Lateritic Soil Stabilization by Addition of Steel Slags

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ABSTRACT: The addition of electric arc furnace slag and ladle furnace slag on strength improvement of lateritic soil was studied in this work. Liquid limit, plasticity index, and the California bearing ratio of lateritic soil mixed with the slags were determined in comparison to those of ordinary lateritic soil. A scanning electron microscope was used to confirm the effect of those two slags on microstructures related to chemical components of raw materials and the strength of lateritic soil. The deterioration of California bearing ratio, liquid limit, and plastic index values were obtained when the electric arc furnace slag was mixed in lateritic soil. Meanwhile, the California bearing ratio of lateritic soil was highly improved with the addition of ladle furnace slag, owing to the hydration reaction between water and excess lime in ladle furnace slag with free silica in lateritic soil. The values of the plasticity index were also comparable to the ordinary lateritic soil. Microstructures confirmed a highly compacted surface of mixed lateritic soil with ladle furnace slag. The ladle furnace slag is therefore one of the promising alternative low-cost materials for the soil-stabilizing application.

KEYWORDS: Steel slags, Soil stabilization, Construction, Mechanical properties, Improvement.

1. INTRODUCTION

Lateritic soil is a subbase material in road construction. Although the lateritic soil is cheap and suitable for use in large-scale construction, it has low strength but high plasticity and water sensitivity due to the high content of fine particles (Maignien, 1964). This affects the critical shrinkage during the dry season and swelling in the wet season. Soil stabilization techniques are used to improve the strength and plasticity index of natural aggregate for construction works (Pippala, 2016). To reduce the cost of large-scale construction, many researchers have continuously searched for a low-cost alternative stabilizing material from other industries (Faleschini et al., 2016; Přikryl et al., 2016).

Steel slag is one of the main by-products in the steel-making process (Silva et al., 2016). It is produced with a high temperature to separate metallic and non-metallic materials in the steel-making process. In each ton of steel, the electric arc furnace (EAF) and the ladle furnace (LF) slag in which chemical compositions relatively similar to those of cement and lime are predominantly produced (Akinwumi, 2014). EAF slag containing high ferric oxide (Fe_2O_3) is one of the primary by-products of the steel-making process. Meanwhile, LF is an enriched calcium oxide (CaO) slag due to it is from the final stage of steelmaking in which lime (CaO) and dolomitic limestone ($CaMg(CO_3)_2$) are added (Shi, 2004; Tsakiridis et al., 2008). From an earlier study, the steel slag was used as an aggregate material in cement-lime mixes to improve strength (Heidrich and Woodhead, 2010; Radenovic et al., 2013; Ortega-L´opez et al., 2014). It was also revealed suitability in the stabilization of some plastic soil (Manso et al., 2013). Nevertheless, using both EAF and LF steel slag in the stabilization of lateritic soil for road construction has never been reported so far. The utilization of industrial wastes is considered not only under the sustainable concept, but also the eco-friendly materials in large-scale constructions. This is a challenge in the research of soil improvement under the construction requirement when the properties of construction material are not readily available or the costs are extremely expensive.

Therefore, this research was aimed to comparatively study the EAF and LF slags in stabilizing the strength of lateritic soil. The liquid limit, plasticity index, and the California bearing ratio of each lateritic soil contained EAF slag and LF slag were determined and compared with ordinary lateritic soil. Chemical compositions and microstructures of mixed lateritic soils with steel slags were analyzed by X-ray fluorescence and scanning electron microscopy. The relationship between those analyzed results and the strength of lateritic soil mixes was also investigated and discussed.

2. MATERIALS AND METHOD

2.1 Materials Testing

The steel slags were obtained from Siam Yamato Steel Company Limited, Rayong, Thailand. The EAF slag, known as black slag, is a primary product from the steel making process, whereas, LF slag called the secondary refining slag or the white slag is produced from the steel refining process as shown in Figure 1. While, Lateritic soil (LS) was obtained from Chachoengsao province, Thailand. The grain size distribution of LS was determined by sieve analysis. Liquid limit (LL), plastic limit (PL), and plasticity index (PI) of LS were obtained using Atterberg's limits test (ASTM D4318). The chemical compositions of LS and both slags were analyzed by X-ray fluorescence (XRF: Horiba XGT 5200).

