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Experimental Investigation on the Shear Strength Parameters of Sand-Slag Mixtures

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Abstract**—**Utilizing waste materials in civil engineering applications has a positive influence on the environment by reducing carbon dioxide emissions and issues associated with waste disposal. Granulated blast furnace slag (GBFS) is a by-product of the iron and steel industry, with millions of tons of slag being annually produced worldwide. Slag has been widely used in structural engineering and for stabilizing clay soils; however, studies on the effect of slag on sandy soils are scarce. This article investigates the effect of slag content on shear strength parameters through direct shear tests and unconsolidated undrained triaxial tests on mixtures of Perth sand and slag. For this purpose, sand-slag mixtures, with slag contents of 2%, 4%, and 6% by weight of samples, were tested with direct shear tests under three normal stress values, namely 100 kPa, 150 kPa, and 200 kPa. Unconsolidated undrained triaxial tests were performed under a single confining pressure of 100 kPa and relative density of 80%. The internal friction angles and shear stresses of the mixtures were determined via the direct shear tests, demonstrating that shear stresses increased with increasing normal stress and the internal friction angles and cohesion increased with increasing slag. There were no significant differences in shear stresses parameters when slag content rose from 4% to 6%. The unconsolidated undrained triaxial tests demonstrated that shear strength increased with increasing slag content.

Keywords**—**Direct shear, shear strength, slag, UU test.

I. Introduction

SHEAR strength is one of the most important soil characteristics required for analysing and designing geotechnical applications, such as foundations, slopes, embankments and retaining walls [1]. Shear strength refers to the maximum stress that a soil can withstand before reaching failure conditions [2]. In granular soils, shear strength is a combined effect of friction and interlocking forces between soil grains. Conversely, in fine soils, the shear strength is produced from soil particles cementing together, or in other words, their cohesion. Shear strength characteristics, for instance the internal friction angle and cohesion, have been extensively investigated by the implementation of both in situ and laboratory tests, such as the direct shear box, ring shear, cone penetrometer and triaxial apparatus. Variations in strength and density, low bearing capacity and high permeability are negative properties of sandy soils which can cause problems for construction [3]. Numerous studies have researched methods to reduce the negative properties of sandy soil by mixing it with additives such as cement, lime, clay, and fly ash. There has been recent interest globally in the use of slag in different civil engineering applications, due to the environmental and economic advantages. Using Slag has a positive influence on the environment, as it reduces carbon dioxide emissions and other issues associated with waste disposal; most countries in the world, including Australia, are manufacturing millions of tons of slag annually [4], [5]. The production of one ton of Portland cement generates 0.95 tons of CO_2; however, production of the same amount of slag produces 0.07 tons of CO_2 [6]. Additionally, using slag in construction engineering may reduce the cost of building and conserve resources. Slag is a by-product of the iron and steel industries which can be classified into different types based on the production method used. Blast furnace slag is a by-product of iron made in a blast furnace, which can be divided into three categories (those being air-cooled, granulated, and expanded slag). Slag has been widely utilized in structural engineering, but has more recent application in geotechnical engineering [6], [7]. According to the Australian Slag Association [8], 80% of the 3.4 million tons of slag which was produced in Australia in 2009 was used in the construction of buildings and roads. In geotechnical engineering, slag has been utilized widely for improving the properties of clay soils, but published research on the use of slag (without other additives) for improving sandy soils is limited. Slag reacts to water contact in the same way as Portland cement; however, it takes a long time to complete its chemical reaction, which is why it is sometimes blended with a chemical activator [9]. According to [10], the geotechnical characteristics of GBFS, such as a high internal friction angle, light weight, and high permeability, make it useful for the backfilling of quay-wells, sand mats, and lightweight embankments. Many researchers have found that the shear strength of slag-stabilized sand was increased by using a chemical activator with the slag [6], [11], [12]. The present study was recently started by the authors in collaboration with an investigation into the effects of slag content on the shear strength characteristics of sandy soils. The aim was to examine the possibility of improving the shear strength of sandy soils by using waste materials, such as slag. It is apparent from the literature review that numerous investigations have been conducted on the effects of slag contents on clay soils, while research into the effect of slag on the shear strength of sandy soils is limited. Therefore, this study aimed to explore the properties of clean sand compared to sand mixed with various slag contents (2%, 4%, and 6%, by weight), using direct shear tests and unconsolidated undrained triaxial tests. Additionally, this work is a part of ongoing

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research in Curtin University [13], [14].

