The behavior of sand modified with steel slag and the effect of microstructure

Le comportement de la sable modifié par l'emploi de scories du fer et l'influence de sa compositition structurale

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ABSTRACT
This paper describes the behavior of waste materials used as an alternative to enhance the mechanical characteristics of sandy soil and mitigate strains at a different stress level. This research aims to investigate the benefits of using slag waste material as available as a cheap inclusion to improve the shear strength of sandy soil. A series of direct shear tests studied the main parameters of natural and reinforced sand. The microstructure behavior of the tested materials and sandy soil was investigated using a light microscope. The study revealed that at the same stress level the existence of such materials can effectively increase the shear strength and is mainly related to microstructures of slag. This technique is an effective method to decrease the vertical deformation and mitigate the strain under a different stress level. The conclusions of this paper support the use of waste materials as an environmentally acceptable cheaper inclusion in soil improvement applications.

RÉSUMÉ
Cette rechere a pour objet d'étudier le comportement du sol sablonneux et ses caractéristiques mécaniques en employant les scories du fer comme l'un des dechets industriels abondants dans l'environnement. On a fait des experimentations en employant directement la boite a couper en ce qui concerne le sol sablonneux et celui auquel on a ajoute les scories du fer, et on a étudié les caractéristiques mécaniques du sol amélioré par ces scories, comme les reactions et l'effondrement, ainsi que l'influence de tous ces facteurs et leurs relation avec la structure microscopiques des scories. On a trouve que l'emploi de ces scories comme une sortes de renforcement du sol et aboutit a une augmentation claire dans la résistance du sol et deminue les reaction verticals dans toutes les etapes et par la meme a former les soutiens entre les sables qui about it a augmenter les caracteristiques mecaniques de la sable.

Keywords**:** waste materials, slag, sand, microstructure, shear strength

1 INTRODUCTION

Civil engineers around the world are seeking new alternative materials now required for cost effective solutions for ground improvement and also for conservation of scarce natural resources. There, is also a ban on new quarries ,due to environmental concerns. Thus there is a growing need for a material that can partially replace sand and provide improved properties. In this context, using a waste product in the form of steel slag holds promise as an alternate material that can be used with sand. Steel slag forms in a steel furnace and it has been used for a wide range of civil engineering applications (Ramaswamy & Aziz 1992).

The estimated municipal solid waste production in Egypt through the 2007 was on the order of 3.5 million tones per year. A large number of laboratory investigations have been conducted on fiber-reinforced materials. The results of direct shear tests performed on sand specimens reinforced with discrete randomly distributed fibers by (Gray & Ohashi 1983) indicated to increase shear strength of sand. These results were supported by a number of researchers using consolidated drained triaxial tests (Gray & Al -Refeai 1986; Gray & Maher 1989; Al-Refeai 1991). In addition, (Ahlrich & Tidewell 1994 and Webster & Santoni 1997) studied the behavior of stabilizing sands with monofilament fibers. (Benson & Khire 1994) used a high density reclaimed strips of polyethylene to reinforce sand. (Bueno 1997) conducted laboratory study on mechanically stabilized soils with short thin plastic strips of different lengths and contents. (Dutta et al., 2004) studied the engineering properties of sand reinforced by waste plastics. Thus, it is evident that most of the papers in the literature concerned with the use of fibers, geotextiles, geogrids and only waste plastics in enhancement the characteristics of sand but, the stabilization of sand with random oriented discrete elements in the form of steel slag particles has not been thoroughly investigated.

The main objectives of the present investigation are to study the effect of using steel slag particles as waste material for stabilizing and improving the engineering characteristics of sandy soil based on both its microstructure and surface textures.

2 TESTING MATERIALS

Dry silica sand as selected for use in this study because its unit weight can be readily controlled and nearly identical specimens could be easy constructed. The particle size distribution curve for adopted sand is shown in figure1. The mean grain size of the tested sand, $D_{50\%}$ = 0.4 mm, the uniformity coefficient is Uc = 26 and a specific gravity of 2.68. The estimated grain angularity according to (Lee 1964) is around 300. The minimum dry density $\gamma_{d\ min}$ = 15.6 (kN/m^3) and the Compacted dry density $\gamma_{d\ max}$ = 18 (kN/m^3). The sand has a peak friction angle of 24^o for minimum density and 30^o for maximum density. The steel slag was selected from waste products of last mentioned factories which founded in Egypt. Its particle size distribution curve is also plotted in figure1. The mean grain size of the tested slag, $D_{50\%}$ = 0.20 mm, the uniformity coefficient is Uc = 2.5, coefficient of curvature is Cc =0.576, grain angularity is around 1100 and specific gravity of 2.83. The minimum dry density for slag, $\gamma_{d\ min}$ = 16.85 (kN/m^3) and the Compacted dry density $\gamma_{d\ max}$ = 19.80 (kN/m^3).