(a) EAF (black slag)

(b) LF slag (white slag)

Figure 1 Steel making slags

2.2 Testing Conditions and Method

The EAF and LF slags were passed through a 40-mesh sieve (particles smaller than 0.420 mm) before mixing with LS. The testing conditions and names are as follows:

(1) LS refers to ordinary LS
(2) LS/EAF refers to LS mixed with EAF slag 10% by weight (wt%) of dry LS sample as shown in Figure 2(a).

(3) LS/LF refers to LS was mixed with LF slag of 10 wt% of dry LS sample as shown in Figure 2(b).

2.3 Compaction Test

According to ASTM D1557, a function of the dry density and water content of material were determined by the modified proctor compaction with five variations of each LS, LS/EAF, and LS/LF sample. The maximum dry density (MDD) and optimal moisture content (OMC) of LS, LS/EAF, and LS/LF were subsequently used for the analysis of the California bearing ratio. In the preparation of five variations of each LS, LS/EAF, and LS/LF sample, tap water of arbitrary amounts was added to the samples and manually mixed until the color and texture became uniform. The mixture was gradually transferred to the cylindrical molds of 152.4 mm in diameter by the sequential order of five equal layers up to the top surface of the mold. Each layer of mixtures was compacted 56 blows using a 44.48 N hammer dropping from a height of 457.2 mm, which is equivalent to 2700 kN-m/m^3 compaction effort or approximately 4.5 times of the standard proctor test. Then, a subsequent layer was deposited into the mold and proceeded with the same procedure. The weight of the compacted sample in each mold was recorded prior to ejection samples from the molds by an ejector. All the samples were dried in an oven until the final weight was stable and then the water content of each sample was determined.

(a) LS (brown)/EAF

(b) LS/LF

Figure 2 Lateritic soil mixed with slags

2.4 California Bearing Ratio

California bearing ratio (CBR) values describe the strength of a material concerning the bearing capacity of well-graded crushed rock whose CBR is 100% at the MDD. The bearing capacity of materials is governed by water content, dry density, and material types. According to ASTM D1883, the CBR values of the LS, LS/EAF, and LS/LF samples were measured. Each mixture was passed through a 4-mesh sieve before mixing with tap water at the optimum moisture content (OMC) determining from the compaction test. Three samples of each LS, LS/EAF, and LS/LF mixture were transferred in sequential order of five equal layers up to the top of cylindrical molds of 152.4 mm inner diameter and 177.8 mm in height. Each layer of the sample was compacted at 10, 25, and 56 blows using a 44.48 N hammer dropping from 457.2 mm in height. Then, a subsequent layer was deposited into the mold and repeated the same procedure. The samples were subjected to axial loading by a penetration test machine with 50 kN maximum capacity and 0.1×10^{-4} to 6.00 mm/min speed.

In penetration testing, a 10-pound surcharge weight, comprising two five-pound circular discs, was placed on top of the surface of LS, LS/EAF, and LS/LF samples. A steel penetration piston of 50 mm diameter connecting to the proving ring was inserted through the center point and penetration was carried out at a rate of 1.27 mm/min. The load measurements at the deformation of about 0.64 mm, 1.27 mm, 1.91 mm, 2.54 mm, 3.18 mm, 3.81 mm, 4.45 mm, 5.08 mm, 7.62 mm, 10.16 mm, and 12.70 mm were taken for each sample. The LS, LS/EAF, and LS/LF samples were removed from the mold, and then water content was determined. A load of deformation at 0.2-inch (5.08 mm) penetration depth was converted into CBR values of LS, LS/EAF, and LS/LF samples. The resulting CBR values were compared to that of standard crushed rock (i.e., 1500 psi), in which the CBR can be expressed as:

$$CBR\ (\%) = (\textit{Test unit load/Standard unit load}) \times 100 \qquad (1)$$

3. RESULTS AND DISCUSSION

The particle size distribution of lateritic soil is shown in Figure 3. The percent passing sieve No. 2" (50.00 mm), No. 1" (25.00 mm), No. 3/8" (9.50 mm), #10 (2.00 mm), #40 (0.425 mm), and #200 (0.075 mm) were 100 wt%, 100 wt%, 80.99 wt%, 41.8 wt%, 26.66 wt% and 6.5 wt%, respectively. This confirms the well-graded lateritic soil. The chemical composition of EAF slag, LF slag, and LS was demonstrated in Table 1. LS contains comparatively high silica (SiO_2) and ferric oxide (Fe_2O_3). A major composition of EAF is ferric oxide (Fe_2O_3), meanwhile, the LF slag contains a high content of lime (CaO) compared to Portland cement.

