

2.1.2. Portland Cement

According to ASTM C 150, Portland Cement Type II was used in this study. The cement produced in Tehran Cement Factory, had a specific gravity of 3.1 gr/cm^3. It is noteworthy that besides manifesting a good durability when encountering the sulfate attack, the hydration heat of this cement is appropriate, as well. Chemical characteristics of this cement are displayed in Table 3.

2.1.3. Water

Moisture is necessary in soil-cement for hydration process and achieving the maximum density. Potable water or other types of clean water, free of deleterious ingredients such as alkali, acids or organic compounds, can be used in soil-cement to create the chemical reactions of the cement and results in its hardening.

2.1.4. Silica Products

In this research, 3 types of silica products, including one type of , silica fume and two types of nanosilica (NS) with different specific surface areas, produced by Degosa Co. in Germany were used in this research. The silica materials were used in different percentages of 0.25, 0.5 and 0.75% (by the weight of cement) in soil-cement mixture. Table 4 shows the properties of the silica fume and nanosilica materials used in this research. Also Figure 2 shows the gradation of nano particles.

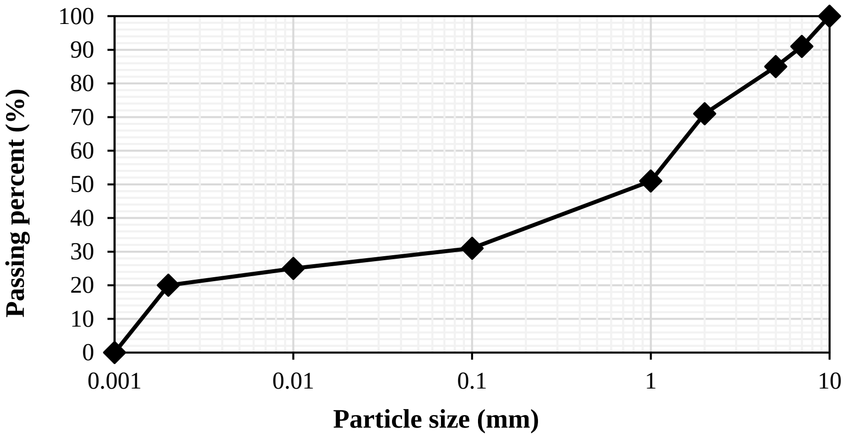

Fig. 1. Gradation curve of the soil used in this research

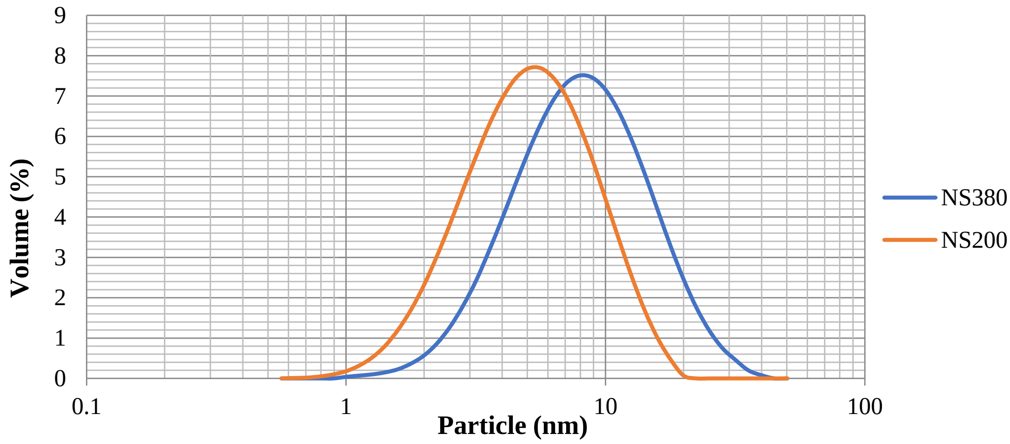

Fig. 2. Gradation of the nano particles used in this research

Table 1. Classification of the soils and physical characteristics of the sand materials

Soil type	Cu	Cc	Unified	AASHTO
Round sand	120	17	SC	A-2-4

Table 2. BET result test

Fine material	Silt	Kaolinite	Bentonite
Middle SSA (m^2/gr)	4	17	67

2.2. Testing Method

2.2.1. Compaction Test

Compaction level is a vital property for soil-cement, which controls the other performance related properties of this material such as strength, permeability and durability. Compaction test is conducted according to ASTM D 698 standard method to determine the maximum dry density and the optimum moisture content of soils. This test is based on the fact that compact ability of soil increases with increasing moisture content, up to a level, beyond which, the additional moisture results in the decrease of density. The moisture level at which the maximum dry density is achieved is known as the Optimum Moisture Content (OMC). In the standard compaction test, soil is mixed with 5 different moisture contents and compacted in three layers in compaction mold using 56 blows of a hammer with a weight of 24.4 N falling at a height of 30 cm. For each moisture content, a point with coordinates of moisture content and dry density is obtained, by which the compaction curve is drawn and the maximum dry density and the optimum moisture content is obtained for the soil. The moisture contents utilized in this test need to be over a range covering the moisture contents less and higher than the OMC. The maximum dry density and the optimum moisture content of the soil-cement mixtures were determined according to ASTM D558 standard test method. In this test, the soil and cement were mixed thoroughly first, after which the required water was added to the mixture of soil and cement. Then, the mixture of soil, cement and water was placed in compaction mold in 3 different layers, and each layer was compacted by 25 blows of a 2.5 kg hammer falling at a height of 30 cm. Using the dry density and moisture content in each test, the compaction curve of each mixture was plotted and the maximum dry density and the OMC was determined the same as used for soil.

