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Stabilization of lateritic soil by ladle furnace slag for pavement subbase material

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Abstract. The effect of ladle furnace slag or LFS on the mechanical properties of the lateritic soil mixes for use as a subbase course material in the pavement structure was investigated. The lateritic soil grade E with the lowest mechanical properties was studied by mixing the LFS in the ratios of 5 to 12 wt%. The pavement material criterion of the Thailand Department of Highways was used to qualify the liquid limit, plasticity index, the California bearing ratio, and the swelling index of the mixed lateritic soil with the LFS. An increase in the California bearing ratio of the lateritic soil under the soaked condition was found to be positively correlated with the increasing LFS. Meanwhile, the liquid limit and the plasticity index decreased, leading to a decrease in the swelling index of the lateritic soil containing LFS. Using LFS reduced the total fine-particle ratio in the soil mixture but effectively enhanced the degree of compaction and swelling tolerance in the lateritic soil mixture. 10 wt% LFS is strongly recommended as a minimum admixture in the lateritic soil due to the highly improved plasticity and the mechanical properties of the lateritic soil for a subbase course material selection under the standard specifications.

Keywords: ground improvement; pavement; reinforced soil; slag; soil stabilization

1. Introduction

The subbase course is the layer between the base course and the compacted subgrade of the pavement structure. The subbase course plays a major role as structural support and also minimizes the intrusion of fine subgrade materials into the pavement and improves drainage. According to the standard specifications from the Thailand Department of Highways, the subbase course generally consists of lower quality materials than the base course but better than the subgrade soils. The California bearing ratio (CBR) is the main criterion to select the subbase course materials for pavement structure. Nowadays, lateritic soil is a low-cost and well-graded granular used in the subbase course layer. A high percentage of fine particles in the lateritic soil somehow make a problem in the pavement structure because of high-water adsorption and plasticity, leading to a high shrinkage in the dry season and a high swelling in the wet season (Maignien 1966, Ogbuagu and Okeke 2019). An improvement of the lateritic soil properties under the standard requirement of construction materials is therefore a challenging issue when the properties of construction materials are not readily available. Soil stabilization techniques have been used to improve the engineering properties (Puppala 2016, Ghareh *et al*. 2019, Onyelowe *et al*. 2021), i.e., strength and plasticity index of the natural aggregate including lateritic soil by mixing traditional stabilizing materials such as cement, lime, bitumen, fly ash, and non-traditional stabilizing materials, e.g. resins, ionic, polymer, to enhance the engineering properties (Kim *et al*. 2018, Kwon *et al*. 2019, Moayyeri *et al*. 2019, Sriraam *et al*. 2019, Muguda and Nagaraj 2019, Onal and Sariavci 2019, Farghaly *et al*. 2020, Bozbey *et al*. 2021).

The use of environmentally and economically friendly recycled materials in construction work have recently much attractive to many researchers (Pasetto and Baldo 2013, Prikryl *et al*. 2016). Steel slag is a recycled material obtained from the iron-steel making process, which is applied to the soil stabilization techniques (Akinwumi 2014, Shi 2004, Tsakiridis *et al*. 2008, Da Silva *et al*. 2016, Sabbar *et al*. 2020). The purpose of using steel slag is not only to reduce metal-industrial waste but also to the economic recovery of the wastes (Koros 2003). Steel slag is produced under a high temperature during metallic and non-metallic materials separation in the steel manufacturing process. From this process, the primary slag products are the blast furnace (BF) iron slag, the basic oxygen furnace (BOF) steel slag, and the electric arc furnace (EAF) steel slag (Poh 2006, Diniz *et al*. 2017). Meanwhile, a secondary refining slag called the ladle furnace (LF) slag or the white slag is produced in a final stage of the steelmaking process (Dippenaar 2004, Setién *et al* 2009, Heidrich and Woodhead 2010). Steel slag has also been considered for use in clayey soil stabilization due to the potentially high free lime (CaO) contents, which can chemically react with clays. The angularity and roughness of the steel slag particles also contribute to a mechanical stabilization mechanism in clayey soil. However, it is unclear which stabilization mechanism is dominating (Alexander and

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Ebenezer 2020).