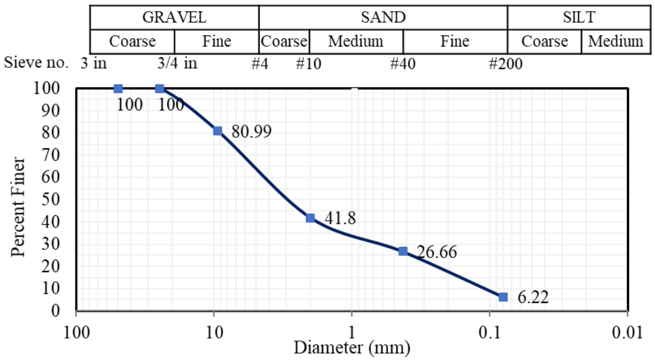

Figure 3 Particle size distribution of lateritic soil (LS)

Table 1 Chemical components of steel slags and lateritic soil compared to Portland cement

Compounds	Mass (%)			
	EAF	LF	LS	OPC
Al_2O_3	2.17	1.88	-	1.60
SiO_2	2.93	4.74	41.03	9.45
CaO	21.29	90.73	-	62.70
Cr_2O_3	2.55	-	1.55	-
MnO_2	12.38	0.33	-	-
Fe_2O_3	58.68	2.32	54.17	3.29
TiO_2	-	-	3.25	-
MgO, SO_3, K_2O	-	-	-	22.96