2.2.2. Uinaxial Compressive Strength Test

Compressive strength is an important property of soil-cement mixture, which is obtained according to ASTM D1633 standard method. The compressive strength is used as a criterion for determination of the minimum cement content required in the mixture. For determining the compressive strength of the mixtures, cylindrical specimens with a diameter of 71 mm and height of 229 mm were made and cured for the desired period. For curing, the specimens were first placed in a vapour room for 12 hours, by placing them in a sealed plastic bag to prevent their perspiration. Then, they were cured for 4 different period of 3, 7, 28 and 90 days, by placing them in water tank with lime water at 24˚C. After which their uniaxial compressive strength was measured by applying compressive load at a constant rate of 140 kPa/sec, until failure. By measuring the ultimate load for breaking the specimen, the compressive strength was measured using Eq. (1).

$$q_u = \frac{P_u}{A} \tag{1}$$

in which q_u: is the compressive strength (MPa), P_u: is the ultimate load required for breaking the specimen (N) and, A: is the loaded surface area of the specimen (mm^2).

Table 3. Characteristics of the experimented cement (Type ∏)

Chemical composition	Loss on ignition	Na_2O	So_3	Mgo	K_2O	CaO	Fe_2O_3	Al_2O_3	Sio_2

Content (%)	2.27	0.12	3.34	2.2	0.78	63.27	3.33	5.21	20.82

Table 4. Silica Product properties

Type	Diameter (nano meter)	Amorphous silica purity	SSA (m^2/gr)	Density (gr/cm^3)
Silica Fume	600	90%	21	0.2
Nano-Sio_2-200	15	99.8%	200	0.15
Nano-Sio_2-380	8	99.8%	380	0.15

2.2.3. Hydraulic Conductivity Test

Permeability is the ability of a material to transmit water. Because of the low permeability of soil-cement, variable head permeability test, which is usually used for fine-grained soils was used in this study. The test was conducted according to ASTM D2434 standard method. In this test, filter paper and porous disc was used at both ends of the specimen. The specimen was connected to a water cylinder at the bottom through an outflow tube, and to an inlet glass tube at the top which was filled with water. While, the water flow through the specimen, the water level was read in the glass tube at the top, at different time intervals. The water level at any time is the difference between the water level in the glass tube relative to the level of water in the cylinder at the bottom, as shown in Figure 3. The permeability of specimen was determined using Eq. (2).

$$k = \frac{a}{A} * \frac{L}{\Delta t} * \ln \frac{h_1}{h_2} \qquad (2)$$

in which *k*: is the permeability (cm/s), *a*: is the cross-sectional area of the water inlet valve (cm^2), *A*: is the cross-sectional area of the specimen (cm^2), *L*: is the height of specimen (cm) and, *Δt*: is the time needed for total head to drop from clearly marked graduations h_1 to h_2 (sec.).

3. Discussion and Results

To achieve the objectives of this research, experiments were planned to be conducted on the soil-cement mixtures containing different types of fines (silt, Kaolinite and Bentonite), and different percentages of microsilica and nanosilica 200 and nanosilica 380. Compaction tests were planned to study the variation of the optimum moisture content, and the maximum dry density of the soil-cement mixtures with type of fines, type and content of silica materials. Uniaxial compressive strength tests were planned to investigate the effects of type of fines, type and content of silica materials and curing time on the compressive strength of soil-cement mixtures. Variable head permeability tests were planned to investigate the effects of type of fines, type and content of silica materials on the permeability of the mixtures. The results are presented and discussed in the following sections.

3.1. Compaction Tests

3.1.1. Effects of the Soil Plasticity Index

In order to investigate the effect of type of fines (particles passing sieve No. 200) on the compaction properties of soil-cement mixture, using the gradation shown in Figure 1, and 0.5% of nanosilica 200 (by the weight of cement), 3 different types of fines, namely silt, Kaolinite and Bentonite were used, and after conducting compaction test, the maximum dry density and the optimum moisture content were determined. US Army Corps of Engineering (1996) suggests $7 \pm 2\%$ (by the weight of dry soil) of cement content as an initial estimation for mix design, and the percentage yielding the highest maximum dry density is considered as the optimum cement content. Figure 4 shows the variation of the maximum dry density with cement content for the mixtures containing different types of fines. As can be seen, the maximum dry density of the mixtures with silt and Kaolinite occurs at 7% of cement content, and that of the mixture with Bentonite occurs at 8% of cement content. The higher percentage of cement content for the mixture containing Bentonite is attributed to the higher plasticity and specific surface area of Bentonite compared with Kaolinite and silt. Higher specific surface area of Bentonite requires more moisture for compaction, which, in turn, more cement is required for filling the voids created by the additional moisture. Moreover, Bentonite is more ductile, which can dissipate the compaction energy, and a fraction of cement is consumed to reduce its ductility and dissipation of energy. This is consistent with the findings of previous studies (Bahmani et al., 2014; Al-Rawas, 2005; Taherkhani et al., 2014).

Figure 5 shows the compaction curves of the mixtures with different types of fines and containing 7% of cement content. As can be seen, the maximum dry density of the mixture containing Bentonite is 3.5% lower, and the OMC is 2% higher than those of the mixture containing silt. This is attributed to the more agglomeration potential of Bentonite after mixing with cement and water, due to the higher specific surface area compared with silt, which results in the reduction of density. This is consistent with the results of previous studies (Bahmani et al., 2014; Al-Rawas, 2005; Ghasabkolaei et al., 2016).

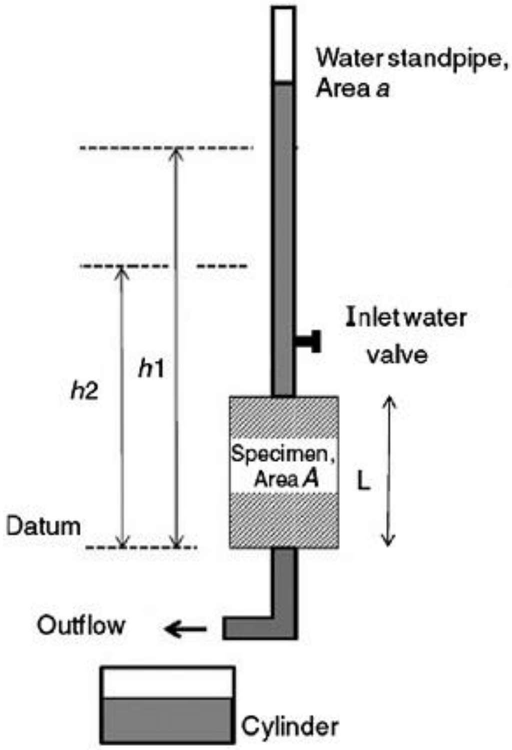

Fig. 3. Schematic of a variable head permeability test equipment (Tajdini et al., 2018)

