



ORIGINAL ARTICLES

Effect of by-product steel slag on the engineering properties of clay soils



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Abstract Clay soils, mainly if they contain swelling minerals such as smectite or illite, may cause severe damage to structures, especially when these soils are subjected to wetting and drying conditions. High expansion and reduction in shear strength and foundation bearing capacity will take place due to the increase in water content of these soils. The engineering properties of these kinds of soils can be improved by using additives and chemical stabilizers. In this work, by-product steel slag was used to improve the engineering properties of clay soils. Lab and field experimental programs were developed to investigate the effect of adding different percentages of steel slag on plasticity, swelling, compressibility, shear strength, compaction, and California bearing ratio (CBR) of the treated materials. The results of tests on the clay soil showed that as steel slag content increased, the soil dry density, plasticity, swelling potential, and cohesion intercept decreased and the angle of internal friction increased. For the CBR, the results of the tests showed an increase in the CBR value with the increase in slag content.

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1. Introduction

Behavior of clay soils with change in moisture content should be given great attention, especially if these soils have a consid-

erable amount of clay minerals susceptible to volume change, such as Montmorillonite (smectite) and illite minerals. In wet seasons, these soils swell and become soft as they gain water, while in dry seasons they shrink and become hard as they lose water. This behavior is expected to cause severe damage to structures that are built on such soils. According to Wyoming Office of Homeland Security (2014) the USA loses about \$2.3 billion/year due to structural damage (including: buildings, roads, pipelines, and others) as a result of the swelling behavior of the expansive soils.

Many studies were carried out to reduce the damage effect of expansive soils (in terms of swelling or strength reduction) on structures. These studies used additives or admixtures as stabilizers (such as lime, cement, fly ash, calcium chloride, olive

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waste, and asphalt), geo-textiles, and compaction-moisture control among other methods. Al-Malack et al. (2016) used fuel oil fly ash (FFA) to stabilize marl soil. In their conclusions, the authors indicated that the treated marl met the durability and strength requirements. Seco et al. (2011) studied the effect of adding different additives (lime, natural gypsum, magnesium oxide, Rice fly ash, coal fly ash, steel fly ash, and aluminum filler) on the swelling and strength behavior of highly expansive clay soil. The results showed that adding 2% of lime with 1% of magnesium oxides tremendously reduced the swelling percentage of the treated clay soil. Onur (2009) investigated the effect of limestone and marble dust on the swelling behavior of expansive soils. The results showed that around 21–28% reduction in the percentage swell was achieved when 5% of dust added to the treated soil. Assa'd and Shalabi (2004) studied the effect of adding fly ash, cement, and lime on the strength of highly plastic clay soil. The results showed that the strength increased when the soil was mixed with lime or cement besides the fly ash. Kumar and Sharma (2004) found that the addition of fly ash reduced the soil plasticity, swelling characteristics, permeability and increased the undrained shear strength of the treated soil. Sobhan and Mashnad (2003) found that the use of plastic strips increased the compressive strength, split tensile and flexural strength of the soil–cement–fly ash composite. Al-Rawas et al. (2002) and Al-Rawas (2002) studied the effect of cement dust, copper slag, slag-cement, and granulated blast furnace slag on the swelling behavior of expansive soils. The results showed that the swell pressure and swell percent of the treated soil had been reduced as a result of particle aggregation. Cokca (2001) found that the increase in the percent of fly ash and curing time decreased the swelling potential, activity, and plasticity of the treated soil. Wild et al. (1999) found that granulated blast furnace slag added to an adequate amount of lime reduced the swelling potential of gypsum-bearing kaolinite clay. Attom and Al-Sharif (1998) concluded that the use of burned olive waste reduced the swelling pressure and plasticity of highly plastic soils. Basma et al. (1998) showed that the use of cement with expansive clay caused a reduction in soil swelling characteristics.

The objective of this study was to investigate the use of by-product steel slag aggregates (SSA) as a stabilizer. Large quantities of steel slag are produced daily in Jordan from steel manufacturing processes. Currently, by-product steel slag material is dumped randomly in open areas. If not recycled or disposed in properly designed landfills, the toxic elements such as Cr, Ni, and Zn (see Table 1) may migrate to and pollute the surface water and groundwater and affect the human life and the environment. In addition to that, the very fine particles of by product steel slag are expected to pollute the air. The investigation of this work focused on the engineering properties of a stabilized clay soil as a sub-grade material used in road pavement and foundation. The investigation considered the effect of SSA on plasticity, swelling behavior, compressibility, shear strength and California bearing ratio (CBR) of the treated clay soil.

