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Experimental Study for the Effect of Additives Silica Fume on the Properties of the Synthetically Contaminated Soil

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This paper aims at studying the impact of the reaction that occurs between contaminants present in the soil and silica fume added on the chemical, physical and mechanical properties of the soil. The soil samples were contaminated in the laboratory with nickel nitrate (Ni(NO3)2). Silica fume (SF) was added to three different ratios (3%, 5%, and 10%). Several laboratory experiments were conducted to study soil characteristics before and after adding silica fume to the contaminated soil. The results revealed that the increment percentage of liquid and plastic limits was obtained with an increase in the percentage of silica fume additive to the nickel-contaminated soil. Notably, the maximum dried densities were decreased by increasing silica fume ratios to the nickel-contaminated soil, while the optimum water content increased with increasing silica fume ratios to the nickel-contaminated soil. The value of organic matter for soil samples was roughly equal numbers ranging from 3.33% to 4.07% (i.e., no change in the organic matter for soil samples mixed with different ratios of silica fume). The coefficient of consolidation (Cv) increased from 0.0026 in a soil sample that was contaminated with nickel ions at a concentration equal to 750 mg/kg without adding silica fume to 0.0755 in a soil sample contaminated with nickel ions at a concentration of 750 mg/kg mixed with silica fume at a ratio of 5% and then decreased to 0.00531 in a soil sample contaminated with nickel ions at a concentration of 750 mg/kg mixed with silica fume at a ratio of 10%.

Keywords: nickel ions, contaminated soil, liquid limit, plastic limit.

Introduction

The contamination of toxic elements in soils has been considered as one of the most critical issues related to the environment worldwide. Because of anthropogenic activities, contamination occurs in the soils. These activities can be caused by rapid industrialization, industrial discharge, pesticide and fertilizer applications, and fossil fuel combustion. Because of the contaminants' toxic effects and non-degradability, the contaminated soil remediation of heavy metals is considered a complicated issue. The persistence of these contaminants when adsorbed onto the soil colloids and other constituents adds more complexity to the negative effect of these toxic chemicals. The distribution of heavy metals in soils depends on several factors: (1) soil adsorptions, (2) adsorbed heavy metal mobility, and (3) adsorbed heavy metal of substitutional potential. The behavior and solubility of heavy metals in soils are affected by the surrounding environmental characteristics like pH, existence of organic matter, total concentration of metals, and redox conditions. Remediation allows soil to be preserved and diminish the effects of contaminants. The soil is a non-renewable natural resource. To minimize the risks of heavy metal contamination, it becomes urgent to use the appropriate treatment methods for the contaminated soils, as reported by Delil and Köleli (2018).

Nickel could exist in different forms in soils; these forms are complex or adsorbed on organic cation surfaces or inorganic cation-exchanging surfaces, water-soluble or inorganic crystalline minerals, chelated metal complexes, or free-ions in a soil solution. The mobility and solubility of Ni^{+2} ions rise when the pH is decreased. Therefore, the pH of the soil is the main parameter controlling nickel mobility, solubility, and sorption, whereas iron-manganese mineral, clay content and the organic matter of the soil are of secondary significance, as indicated by Amal and Ban (2017). Karkush et al. (2013) affirm that the contaminants existing in the soil have different effects on the mechanical, chemical, and physical characteristics of the soil. The impact is mainly dependent on the amount and type of a contaminant. The soil characteristics of polluted soil samples have been affected remarkably by the increment in concentrations of heavy metals. Mahdi and Shahad (2019) studied the impacts of a contaminant (copper sulfate) on the chemical and engineering properties of cohesive soil. Heavy metal contamination causes a reduction in Atterberg's limits, fines percentages, permeability, and optimum water content leads to an increment in maximum dry density as well as specific gravity. The copper sulfate contamination causes a decrement in the shear strength factors, cohesion (c), and internal friction angle (φ) as the concentration of copper sulfate in soil samples increases. However, the concentration of copper sulfate increment leads to a rise in the recompression and compression indices and the initial void ratio. Also, Mahdi and Shahad (2020) report that organic matter, cation exchange capacity (CEC), pH value, and clay minerals were the main geochemical properties for soil that had a significant effect on the absorption of pollutants.

