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Strength Assessment of Mining Soil Treated with Steel Slag as Liner Material for Retention Pond

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ABSTRACT

Clay soil has always been associated with low shear strength and high compression behavior due to the high content of organic matter. The limited amounts of clay available onsite and acid mine drainage (AMD) problems have necessitated the continuous search for the treatment technology potentials. Mining soils, obtained from Selinsing Gold Mine in Raub, Pahang were evaluated to determine their suitability for use as mining soil and steel slag mixtures as compacted retention pond liners for AMD treatment. The studied samples were subjected to classification, compaction, permeability and strength tests. The results indicated that the index properties of the samples met the minimum requirements for use as liners. The compaction test showed that the maximum dry density (MDD) and optimum moisture content (OMC) decreased and increased, respectively, for all studied samples. At OMC, hydraulic conductivities of the compacted soil-steel slag were in the order of $\leq 10^{-9}$ m/s. The results from unconfined compression strength (UCS) tests gave values of 204 kN/m^2 and 61^o for soil cohesion and soil internal friction angle, respectively. Furthermore, the influence of steel slag treatment on strength properties has generally shown an improvement of up to 15% steel slag which gives the acceptable results of stress-strain in respect of its usability as liner material.

Keywords: Hydraulic conductivity, liner, mining soil, steel slag, strength parameters

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INTRODUCTION

Mining industry continues to play an important role in providing basic resource to the construction and industrial sectors, contributing to the economic development of many countries around the world including Malaysia. However, certain types of mine tailings will oxidize with oxygen and water, which results in the formation of acid mine drainage (AMD) (Fashola et al., 2016; Kusin et al., 2018). If not properly managed, the disposal of acid generating mining wastes and dissolution of metals will cause pollution that contaminates surface and groundwater (Kusin et al., 2017; Masri et al., 2017). Therefore, the mining industry relies on diverse types of liners to minimize the effluent migration from tailings impoundments to surface and/or groundwater.

There have been numerous research and procedures that focused on the mitigation measurements of AMD. Previous studies have shown examples of passive treatment in the remediation of acidic water and have been practically applied in the mining site as the systems are environmentally friendly and cost-effective (Fashola et al., 2016; Miguel et al., 2015; Muhamad et al., 2017; Molahid et al., 2018; Zahar et al., 2015;). The use of retention pond as a treatment system represents an alternative to chemical treatment techniques. The systems are constructed directly on mine tailings impoundments which have been discussed by Lagos and Geo (2011). In these systems, liner materials have become critical components particularly in the design and performance of mining treatment systems.

Commonly, the liner materials used are, for example, clay (Rowe et al., 2004; Wagner & Schnatmeyer, 2002) or geosynthetic clay (Wagner & Schnatmeyer, 2002). The characteristics of used materials can strongly influence the performance of liner. In order to reduce the cost of construction due to lack of availability of the clay onsite, utilization of possible alternative materials has been proposed, such as soil-POFA mixtures (Nik Daud& Mohammed, 2014), shale-clay mixtures (Li et al., 2017), soil from ore treatment (Miguel et al., 2015), and steel slag (Herrmann et al., 2010). Instead of using clay soil as a liner, mining soil that possesses suitable geotechnical characteristics can be considered as an alternative material.

A recent study by Rowe et al. (2004) outlined that liners could either be artificially synthesized seals or compacted clay liners and should have hydraulic conductivity of less than or equal 10^{-9} m/s. The specified maximum hydraulic conductivity also conforms to the United States Environmental Protection Agency (USEPA, 1989). According to Benson et al. (1994), Rowe et al. (2004) and Nik Daud and Mohammed (2014), soil samples that have the characteristic as presented in Table 1 mostly meet the requirements for liner materials. The selection and performance standards for assessing the suitability of the materials intended for hydraulic barriers in retention pond are low hydraulic conductivity and adequate shear strength.

