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Effect of slag and bentonite on shear strength parameters of sandy soil

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Abstract. A series of direct shear tests were implemented on three different types of specimens (i.e., clean Perth sand, sand containing 10, 20 and 30% bentonite, sand containing 1, 3 and 5% slag, and sand containing 10, 20 and 30% bentonite with increasing percentages of added slag (1%, 3% and 5%). This paper focuses on the shear stress characteristics of clean sand and sand mixtures. The samples were tested under different three normal stresses (100, 150 and 200 kPa) and three curing periods of no curing time, 7 and 14 days. It was observed that the shear stresses of clean sand and mixtures were increased with increasing normal stresses. In addition, the use of slag has improved the shear strength of the sand-slag mixtures; the shear stresses rose from 128.642 kPa in the clean sand at normal stress of 200 kPa to 146.89 kPa, 154 kPa and 161.14 kPa when sand was mixed with 1%, 3% and 5% slag respectively and tested at the same normal stress. Internal friction angle increased from 32.74° in the clean sand to 34.87°, 37.12° and 39.4° when sand was mixed with 1%, 3% and 5% slag respectively and tested at 100, 150, and 200 kPa normal stresses. The cohesion of sand-bentonite mixtures increased from 3.34 kPa in 10% bentonite to 22.9 kPa, 70.6 kPa when sand was mixed with 20% and 30% bentonite respectively. All the mixtures of clean sand, different bentonite and slag contents showed different behaviour; some mixtures exhibited shear stress more than clean sand whereas others showed less than clean sand. The internal friction angle increased, and cohesion decreased with increasing curing time.

Keywords: sand; bentonite; slag; shear strength; shear strength parameters; direct shear test

1. Introduction

Shear strength of soil is one of the essential factors to be considered in analysing and designing many of geotechnical applications such as shallow foundations, roads, embankments, earth dams and slopes (Das and Sobhan 2014). Cohesion and internal friction angle are the major parameters used to assess the shear strength of soil (Budhu 2010). There are various apparatuses which can be used to determine the shear strength parameters such as the direct shear box, ring shear, laboratory vane, cone penetrometer, triaxial apparatus and plain strain device. Sandy soil covers broad areas around the globe, and it has many properties which may create problems during construction such as variation in density and strength in various positions, high permeability that increase the possibility of failure, low bearing capacity, and high ground water level (Shooshpasha and Shirvani 2015). Numerous studies have investigated the effects of mixing sandy soil with additives such as cement, lime, fly ash, bitumen, and clay or mixtures of these additives on shear strength parameters.

Recently, sand-active clay/bentonite combination mixture has been used in diverse engineering applications due to the availability and plenty of treated bentonite (Elkady *et al.* 2014). There are many examples of using sand-bentonite mixtures in projects such as barrier in landfill to prevent adverse impacts of waste materials on underground soil and water (Akgün *et al.* 2006, Sivapullaiah *et al.* 2000), slurry cut-off walls to prevent the landfill materials from water (Evans 1993), and sand-bentonite admixtures have been considered as attractive landfill materials for radioactive nuclear wastes (Dixon *et al.* 1985). Although there are differences in the chemical activity and particle size distribution between sand and bentonite but their mechanical stability and low permeability are the main benefits of sand-bentonite mixtures (Ghazi 2015). The properties of sand-bentonite mixtures have been evaluated in many previous studies. Mishra *et al.* (2010) argued that the response of soil-bentonite blends is dependent on mineralogical, chemical and physical characteristics of bentonite. Kenny *et al.* (1992) and Akgün *et al.* (2006) have pointed out the maximum dry density increased with increasing bentonite content up to 20%. However, a number of studies showed that significant differences do exist, albeit findings are somewhat contradictory. For instance, Komine and Ogata (1999) found that using bentonite up to 30% increases the maximum dry density (MDD) and decreases the optimum moisture content (OMC). On the other hand, Chalermyanont and Arrykul (2005) have argued that MDD decreased and OMC increased with increasing bentonite content up to 9%. Howell *et al.* (1997) showed that there was no significant effect of curing time on compaction of sand-bentonite mixtures. Howell *et al.* also argued that mixing dry sand with bentonite before adding water showed greater maximum dry density than mixing wet sand with bentonite. Watabe *et al.* (2011) reported that the compressibility of sand-bentonite mixture decreased with