Fattah et al. (2015) refer to the chemical stabilization method which shows the usage of the method of adding a binder to enhance the geotechnical performance of soft clay-like mechanical and chemical characteristics of the soil. Also, they have investigated the characteristics of soft clay soil mixed in different percentage with stabilizers, lime and silica fume. A grey-colored densified silica fume (SF) is utilized. It is a pozzolanic matter having a high amount of amorphous silicon dioxide and includes very fine spherical particles. Lime reacts with soft clay to create diminished plasticity, increased strength, and workability. Three rates were utilized for lime (2%, 4%, and 6%) and three rates were utilized for SF (2.5%, 5%, and 10%), and the optimal rate of SF was mixed with the rates of lime. Kawther (2018) suggested the utilization of SF as an adjustment of fine-grained soils to change unwanted characteristics of the local soil and make new valuable soils. SF and clay material are utilized to alter the engineering characteristics to be appropriate, and their fulfilment is attributed to their pozzolanic reactivity. Four rates of SF were utilized, which were 0%, 3%, 5%, and 7%. Grouping, California Bearing Ratio (CBR), compressive strength swell and swell pressure, compaction characteristics, and specific gravity experiments have been used on the prepared and adjusted soils. The results revealed that the SF increment led to a decrement in the liquid limits and plasticity indexes. The increment of SF led to an increment in the plastic limit and optimum water content, whereas the maximum dried unit weight values were lowered. The compressive CBR, the strength of shear, swell, and swell pressure are enhanced by utilizing SF with the goal of SF being realized as a useful material in further improving the characteristics of the soil. As it was derived from the research conducted by Saeid and Hamed (2020), the impact of lead nitrate as a hazardous environmental contaminant was investigated by experimental tests to evaluate its physical and chemical effects on soils. Artificially contaminated soil samples were made by utilizing sand and two types of clay. Consolidation, unconfined compression, direct shear, and electrical resistivity tests were performed. Additionally, the effect of lead cations on the pH, particle size distribution, and Atterberg limits of soils were assessed. In general, the existence of Pb^{+2} in mixes containing bentonite increased the strength of shear because of the flocculated structure and the replacement of sodium cations by H+, along with the diminishing of double-layer thickness. Nonetheless, the sand–kaolinite mix strength diminishes with the increment of Pb^{+2} ion concentration because of the broken bonds and rearranging of kaolinite particles to form weaker mixtures, the strength of sand–kaolinite mixtures decreases with the increase of lead concentration. Entessar et al. (2021) have utilized SF as an industrial by-product to improve the hydraulic characteristics to be utilized for landfill lining layers and prevent movement of leachate into the surrounding environment. SF was mixed with soil to improve the permeability by 5% and 10% weight proportion. The outcomes showed that SF increased the plasticity and flow properties of the stabilized soil. Adding 5% and 10% SF to surface soil reduces the permeability up to 46% and 57%, respectively. It was inferred that SF occupied pore space between soil particles and a thick matrix was created. These textural events caused an enhancement in permeability properties, which is the main concern in the design of the MSW lining layer. The aim of this work was to assess the impact of the addition of different percentages of silica fume (SF) to the soil contaminated with nickel ions on its mechanical, chemical, and physical properties.

Materials and Methods

Soil

The soil utilized in this work was obtained from the University of Babylon, Iraq (Hilla City). It was collected from the site soil near the Department of Environmental Engineering at around 50 cm depth under the grounds. It was cleansed, dried, and well sorted with additional sieving to achieve satisfying uniformity. The physical and chemical characteristics of the used soil are explained in *Table 1*.

Table 1. *The physical and chemical characteristics of the native soil sample utilized in the present work.*

Property	Value
Atterberg limits	
Liquid limit, LL (%)	17.72
Plastic limit, PL(%)	16.367
Plasticity index (%)	1.353
Particle size distribution	
Sand (%)	0
Silt (%)	78
Clay (%)	22
Specific gravity	2.58
Optimum water content, OWC (%)	13.8
Maxiumam dry density, MDD (g/cm^3)	1.003
Porosity (%)	31.12
pH	7.5
Electric conductivity, EC (μs/cm)	8.54
Organic content (%)	2.06
$CaCO_3$ (%)	23.934
Sulfate ions, SO_3 (mg/L)	1.47
Chloride ions, Cl^{-1} (mg/L)	7.197
Total suspended solids, TSS (mg/L)	6000

Materials

Contaminants

To simulate the soil's nickel contaminant, a solution of $Ni\ (NO_3)_2$ was used. The prepared solution was added to the specimen to obtain a representative concentration. For example, for preparing a soil specimen with a nickel concentration of 750 mg/kg and an initial moisture content equal to 40% by weight, 3.9 g of $Ni(NO_3)_2$ was dissolved in 400 mL of distilled water, and the solution was added to 1 kg of dried soils. This is in accordance with the same procedure adopted by Faisal and Hussein (2015).