II. Materials

The materials used for the present study are divided into normal sand soil, and mixtures of sandy soil with the additives. The sand soil used for this study was obtained from Perth, Western Australia. This sand is classified as poorly graded sand (SP), according to the Unified Soil Classification System (USCS). Typical particle size distribution (PSD) curves for the materials are shown in Fig. 1. Important parameters obtained from the PSD are listed in Table I. The slag used in these experiments was GBFS, made by BGC Cement in Western Australia. It was coloured off-white, with a relative density of 2.85-2.95, bulk density loose of 1-1.1 ton/m^3, and surface area of 400-600 m^2/kg. The chemical properties of the slag are presented in Table II. Scanning electron microscope (SEM) images of the sand and slag are shown in Fig. 2.

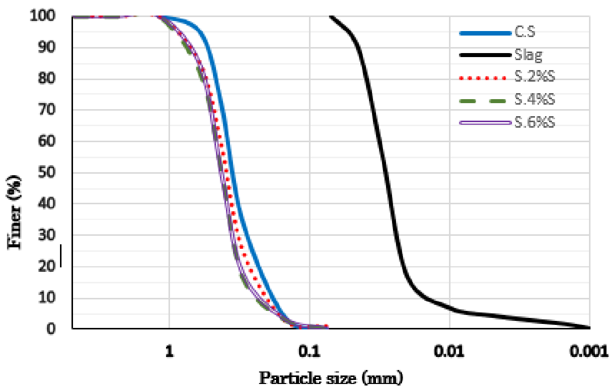


Fig. 1 Particle size distribution for the soil mixtures used in this study

TABLE I
Properties of Mixtures Used in This Study

Materials	(D_{10}) (mm)	D_{30} (mm)	(D_{50}) (mm)	D_{60} (mm)	(C_u)	(C_c)	(Gs)
C.S	0.17	0.26	0.35	0.38	2.235	1.046	2.580
S.2%S	0.206	0.327	0.39	0.455	2.209	1.141	2.613
S.4%S	0.245	0.354	0.422	0.466	1.902	1.098	2.630
S.6%S	0.242	0.355	0.422	0.467	1.930	1.115	2.640

(C_u = Coefficient of uniformity; C_C = Coefficient of curvature; G_s = specific gravity).

TABLE II
Chemical Element Proportions of GBFS, Mean Percent by Weight

Elements	(Al_2O_3)	(CaO)	Silica, amorphous	Sulphur
(%)	5-15	30-50	35-40	<5

III. Testing Program

The testing program included four sample types produced by dry-mixing clean sand with three different contents of slag (2%, 4% and 6%); the sample types are summarized in Table III. A series of compaction tests, small box direct shear tests, and unconsolidated undrained triaxial tests were conducted under different test conditions.

TABLE III
Summary of Sample Types

Materials	Symbol
Clean Sand	C.S
Sand + 2% Slag	S.2%S
Sand + 4% Slag	S.4%S
Sand + 6% Slag	S.6%S

