Effect of metakaolin and silica fume on the engineering properties of expansive soil

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Abstract. Characteristics of the expansive soil should be studied due to the effects and problems of this soil on the structures that build on it, also, its spread in large areas in the world. Some of these problems are the cracks and large damages on the structures due to the differential settlement of the soil. These problems occur due to the swelling and shrinkage characteristics of the soil when it is affected by changeable water content. The need for the stabilizers to overcome these problems appears due to a large amount of loses money caused by the expansive soil's problems. This study used silica fume and metakaolin which considers stabilizer agents that used to treat the expansive soil. Silica fume is an industrial material obtained by condensation operation to the smoke that produced from the production process of the ferrosilicon metal. While metakaolin is a a pozzolanic material obtained from the burning of kaolin rock to (700–800) °C. The soil used in this study classified as CH soil. The treated samples were prepared by mixing the soil with (5%, 10%, and 15%) of the two additives. From the results, it was found that Atterberg limits were increased with the adding silica fume and decreased with Metakaolin. Specific gravity decreased with silica fume while it is increased with Metakaolin. The maximum dry unit weight decreased, and the optimum water content increased with silica fume and the opposite occur with metakaolin. The results showed that the swelling present improved with both additives.

Keywords: Expansive soil, improvement, stabilization, silica fume, metakaolin, natural pozzolanic materials.

1. Introduction
Expansive soils are considered one of the soils that have a large change in volume (swelling or shrinking) during seasonal change which causes a decrease and increases in water level [1-4]. Chen [5] stated that this phenomenon occurs in the expansive soils due to the montmorillonite minerals which are mostly contributing to it. In places that have large changes in the seasons during the year, the soil will suffer from drying and wetting. This soil shows cracks that appear on the surface of the ground during the drying seasons and become sticky during the rainy season, this will make some movement in the soil mass and therefore, structures like pavements, canal bed, retaining walls, light building, and linings that constructed on this kind of soil will suffer from many problems like cracking and severe damages [6]. Additive materials can be used in different stabilization methods, to resolve or reduce the swelling and shrinkage of the soil [7-9]. One of them is the treatment with chemical additives [10]. This method depends on the nature of the stabilizer agent that used to stabilize the soil. The industrial additives like cement, lime etc. can be used, such additives need complicated operations to product and highly cost-effective [11]. The pozzolanic agents like metakaolin, rice husk ash, etc. are also used as an alternative to the mentioned materials. These materials are low in cost and simple in production. Silica fume is a by-product pozzolanic material which have a spherical particles shape and softer than cement particles by 100 time. Metakaolin is a pozzolanic material which dehydrated from kaolin rock under temperature about 750°C [12],[13] stated that about 87% of the swelling pressure of silty-clay
soil can be reduced by stabilizing with silica fume (from 5% to 15%). They also stated that using 5% to 10% of silica fume increased the strength of the soil. [14] used different percentages and combinations of lime and silica fume and discovered that the free swell, maximum dry density, plasticity index, and liquid limit were reduced, while optimum moisture content, plastic limit, California Bearing Ratio (CBR), and unconfined compression strength were increased. [15] found that the use of silica fume causes a reduction in expansive soil plasticity and its swelling pressure.

The effect of metakaolin on the geotechnical properties of cohesive soils has been studied [16]. Using 2% to 12% of metakaolin caused a reduction in soil-specific gravity and its optimum compaction water content. The pozzolanic reaction of metakaolin affected the grain size disruption of the soil. At 10% of metakaolin, more than 90% of the swelling was reduced. Further studies using metakaolin, [17], showed the optimum percent of the metakaolin in expansive soil stabilization is 6%, at this content the strength and the durability values were increased. Some studies used silica fume (up to 30%) after mixing with materials like granite powder to stabilize the expansive soil [18]. It was noted that the combination of 20% silica fume and granite powder improved the CBR value of the soil and reduced its liquid limit and optimum moisture content.

Both of these materials (silica fume and metakaolin) were adopted in this paper as additives to stabilize the expansive soil. This paper aims to investigate the ability to use local pozzolanic materials for stabilization expansive soil and make the soil appropriate as a construction material by improved its properties. The experimental program of this paper includes conducting Atterberg limits tests, specific gravity tests, compaction tests, and swelling tests. The effect of adding different contents (0, 5, 10, and 15)% of silica fume and metakaolin on the basic, compaction, and swelling properties of expansive soil have been studied.

2. Materials and experimental tests
The soil sample was prepared by many trials of a combination between bentonite and kaolin soils. The selected sample of this study includes combination of 20% local bentonite and 80% local kaolin (depending on the plasticity index values). The physical properties of the soil showed that it has a liquid limit, plastic limit, and plasticity index values of 67, 29, and 38%, respectively. The specific gravity of the soil was 2.67. The grain size analysis showed that the silt and clay content of the soil is 17 and 83%, respectively. Accordingly, the soil considered as CH soil according to ASTM D 2487 [19]. It should be mentioned that all soil's properties have been determined according to ASTM specifications.

In this study, the first additive selected is silica fume. It was manufactured by "CONMIX company" has been used. The physical and chemical properties of this material indicated that the particles size silica fume is smaller than those of cement particles (with 100 times), it has a specific gravity of 2.302, and it consists of calcium hydroxide which produces the calcium silicate hydrate gel that working as a bonding agent for the soil particles when reacting with water. The results of chemical test showed that the main chemical compound of silica fume is silica, its content exceeds 90%.