Silica Fume

Silica fume is considered the generator of the ferrosilicon alloy and silicon. It is made via silicon metal manufacturing, and its shape is gray-lighted. During the production of silicon metal, silica ash as an oxidized vapor rises. These oxidized vapors are later condensed, cooled, and produced as SF. SF appearance is spherical, which is very fine-sized processing, with a surface area of around 20,000 m^2/kg. The chemical and physical SF characteristics are shown in *Table 2*, as indicated by Mohamed et al. (2020).

Table 2. *Chemical composition of silica fume (Mohamed et al., 2020)*

Physical properties	
Specific gravity	2.2
Mean grain size(μm)	0.15
Colour	Light to low grey
Chemical compositions(%)	
Silicon dioxide (SiO^2)	85
Aluminium oxide (Al^2O^3)	1.12
Iron oxide (Fe^2O^3)	1.46
Calcium oxide (CaO)	0.2–0.8
Magnesium oxide (MgO)	0.2–0.8
Sodium oxide (Na^2O)	0.5–1.2
Potassium oxide (K^2O)	
Loss on ignition	<60

Experimental Setup

Batch experiments were carried out to investigate the effectiveness of nickel ion contaminated soil that was mixed in different ratios with SF on mechanical, chemical, and physical characteristics of contaminated soil. This is done in accordance with the procedures adopted in many studies such as Kalkan and Akbulut (2004), Shivangi and Trivedi (2016), Entessar et al. (2021) and Ahmed et al. (2021). The artificially contaminated soil spiking was planned to provide around 750 mg/kg as the target concentration. The amended soil was sited in a small container plastic and incubated for 4 weeks at laboratory temperature. This is because the distribution of soil Ni^{+2} in dissimilar portions reaches balance in the soil after 4–6 weeks of incubation for all ranks of metal modification, as reported by Yu et al. (2004). The soil samples were equilibrated in wet conditions and then dried, to reduce the inconsistency between the artificially polluted soil and the field-polluted soil (Jiang et al., 2011). According to the previous studies such as Shivangi and Trivedi (2016), Kawther (2018), and Entessar et al. (2021), the contaminated soil was mixed with silica fume at 3%, 5%, and 10% weight ratios. Table 3 shows a summary of the scope of experimental work to study the influence of the mixing of various ratios of SF with the nickel-contaminated soil on the mechanical, chemical, and physical characteristics of the contaminated soil. For example, CNS1 means a soil sample that is contaminated with nickel ions at a concentration equal to 750 mg/kg without adding SF, while CNS2, CNS3, and CNS4 represent soil samples contaminated with nickel ions at a concentration of 750 mg/kg mixed with SF at a ratio equal to 3%, 5%, and 10%, respectively.

Table 3. *Details of soil samples*

Name of test	Experiment Designation	Concentration (mg/kg)	SF (%)
CNS1	Soil sample contaminated	750	0
CNS2	Nickel-contaminated soil mixed SF	750	3
CNS3	Nickel-contaminated soil mixed SF	750	5
CNS4	Nickel-contaminated soil mixed SF	750	10