2. Materials

2.1. Clay soil

The soil used in this study was brought from the western part of the city of Amman (along Mecca Street). The soil physical

Table 1 Properties of the used materials.

Property	Clay soil	Steel slag
Specific gravity	2.71	^Y FA: 3.2 ^Y CA: 3.1
Liquid limit, %	51.9	Non-plastic
Plastic limit, %	27.9	Non-plastic
Plasticity index, %	24	Non-plastic
Minerals or chemical composition (ppm)	Major: quartz Minor: smectite Trace: illite, calcite, dolomite, and kaolinite	Cr = 0.063 Ni = 0.004 Fe = 0.019 Zn = 0.021 Pb = 0 Cu = 0 Cd = 0
Abrasion loss at 500 revolution, %		16.4
Abrasion ratio (100/500), %		11.5
Absorption, %		FA: 4.5 CA: 2.3
Soil activity	1.2	–
Maximum dry density (mod. proctor), kN/m ³	18.02	–
Optimum water content (mod. proctor), %	15.6	–
Gravel size %	3.1	91
Sand size %	10.3	9
Silt size %	64.1	0
Clay size %	22.5	
Classification (USCS)*	CH–MH	GP

^Y FA: Fine Aggregates, CA: Coarse Aggregates.

* Sieve # 200 (0.075 mm) separates between fine and coarse grains.

and chemical properties were measured and these include: grain size distribution, plasticity, specific gravity, and clay minerals. X-ray diffraction analysis showed that the soil consists of quartz as a major mineral constitute, smectite as minor mineral, and trace amounts of illite, calcite, dolomite, and kaolinite. The soil plasticity index and activity were 24 and 1.2, respectively. According to Skempton's (1953) activity classification, the soil is classified as "normal". Table 1 summarizes the used soil properties and Fig. 1 shows its grain size distribution. According to the Unified Soil Classification System (USCS) the soil was classified as CH–MH (highly plastic clay and silt).

2.2. Steel slag aggregates

The steel slag aggregates (SSA) were obtained from the United Iron and Steel Manufacturing Company, Amman. The aggregates that passed 1.0 inch sieve were used in this study. The specific gravity of the fine and coarse portions of the aggregates were 3.2, 3.1 respectively. The chemical tests showed that the aggregates were free of Cadmium (Cd) and Copper (Cu) elements, as shown in Table 1. The results of the grain size distribution of the used aggregates are shown in Fig. 1.

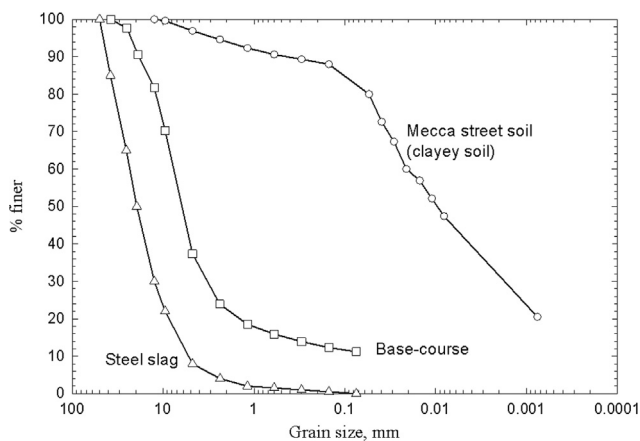


Figure 1 Grain size distribution of the used materials.

According to the USCS, the material is classified as GP (poorly graded gravel).

Fig. 2 shows the locations of the collected samples (clay soil and steel slag) within the districts of the capital city of Jordan, Amman.

3. Testing program

To achieve the objectives of this study, a testing program was designed to investigate the behavior of the treated clay soil. The tests included Atterberg limits, swelling, unconfined compressive strength, direct shear, and California bearing ratio (CBR). These tests were performed at different percentages of steel slag added to the treated soil at the conditions of opti-

imum water content and maximum dry density that were determined from Modified Proctor Compaction test. Table 2 summarizes the performed tests at different percentages of steel slag.