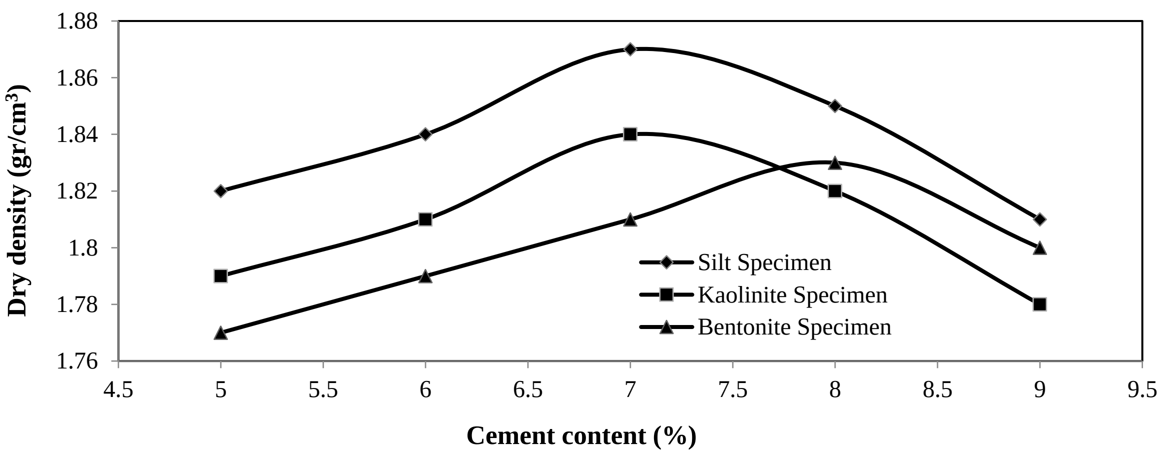

Fig. 4. Effect of cement content on the maximum dry density of the mixtures with different types of fines

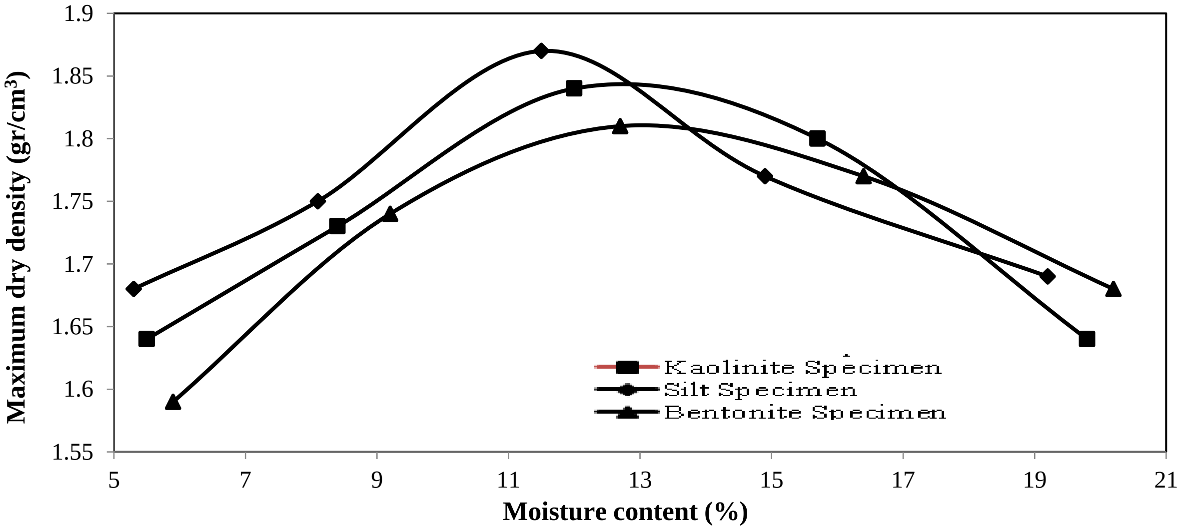

Fig. 5. Effect of type of fines on the dry density and optimum moisture content

3.1.2. Effects of Silica Product Types

The effects of silica material type on the compaction properties have been investigated. To this end, 0.5% (by the weight of cement) of different silica materials, including , silica fume, nanosilica 200 and nanosilica 380, with different specific surface areas, were added to a soil with the same grading, as shown in Figure 1, with the same fines of silt, and were subjected to the compaction tests. A mixture with the same soil and without any silica materials was also used as control mixture. Figure 6 shows the compaction curves of the mixtures. As can be seen, the mixtures containing silica materials have noticeably higher OMC and lower maximum dry density than the control mixture. According to the results, the maximum dry density of the control mixture is 3.5, 6.5 and 6% higher than those of the mixture containing, silica fume, nanosilica 200 and nanosilica 380, respectively. The optimum moisture content of the control mixture is also 0.5, 2.5 and 3% lower than those of the mixtures containing microsilica, nanosilica 200 and nanosilica 380, respectively. Decrease of the maximum dry density is attributed to the increase of friction between soil particles due to the filling of voids between them by the silica products, requiring more energy for densification. In addition, the decrease of the maximum dry density has been attributed to the acceleration of Calcium-Silicate-Hydrate (CSH) gel formation as a result of silica materials presence, resulting in reduction of comp actability due to the dissipation of compaction energy (Bahmani et al. 2014). Moreover, silica materials have higher specific surface area and are more tending to react with water, resulting in the increase of the optimum moisture content.

3.1.3. Effects of Silica Product Content

In order to investigate the effect of silica materials content on the soil-cement compaction properties, nanosilca 200 was added at different proportions of 0.25, 0.5 and 0.75% to the mixture of soil and cement, and were subjected to compaction tests. Soil gradation, cement content and type of fines were the same in the mixtures. Soil gradation of the mixtures was as shown in Figure 1, the same fines type of silt and the same cement content of 7% were used in the mixtures. The mixture without nanosilica was also used as control mixture. The same was followed for investigating the effects of silica type on the compressive strength and permeability of soil-cement mixture, which the results will be presented later in this paper.