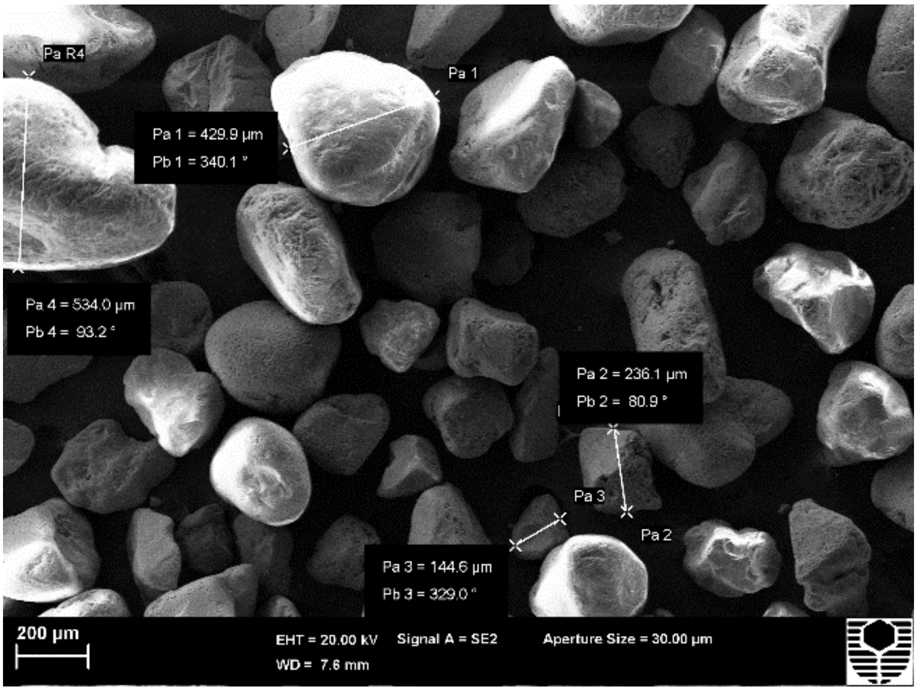
IV. Compaction Test

The results of standard compaction tests are presented in this section. The tests were designed to present the effect of different slag contents on the maximum dry density and optimum moisture content of the sandy soil. Four compaction tests were conducted on the clean sand and sand mixed with 2%, 4%, and 6% slag. All tests were implemented according to Australian Standard AS 1289.5.1.1. Fig. 3 displays the results, showing how the maximum dry density increased and optimum moisture content decreased with increasing slag content.