4. Results and discussion

4.1. Plasticity of clay soils

Results of liquid limit (LL) and plasticity index (PI) tests of the treated clay soil are shown in Fig. 3. In this figure, it can be seen that both liquid limit and plasticity index decrease almost linearly with the increase in steel slag content. Reduction in LL and PI of the treated soil is expected due to the non-plastic nature of the steel slag particles (the slag is granular materials classified as GP, Table 1). It is important to notice that the added steel slag changed the treated soil classification from CH–MH (highly plastic clay and silt) to CL–ML (low plastic clay and silt).

4.2. Swelling potential of the clay soil

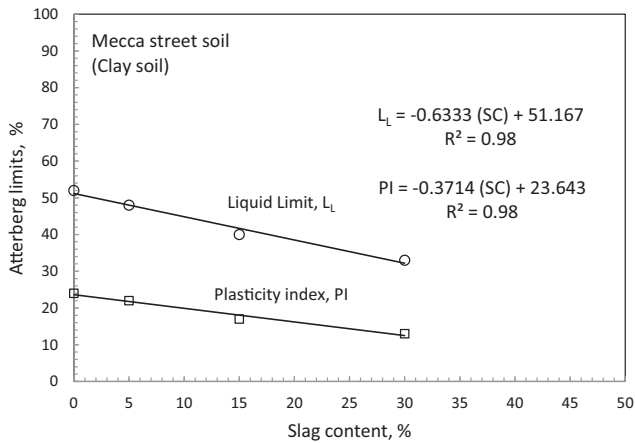
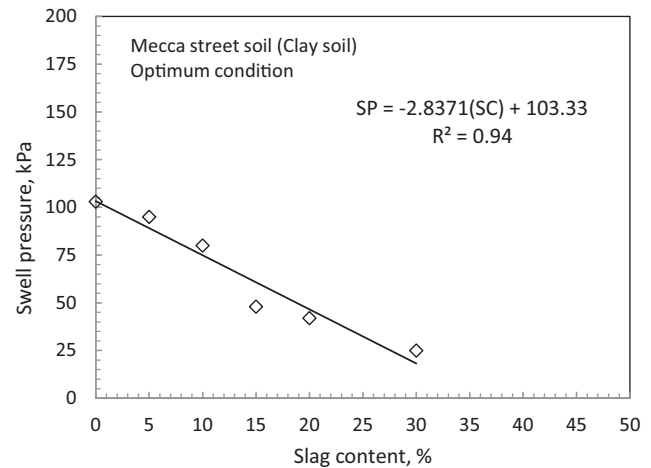
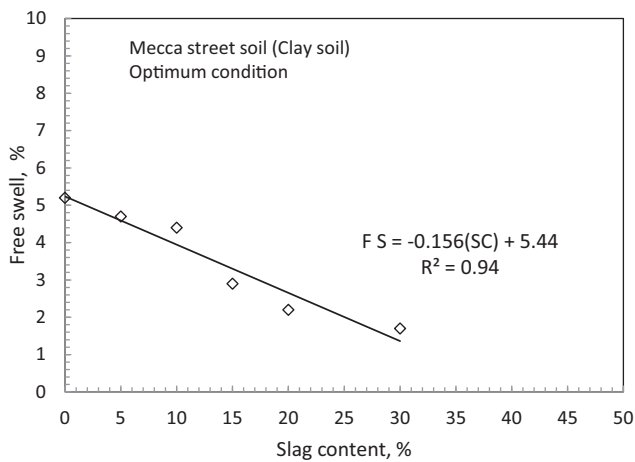
In order to investigate the effect of steel slag on the swelling potential of the clay soil, swell tests were performed at optimum water content condition using different percentages of steel slag. Fig. 4 shows that as the steel slag content increases, the percentage of free swell decreases almost linearly. The free swell of the treated soil was reduced from 5.1% for 0% steel slag to 3% for 15% steel slag, and to 1.7% for 30% steel slag. In this figure, the free swell is defined as the change in the sample thickness with respect to its initial thickness. The results of zero swell tests showed that the swell pressure decreases with



Figure 2 Locations of the used materials within the districts of Amman – Jordan.

Table 2 Testing program of the stabilized clay soil.