Figure 7 shows the compaction curves of the control mixture and the mixtures containing different percentages of nanosilica 200. As can be seen, the maximum dry density of the mixtures containing 0.25, 0.5 and 0.75% of nanosilica are 1.76, 1.85 and 1.82 gr/cm^3, respectively, and the OMC of the mixtures are 12.5, 11 and 12.2%, respectively. Beyond a certain amount of nanosilica content, the increase of nanosilica results in the reduction of compact ability of the mixture. This is attributed to the accumulation and agglomeration of nanosilica particles at higher contents. According to the micro structural test results, Ferekel and Hellmig (1999) found that agglomeration of nanosilica particles results in the increase of the thickness of C-S-H gel between particles leading to the decrease of density.

Comparing the results in Figures 6 and 7 indicates that the type of silica material is more effective than its content on the compaction properties, which is attributed to the microstructure of the mixtures. The higher the specific surface area, the higher the reactivity of the silica materials.

Figure 7 shows that the optimum content of nanosilica 200 is 0.5%, indicating that, the maximum dry density does not necessarily decrease with increasing nanosilica content. The same compaction tests were conducted to determine the optimum content of nanosilica 380 and silica fume, which the results are shown in Figure 8. As can be seen, the optimum microsilica and nanosilica 380 contents are 0.75 and 0.5% (by the weight of cement), respectively. This can be described by the dispersion effects, as used by different researchers (Bahmani et al., 2014; Al-Rawas, 2005; Taherkhani et al., 2014). According to this effect, by increase of the fineness of nanoparticles in the mixture, instead of reaction with cement and water, they agglomerate and form nano-clusters, which do not disperse in the mixture and react with cement.

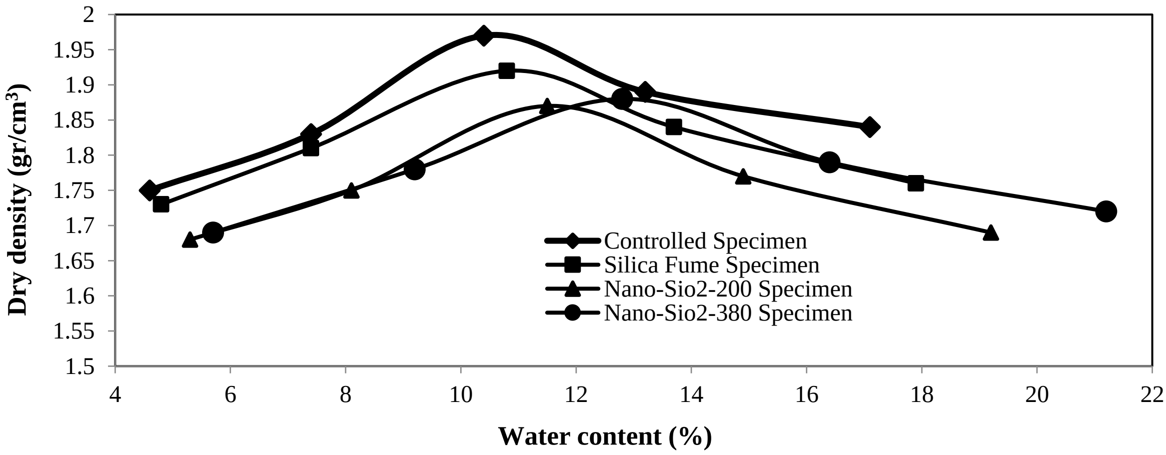

Fig. 6. The effects of type of silica material on the compaction properties

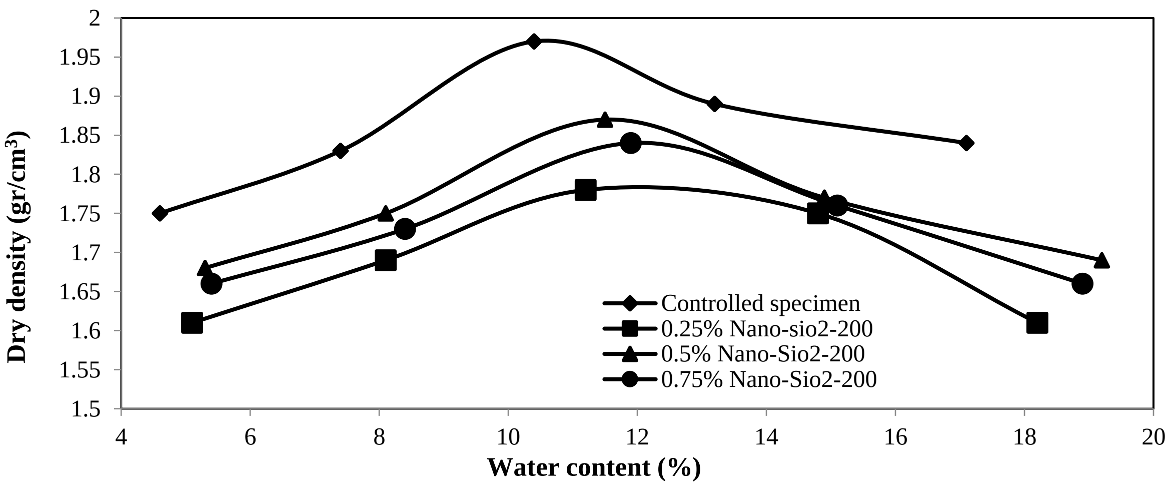

Fig. 7. The effect of nanosilica 200 content on the dry density and optimum moisture content