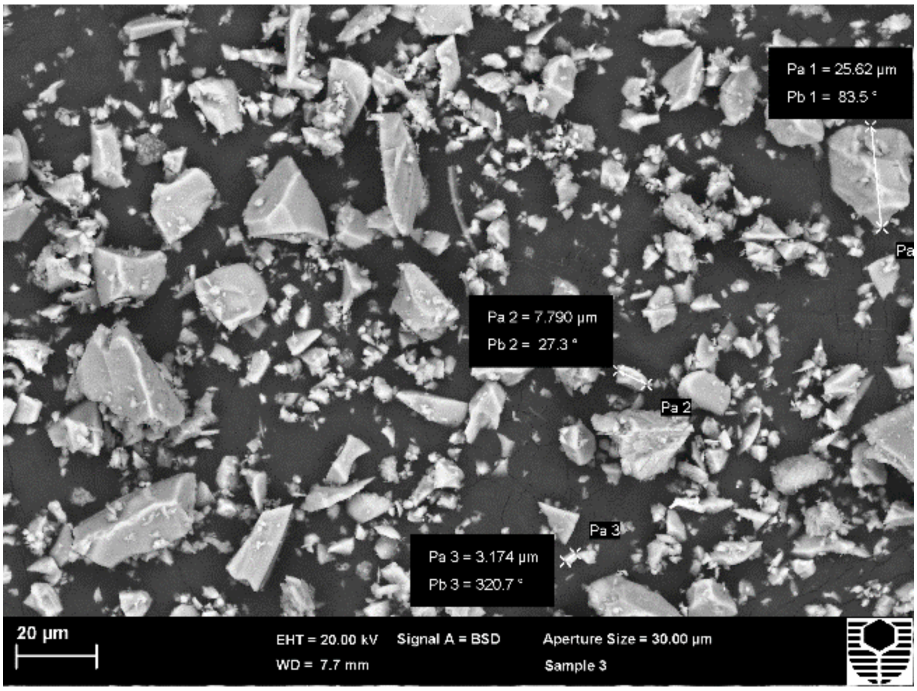
V. Direct Shear Test

A series of direct shear tests were conducted to determine the effect of slag content on shear strength parameters, such as the internal friction angle and cohesion of the mixtures. The clean Perth sand was mixed with three different slag contents (2%, 4%, and 6%) based on the dry weight of the sand. Samples were tested with three normal stresses of 100 kPa, 150 kPa, and 200 kPa. A direct shear box with dimensions 60 mm x 60 mm x 30 mm was used in the experiment. Dried sandy soil and slag were mixed carefully until a homogenous blend was reached, then water was added to the soil slag mixtures. All samples were prepared at their optimum moisture content and maximum dry density. The soil was placed in the mould in three identical layers and compacted gently using a small tamper until it reached the determined dry unit weight. Direct shear tests were conducted as per Australian Standard AS 1289.6.2.2 (1998). A shear strain rate of 0.3 mm/min was used and all samples were tested at zero days curing time. Fig. 4 shows the comparison of shear stresses for sand – slag mixtures under three different normal stresses (100 kPa, 150 kPa, and 200 kPa). As can be seen from this figure, the shear stress for all mixtures increased with increasing normal stress. Figs. 5 (a)-(c) show typical stress-strain curves for clean sand and the mixtures when subjected to varying normal stress. Also, it illustrates peak shear stress increased with increasing slag content up to 4%, but there was no significant difference in results when slag content increased from 4% to 6%. Figs. 6 (a)–(d) show the failure envelope of the clean sand and sand-slag mixtures; the failure envelope was defined based on Mohr-Coulomb failure criterion. It is evident from the results that shear stress increased with increasing slag content. The angle of internal friction (ϕ) increased and cohesion (c) decreased with increasing slag content up to 2%. However, the internal friction angle decreased and cohesion increased with increasing slag content up to 6%, but there was slight effect of the slag content on the shear strength characteristics, when slag increased from 4% to

6% when the direct shear tests were conducted. The effect of varying of slag content on angle of internal friction and cohesion of mixtures is shown in Figs. 7 and 8. The positive impact of slag content on the shear strength of sandy soil may be connected to the role of slag in filling the voids between sand particles; this increases the connection between sand particles, consequently increasing the internal friction angle and cohesion.



(a)



(b)

Fig. 2 Scanning electron microscope images of test materials: (a) clean sand; (b) GBFS slag