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increasing sand fraction. Fan *et al.* (2014) noted that the compressibility of sand-bentonite mixture was very sensitive to bentonite and moisture content. Gleason *et al.* (1997) pointed out that the permeability of sand-calcium based bentonite mixture was higher than sand-sodium based bentonite mixture. Additionally, many previous studies found that the permeability of sand-bentonite mixture decreased with increasing bentonite content (Borgesson *et al.* 2002, Fan *et al.* 2014). The effect of bentonite content on the stress-strain response of sand-bentonite mixtures has been evaluated in the past by many researchers. For example, Cho *et al.* (2002) argued that the unconfined compressive strength and Young’s modulus increased with increasing bentonite content. Chalermyanont and Arrykul (2005) found that the internal friction angle and cohesion of sand-bentonite mixture increased as the bentonite content increased. Gueddouda *et al.* (2008) performed an unconsolidated and undrained direct shear test on saturated and unsaturated sand-bentonite mixtures and they noticed that the cohesion in the unsaturated case was greater than the saturated case. Gueddouda *et al.* noticed that the good shear strength was obtained when sand was mixed with 12% and 15% of bentonite. Elkady *et al.* (2015) observed that the maximum shear strength of sand-clay mixtures was with 30% clay. Chen and Meehan (2011) conducted a number of unconsolidated-undrained triaxial tests on reconstituted sand-bentonite mixtures, and they found that the undrained strength of mixtures decreased when the bentonite content increased, while the undrained strength decreased with decreasing confining pressure. Ghazi (2015) pointed out that the shear strength of sand-bentonite mixtures and internal friction angles decreased as the bentonite content increased. However, cohesion, unconfined compressive strength and Young’s modulus increased with increasing bentonite content. In recent years, there has been an increasing interest in using waste materials in different geotechnical applications. Rising amount of waste materials has encouraged researchers to find alternative ways to use them in various applications. For example, slag is one of the waste materials that have been extensively utilised in different civil engineering applications. The main reasons for using slag are environmental and economic considerations because it could be cheaper than other cementing agents due to the fact it is a by-product material. Moreover, the amount of carbon dioxide generated from producing slag is very low when compared with producing cement or lime (Veith 2000). Slag has been widely used in the stabilisation of clay soils. However, the research on using the slag in stabilising sandy soils is still very limited. Matsuda *et al.* (2008) reported that the geotechnical characteristics of slag such as light weight and high internal friction angle make it useful for light weight embankments and quay-wells. Furthermore, other studies by Park *et al.* (2011), Rabbani *et al.* (2012) and Yi *et al.* (2013) have pointed out using chemical activators such as sodium chloride, or calcium chloride may improve the shear strength of sand-slag mixtures. Although there are a significant number of experimental works which have been conducted in the literature, the studies on the effect of waste materials such as slag on shear strength parameters of sandy soils are still limited. Also, in the most cases which have been reported in the literature, the tests were performed on mixtures of sand soil with one type of additives. Therefore, this study aimed to experimentally investigate the individual and combined effects of two types of additives on shear strength parameters of sandy soil. For this purpose, the results of direct shear tests conducted on samples of Perth sand containing 10%, 20%, and 30% of bentonite, different slag contents (1%, 3% and 5%) by weight, and sand mixed with both of bentonite and slag are presented. Also, this study is part of ongoing research at Curtin University (Sabbar *et al.* 2016, Sabbar *et al.* 2017a, b).

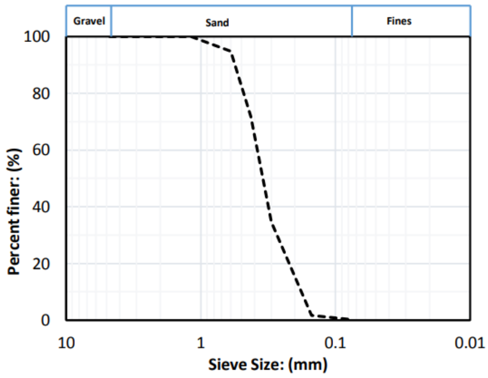


Fig. 1 Grain size distribution curve of Perth sand

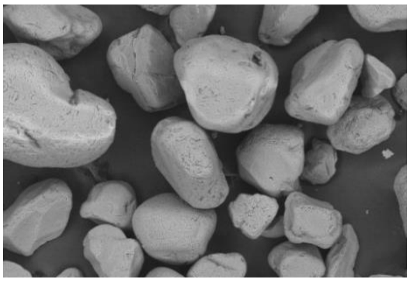
Table 1 Properties of Perth sand

Effective grain size (D_{10})	D_{30}*	Medium grain size (D_{50})	D_{60}*	Coefficient of uniformity (C_u)	Coefficient of curvature (C_c)	Specific gravity of solids (Gs)
0.17 mm	0.26 mm	0.35 mm	0.38 mm	2.235	1.0464	2.61

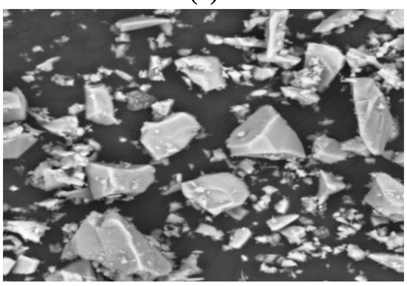
*D_{30} and D_{60} are the diameters equal to percent finer 30% and 60% respectively

Table 2 Chemical elements proportions of bentonite, mean percent by weight (Unimin Australia limited 2009)

Elements	(SiO_2)	(Al_2O_3)	(TiO_2)	(Fe_2O_3)	(CaO)	(Na_2O)	(MgO)	(K_2O)	Loss on ignition
(%)	63.6	14.6	0.4	2.8	0.3	1.3	2	0.5	14.5

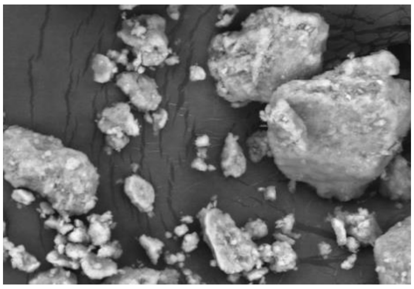


(a)