The analysis of samples

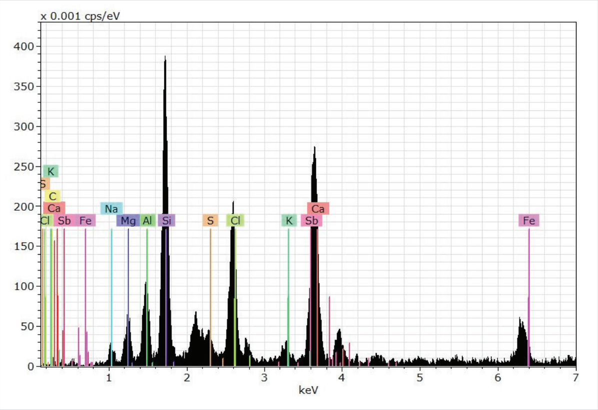
The effect of contaminated soils mixed with SF (waste by-products) was investigated. SF is considered the best by-product that can be used for many utilizations (Mohamed et al., 2020). These were achieved by examining mechanical, chemical, and physical characteristics. The procedure adopted in this study is similar to that adopted by a number of reseachers such as Karkush et al. (2013), Mahdi and Shahad (2019) and (2020) and Saeid and Hamed (2020). The physical tests consisted of the Atterberg limits: liquid limit (LL) and plastic limit (PL), max. dried density (MDD), and optimum water content (OWC). The chemical properties of soil samples are pH, organic matter content (OMC), calcium carbonate ($CaCO_3$), sulfate ions (SO_3), chloride content (Cl^{-1}), and total suspended solids (TSS), whereas the mechanical properties are represented by the soil compressibility, which is obtained by 1-D consolidation experiments and shear soil strength tests, according to the procedure adopted by many studies such as Mahdi and Shahad (2020).

Results and Discussion

Results of native soil analyses

The pH of the native soil was equal to 7.5, and the calcium carbonate content was equal to 23.934%, which was responsible for the high buffering capacity of the soil. Depending on particle-size distributional analyses, the soil was classified as silty clay soil. As demonstrated in *Table 1*, the liquid limit and plastic limit were equal to 17.72% and 16.367%, respectively. According to the EDS curve for native soil and as shown in *Fig. 1*, relatively high concentrations of Si, Ca, K, S, Cl, Mg, Al, Na, Mg, Sb, and Fe were noticeable.

Fig. 1. *EDS for the composition of the native soil sample*



Effect of mixed silica fume with nickel-contaminated soil on the physical properties

To determine the classification of soils in geotechnical engineering and as a basis for evaluation of both water retention capacity and mechanical properties, Atterberg limits are utilized. This would potentially be used as a parameter for smectite's geo-environmental performance (Goodarzi et al., 2015). *Fig. 2* and *Table 4* (this arrangement was dependent on the previous study by Karkush et al. (2013)) show the effect of the SF addition at different ratios to the nickel-contaminated soil on the plastic limit and liquid limit. An increment in the percentage for liquid and plastic limits was obtained with an increase in the percentage of SF additive to the contaminated soil. The results of the LL and PL showed the same trend that was observed in the previous study by Entessar et al. (2021). It may be observed from this that as the proportion of silica fume increases, the plastic and liquid limits of the soil samples are markedly increased. This increment in soil plasticity is essential for soil resistance to deformation and rupture, as well as for avoiding the failure pattern in the landfill liner layer. As is known, soil with high

Fig. 2. *Effect of addition of various ratios of silica fume on the liquid and plastic limits*

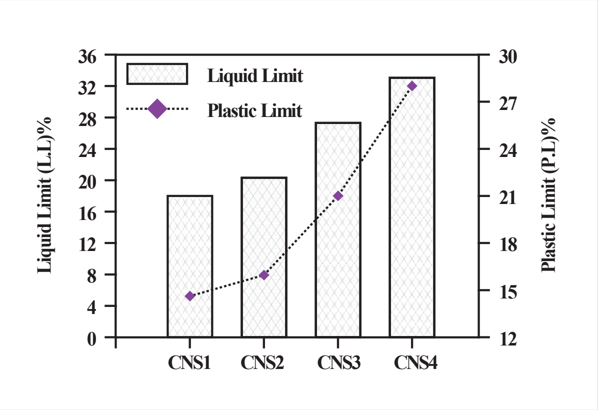


Table 4. *The obtained results from standard proctor compaction tests*

Soil sample	CNS1	CNS2	CNS3	NS4
Liquid Limit, LL (%)	18	20.3	27.3	33.04
Plastic Limit, PL (%)	14.616	15.954	21.003	28.002

plasticity absorbs water at a rate many times its weight, as cited by Entessar et al. (2021). These outcomes were sorted with the previous research. Karkush et al. (2013) showed that the plastic and liquid limits were raised in all soil samples as the concentration of pollutants that mixed with native soil increased. These actions cause inherent variations of structure and composition in the lattice of the clay mineral itself.