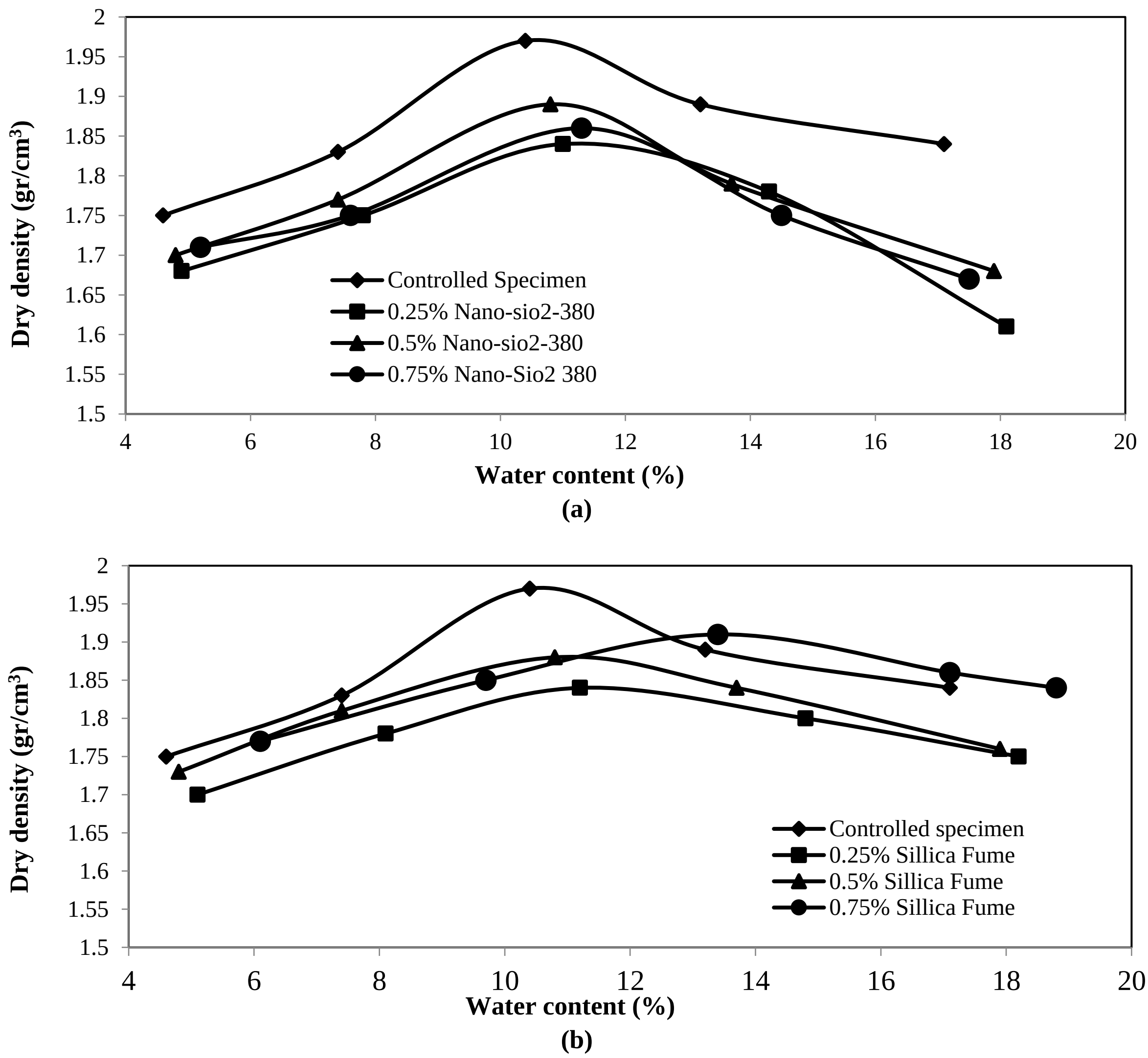

Fig. 8. The effects silica fume and nanosilica 380 on the dry density and optimum moisture content: a) Compaction curves of the mixtures containing microsilica and; b) Compaction curves of the mixtures containing nanosilica 380

Comparing the compaction curves of the mixtures containing microsilica and nanosilica shows that the compaction curves of the mixtures containing, silica fume (Figure 8a) is wide bell-shaped, while the mixtures containing nanosilica have sharper bell-shaped compaction curve, indicating that the mixtures containing nanosilica is more sensitive to moisture content than, silica fume, which is due to the higher tending to react of nanosilica with water.

3.2. Uniaxial Compressive Strength Test of the Samples

3.2.1. Effects of Fine Types

Exploring the literature reveals that previous studies have mainly focused on investigating the effects of nano-particles on the mechanical properties of conventional concrete (Madani et al., 2014). For example, Madani et al. (2012), Taherkhani et al. (2014) and Choobbasti et al. (2018) have investigated the effects of nano-silica on the durability and strength parameters of Portland cement concrete. However, the use of nano-silica in soil-cement has not been studied yet, and soil-cement is far different from conventional concrete and needs to be investigated.

In present study, it has been attempted to, in addition to the consideration of sand as the skeleton of soil-cement mixture, the effects of fines (the particles finer than 0.075 mm), which are commonly exist in any soil type on earth, be investigated. According to ACI 136, the materials passing sieve No. 200 are not allowed to be used in conventional concrete. Soil-cement mixtures with the same grading and 3 different types of fines (silt, Bentonite and Kaolinite), have been used in compressive strength test to be able to evaluate the influence of type of fines on the strength properties of soil-cement. In these mixtures, 0.5% of nanosilica 200 and nanosilica 380 of cement have been used. Figure 9 shows the compressive strength of the mixtures with different types of fines and cured at different ages of 3, 7, 28 and 90 days for nanosilica 200.

As can be seen in Figure 9, the compressive strength increases with increasing curing time. It can also be seen that, the increase of 7-day compressive strength compared with 28-day compressive strength of the mixture containing Bentonite is higher than those of the other mixtures. This difference is attributed to the higher specific surface area of Bentonite fines compared with the silt and Kaolinite fines. Results also show that, the 90-day compressive strength of the mixture containing Bentonite is approximately 35% higher than the 7-day compressive strength, while, the figure for the mixture containing silt is approximately 115%. This can be described by the acceleration of hydration reaction by the increase of material energy with increasing specific surface area, which, in turn, leads to the increase of clusters of CSH gel formation and strength attainment.

It is worth mentioning that the Pozzolanic reactions in a soil containing clay occurs by composition of the calcium oxide in cement and the hydroxide in water with the aluminate in Kaolinite and silicate in Bentonite. This reaction needs time, over which the calcium silicate hydrate (CSH) gel in the mixture containing bentonite, and calcium aluminate hydrate (CAH) in the mixture containing Kaolinite are generated and results in the increase of strength.