(b)

Fig. 2 Scanning electron microscope (SEM) images of test materials, (a) sand, (b) slag and (c) bentonite



(c)

Fig. 2 Continued

Table 3 Physical characteristics of slag (BGC cement 2013)

Appearance	Bulk density (loose)	Relative density	Surface area	Specific gravity
Coarse off-white granular solid	1-1.1 tone / m^3	2.85-2.95	400-600 m^2/kg	2.8 – 3.1

Table 4 Chemical elements proportions of GBFS, mean percent by weight (BGC cement 2013)

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

2. Materials

The sandy soil used in this study was obtained from Perth city located in Western Australia. The sand used for experiments was clean sand, and the grain size distribution of this soil is shown in Fig. 1. The sand used in present work was clean sand (99.98% sand and 0.2% silt). The sand was classified as poorly graded sand (SP) according to Unified Soil Classification System (USCS), and its properties are shown in Table 1. Das and Sobhan (2014) argued that the poorly graded sand has approximately same particles sizes. The bentonite used for this study is sodium-based bentonite containing a significant percentage of the active mineral species montmorillonite, made by Unimin Australia Limited, in Queensland. The chemical properties of bentonite are shown in Table 2. It is apparent from this table the largest chemical compositions are SiO_2 and Al_2O_3 with an average content of 63.3% and 14.6% by weight. Slag can be defined as the by-product of the iron and steel-producing process (Higgins 2005). Based on techniques used to manufacture iron, slag can be divided into many types. Slag is named blast furnace slag when a blast furnace is used to produce iron. Slag is a new interest in geotechnical engineering. However, it is widely used as an additive in structural engineering (Allan & Kukacka 1995; Yi *et al.* 2013). The slag used in present study is granulated blast furnace slag (GBFS), made by BGC Cement in Western Australia. The physical and chemical properties of this slag are presented in Tables 3 and 4. From data listed in Table 4, we can see that the main chemical compounds of GBFS slag which was used in this study are Al_2O_3, CaO, amorphous Silica and Sulphur. These phases are similar to main chemical compounds of Portland cement. Slag has the ability to react with water like Portland cement but with slower reaction rate than Portland cement. Scanning electron microscope (SEM) images of sand, bentonite, and slag are shown in Fig. 2. The SEM pictures show that a clear contrast in size and shape of particles between host sand and additives (i.e., bentonite and slag) existed. Perth sand has bigger particles size than bentonite and slag. Almost all sand particles have the same size with rounded and subrounded shapes. Slag particles have an angular shape, with various sizes. Bentonite particles have a flaky shape with a smooth surface.

3. Specimens preparation

For direct shear tests, cubic (60 mm×60 mm×25 mm) specimens were used. The samples were prepared by dry mixing of bentonite and slag with oven dried sand. The mixtures were blended carefully until a homogenous mixture was reached, then water was added to the soil additives blend. The amount of bentonite and slag for each mixture was computed depending on the weight of dry sandy soil. All samples were prepared at their optimum water content, and maximum dry density, matching to the values achieved in standard Procter compaction tests performed on both treated and untreated sandy soil. The results of standard Procter compaction tests are not presented here; they will be reported in forthcoming publications. The soil was placed in the mold in three identical layers and compacted gently by using small tamper until the determined dry unit weight was reached. The specimen was then saturated by filling the shear box with water before applying the normal stress. For investigating the effect of curing time on shear strength parameters, one mixture was selected and it was placed in plastic bags and stored at a controlled room temperature until the desired time.

4. Laboratory testing program and results

A total of 54 direct shear tests were conducted according to the procedure of Head and Epps (2011) in order to

Table 5 Summary of types of samples

Symbol	Material
C.S	Clean sand
S.1%S	Sand + 1% slag
S.3%S	Sand + 3% slag
S.5%S	Sand + 5% slag
S.10%B	Sand+10% bentonite
S.20%B	Sand+20% bentonite
S.30%B	Sand+30% bentonite
Mix 1	Sand + 1% slag + 10 % bentonite
Mix 2	Sand + 1% slag + 20 % bentonite
Mix 3	Sand + 1% slag + 30 % bentonite
Mix 4	Sand + 3% slag + 10 % bentonite
Mix 5	Sand + 3% slag + 20 % bentonite
Mix 6	Sand + 3% slag + 30 % bentonite
Mix 7	Sand + 5% slag + 10 % bentonite
Mix 8	Sand + 5% slag + 20 % bentonite
Mix 9	Sand + 5% slag + 30 % bentonite