Test	Standard	% Used of steel slag
Plasticity	ASTM D4318	0, 5, 15, 30
Unconfined compression	ASTM D2166-85	0, 5,10, 15, 20, 30
Direct shear	ASTM D3080-90	0,15, 30,100
Free swell	ASTM D4546-90	0, 5,10, 15, 20, 30
CBR test	ASTM D1883-87	0, 15, 30
Compaction	ASTM D698, D1557	0, 15, 30
Specific gravity	ASTM D854	0
Grain size analysis	ASTM D422	0
Classification of materials (USCS)	ASTM D2484	0

**Figure 3** Atterberg limits of the treated clay soil.**Figure 5** Variation of the treated clay soil swell pressure with steel slag content.**Figure 4** Variation of the treated clay soil swell with steel slag content.

the increase in steel slag content. Fig. 5 shows that the swell pressure decreased from 110 kPa for 0% steel slag to 55 kPa for 15% steel slag and to a value of 25 kPa for 30% steel slag. If the ratio of swell pressure in kPa to swell value in percentage is considered, this ratio is 20 for 0% steel slag and 15.2 for 30% steel slag (i.e. the ratio decreases with the increase in steel slag content). The decrease in swell value and swell pressure

with the increase in steel slag content is due to the non-plastic nature of the steel slag aggregates.

4.3. Unconfined compressive strength and optimum compaction

Unconfined compression tests were conducted on 3.6 cm × 7.6 cm samples of clay-slag prepared at the optimum compaction conditions of 0% steel slag content compaction curve. Different percentages of steel slag were added to the clay for UCS tests at the maximum dry density and optimum water content of the soil based on the soil dry density and water content compaction curve that was obtained from the compaction test of just pure clay soil. The results of the tests indicated that the unconfined compressive strength (UCS) decreased with the increase in steel slag content, as shown in Fig. 6 (curve A). As can be seen in this figure, the UCS of the clay soil decreased from 500 kPa for 0% slag to 150 kPa for 30% slag. In addition, the results showed that the rate of strength reduction of the treated clay soil is significant in the range of low percentages of steel slag content. For soil-slag samples tested for UCS at maximum dry density and optimum water content obtained from the compaction curve of soil-slag, curve B in Fig. 6 indicates that the UCS decreases with the increase in slag content then slightly increases for slag content greater than 15%. Fig. 7 shows the compaction curves of the soil-slag at different steel slag contents, which represents the results of UCS of curve B of Fig. 6.

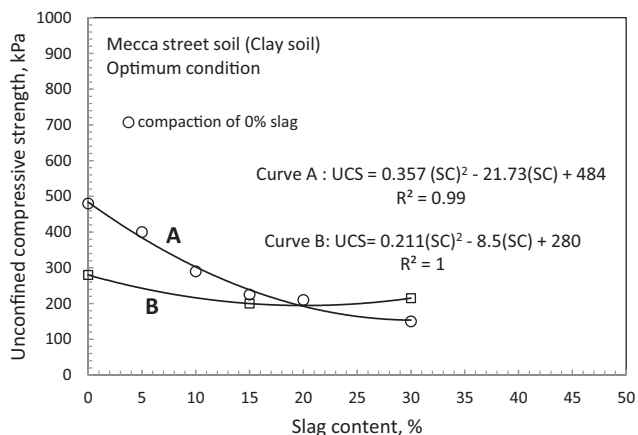


Figure 6 Unconfined compressive strength of the treated clay soil with steel slag content.

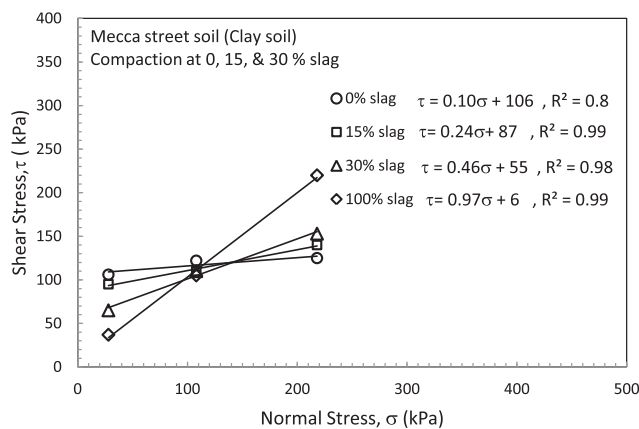


Figure 9 Shear strength failure envelopes of the treated clay soil using different compaction curves.