Table 1
Properties requirements for liner materials

Properties	Limiting value		
	Benson et al. (1994)	**Rowe et al. (2004)**	**Nik Daud et al. (2014)**
Gravels (%)	-	< 50	-
Clay (%)	> 15	-	-
Fines (%)	> 30	> 15 – 20	≥ 20 – 30
Plasticity index (%)	> 7	> 7	≥ 7
Liquid limit (%)	> 20	-	> 20
Hydraulic conductivity (m/s)	$\leq 1 \times 10^{-9}$	$\leq 1 \times 10^{-9}$	$\leq 1 \times 10^{-9}$

Thus, this paper provides information on the properties of mining soil and steel slag mixture as an improved retention pond liner material. This study aims to assess the compressive strength, obtained by the mining soil-steel slag mixtures.

MATERIALS AND METHODS

Materials

Native mining soil samples, exploited in this study were obtained from Selinsing Gold Mine area in Raub, Pahang, Malaysia (GPS coordinate: $4^0$15’42.86” N $101^0$46’52.75” E) (Figure 1). Three samples of soils from the same location were collected using a hammer, digger and shovels about 20-50 cm from the surface soils. Disturbed soil samples were collected and sealed in a polyethylene bag to retain the soil moisture in accordance with BS 1377-1 (Road Engineering Standards Policy Committee, 1990).

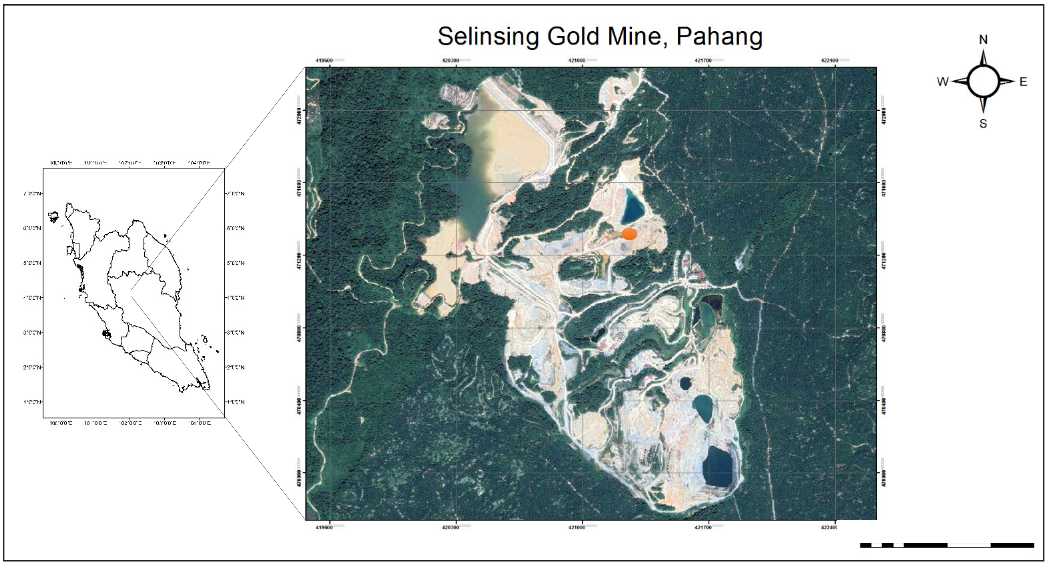

Figure 1. Location map of mining soil study area

The soil was characterized according to its typical physical properties from a laboratory test (Table 2). Soil specimens were prepared based on their average moisture content level before they were dry-mixed with steel slag at designated optimum proportion.

Table 2
Physical properties of untreated mining soil (Masri et al., 2017)

Properties	**Mine soil**
pH	4.4
Mechanical analysis	
Sand (%)	1.19
Silt (%)	91.05
Clay (%)	7.81
Moisture content (%)	25.39
Specific gravity of soil (g cm^{-3})	2.17
Specific Surface Area (m^2/gm)	50.00
Atterberg limits	
Liquid limit (LL)	47
Plastic limit (PL)	26.45
Plasticity index (PI)	20.55
Mineralogical composition	Kaolinite, Illite
Chemical composition	
SiO_2 (%)	75.26
Al_2O_3 (%)	19.25
K_2O (%)	4.11
Fe_2O_3 (%)	-

Meanwhile, steel slag samples were obtainable as by-products in metallurgical industry in the form of fine aggregates. The steel slag examined in this study (Table 3) was provided by a steel production company in Selangor.