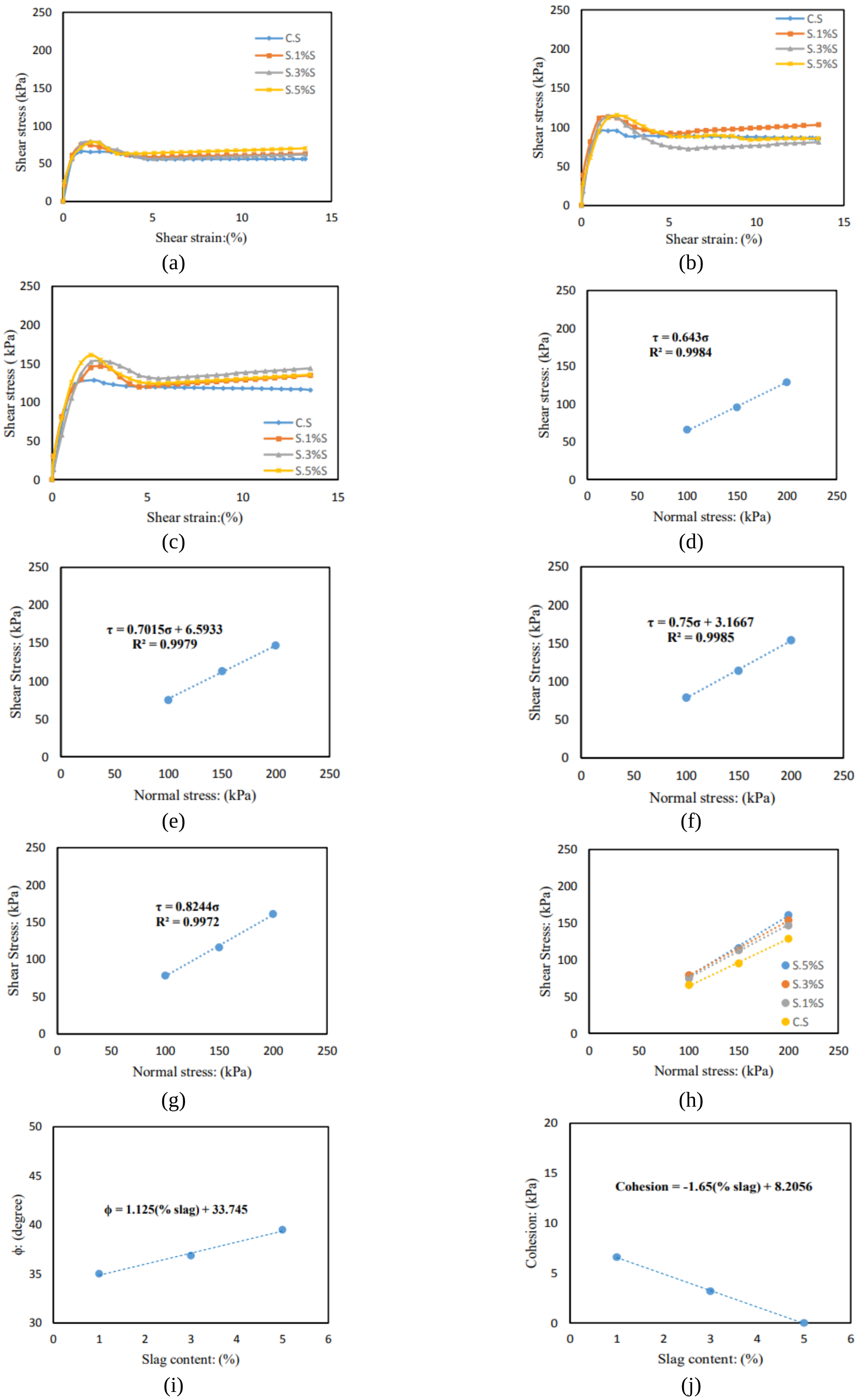


Fig. 3 Effect of slag on shear strength of sandy soil for 0 curing time in direct shear test: (a) normal stress 100 kPa,(b) normal stress 150 kPa,(c) normal stress 200 kPa, (d) C.S, (e) S.1%S, (f) S.3%S, (g) S.5%S, (h) compression between all mixtures, (i) internal friction angle vs slag content and (j) cohesion vs slag content

calculate the cohesion and internal friction angle of mixtures, starting with pure sand samples, moving forward to the sand mixed with different fines contents such as (10%, 20%, and 30%) bentonite and (1%, 3%, and 5%) slag, finally to the sand-bentonite mixtures with added slag. All tests were conducted using a conventional direct shear apparatus according to AS 1289.6.2.2-1998 to investigate the effect of bentonite and slag on shear strength parameters of sandy soil. The normal stresses of 100, 150, and 200 kPa were selected for all samples, which have been used in many studies (Amsiejus *et al.* 2013, Bareither *et al.* 2008, Liu *et al.* 2014, Osano 2009). The shearing rate was 0.3 mm/min and consolidation time of 24 hours was used for all samples. All samples were tested with no curing time and selected samples were tested with curing time of 7 and 14 days. Table 5 has listed the types of samples that were used in this study.