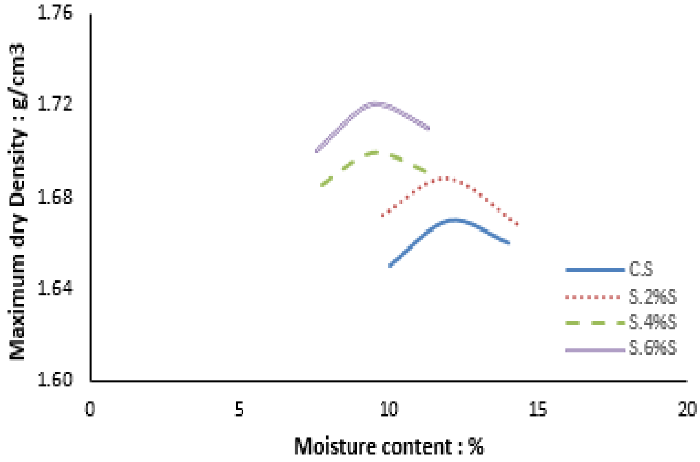


Fig. 3 Effect of slag content on the compaction curve

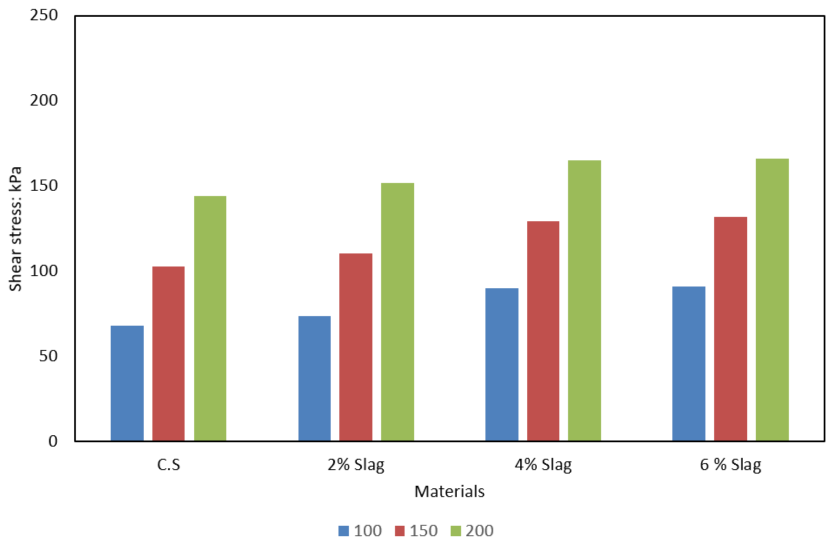
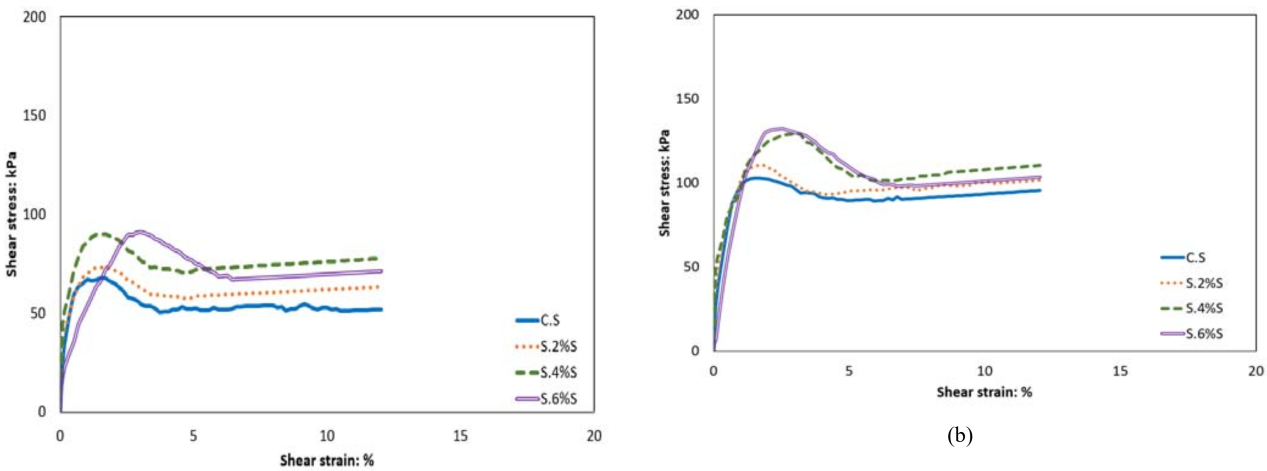
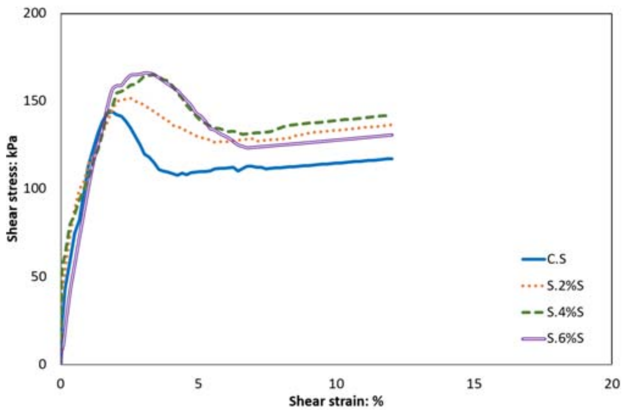