Previous studies have shown that due to their stronger bonding in transition zone, the non-plastic fines attain much higher strength than the plastic fines. The reason is that, although the formation of bonding gel increases with increasing plastic fines, however their agglomeration, decreases the efficiency of transition zones, which are the most important micromechanical interaction part of cement-based materials (Bahmani et al., 2014; Al-Rawas, 2005; Taherkhani et al., 2014).

3.2.2. Efficacy of Silica Product Types

A number of studies have been conducted on the effects of nanosilica on the properties of cement based materials; however, the results are not consistent and sometimes are contradictory. As an example, Khaloo et al. (2011) found that at equal water to cement ratio, 3% replacement of cement with nanosilica resulted in 105% increase in 28-day compressive strength. On the other hand, Ji (2004) reported that at equal water to cement ratio, replacing 3% of cement with nanosilica with average particle size of 15 nanometer results in 8% reduction in 28-day compressive strength. This contradiction is attributed to the difference between the type and specific surface area of the nanosilica used in these studies.

In this research, in order to investigate the effect of type of nanosilica particles on the mechanical properties of soil-cement, were subjected to uniaxial compressive strength test. Figure 10 shows the strength gaining trend of the mixtures containing silica materials and the control mixture without silica materials.

As can be seen, the compressive strength of the mixtures containing microsilica and nanosilica is considerably higher than that of the control mixture. The 7-day compressive strength of the mixtures containing, silica fume, nanosilica 200 and nanosilica 380 are, respectively, 14, 19 and 22% higher than that of the control mixture. These values associated with the 90-day compressive strength are 2, 3 and 5.5%, respectively.

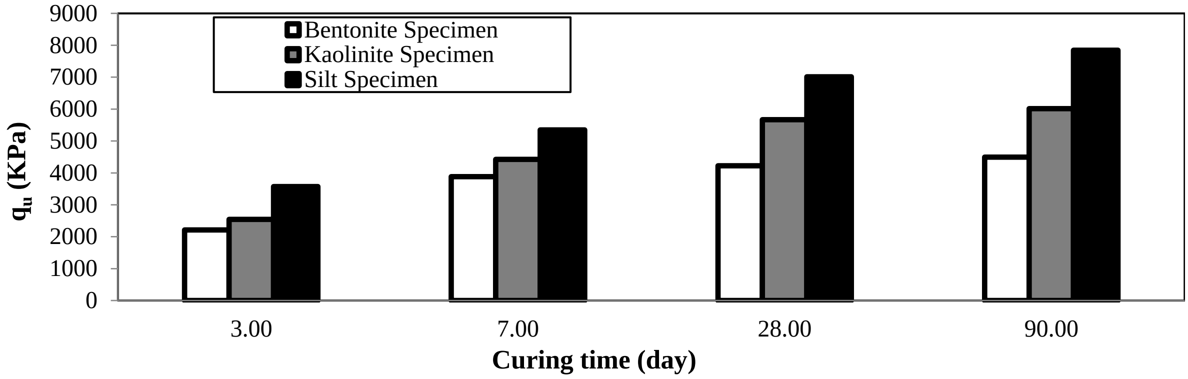

Fig. 9. The uniaxial compressive strength of soil-cement mixtures with different types of fines

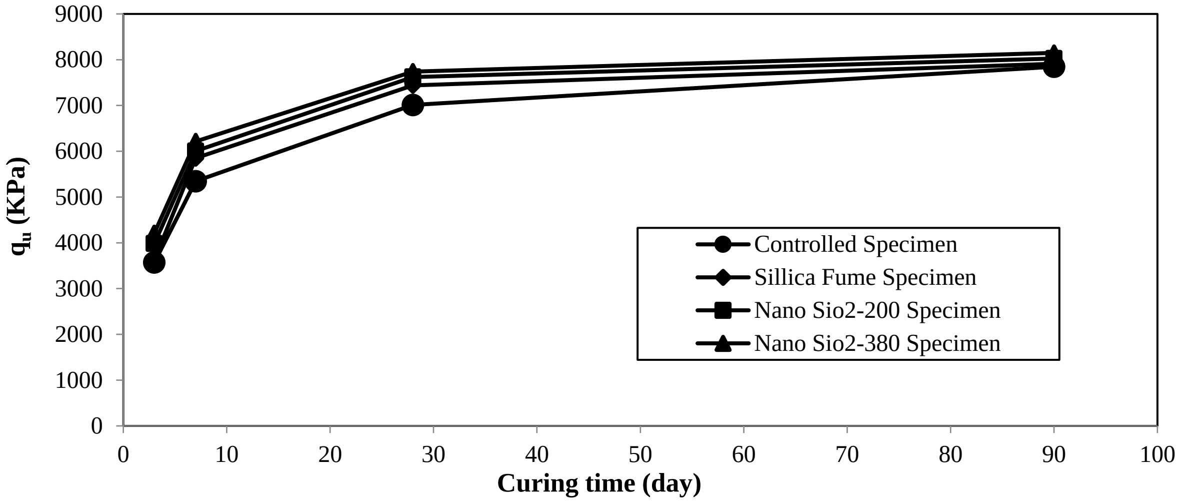

Fig. 10. Strength gain of soil-cement mixtures

The results reveal that the addition of nanosilica into the soil-cement is mainly influential on the 7 and 28-day compressive strength. This is because the pozzolanic reactions occur mainly during the period between 7 to 28 days, and the addition of nanosiilica accelerates the reactions and is not significantly effective on the strength of the mixture over the long period of 90 days. Due to the acceleration of strength gain at the early ages of soil-cement mixtures, using nanosilica in soil-cement mixture can be considered in practical applications such as cofferdams. Due to the fact that hydraulic structures are nearby water and cycles of wet-drying could decrease the performance of these structures, achieving to a minimum compressive strength is necessary. So, using nanosilica is a good solution for dams, etc.

3.2.3. Efficacy of Silica Product Content

In order to investigate the effects of silica materials content on the compressive strength of the soil-cement. Figure 11 shows the compressive strength of the mixtures at different ages of 3, 7, 28 and 90 days. As can be seen, the compressive strength of the mixture containing 0.5% of nanosilica 200 is higher than that of the other mixtures, which can be described by the relation between the compressive strength and compaction of soil-cement. The highest dry density of soil-cement is obtained at 0.5% of nanosilica 200.