4.1 Effect of slag on shear strength of clean sand

A series of direct shear tests were conducted to investigate the behaviour of sand-slag mixtures and to determine the effect of slag content on the internal friction angle and cohesion of the treated sandy soil. The clean Perth sand was mixed with three different slag contents (1, 3, and 5%) based on the dry weight of sand. Samples were tested with three normal stresses 100, 150, and 200 kPa. Figs. 3(a)-3(c) compare the shear stress-strain relations of the clean sand and three sand-slag mixtures. Fig. 3 shows the shear strength of C.S was less than that of sand-slag mixtures and the shear strength of mixtures increased with increasing slag content. The peak shear stress of C.S rose from 128.6 kPa to 146.8 kPa, 154 kPa, and 161.1 kPa when clean sand was mixed with 1, 3, and 5% slag respectively at normal stress of 200 kPa. Figs. 3(a)-3(c) show there is a slight difference in the peak shear strength of three mixtures (S.1%S, S.3%S and S.5%S) at normal stress of 100 and 150 kPa. However, the peak shear strength for (S.5%S) was more than (S.1%S), and (S.3%S) mixtures at normal stress of 200 kPa. Figs. 3(d)-3(h) show the failure envelope of clean sand and sand-slag mixtures; the failure envelope defined based on the Mohr-Coulomb failure criterion. It is evident the shear stresses increased with increasing slag content. Also, Fig. 3(i) shows that the internal friction angles rose from 32.7° in C.S to 34.87°, 37.12°, and 39.37° when clean sand was mixed with 1, 3 and 5% slag respectively. Fig. 3(j) shows there was a clear trend of decreasing cohesion of mixtures with increasing slag content. The above finding is consistent with the study by Budihardjo *et al.* (2015). They found that the shear strength of sand-slag mixtures increased with increasing slag content. The positive impact of slag content on the internal friction angle and negative impact on the cohesion of sandy soil could be related to the mechanical rather than chemical effects of slag. The effect of slag content on the internal friction angle could be linked to the role of slag in filling the voids between sand particles and increased the friction between them. The angular shape of slag grains shown in Fig. 2(b) may help to increase the friction between slag and sand particles. As mentioned earlier the previous studies on the effect of slag on the shear strength parameters of sandy soils are still limited. Many of previous studies have reported that the slag reduced the expansion of expansive soils and enhanced the shear strength of soft clay soils

4.2 Effect of bentonite on shear strength of clean sand

The results of direct shear tests of C.S, S.10%B, S.20%B and S.30%B are shown in Fig. 4. These tests were performed with three different normal pressures of 100, 150, and 200 kPa. Figs. 4 (a)-4(c) show there was no peak shear stresses in S.10%B, S.20%B and S.30%B and there was a slight effect of bentonite content of all mixtures at normal stress of 100 kPa. However, there was a considerable effect of bentonite shown in S.10%B and S.20%B at 200 kPa normal stress. Also, at normal stress of 100 kPa, S.30%B showed the highest shear stress 84.28 kPa. Whereas S.30%B exhibited the lowest value of shear stress 98.91 kPa at normal stress 200 kPa and there was no significant difference between S.10%B, and S.20%B 101.83 kPa, and 102.01 kPa respectively. The mixture S.30%B showed the lowest value of shear stress 98.91 kPa at normal stress 200 kPa. Fig. 4(g) presents the Mohr-Coulomb failure envelope for all mixtures; it showed that the shear strength of clean sand was increased with bentonite content 10% while the shear stress reduced with bentonite content 20% and 30% respectively. The research of Gueddouda *et al.* (2008) also found the maximum shear strength of the sand-bentonite mixture can be obtained when the bentonite content was in the range of 12-15%. Figs. 4(h) and 4(i) show the cohesion of mixtures increased from 0 kPa in C.S to 3.34 kPa, 22.9 kPa, and 70.6 kPa with bentonite content of 10, 20, and 30% respectively while the internal friction angle reduced from 32.74° in C.S to 7.37° in S.30%B. Research findings by Ghazi (2015) and Chalermyanont and Arrykul (2005) also indicate the internal friction angle decreased, and cohesion increased with increasing bentonite content. The reason for reducing the shear stress of mixtures with increasing bentonite content could be related to the behaviour of mixtures that is dominated by bentonite due to using the high percentage of bentonite 20 and 30%. Mixing sand soil with a high proportion of bentonite may produce an unstable soil fabric because bentonite swells when mixed with water and this leads to reducing the contact between sand particles. Also, as can be seen from Fig. 2(c), the bentonite particles have a smooth surface which could minimise the friction between sand particles. Consequently, the cohesion of mixtures increased and internal friction angle decreased.

4.3 Behaviour of sand-slag-bentonite mixtures

Fig. 5 compares the behaviour of C.S and sand-slag-bentonite mixtures, called Mix 1 (sand, 1% slag, 10% bentonite), Mix 2 (sand, 1% slag, 20% bentonite), Mix 3 (sand, 1% slag, 30% bentonite), Mix 4 (sand, 3% slag, 10% bentonite), Mix 5 (sand, 3% slag, 20% bentonite), Mix 6 (sand, 3% slag, 30% bentonite), Mix 7 (sand, 5% slag, 10% bentonite), Mix 8 (sand, 5% slag, 20% bentonite), and Mix 9 (sand, 5% slag, 30% bentonite). The aim of mixing sandy soil with two different types of the additives was to evaluate