The second additive of this study is the metakaolin. It is a thermal pozzolanic activated material. It was produced by the calcination process of kaolin at 750°C for one hour (according to Equation 1), Nita et al. [12].

\[ \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \xrightarrow{750°C} \text{Al}_2\text{O}_3+2\text{SiO}_2+2\text{H}_2\text{O} \]

The produced material is fine-grained and has a specific gravity of 2.70. The results of the chemical test indicated the silica and alumina are the main chemical compounds of metakaolin, their content exceeds 90%.

On the other hand, the samples for the testing program have been prepared by dry mixing of the soil with the selected additive. The selected contents of silica fume and metakaolin were (0, 5, 10, and 15)% by dry weight of the soil. The testing program carried out in this paper includes the determination of the grain size distribution from sieve analysis, carried out according to ASTM d 422
determination the specific gravity (the test carried out depending on the (ASTM D-854 [21]), the Atterberg limits values (all the samples tested according to (ASTM D 4318 [22]). The standard compaction test also included in the testing program; the test carried out according to ASTM D 698 [23]. Finally, the swelling potential of the soil was investigated before and after treatment. The samples prepared for this test depending on the curve of the compaction test at 60% degree of saturation to evaluate the required moisture content. The tests made according to (ASTM D4546 [24]).

3. Results and discussion
The effect of adding silica fume and metakaolin on the specific gravity (Gs) values of the expansive soil is shown in Figure 1. It can be seen that when the silica fume amount increased, the specific gravity of the soil decreased since the specific gravity of silica fume is less than the specific gravity of the soil. On the contrary, the specific gravity increased with the increase of the metakaolin. The increase occurs since the specific gravity of metakaolin (2.7) is larger than the prepared soil. In general, it appears that the reduction effect of silica fume to specific gravity was larger than the increasing effect in specific gravity when using metakaolin, this is due to the large difference of specific gravity of the soil and silica fume while the difference becomes lower with the metakaolin.

![Figure 1. Effect of additives on the specific gravity](image)

Figure 1. Effect of additives on the specific gravity

The effect of additives on Atterberg limits values (liquid limit, plastic limit, and plasticity index) are shown in Figure 2. From the results, it can be noticed that the liquid limits, plastic limits, and plasticity index of the soil were increased with the increase in silica fume content and reached the maximum values with the 15% silica fume. Depending on the soil type, this increasing occurs due to the cation exchange that occurs between the soil and the silica fume resulting in increasing the double-layer thickness [25-28].

Reexamination of Figure 2 shows that the LL, PL, and PI reduce with the adding of metakaolin and reached the lowest values with the soil mixed with 15% metakaolin. This could occur due to the reaction of cation exchange took place resulting in reducing the double-layer thickness which increasing the attraction forces that led to more flocculation of the particles.

![Figure 2. Effect of additives on Atterberg limits.](image)
The effect of additives on the compaction properties of the soil is illustrated in Figure 3. As shown, the adding of silica fume increased the optimum moisture content (OMC) from 28.92% to 29.74% and decreased the maximum dry unit weight (MDD) from 14.05 kN/m$^3$ to 13.55 kN/m$^3$ with 15% silica fume. The increase in the OMC is occurred because of that the surface area of the soil has been increased with the addition of silica fume. Therefore, more water is needed to compact the mixtures and increasing the OMC. In the same way, the reduction in MDD occurs by reducing the specific gravity of the soil when replaced with silica fume which is much lower than the prepared soil. On the other hand, metakaolin has increased the $\gamma_{dmax}$ to 14.90 kN/m$^3$ and decreased the OMC to 27.14% with a metakaolin content of 15%.

![Figure 3. Effect of additives on compaction properties](image)

The results of the swelling test are shown in Figure 4. Treated samples of soil with silica fume shows a reduction in swelling percent from (7.29% to 4.5%) at 15% of Silica fume. This improvement in the swelling parameters is due to the pozzolanic reaction between the soil particles and silica fume. Same results achieved with Al-Soudany [29] and Al-Azzawi et. al [30]. Figure 4, also, shows an improvement in free swell with adding metakaolin from (7.29% to 4.8%) at 15% of metakaolin with sudden increment in the free swell at 10% due to the reduction in water content from 2.15% at 5% Metakaolin to 20% at 10% Metakaolin. Same results obtained with Ahmed and Hamza [31].
4. Conclusions
According to the results obtained from the experimental work, the following conclusions are obtained:
1. The specific gravity of expansive soil increased with the addition of different contents of silica fume (from 2.666 to 2.572), while it increased when adding metakaolin (to 2.674).
2. The adding of silica fume to expansive soil increased liquid limits, plastic limits, and plasticity index to 15% of silica fume. All the results were decreased with the adding of metakaolin.
3. From the compaction test, it was noticed that with the addition of silica fume the maximum dry unit weight decreased and the optimum moisture content increased. The opposite occurred with the addition of metakaolin.
4. The free swelling test showed that when adding 15% of silica fume, the free swell of the soil reduced from (7.29% to 4.5%)) and adding 15% of metakaolin decreased it to 4.8%.

The final results of this paper showed that the swelling present improved with both additives. The optimum content of silica fume and metakaolin is 15%.
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