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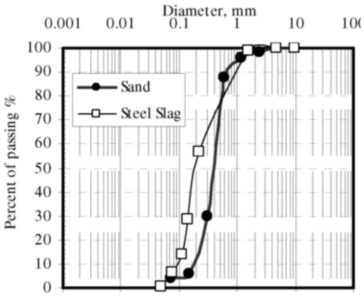

Figure1. Particle size distribution curve for tested sand and steel slag.

3 EXPERIMENTAL PROCEDURE AND INVESTIGATED PARAMETERS

Effectively, the shear strength of soil-slag mixtures should be evaluated using triaxial shear tests. However, testing mixtures of soil and steel slag in triaxial is extremely difficult, because the steel slag has sharp edges as illustrated in microstructure figures, this sharp textures can cause damage for the confined membrane. In general the metallic slag yet adequately complaint in triaxial. So, the direct shear box was used to evaluate the shear strength of such mixtures.

A series of direct shear tests were conducted for dry sand and mixture at different studied parameters. These parameters are:
1- The percentage of steel slag content (10, 30, 50 and 75%),
2- The vertical confining pressure (σ = 50 kN/m^2, 100 kN/m^2, 150 kN/m^2 and 200 kN/m^2),
3- The unit weight of sand slag mix. (γ_{mix} = 15.50 kN/m^3, 16.40 kN/m^3 and 17.50 kN/m^3).

A microstructure of tested slag and sand was investigated by a light microscope and digital camera to obtain a variety of images. Figure 2 shows the particle arrangement and surface textures for all tested materials.

4 DEFINITION OF FAILURE

Some specimens tested at low normal stress exhibited a distinct peak shear stress at displacement less than 1.50 cm within the range of maximum lateral displacement of direct shear apparatus. In this case, the shear strength was reported as a peak shear stress. However, for the majority of the tests, at high confining stress, a peak shear stress was reached after 1.5 cm of displacement. Instead, the shear stress continued to increase throughout the test. Specimens for which no peak shear stress was observed, shear stress at a displacement of 1.2 cm was reported as shear strength.

5 RESULTS AND DISCUSSIONS

5.1 Strain Volume Change Behaviour

It is obvious that, at the same mentioned density of mix, the specimens were compressed during shear as shown in Figures 3 to 6, which in turn modifying the vertical strain response. The vertical strains were decreased with the increase of slag content. The slag can effectively affect on dilation rang of sand. Specimens with low slag contents dilated during the shear process compared with specimens of greater slag contents. Greater dilation obviously occurred with the increase of vertical confining pressure as plotted in figure 5 and 6. The decreasing of dilation at higher slag content was probably caused by active interlocking between sand slag particles. In the pure sand specimens the strains were occurred due to initial locking and relative movement/sliding between sand particles. While, the existence of slag was filled the voids between sand grains. Hence, the expected vertical strains and horizontal displacement were decreased and caused effective interlocking. In addition, the slag microstructure and its surface texture can play important role in preventing the sliding between sand particles and decreased the possibility of strains occurrence as distinctly shown in figure 2.

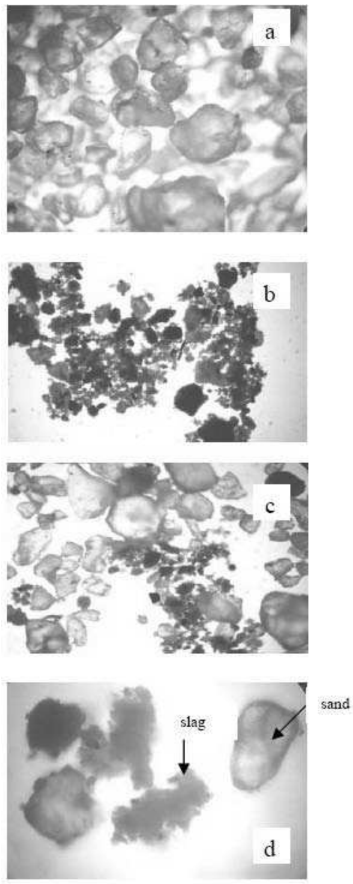

Figure 2: Microstructures of tested samples with magnification X100. a- Sand samples. b- Steel slag sample. c- Sand mixed with slag. d-Slag and sand with magnification X200.