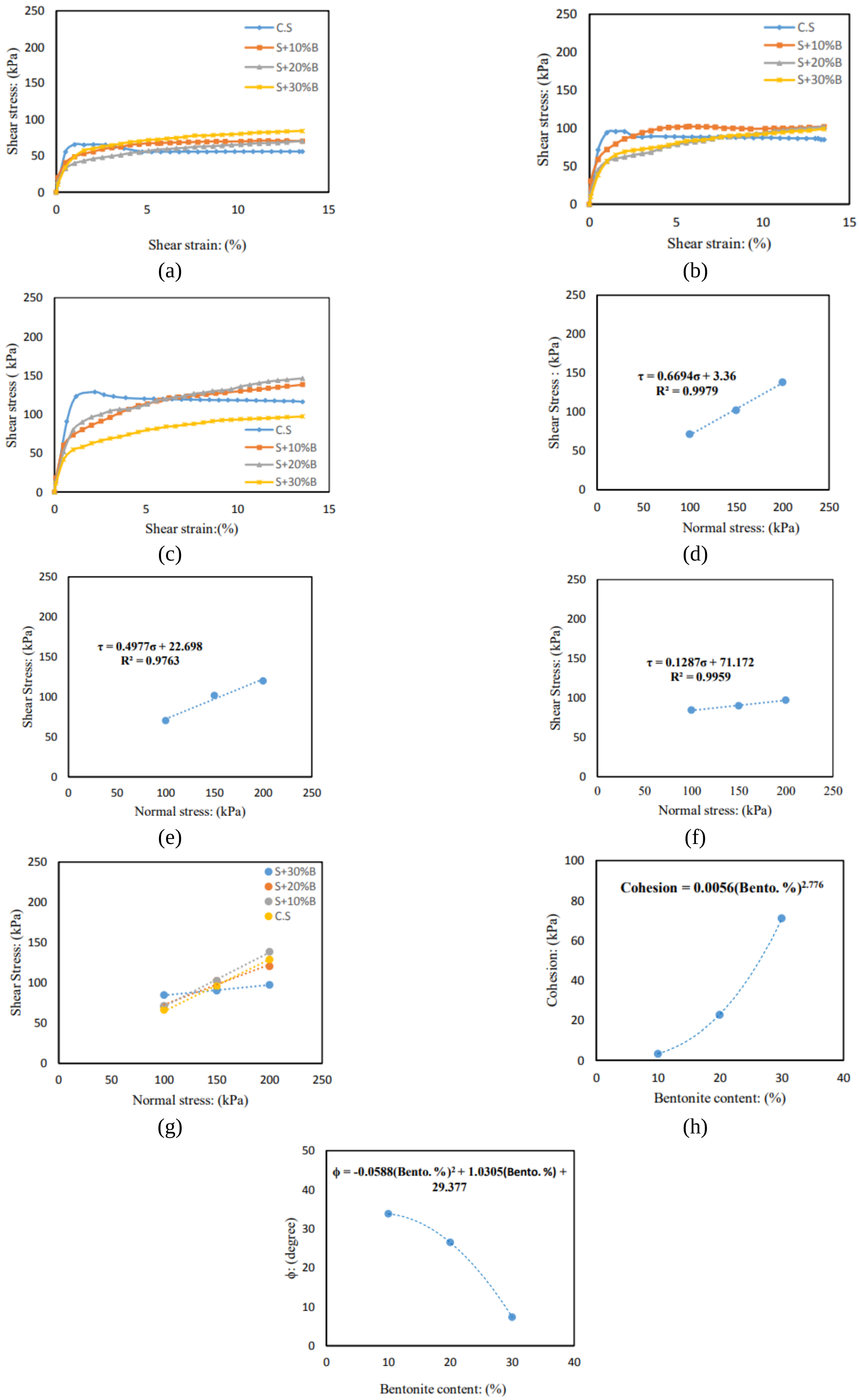


Fig. 4 Effect of bentonite on shear strength of sandy soil for 0 curing time in direct shear test: (a) normal stress 100 kPa, (b) normal stress 150 kPa, (c) normal stress 200 kPa, (d) S.10%B, (e) S.20%B, (f) S.30%B, (g) compression between all mixtures, (h) internal friction angle vs bentonite content and (i) cohesion vs bentonite content

