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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.

1. Introduction

Behavior of clay soils with change in moisture content should be given great attention, especially if these soils have a considerable 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 Homland Security (2014) the USA looses 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.

Table 1 Properties of the used materials.

Property	Clay soil	Steel slag
Specific gravity	2.71	[¥]FA: 3.2 [¥]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

[¥] FA: Fine Aggregates, CA: Coarse Aggregates.

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

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 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.