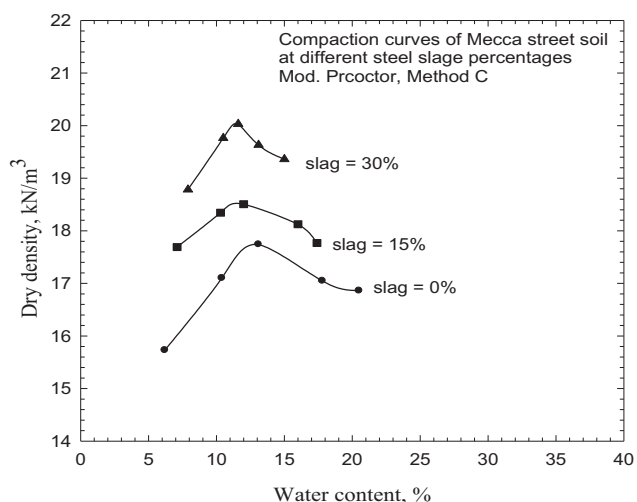


Figure 7 Compaction curves of the clay soil at different steel slag content.

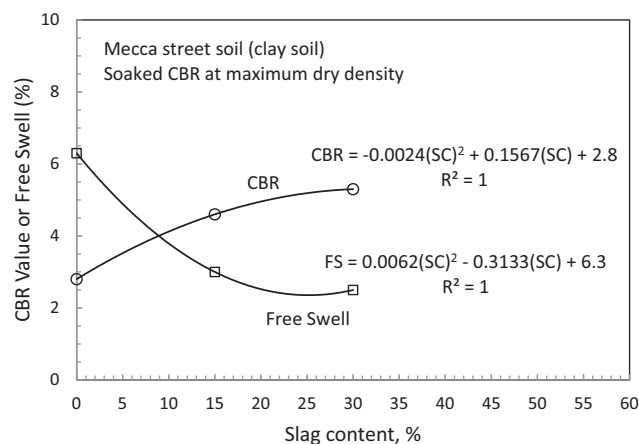


Figure 10 Variation of CBR value and swell of the treated clay soil with steel slag content.



Figure 8 Manufactured large scale direct shear device.

4.4. Direct shear test results

Large scale direct shear tests (25 cm × 25 cm cross-sectional area) were conducted on clay soil passing 19 mm sieve size.

Special large size direct shear device was designed and manufactured. Fig. 8 shows the manufactured direct shear device and its components. Consolidated Undrained (CU) tests were performed at the optimum water content conditions of the corresponding clay soil-steel slag compaction curves with 0%, 15%, 30%, and 100% steel slag contents. The results in Fig. 9 show that as the steel slag content increases, the cohesion intercept decreases and the angle of internal friction increases. The increase in angle of internal friction and decrease in cohesion intercept with the increase in steel slag content is due to the frictional nature (the grains are angular and rough) of the steel slag, which can be observed clearly for the case of 100% steel slag.

4.5. California bearing ratio (CBR) test results

Soaked CBR tests (samples were emerged in water for 96 h before testing) were conducted on the clay soil at the optimum water content conditions of the compaction curves of the 0%, 15%, and 30% steel slag content. The results in Fig. 10 show that as the steel slag content increases, the CBR value increases. Also, this figure shows that the CBR value and the

free swell are in a reverse relation as the percentage of steel slag content increases.

5. Conclusions

An experimental program was conducted to investigate the effect of using by-product steel slag as a stabilizer on clay soils. In general, the results show that the steel slag can effectively be used to improve the engineering properties of clay with awareness to the percentages that should be used. Good statistical correlations were derived between the intended engineering property and the steel slag content. Specifically, the following conclusions can be drawn from this study:

1. The increase in steel slag aggregate content decreases the plasticity and increases the maximum dry density of the clay soils.
2. Based on large scale consolidated undrained shear strength tests, the cohesion intercept of the clay soil decreases with the increase in steel slag content while opposite behavior is expected for the angle of internal friction.
3. Presence of steel slag as a stabilization material improves the swelling potential of the clay soils. Both, percentage of free swell and swell pressure decrease almost linearly with the increase in steel slag content.
4. Unconfined compressive strength of the treated clay soils with steel slag depends on the initial compaction conditions of the soil. While the zero slag compacted soil shows a decrease in UCS with the increase in slag content, the compacted soil at different steel slag content shows almost a slight change in UCS with slag content.
5. CBR value of the treated clay soil was found to increase with the increase in steel slag content, and it is in a reverse relation with the free swell value.

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