Kalkan and Akbulut (2004) determined the optimum water content and maximum dry unit weight relationships through standard proctor tests. These were done on both raw clay and SF–clay composite samples. The soil samples were compacted according to the standardized proctor compaction procedure on the soil samples CNS1, CNS2, CNS3, and CNS4 to evaluate their optimal water contents and max. dried density (MDD). The obtained results are explained in *Table 5* and show that the highest optimum water content was equal to 14.5% for CNS4, while the lowest optimum water content was equal to 8% for CNS1. It was observed that the maximum dry density in CNS1 (2.04 g/cm^3) was higher than in CNS4 (1.6 g/cm^3). *Fig. 3* shows the effect of the SF addition at different ratios to the nickel-contaminated soil on the maximum dried density and optimal water content for soil samples CNS1, CNS2, CNS3, and CNS4. It was noticed that the max. dried density decreased with increasing SF ratios in the nickel-contaminated soil. Meanwhile, the optimal water content increased with increased SF ratios to the nickel-contaminated soil. These results, at this point, were in agreement with the previous research. Kalkan and Akbulut (2004) stated that they raised the optimal moisture content and diminished the max. dried density for the same compaction efforts when SF was added to clay samples. The significance of these variations is based on the SF amount added as well as the chemical structure of clay minerals. In comparison with the raw clay sample, SF increased the total particle surface of the composite, depending on its amount. As a result, the composite samples' optimal water content increased. Of course, as the optimal water content incremented, the maximum dried density of the composite samples decreased gradually.

Table 5. *The obtained results from standard proctor compaction tests*

Soil sample	Max. dry density, MDD (g/cm^3)	Optimum water content, OWC (%)
CNS1	2.04	8
CNS2	1.96	13
CNS3	1.84	14
CNS4	1.6	14.5

Fig. 3. *Effect of addition of various ratios of silica fume on maximum dry density and optimum water content*

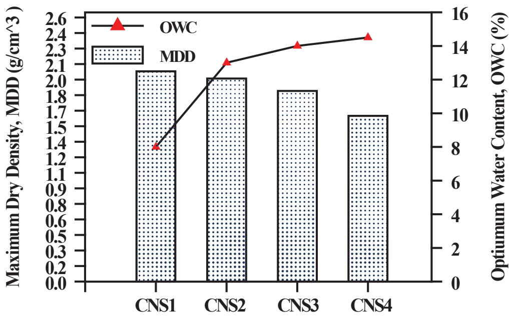
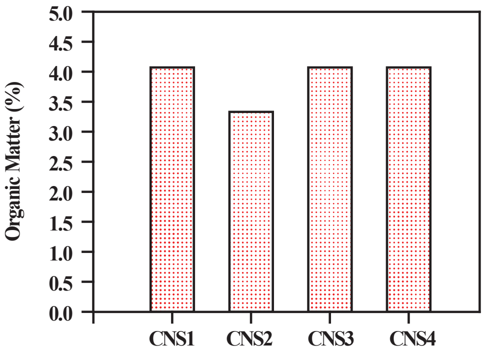


Fig. 4 shows the amount of organic matter content in the soil samples that was mixed with different ratios of SF. It is noticeable that the values of organic matter for CNS1, CNS2, CNS3, and CNS4 were approximately equal, ranging from 3.33% to 4.07% (i.e., no change in the organic matter for soil samples mixed with different ratios of SF), whereas the value of organic matter for native soil (as explained in *Table 1*) (2.06) was lower than that for CNS1 (4.07). And the liquid limit (LL) for

Fig. 4. *Effect of addition of various ratios of silica fume on organic matter for the contaminated soil.*



native soil and CNS1 was equal to 17.72% and 18%, respectively. It was observed that the liquid limit slightly increased with increased organic matter for two types of soil samples. Pradeep and Vinu (2015) showed that organic matter-induced higher water holding capacity and organic matter-induced soil particle aggregation are two major contributors affecting the plasticity properties of organic soil. High water holding capacity causes the organic matter-linked soil particles to act as plastics or liquids at high wet levels.