Table 3
Properties of steel slag (Zahar et al., 2015)

Parameter	**Value**
BET surface area, m^2/g	30.268
Pore volume, cc/g	0.028
Pore radius, Å	15.364

The collected soil samples were air-dried, crushed and pulverized into fine grained particles in order to minimize the effects of particles size on the hydraulic conductivity of the compacted soil-steel slag. As indicated by Daniel and Benson (1990), the hydraulic conductivity of the liners increased when large particles sizes presented in the compacted soil liners.

Methods

The sample classification tests (pH, grain size distribution, specific gravity and Atterberg limits), compaction tests, permeability tests and strength tests were carried out on the samples in accordance with British Standard (BS) methods (1990). The collected soil samples were categorized parallel with requirements by the Unified Soil Classification System (USCS) using results from sieve analysis, liquid limits and plastic limits test (ASTM D2487-11).

All assessments were conducted on the mining soil treated with 0, 5, 10, and 15% steel slags by mass of the soil, respectively. Moisture content was determined immediately after sampling to obtain the initial moisture content of the material in order to avoid variations in results. Afterwards, the soil samples were air-dried at room temperature because high temperature possibly will cause some alterations in composition. The larger materials which included stones were removed and particle size < 2 mm was used for the analysis in accordance with standard methods for materials (Road Engineering Standards Policy Committee, 1990).

Compaction was performed following BS 1377-4 for Standard Proctor. In order to come up with the optimum moisture content (OMC), initially, several specimens of samples were prepared and tested at different moulding water contents. Thus, the indication of maximum dry density (MDD) from the samples was set as a reference for all tests with modified soil, prepared with steel slag.

The permeability tests were done under falling head conditions using a rigid-wall compaction mold permeameter in accordance with the procedures, described in BS 1377-6 (Road Engineering Standards Policy Committee, 1990). The compacted samples were retained inside the compaction mold permeameter and initially, the water was allowed to seep through the compacted samples for at least 72 h. The tests continued until the hydraulic conductivity was constant in which at least four hydraulic conductivity values were acquired over the period of time.

Unconfined compression strength (UCS) test was performed according to BS 1377-7. The studied samples were prepared following exact water content and unit weight of Standard Proctor compaction. The UCS test is capable to yield more reliable measure of strength. This is particularly true for fissured, compacted soils, in which the confining pressure retains the specimen intact under load (Rauch et al., 2002). In this test, treated samples were initially trimmed into test specimens measuring 100 mm high by 50 mm in diameter. Incremental strain rate of 1.5 mm per minute was applied during shearing procedure (BS 1377-7).

RESULTS AND DISCUSSIONS

According to USCS (Unified Soil Classification System), the examined soil can be classified as inorganic clay with low plasticity, CL (Masri et al., 2017). The basic characteristics of the pulverized samples were presented in Table 4. The pH of the mining soil samples was low indicating strongly acidic soil condition. The mixture of mining soil-steel slag, however, produced differences in the pH of the samples ranging between 6.7 and 10.5 as steel slag was mildly alkaline. There was a decrease in values across each parameter with the increase in steel slag content.

Table 4
Geotechnical properties of the studied samples

Properties	Mining soil	5% Steel Slag	10% Steel Slag	15% Steel Slag
pH	4.4	6.7	8.8	10.5
Moisture content (%)	25.39	-	-	-
Specific gravity of soil (g cm^{-3})	2.17	2.05	1.93	1.87
Atterberg limits				
Liquid limit (LL)	47	45	41	38
Plastic limit (PL)	26.45	25.63	24.09	23.71
Plasticity index (PI)	20.55	19.37	16.91	14.29

According to Qian et al. (2002), the liquid limit and plasticity index of a soil liner should be at least 20% and ≥ 7%, respectively, because low hydraulic conductivity is attributed to higher liquid limit and plasticity indices. As a result, the soil and soil-steel slag mixture have generally met these criteria.

Compaction test were conducted to simulate the right mixture of moisture and load on a soil that would raise the density of such soil, thus, reducing soil settlement when subjected to dynamic load. The optimum moisture content of the mining soil-steel slag mixtures, obtained from the compaction curve was shown in Figure 2.