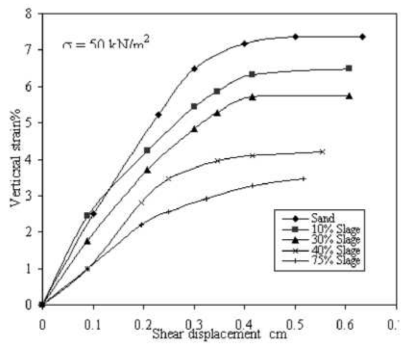

Figure 3. Relationship between vertical strain and shear displacement for different slag percentages.

Moreover, the increase of both vertical confining pressure and slag contents were increased the vertical strains because the sand slag mixture gets stiffer at the level of stress increases until reaching to fully interlocking as confirmed in conjunction figures. Generally, the reinforced sand by steel slag is decreasing the ability of particles mix to move up relative to each other under shear force.

5.2 Stress-deformation Behavior

The reinforcement of sand by slag was tended to increase the ultimate shear strength and limit reduction in post peak shearing resistance (figure 7 and 8). The presence of slag which acted as a fiber limited the amount of horizontal and vertical deformation or dilation under higher density mix. The results shown in figure 7. It was noticed that, the shear stress deformation response was affected by the slag content. Increasing the slag content caused a progressive increase in peak strength with less and less shear displacement as illustrated for slag content 10% and 50%. Contrary, for slag content more than 50% no peak occurred. Furthermore, figure 7 again justifying that the slag increases the frictional resistance between sand grains. It also, increases the improvement range of shear strength due to resulting densification. The added slag to sand can be controlled and limited the horizontal movement as clarified in figure 7, which explains that, under the same normal stress, as the slag content increased the shear displacement definitely decreased. On the other way, the shear stress deformation response was also, affected by vertical normal stress (Figure 8). Increasing the vertical pressure caused a progressive increase in peak strength. For unreinforced sand, interlocking was decreased as the confined stress increased, because the particles become flatted at contact points, sharp points, sharp corners are crushed, and particles break. Even though these actions result in dense specimen, they make it easier for occurrence the shear deformation. But in reinforced case, slag increases the degree of interlocking and decreases the crushing. Also it raises the failure level and delays the failure as compared with unreinforced sand. As the level of vertical normal stress is increased, the chance to sand slag mixture to get stiffer thus, the shear resistance is effectively increased and the shear displacement decreased until reaching the peak failure as shown in figure 8. After reaching to peak failure, yielding zone was obtained. It was distinctly observed over shear displacement 1.2 cm. This yielding is the result of fracturing and crushing of sand slag particles, which permits large relative motions between particles mix. Distinct propping sounds can be heard at this stage of loading. It can be distinctly heard at higher confining pressure. Microscopic examination that analyzed after testing and compared with others before testing show that considerable particles degradation actually occurred for mix specially for slag particles.

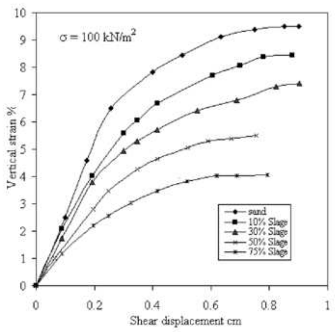

Figure 4. Relationship between vertical strain and shear displacement for different slag percentages

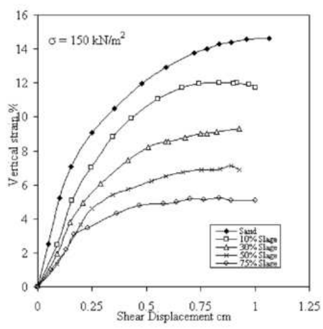

Figure 5: Relationship between vertical strain and shear displacement for different slag percentages.

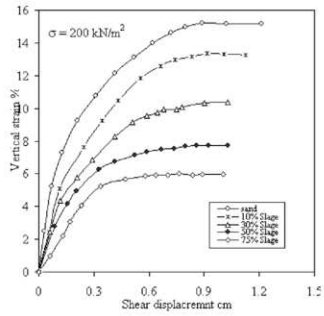

Figure 6. Relationship between vertical strain and shear displacement for different slag percentages.

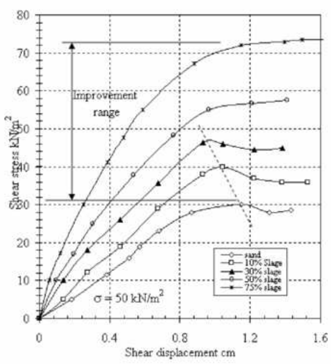

Figure 7. Shear stress versus shear displacement for different slag percentages.