Delil and Köleli (2018) reported that the solubility of heavy metal ions in soil depends on the heavy metal structure and the chemical compounds, pH, and Eh (redox potential) methodologies. For some of them, pH is a crucial parameter that affects the desorption and mobility of metals from polluted soils. It was realized that the pH value for the contaminated soil (CNS1) was 8, whereas the pH value for the native soil (uncontaminated soil) was 7.5. The difference in pH value between the two types of soil samples was small, because they were soil samples, with the highest pH buffering capacity due to its high salt content, such as calcite, carbonate, or other types. It was noticeable that the amount of calcium carbonate ($CaCO_3$) for native and contaminated soil (CNS1) was equal to 23.934% and 19.35%, respectively. For CNS2, $CaCO_3$ was 24.673%, and then decreased to 22% and 20.011% for CNS3 and CNS4, respectively. Also, it was noticeable that the soil pH increased with the increase in the percentage of SF additive to the contaminated soil, which reached 9.5. This is depicted in *Fig. 5.*

Fig. 5. *Effect of addition of various ratios of silica fume on soil pH and calcium carbonate content*

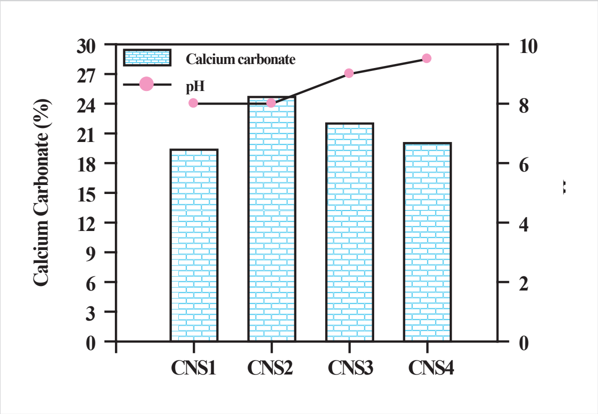


Table 6 shows that the amount of sulfate ions was 1.47, 1.32, 1.38, 1.42, and 1.25 mg/L in the native soil, CNS1, CNS2, CNS3, and CNS4 soil samples, respectively, corresponding to a reduction of 10.2%, 6.12%, 3.4%, and 15%, as compared with the native soil. It was noticed that the reduction decreased with increasing percentage of SF addition to the contaminated soil, except in CNS4. In *Table 6*, the value of chloride ions was 7.197, 8.797, 5.998, 5.198, and 5.998 mg/L in the native soil, CNS1, CNS2, CNS3 and CNS4 soil samples, respectively, corresponding to a reduction of −22.3, 17, 28, and 17%, respectively, as compared with the native soil. It was noticeable that the reduction increased as the percentage of SF addition to the contaminated soil increased, except in CNS4, whereas Mahdi and Shahad (2019) showed that the increase in chloride content may be caused by the chemically based reactions of the compounds of contaminants and the mineral compounds of the soil samples, which lead to the generation of Cl^{-1}.

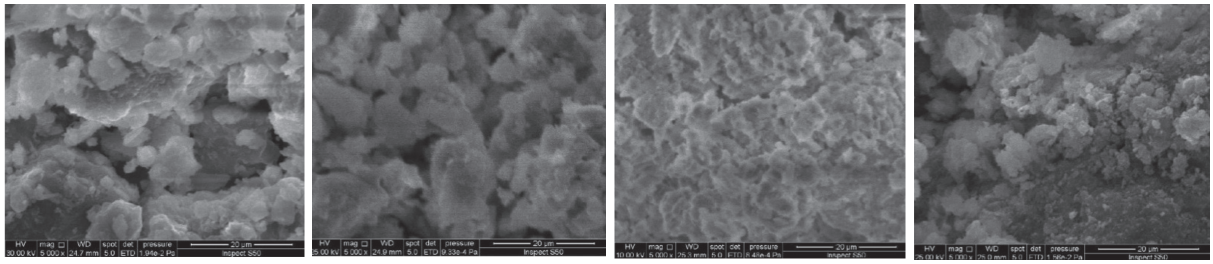
Table 6. *The concentration of sulfate and chloride ions for various soil samples*

Soil samples	Sulfate ions (mg/l)		Chloride ions (mg/l)	
Native soil	1.47	Reduction (%)	7.197	Reduction (%)
CNS1	1.32	10.2	8.797	−22.3
CNS2	1.38	6.12	5.998	17
CNS3	1.42	3.4	5.198	28
CNS4	1.25	15	5.998	17