Fig. 4 Shear stresses for sand – slag mixtures under different normal stresses



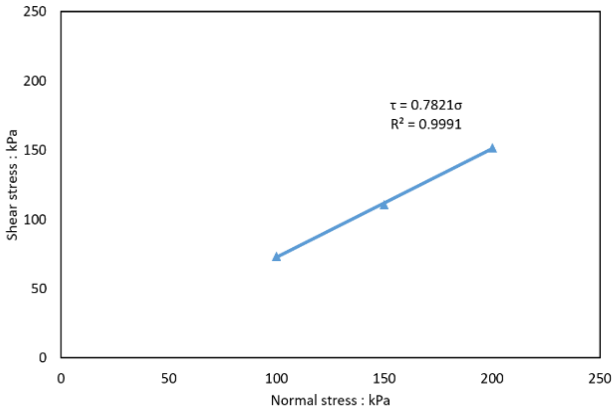
(a)

(b)

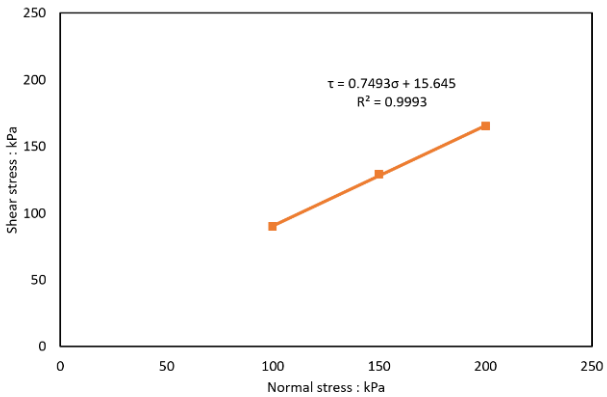


(c)

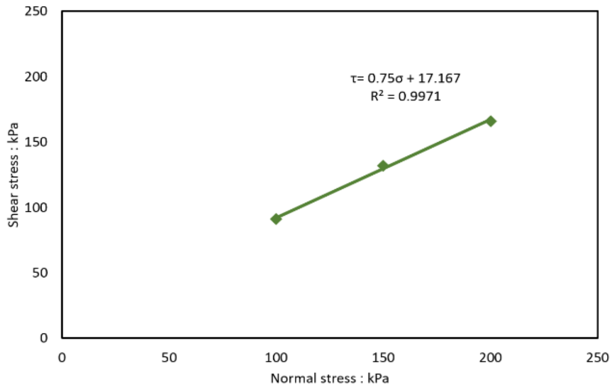
Fig. 5 The effect of slag on the shear strength of sandy soil under different conditions: (a) normal stress 100 kPa; (b) normal stress 150 kPa; (c) normal stress 200 kPa



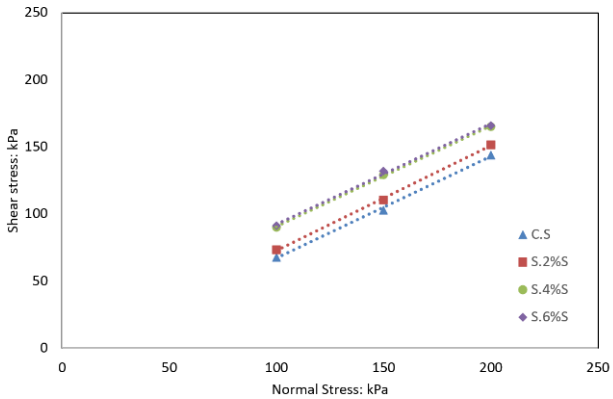
(a)



(b)



(c)



(d)

Fig. 6 Failure envelope for mixtures: (a) S.2%S; (b) S.4%S; (c) S.6%S; and (d) comparison between all mixtures