As mentioned earlier, soil-cement is different from conventional concrete, and thus, it should not be expected to the compressive strength be increased with increasing nanosilica content. In conventional concrete, in addition to accelerating the hydration and pozzolanic reactions, nanosilica acts as a filler, which in soil-cement is done by the particles finer than 0.075 mm. This issue has also been pointed out by Bahmani et al. (2014) who investigated the properties of soil-cement with low plasticity clay. When nano-particles are used at its optimum content, lower water is required, leading to the decrease of the voids in the matrix. Soil-cement behavior is more like soil rather than concrete.

3.3. Hydraulic Conductivity

3.3.1. Effect of Type of Fine

Durability of cement-based materials is an indication of their service life under a certain environmental conditions. Environmental conditions are the main factors in durability. According to ACI 201, durability of cement-based materials is their ability to withstand weathering, chemical attack, wear or any process which leads to damage. Therefore, a durable material preserves its initial shape, quality and serviceability under the exposed conditions. Considering the durability of construction materials is important for reducing the maintenance and reconstruction costs, which constitute the majority of funding in construction industry. In developed countries, it is estimated that, more than 40% of the funds in construction industry is spent for maintenance of existing structures, and less than 60% is spent for constructing new structures (Brenner, 2003).

Durability of cement-based materials is more complex than their mechanical properties. The mechanical properties of these materials, specially the compressive strength, have been investigated in recent century, and their different aspects have been realized, although there are still some aspects unknown. However, durability is more complex due to its different mechanisms and tests methods.

One of the most important issues in durability of cement-based materials is their performance against water, such as moisture absorption and permeability. Permeability tests of cement-based materials (e.g. plastic concrete) against water has traditionally been dealt with Darsi equation and their permeability is obtained using Eq. (2).

In order to investigate the effects of type of fines on the permeability of soil-cement mixture, mixtures were made with the same grading as shown in Figure 1, different percentages of nanosilica 200, 7% of cement content and different types of fines including silt, Kaolinite and Bentonite, and were subjected to variable head permeability test. The control mixture was also used for comparison. Figure 12 shows the permeability tests results. As can be seen, the mixture containing Bentonite has a lower permeability than the other mixtures, which is attributed to the different physical and mechanical reactions of this mixture. In chemical view, the mixture with Bentonite contains more silica than the other mixtures, which in turn, increases the pozzolanic reactions and formation of binding gel, and is the main factor against water permeability. Using electron microscope and X-ray spectra methods, previous studies have shown that the binding gel comprises about 70% of the soil-cement mixture (Ji, 2004; Bahmani et al. 2014). In physical view, Bentonite particles are finer than silt and Kaolinite, leaving much less voids in the mixture. In plastic concrete containing Bentonite, at the same water to cement ratio, a slight increase of Bentonite resulted the permeability to be increased by 10 times (Brenner, 2003). It is worth mentioning that due to this property, Bentonite is used in cut-off wall in dam construction. For example, the permeability of the mixture containing 0.5% of nanosilica and Bentonite is 2.5 times higher than the control mixture.

3.3.2. Influence of Silica Product Types

In order to investigate the effect of type of silica material used in the mixture, i.e., silica fume, nanosilica 200 and nanosilica 380, different proportions of those materials were added to the mixture of soil and cement, with the same grading (Figure 1) and type of fines (silt), were subjected to permeability tests. Figure 13 shows the permeability tests results on the mixtures containing different types of silica material. As can be seen, the mixtures containing nanosilica 380 have lower permeability than the others. This is attributed to the effect of this silica material on accelerating hydration and pozzolanic reactions and formation of binding gel which fills the voids and reduce the permeability. Catalyst activities occur generally on the surface of catalyses materials, and, the specific surface area and surface forces increases with decreasing the size of particles. Therefore, nano-particle catalyses are superior to the particles with larger dimensions for reducing the permeability.

3.3.3. Effects of Silica Material Content

It is seen in Figures 12 and 13 that the permeability of the soil-cement mixtures containing nanosilica 200 and nanosilica 380 decreases with increasing the nanosilica content, up to 0.5%, beyond which the permeability decreases slightly. Also, these figures show that the lowest permeability of the mixtures containing silica fume, is associated with the mixture containing 0.75% of silica fume. These results are consistent with the compressive strength tests outputs, indicating that the optimum content of silica materials in soil-cement mixture results in the optimum performance in terms of strength and permeability. The difference between the optimum content of, silica fume and nanosilica can be described by the fact that at higher nanosilica content, increases their agglomeration and aggregation in different places in the mixture, decreases their chemical and physical influences. However, for, silica fume, their agglomeration creates, at most, particles close to the size of clay particles, which is not significantly effective on reducing the permeability.

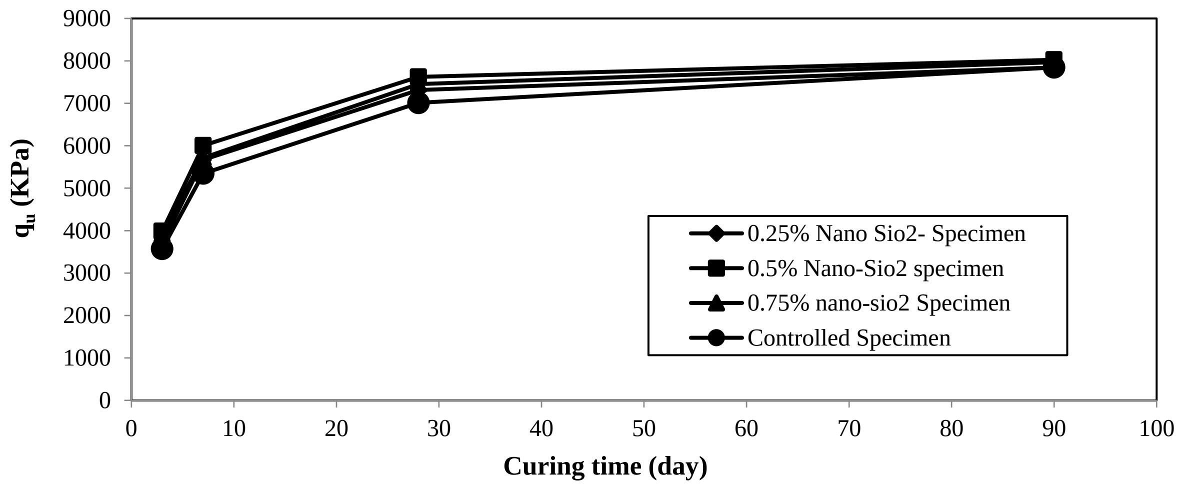

Fig. 11. Strength gain of the mixtures containing different percentages of nanosilica 200