Scanning electron microscope (SEM) of soil samples

The scanning electron microscope (SEM) was employed to describe the effect of the addition of different ratios of SF to the silt or clay particles, on the pore structure, as cited by Kalkan and Akbulut (2004). An SEM for CNS1, CNS2, CNS3 and CNS4 was magnified to a 20 μm scale. *Fig. 6* explains the morphological properties of soil samples before and after the addition of SF to the contaminated soil with nickel ions. *Fig. 6a* shows that the shape of the surface of CNS1 is covered with a thin layer of white color due to the saturating of soil particles with traces of contaminants (nickel ions). The sorption, as a result, has considerably been reduced so that no

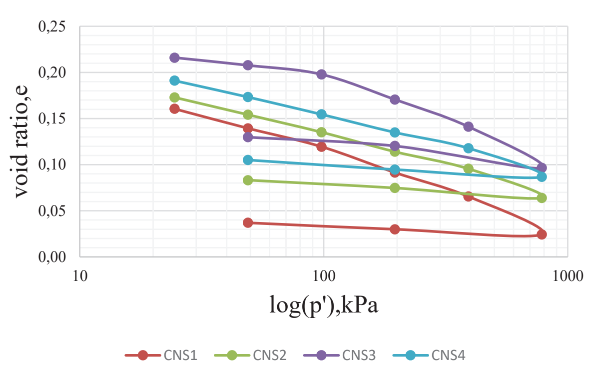
Fig. 6. *SEM images for the samples (CNS1, CNS2, CNS3, and CNS4) of a) contaminated soil with nickel ions, b) 3% addition silica fume, c) 5% addition silica fume and d) 10% addition silica fume*



(a) *(b)* *(c)* *(d)*

more contaminants are sorbed thereafter (Hayder & Ayad, 2018). The pore spacing between soil particles for CNS1 was larger as compared with CNS2, CNS3 and CNS4 (where 3%, 5% and 10% SF was added to the contaminated soil with nickel ions, respectively), as shown in *Fig. 6 b*, *c* and *d*. The shape of the surface for CNS3 was found to be a denser structure than that for CNS1, CNS2, and CNS4. Our results agreed with previous research (Kalkan & Akulut, 2004), which stated that samples with 30% silica fume content depict a denser structure than specimens with 0%, 10%, and 20% silica fume content,because of the SF covering the surrounding clay and silt particles and filling the voids in the specimen. As a result, in the 10% silica fume specimen, grain surfaces were partially covered by SF (silica fume microparticles), while the majority of the pores remained air-filled; whereas the soil particles in the specimen with 20% SF were covered by fume at remarkable rates, and the micropore was filled by fume.

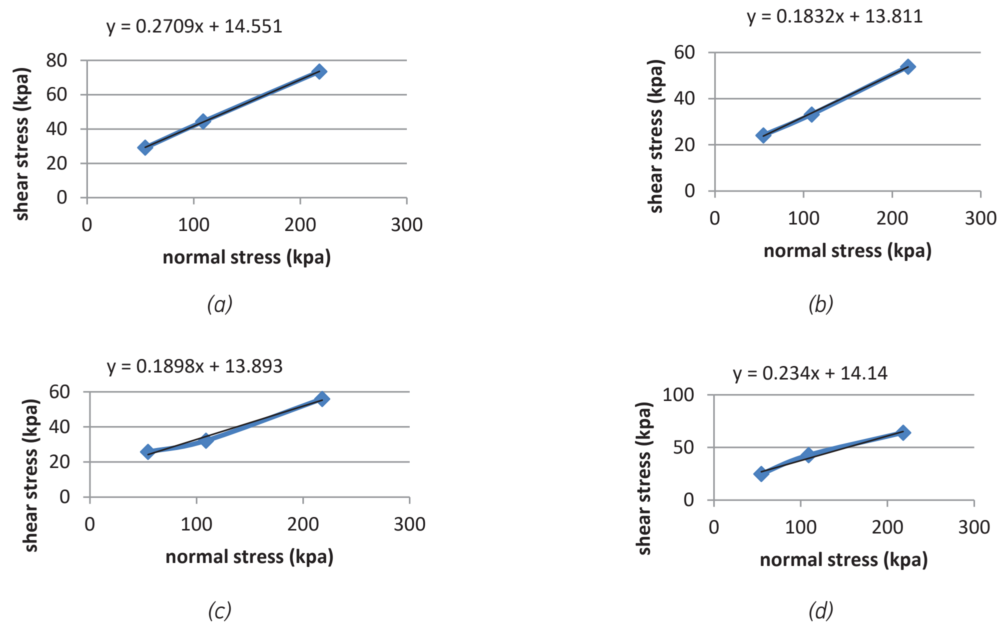
Fig. 7. *Consolidation curves as a function of the silica fume ratios added to the contaminated soil with nickel ions*