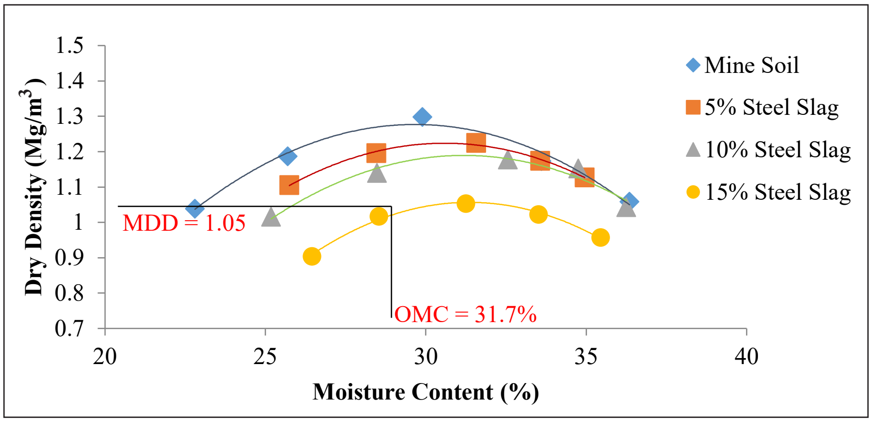

Figure 2. Compaction curves for mining soil and mining soil-steel slag mixture

Table 5 summarizes the relationship between MDD and OMC with steel slag content, clearly shows that as the steel slag content increases, OMC increases significantly, but MDD decreases. Increment in MDD with steel slag content was partly associated with steel slag's higher specific gravity compared it with that of the mining soil.

Table 5
MDD and OMC of studied samples from compaction tests

Parameter	Mining soil	5% Steel Slag	10% Steel Slag	15% Steel Slag
MDD, Mg/m^3	1.27	1.23	1.19	1.05
OMC, %	29.0	30.5	31.3	31.7

The variation findings in the MDD and OMC of the studied samples possibly associated to the differences in the plasticity. The plasticity index of 15% steel slag mixture was lower than that of the mining soil (Table 4). It was therefore expected that mining soil, treated with 15% of steel slag possess a greater affinity for water. This greater affinity for water appeared in the higher OMC and lower MDD, compared with other samples. For instance, Nik Daud and Mohammed (2014) indicated that as the plasticity index decreased, OMC increased, and the MDD decreased.

Table 6 shows that the hydraulic conductivity values generally decrease with higher steel slag content and they can be categorized as very low (Nik Daud & Mohammed, 2014). Similarly, Afolagboye et al. (2017) reported that the low hydraulic conductivity of the fine contents provided a more tortuous flow path for water to flow. All studied samples yielded hydraulic conductivities which were all in the order of 10^{-9} m/s at all different moulding water contents.

Table 6
The variation of hydraulic conductivity with steel slag content

Steel Slag Content (%)	Hydraulic Conductivity (m/s)
0	6.603×10^{-5}
5	1.182×10^{-6}
10	7.250×10^{-7}
15	1.952×10^{-8}

The material used in the construction of compacted liners should be strong enough to withstand shear failure caused by the load imposed by the overlying waste materials. Daniel and Wu (1993) recommended that the minimum soil strength to be used as compacted soil liners should be 200 kN/m^2. The shear strength values decreased with an increase in moulding water contents for all samples, whereas the presence of steel slag substance led to an increase in shear strength values (Figure 3).

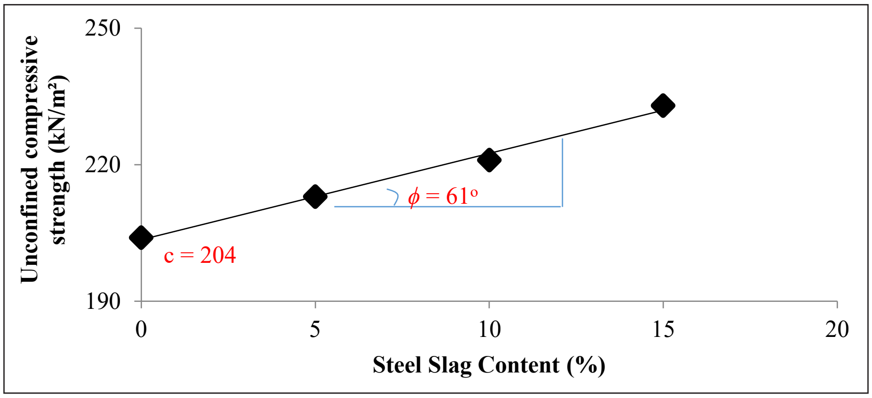

Figure 3. Variation of Unconfined Compressive Strength (UCS) with steel slag content
Shear parameters: c – cohesion & ϕ -internal friction angle