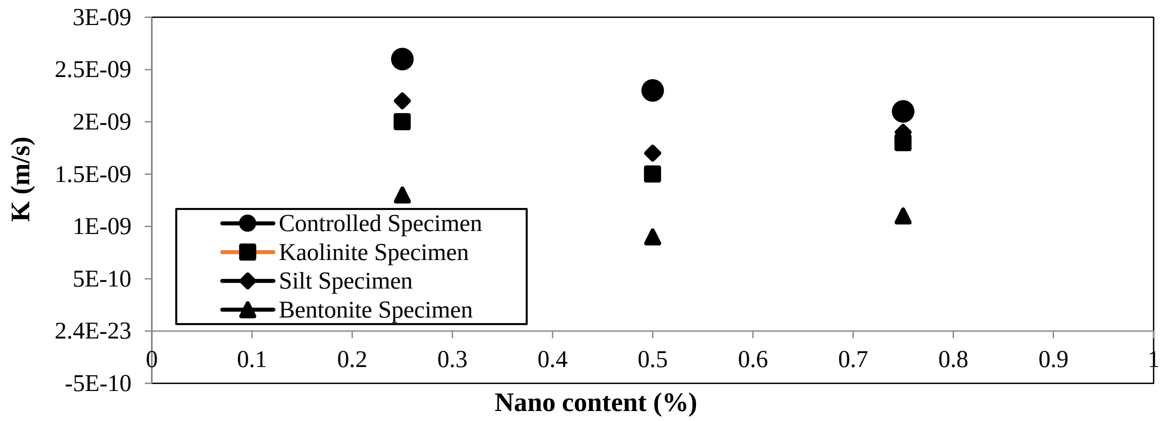

Fig. 12. Permeability of the mixtures with different types of fines

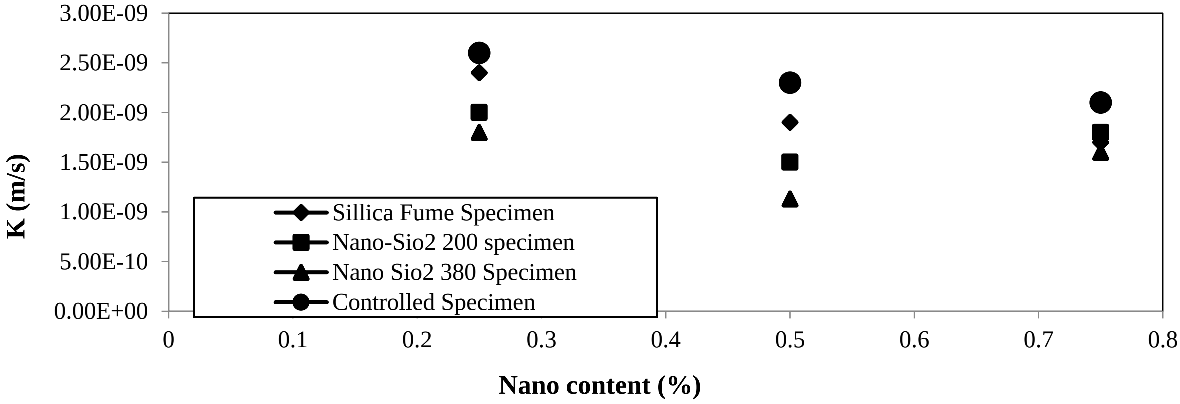

Fig. 13. Permeability of soil-cement mixtures with different silica materials

4. Conclusions

In this study, compaction, compressive strength and permeability tests were conducted on the soil-cement mixtures, in which different proportions of three different types of silica materials with different specific surface areas, and three different types of fines have been used. The main findings of this research are as follow:

- The compaction tests results show that the optimum content of a silica material in the soil-cement mixture, to achieve the highest dry density, depends on the specific surface area of the materials, such that the optimum content of nanosilica is 0.5% and that of, silica fume is 0.75%. Beyond the optimum content, due to their surface attraction, nanosilica particles tend to agglomerate and prevent achieving higher density.
- The compaction curve of soil-cement mixtures containing silica fume is wide bell-shaped, and the mixtures containing nanosilica is sharp bell-shaped, which is due to the more tending to reaction with water of nanosilica as a result of its higher specific surface area.
- The compressive strength tests results show that the mixtures containing Bentonite gain their strength earlier than the others. After gaining their strength at early ages, their hydration process almost cease. The reason is that, they have higher energy at the initial stage of reaction and faster hydration process, resulting in the completion of their pozzolanic reactions at a short period.
- The majority of the strength of the mixtures containing nanosilica is gained at their early days of curing, and at 90 days of curing, their strength is approximately the same as the control mixture, indicating short term effectiveness of nanosilica on the compressive strength of soil-cement.
- The minimum permeability of the soil-cement mixtures is achieved at the optimum contents of, silica fume, nanosilica. Also the mixture containing nanosilica 380 has lowest permeability than the mixtures containing nanosilica 200 and silica fume. This is attributed to the higher specific surface of nanosilica 380, which produce more calcium silicate hydroxide gel in the mixture and has better ability to fill the nano-size voids in the mixture.
- Using nanosilica would improve the soil cement properties in two methods. Firstly, nanosilica with high specific surface area could increase the speed of reactions between cement-water-nanosilica and produces Calcite-Silicate-Hydrate gel which could fill the pores and cracks. It leads to increase of compressive strength and decrease of permeability. Secondly, nanoparticles are so small which could fill pores and increase density of materials.

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