Effect of mixed silica fume with nickel-contaminated soil on the mechanical properties

As cited by Mahdi and Shahad (2019), consolidation is a process in which pore water is slowly squeezed out of soil particles when pressure is applied. *Fig. 7* and Table 7 (this arrangement depends on the previous study conducted by Mahdi and Shahad, 2019 and 2020) show the major parameters for the consolidation test, such as compression index (Cc), recompression index (Cr), pre-consolidation pressure (Pc), and coefficient of consolidation (Cv), as described by Mahdi and Shahad (2019). It was noticed that the value of the coefficient of consolidation (Cv) increased from 0.0026 at CNS1 (when no SF was added to the contaminated soil with nickel ions) to 0.0755 at CNS3 (when 5% SF was added to the contaminated soil with nickel ions) and then decreased to 0.00531 at CNS4 (when 10% SF was added). While Mahdi and Shahad (2019) stated that the coefficient of consolidation significantly decreased with the increased content of copper sulfate in the tested samples, it was observed that the amount of compression index (Cc) decreased with the increased SF ratio, whereas the value of the recompression index (Cr) increased with the increased SF ratio added to the contaminated soil with nickel ions. The results of this study are in excellent agreement with those obtained by Ahmed et al. (2021), who found that the effects of silica fume on the clay soil's behavior are reflected by the effects of this material on compression index (Cc) and rebound index (Cr) values. In fact, the soil with the compression index Cc and rebound index Cr has less tendency to settlement and vice-versa. SF has an important effect on the rebound index values of clay soil. The general trend reveals that the silica fume reduces the consolidation parameter values of the clay soil. A very slight reduction can be seen at low silica fume content, less than 10%, especially for the rebound index value. This may be due to the increase in the cation concentration where the thickness of the diffuse double layer is reduced, resulting in the flocculation of the clay particles and a decrease in soil compressibility. *Fig. 8* shows the results of direct shear tests conducted for CNS1, CNS2, CNS3, and CNS4.

Fig. 8. *Results of direct shear as a) CNS1, b) CNS2, c) CNS3 and d) CNS4*



(a) *(b)* *(c)* *(d)*

Table 7. *Consolidation testing results*

Soil type	Cc	Cr	Pc (KPa)	mv (m^2/KN)	cv (cm^2/s)
Native soil	0.171	0.014	180	0.000166	0.00650
CNS1	0.111	0.010	190	0.000105	0.00260
CNS2	0.083	0.016	300	0.000076	0.00645
CNS3	0.105	0.028	106	0.000115	0.00755
CNS4	0.080	0.015	200	0.00007	0.00531

Conclusions

The conclusions obtained from a set of laboratory tests which were carried out to study the soil characteristics before and after adding silica fume to the contaminated soil are as follows. The increment percentage for liquid and plastic limits was obtained by increasing the percentage of silica fume additive to the contaminated soil. It was noticed that the maximum dried densities decreased with increasing silica fume ratios added to the nickel-contaminated soil. Meanwhile, the optimum water content increased with increasing silica fume ratios added to the nickel-contaminated soil. The value of organic matter for soil samples was roughly equal, ranging from 3.33% to 4.07% (i.e., no change in the organic matter for soil samples mixed with different ratios of silica fume). The value of the coefficient of consolidation (Cv) increased from 0.0026 at CNS1 (when no silica fume was added) to 0.0755 at CNS3 (when 5% silica fume was added to the contaminated soil with nickel ions) and then decreased to 0.00531 at CNS4 (when 10% silica fume was added).

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Nomenclatures	
Cv	coefficient of consolidation
Cc	Compression index
Cr	Recompression index
Pc	pre-consolidation pressure

Abbreviations	
OMC	Organic Matter Content
MDD	Maximum dry density, g/cm^3
OWC	Optimum water content, %
LL	Liquid limit, %
PL	Plastic limit, %
CNS1	Soil sample contaminated with nickel ions
CNS2	Nickel-Contaminated soil mixed SF
CNS3	Nickel-Contaminated soil mixed SF
CNS4	Nickel-Contaminated soil mixed SF