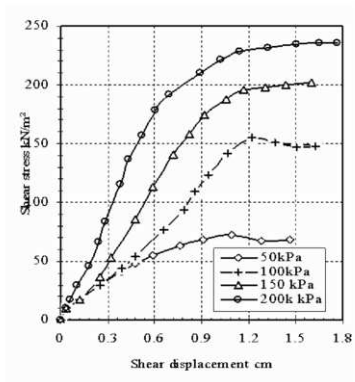

Figure 8: Shear stress versus shear displacement at different vertical confining pressure (Slag content 75%).

5.3 Strength envelope

Shear strength envelopes for sand slag mixtures are developed for various mix designs. Mixtures having high unit weight (γ_{mix} = 17.5 kN/m^3) and slag content had strength envelope nonlinear (figure 9). Similar strength envelopes for sand reinforced with randomly oriented discontinuous inclusions have been reported by (Gray & Ohashi 1983), (Gray & Al Refeai 1986), (mahr & Gray 1990) and (Benson & Khir 1994). Nonlinear strength envelopes are obtained for mixtures with high slag content (50 % and 70%) and over rang of confining pressure more than 100 kN/m^2 as presented in figure 9. Therefore, it is unlikely that this behavior is strictly the result of boundary effects in the direct shear apparatus.

The principle goal of this study was to demonstrate that slag can be used to increase the strength of sand. Hence, it was not clearly established whether or not the strength envelopes for mixtures having high slag content and at maximum dry density were curvilinear or bilinear figure 9.

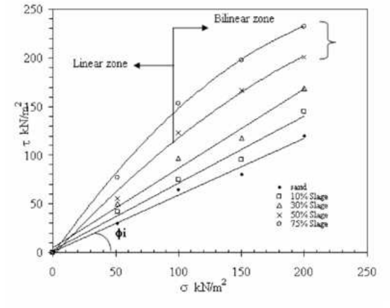

Figure 9: Strength envelopes for sand reinforced with varying slag content.

The slope of the initial portion of the envelope was defined as the initial friction angle ϕi. This angle was affected by both slag content and vertical normal stress. It has been found that, the initial friction angle was increased with the increase of slag content and mixture unit weight as confirmed by figure 10. All reinforced specimens had initial friction angle (ϕi) higher than of pure or unreinforced sand having similar unit weight.

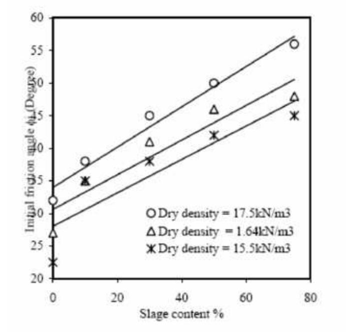

Figure 10. Initial friction angle versus slag content (γ_{Dry} = 17.5 kN/m^3).

It is important to note that the improvement in the mechanical properties is originally attributed to the microstructure of sand/slag particles and the development of the interconnecting supports between them. These supports were significantly developed at both high density mix and high confining stress. It was constructed during the interlocking process. The slag particles which founded between sand grains acted as discrete supports. These supports can prevent the expected failure modes as, sliding, distortion and bending between unreinforced sand as illustrated in figure 11. For these reasons, reinforced sand by slag is most important with regard to embankment construction and helping guide in selection of materials to be used in man made fill as well as its uses in foundation improvement techniques.

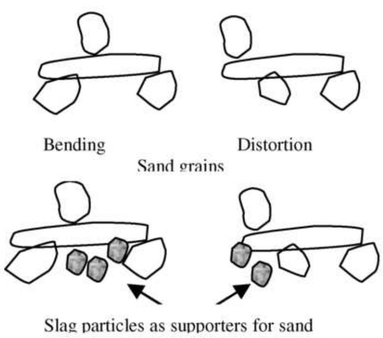

Figure 11: Interconnecting supports and failure mode.

6 CONCLUSIONS

Direct shear tests were run on sand reinforced with steel slag at different normal stress levels, slag content and variable mixture density. The microstructure of tested materials was distinctly studied. Test results showed that slag can increase the shear strength and modify shear stress behavior of sand in significant manner. The following conclusions emerged from the study are:

1) The existence of steel slag as reinforced element has a considerable effect on decreasing and mitigating the vertical and horizontal deformation of sandy soil under different stress levels.
2) The adopted slag can significantly decrease the dilation of sand at highly coffining stress and slag content.
3) Based on microstructure of sand slag mixture, the mechanical characteristics of mix are increased and the interconnecting supports are produced.
4) At high slag content and confining stress, the failure envelopes become bilinear and shear strength is remarkably increased.
5) The initial friction angle of reinforced sand is affected and varied linearly by both slag content and mix density.
6) Reinforced sand by steel slag have economic consideration, it is most important with regard to embankment construction and helping guide in selection of materials to be used in man made fill in addition to its uses in foundation improvement techniques.

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