The LF slag is enriching calcium oxide (CaO) slag since it is produced from an additional refining step after the BOF or EAF process. In this step, lime (CaO) and dolomitic limestone ($CaMg(CO_3)_2$) are added to the electric furnace as fluxing agents during steel making (Radenovic *et al.* 2013, Ortega-L´opez *et al.* 2014). Earlier research showed that the compacted LF slag significantly enhanced almost 4 times of unconfined compressive strength (UCS) within 7 days of curing, while the plasticity and swelling index reduced to < 0.50% (Maghool *et al.* 2016a, b). This indicates that the LF slag can be used as a supplementary cementing material in civil engineering work (Serjun *et al.* 2013). Engineering properties of LF slag mixed with natural clayey soil have been studied and reported (Manso *et al.* 2013). The plasticity index, bearing capacity, durability, and cost of the soil and slag mixes are comparable to those of the soil and lime mixtures. The improved engineering properties of the LF slag with clayey soil indicate that the LF slag has enough efficiency to use in soil stabilization.

According to the earlier reports, the solely compacted LF slag can enhance the UCS without increased swelling. Also, the favorable effects of using high CaO steel slag can be attributable to chemical reactions in clayey soil stabilization. The hypothesis of this study, the LF steel slag containing high CaO contents and angularity particles could probably contribute to a mechanical stabilization of lateritic soil subbase material in the pavement structure. This research, therefore, is aimed to improve the mechanical properties of the poor-grade (grade E) lateritic soil subbase material in the pavement structure by mixing the ladle furnace (LF) slag. In this research, the lateritic soil samples with 0 wt%, 5 wt%, 10 wt%, and 12 wt% LF slag were prepared. The liquid limit (LL), plasticity index (PI), swelling index, and the California bearing ratio (CBR) under the soaked condition for 96 h of the LF-mixed lateritic soil samples were characterized and compared. The effect of the LF slag content on the mechanical-property improvement of the lateritic soil grade E was investigated and reported. The standard specifications of pavement materials from the Thailand Department of Highways were subsequently used to identify the quality of the pavement subbase material prepared from the LF-mixed lateritic soil. The CBR under soaked conditions was further used to simulate the post-flood pavement damage. Moreover, the chemical and mineral compositions of solely LF slag and lateritic soil, also the microstructures of the compacted LF-mixed lateritic soil samples were examined and discussed concerning their mechanical properties. The possibility of using low-cost industrial waste to improve the ordinary construction material without the environmental impact is going to be revealed by the outcome of this research.

2. Materials

2.1 Lateritic soil

According to the American Association of State Highway and Transportation Officials (AASHTO) criteria, the Thailand Department of Highways has classified the grade of lateritic soil base on the grain size distributions for applying as a subbase course material as shown in Table 1. Lateritic soil is classified into five grades; A, B, C, D, and E. Grade A is the best property of the lateritic soil with the highest maximum dry density and CBR values, but the lowest optimum water content value. Meanwhile, the last order grade is E in which the lateritic soil has the lowest maximum dry density and CBR, but the highest optimum water content value (Ruedeeviroj and Duangdeun 2005).

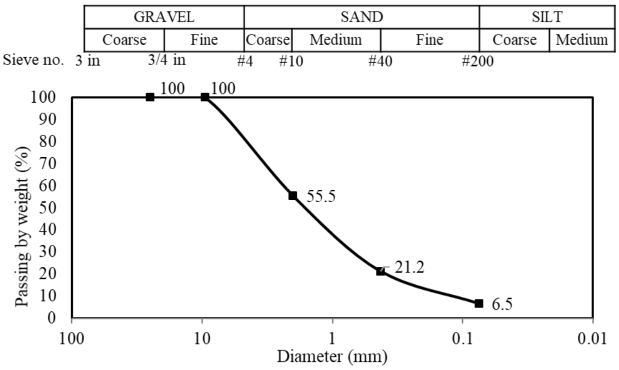

Fig. 1 Grain sizes distribution of lateritic soil

Table 1 Grain size distributions of subbase course classification by the Thailand Department of Highways (DH-S 205/2532 1989)

Sieve size	Percent passing by weight (%)				
	Grade A	Grade B	Grade C	Grade D	Grade E
2” (50.00 mm)	100	100	-	-	-
1” (25.00 mm)	-	-	100	100	100
3/8” (9.50 mm)	30-65	40-75	50-85	60-100	-
No.10 (2.00 mm)	15-40	20-45	25-50	40-70	40-100
No.40 (0.425 mm)	8-20	15-30	15-30	25-45	20-50
No.200 (0.075 mm)	2-8	5-20	5-15	5-20	6-20

Table 2 Standard specifications of pavement materials from the Thailand Department of Highways

Pavement material	LL (%)	PI (%)	Soaked CBR (%)	Swell (%)	Compaction
Base course (DH-S 201/2544)	≤ 25	≤ 6	≥ 80	≤ 0.50	95%Modified Proctor
Subbase course (DH-S 205/2532)	≤ 35	≤ 11	≥ 25	≤ 4	95%Modified Proctor
Selected material A (DH-S 208/2532)	≤ 40	≤ 20	≥ 10	≤ 3	95%Modified Proctor
Selected material B (DH-S 209/2532)			≥ 6		
Subgrade (DH-S 102/2532)	-	-	-	≤ 4	95%Modified Proctor