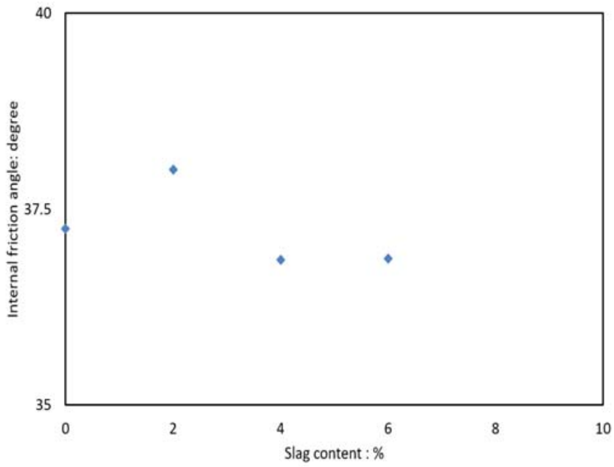


Fig. 7 Internal friction angle vs. slag content

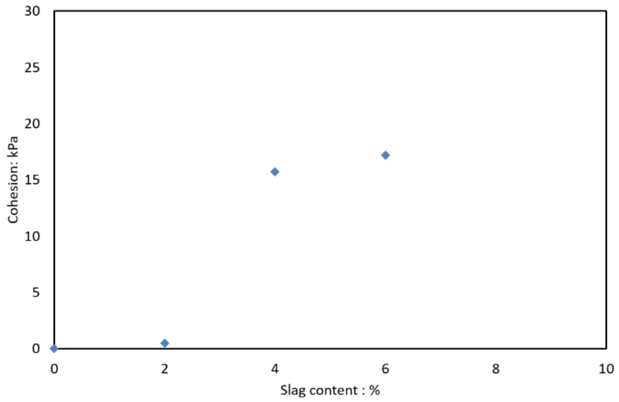


Fig. 8 Cohesion vs. slag content

VI. Unconsolidated Undrained (UU) Triaxial Tests

Fig. 9 illustrates the stress-strain curves from UU triaxial tests on sand-slag specimens at the confining pressure of 100 kPa. UU triaxial tests were conducted on cylindrical specimens of 50 mm diameter and 100 mm height (H/D = 2). All samples were prepared at their optimum moisture content and 80% relative density by using the compaction method (as adopted in many previous studies). Shearing was started after 10 minutes of applying confining pressure to allow samples to stabilize and equilibrate before applying the axial load. All UU triaxial tests in the current study were conducted under strain-controlled circumstances at a constant strain rate of approximately 1 mm/minute. The effect of slag content on the stress-strain behaviour of the slag-sand samples are shown in Fig. 9. The undrained shear strength of samples increased significantly with increasing slag content up to 4%, but there was slight increasing in deviator stress when slag content rose from 4% to 6%.

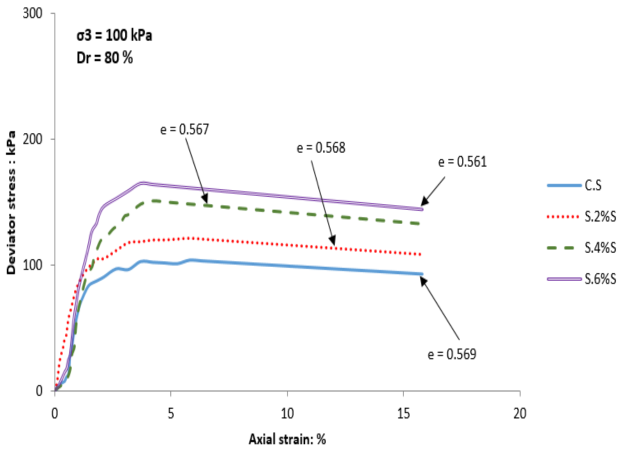


Fig. 9 Stress-strain curves for tests on sand-slag specimens

VII. Summary and Conclusion

The present study aimed to investigate and understand the effect of slag content on the physical properties and shear strength of low-cohesion soil. A series of compaction, direct shear and unconsolidated undrained triaxial tests were performed under different test conditions. Three different percentages of slag were added to the sand (2%, 4%, and 6%) and the results revealed real potential for the use of slag in soil mixtures for construction. The direct shear tests were conducted under three normal stress levels (100 kPa, 150 kPa, and 200 kPa) and the samples prepared at the maximum dry density and optimal moisture content. Unconsolidated undrained triaxial samples were tested under one confining pressure of 100 kPa and samples prepared at a relative density of 80%. Slag appeared to increase the maximum dry density and reduce the optimum moisture content in all soil mixtures tested. The greatest improvement in shear strength parameters (tested with direct shear and unconsolidated, undrained, triaxial tests) was found when sand was mixed with 4% slag.

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