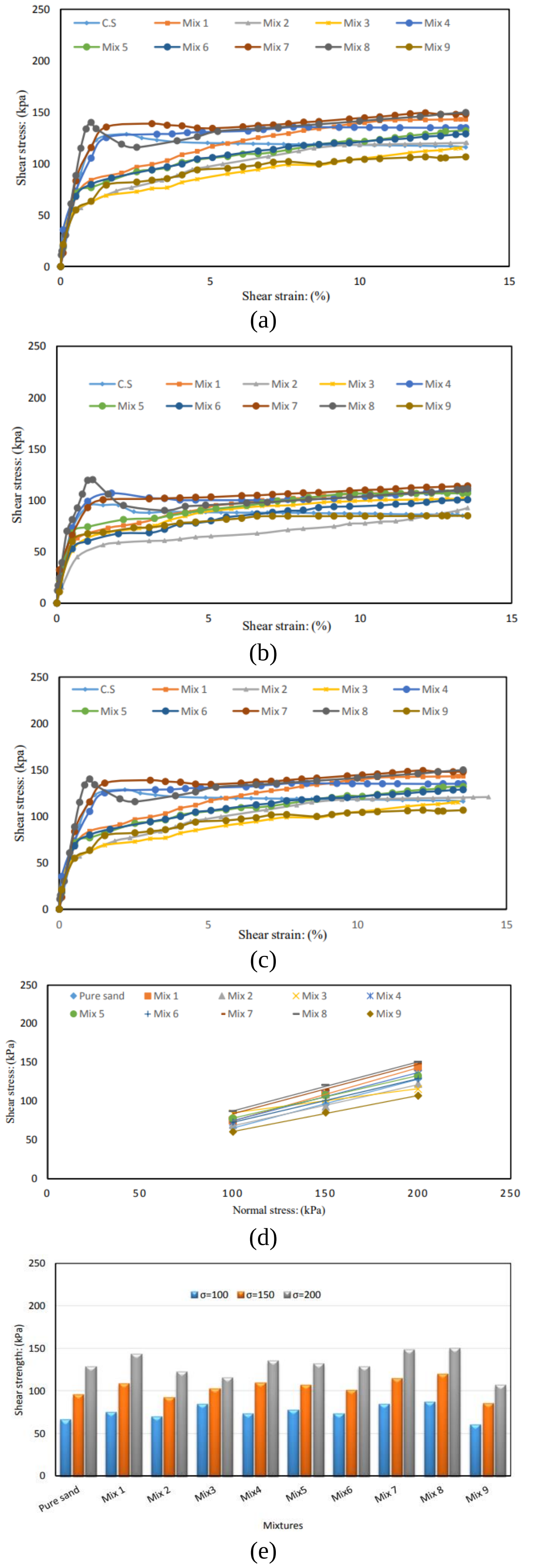


Fig. 5 Behaviour of sand-slag-bentonite mixtures no curing time in direct shear test: (a) normal stress 100 kPa, (b) normal stress 150 kPa, (c) normal stress 200 kPa, (d) failure envelope for all mixtures and (e) comparison of shear stresses of all mixtures

Table 6 Internal friction angles and cohesions of sand-bentonite- slag mixtures

Materials	C.S	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9
Cohesion (kPa)	0	5.7502	15.173	53.752	12.667	22.87	16.378	19.998	23.965	14.353
Φ (degree)	32.741	34.438	27.896	17.26	31.8	28.8	29.331	32.48	32.305	24.85

the effect of a combination of two different additives on the shear strength parameters. A series of direct shear tests at three different normal stresses of 100, 150, and 200 kPa were conducted on specimens prepared from the above-mentioned mixtures. Figs. 5(a)-5(e) indicate that the samples of nine mixtures exhibited variant behaviours, some of them exhibited shear strength higher than C.S such as Mix 4, Mix 7, and Mix 8; however other mixtures showed shear stress less than C.S at three normal stresses. Also, Mix 7 and Mix 8 showed peak shear stress followed by a reduction in shear stress until they reached the ultimate state, while Mix 1- Mix 6 and Mix 9 showed gradual increment in shear stress without peak values. Fig. 5(d) shows that Mix 8 exhibited the highest value of shear stress, whereas the Mix 9 showed the lowest value. Table 6 presents the internal friction angles and cohesions of all mixtures with values of clean sand; Mix 3 showed highest values of cohesion 53.7 kPa and lowest value of internal friction angle 17.2°. However, Mix 1 showed lowest cohesion 5.75 kPa and highest internal friction angle 34.4°. The behaviours of Mix 1 and Mix 3 illustrate the significant effect of bentonite content on the shear strength parameters of sandy soil. Both Mix 1 and Mix 3 had lowest slag content but different bentonite contents. Mix 1 had the lowest slag and bentonite contents which indicated that the behaviour of this sample is not dominated by bentonite. Therefore, they showed the lowest cohesion, and highest internal friction angles as a result of contribution by both slag and bentonite in improving soil fabric by increasing friction between sand particles. In contrast, the behaviour of Mix 3 which had the lowest slag but highest bentonite content was completely dominated by bentonite, so it showed the highest cohesion and lowest internal friction angle. Another reason for the unstable behaviour of sand-bentonite-slag mixtures may be attributed to the different chemical compositions of bentonite and slag shown in Tables 2 and 4. Also, using high percentages of bentonite may affect the stability of sand fabric. These findings are consistent with findings of past studies by Ghazi (2015) and Chalermyanont and Arrykul (2005), which considered the fine has a significant effect on the shear stress parameters and the shear stress decreased with increasing the bentonite content.

4.4 Effect of curing time

For investigating the effect of curing time on shear strength parameters, Mix 9 was selected and tested at 0, 7 and 14 days. Fig. 6(a) shows the shear stress increased from 85 kPa at 0 days to 97.9 kPa and 95 kPa at 7 and 14 days respectively at normal stress of 150 kPa. Also, the shear stresses rose from 106.6 kPa at 0 days to 123.9 kPa and 128.4 kPa at 7 and 14 days with normal stress of 200 kPa.