The estimated cohesion, c and the angle of internal friction, (ϕ) from the Mohr envelopes were shown in Figure 3. The increase in strength with steel slag content of up to 15% possibly attributed to the formations of cementations product through pozzolanic reactions and hydration of cementations material that coated and bound the soil particles to produce stronger matrices (Amadi et al., 2012; Nik Daud & Mohammed, 2014). Test results (Figure 3) confirmed that the soil possessed a higher strength than the recommended minimum strength when it was mixed with steel slag (Nik Daud & Mohammed, 2014).

A typical stress-strain curve for studied samples was presented in Figure 4. In this study, specimen failure was defined as the maximum axial stress or when no peak was reached during the test. Peak axial stress in the UCS test was 7.32 kN/cm^2 and it was found at 8.71% strain for 10% steel slag mixtures. Generally, the shapes of the stress-strain curves differ significantly between low and high steel slag contents.

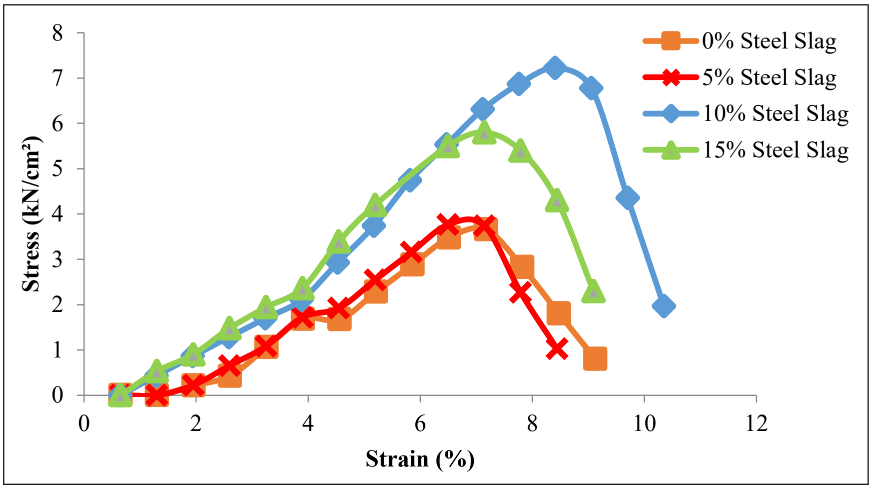

Figure 4. Relationships of stress-strain from UCS test

From the UCS test, the samples exhibit brittle characteristic in terms of rapid drop in the post-peak stress with increment in strain, which is parallel to the characteristics of the structured natural clays (Horpibulsuk et al., 2009). Figure 4 shows that only 10% steel slag are enough to fill up the voids at optimum moisture content. Thus, for steel slag mixtures, it can be seen that less than 15% mixture are able to fill up the voids of the sand. From this study, the employment of up to 10% of steel slag is appropriate for a retention pond liner. Going for higher steel slag ratios will increase the compressibility and stress of the liner material that result in light structure problems (Dafalla, 2017).

CONCLUSIONS

This study has assessed the effects of steel slag as a strength improvement admixture on mining soil in relation to the design of liners in retention pond. The soil has an adequate amount of fine particles along with good plasticity features which are vital to achieve a low hydraulic conductivity, while MDD and OMC decrease and increase, respectively, with higher steel slag contents. The low hydraulic conductivity and adequate strength, combined with their availability could have made them potential materials to be used as compacted soil liners for environmental protection. Therefore, the results have indicated that the mining soil-steel slag has promising potential as a liner material as it meets the USEPA criteria for waste-containing liner.

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