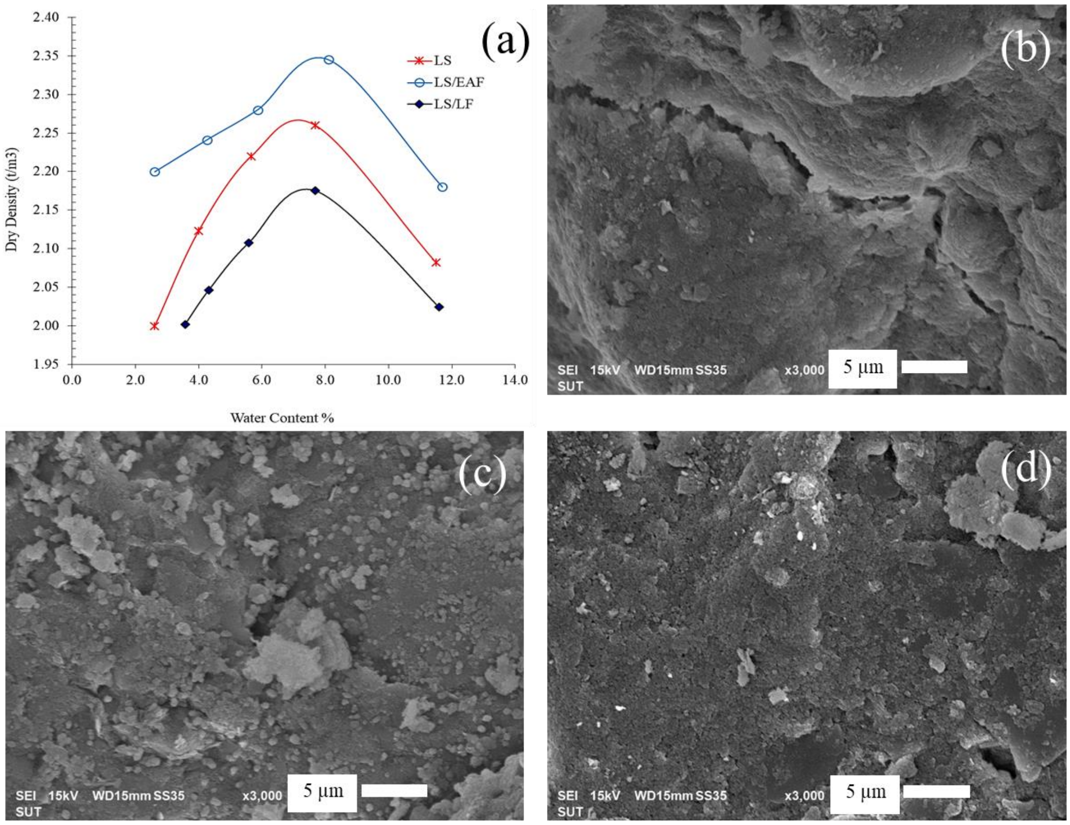

Figure 4 (a) Compaction curves of lateritic soil and lateritic soil mixed with slags and SEM images showed a compacted surface, (b) LS sample, (c) LS/LF sample, and (d) LS/EAF sample

The results of Atterberg's limits test, compaction, and CBR test (95% Modified proctor) of LS, LS/EAF, and LS/LF samples are summarized in Table 2. The LL and PL of LS were 31.20% and 15.25%, respectively. The PI, which is the difference between LL and PL of LS was 15.95%. In comparison to LS, similar LL, PL, and PI values were obtained from mixed LS/LF samples. Meanwhile, a lower LL value was found in LS/EAF samples resulting in a low PI index of the LS/EAF sample. From the compaction test, a function of water content and dry density are presented by the compaction curves in Figure 4(a), in which the top of peak refers to the MDD at the OMC. Each experiment was carried out in triplicate. The average water contents of LS, LS/EAF, and LS/LF were 7.68%, 8.04%, and 7.69% corresponding to MDD of about 2.27 t/m^3, 2.35 t/m^3, and 2.18 t/m^3, respectively. OMC of LS, LS/LF, and LS/EAF samples were relatively similar, indicating the similarity of the percent fine particles in LS and LS mixed with slags. The addition of 10 wt% EAF or 10 wt% LF slag, therefore, did not show a significant effect on the MDD of ordinary LS.

Table 2 also showed the CBR value which is pointed to the strength of soil particles and the percentage of fine particles in the LS mixes. The CBR values were much developed in the LS/LF (99.48%) compared to that of LS (83.54%) and LS/EAF (73.27%). Since the OMC values and the percent-fine particles in LS and LS mixed with slags were relatively similar, the difference in CBR values was likely due to another reason. With a higher content (> 90 wt%) of CaO in LF slag (Table 2), excess CaO could probably react with SiO_2 in LS through a pozzolanic reaction (Chaiyaput, 2019). The CBR value of LS/LF was thus developed faster than the ordinary LS and the LS/EAF sample. Microstructures in Figures 4(b) - 4(d) also confirmed a highly compacted surface of the LS/LF sample in comparison with the ordinary LF and LS/EAF samples. In contrast, the reaction could not take place in LS/EAF with no excess CaO content. Also, the compacted particle strength of EAF slag was much easily broken during compaction following a lower PI index indicating a type of silt material with slightly plastic compared to LS and LS/LF samples (Sower, 1979). Therefore, compared to the LF slag, the EAF slag is not suitable for the strength improvement of LS.

Table 2 Engineering properties of LS, LS/EAF, and LS/LF samples

Properties	Testing conditions		
	LS	**LS/EAF**	**LS/LF**
Compaction (modified): MDD (t/m^3)	2.27	2.35	2.18
Compaction (modified): OMC (%)	7.68	8.04	7.69
95% Modified proctor: CBR (%)	83.54	73.27	99.48
LL (%)	31.2	17.5	33.37
PL (%)	15.25	15.25	19.04
PI (%)	15.95	2.25	14.33

4. CONCLUSIONS

The strength improvement of lateritic soil was studied by mixing two different types of low-cost steel slags from the steel industry. A decrease in California bearing ratio, liquid limit, and plastic index values were observed in the lateritic soil mixed EAF slag. On the contrary, the mixing of LF slag containing high CaO enhanced the California bearing ratio of lateritic soil due to the reaction between excess hydrated CaO in LF slag with SiO_2 in lateritic soil. A highly compacted surface of lateritic soil containing LF slag confirmed this effective improvement. Our preliminary results indicated that the ladle furnace steel slag is a promising low-cost material for lateritic soil stabilizing application, which is a project currently underway for road construction.

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