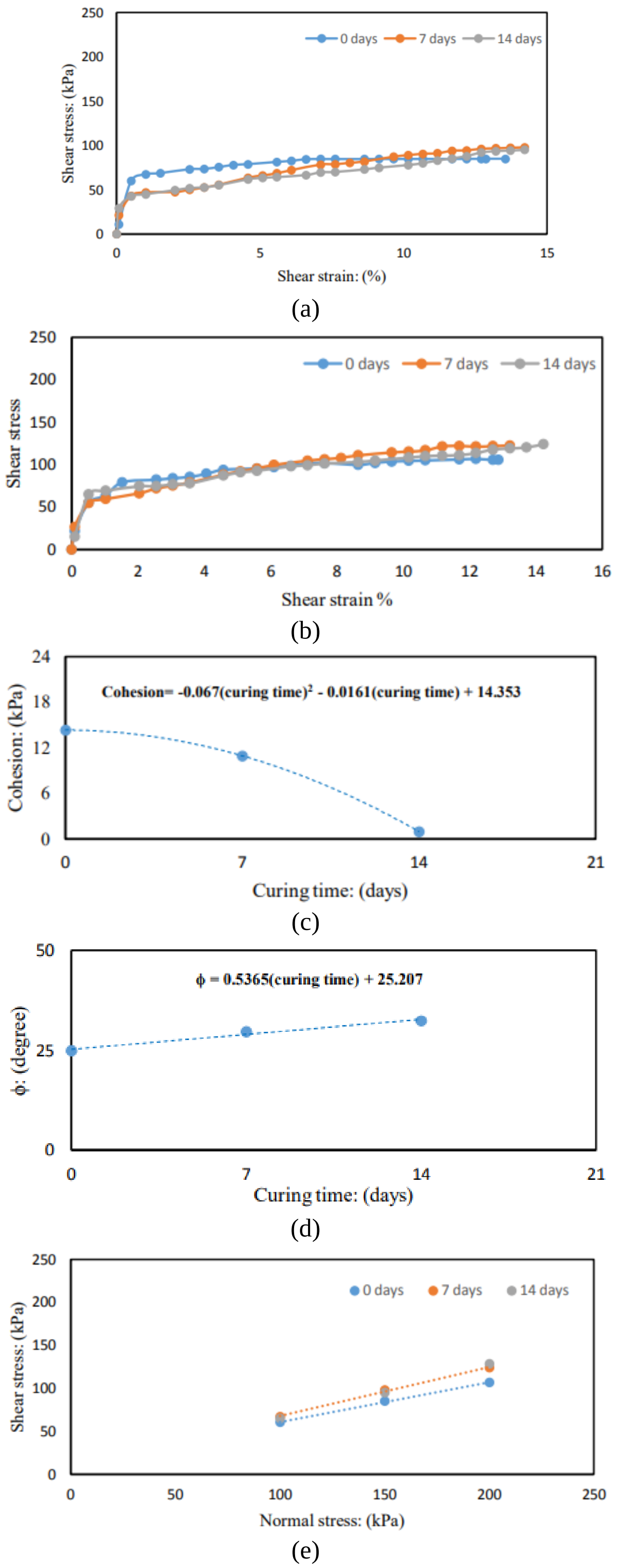


Fig. 6 effect of curing on shear stresses of Mix 9: (a) normal stress 150 kPa, (b) normal stress 200 kPa, (c) cohesion vs curing time, (d) internal friction angle vs curing time and (e) shear stress vs normal stress

Fig. 6(e) indicates that there was a small increment of shear stress with increasing curing time from 0 to 7 and 14 days. However, there was only a slight difference between 7 and 14 days. Internal friction angle increased from 25.2° at 0 days to 29°, 32.72° at 7 and 14 days respectively. However, the cohesion of mixtures decreased with increasing curing time. The above finding indicates that the effect of bentonite is reduced with curing time. However, the effect of slag increased which led to increasing internal friction angle and decreasing cohesion. This behaviour may be attributed to the high percentage of bentonite which has been used here because of different results about the effect of curing time of shear strength of sand- bentonite mixtures that have been reported by various researchers. For instance, El Mohtar *et al.* (2013) indicated that the shear strength of sand increased with curing time when sand was mixed with small percentages of bentonite (up to 5%). However, Howell *et al.* (1997) stated that the curing time does not have an effect on the maximum dry density and optimum confining pressure of sand-bentonite mixtures.

5. Conclusions

A number of direct shear tests were conducted on clean sand and sand mixed with various percentages of bentonite and slag. Samples were prepared by mixing sand, slag and bentonite in dry condition and tested at three different normal stresses of 100, 150 and 200 kPa. The major focus of this study was to investigate the effect of fines content and curing time on shear strength parameters such as internal friction angle and cohesion. The following conclusions can be drawn:

• The results showed shear stresses for clean sand and fifteen mixtures increased linearly with increasing normal stresses.

• The addition of three slag contents (1%, 3% and 5%) improved the shear stress of sand-slag mixtures, and the internal friction angle increased, while cohesion decreased with increasing slag content.

• When the bentonite content varied from 0 to 30 %, the internal friction angle of mixtures decreased drastically from 32.74° in 0% bentonite to 7.37° in 30% bentonite.

• Very high bentonite content can lead to the behaviour of sand-bentonite mixture dominated by bentonite that causes a decrease in contact between sand particles.

• Mixing sandy soil with two different contents of slag and bentonite caused variations in behaviour of all mixtures. The highest values of cohesion and lowest values internal friction angles were in Mix 3 (sand+1% slag+30% bentonite). However, highest values of internal friction angles and lowest cohesions were in Mix 1 (sand+ 1% slag+10%bentonite). These variations in behaviours could be related to differences in chemical compositions of bentonite and slag. Also, possibly due to the significant difference in bentonite and slag contents.

• Curing time had a significant effect on the internal friction angle of Mix 9, while the cohesion of Mix9 reduced with increasing curing time. Also, the shear stress of 7 days curing time was more than 0 day. However, there was only a small difference between 7 and 14 days.

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