For use as a subbase course material in this work, the lateritic soil was obtained from Chachoengsao province, Thailand. The grain size distribution was determined by sieve analysis to identify the lateritic soil grade. The percent passing through sieve no. #10, #40, and #200 of the lateritic soil was 55.50 wt%, 21.20 wt%, and 6.50 wt%, respectively

Table 3 Chemical composition of LF slag and ordinary Portland cement (Type I)

Chemical composition (%wt)	LF slag	Ordinary Portland cement (Type I)
CaO	90.73	62.70
Al_2O_3	1.88	1.60
SiO_2	4.74	9.45
Fe_2O_3	2.32	3.29
MgO, MnO_2, SO_3, K_2O	0.33	22.96

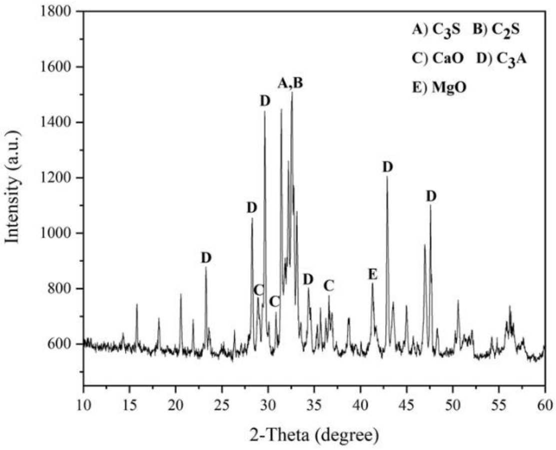

Fig. 2 Mineral composition of LF slag

(Fig. 1). According to a standard no. DH-S 205/2532 of the Thailand Department of Highways showed in Table 1 (DH-S 205/2532 1989), the present lateritic soil was classified into E grade, which is the lowest quality for use as a subbase course material.

The liquid limit (LL), plastic limit (PL), and plasticity index (PI) of lateritic soil were characterized by Atterberg's limits test based on the standard AASHTO T 89 and AASHTO T 90. According to the standard specifications from the Thailand Department of Highways showed in Table 2, the values of LL ≤ 35% and PI ≤ 11% are the control parameters for selecting a subbase course material. In this research, the LL and PL of lateritic soil were 36.29% and 14.31%, respectively. The PI of lateritic soil (PI = LL – PL) was 21.89%, which is below the standard specification of a pavement subbase material. Therefore, the improvement of plasticity and mechanical properties are required for the natural lateritic soil.

2.2 Ladle furnace (LF) slag

Ladle furnace (LF) steel slag was obtained from Siam Yamato Steel Company Limited, Rayong, Thailand. LF slag was prepared by sieving through a 40-mesh sieve in which the particles are smaller than 0.42 mm. The chemical composition of LF slag obtained from the X-ray fluorescence technique (XRF) is shown in Table 3. A major component of about 90% lime or calcium oxide (CaO) was found in LF slag, which is similar to that of ordinary Portland cement (OPC) type I in friendly Eco pavement application. The trace composition of about 10% belongs to SiO_2, Al_2O_3, Fe_2O_3, and MnO_2. Compare to the OPC, a higher content of CaO in LF slag can promote a hydration reaction and improve the CBR value of the soil sample. Considering the leaching issue, Table 3 reveals no leachable heavy metal in the chemical composition of LF slag. It can be sure that there is no toxic leachate and no environmental risk of using LF slag in construction work (Maghool *et al*. 2017). Fig. 2 presents the diffraction pattern reported by XRD showing the main mineralogical phases of the as-received LF slag. The most identified minerals in LF slag are tricalcium aluminosilicate (C_3A) and lime (CaO). Dicalcium silicate (C_2S), tricalcium silicate (C_3S), and periclase (MgO) are also presented as the minor identified minerals.

3. Testing conditions and method

The effect of LF slag as a reinforced material on the engineering properties of lateritic soil samples was investigated. Ordinary-lateritic soil sampling was performed before starting the experiment. The ordinary lateritic soil was separately mixed with the LF slag in the ratio of 5%, 10%, and 12% by weight as an example in Fig. 3. The experiments were randomized and replicated 3 times to get reliable testing data and understand the behavior of LF slag on the strength of the lateritic soil. The design of experiments is presented in the diagram in Fig. 4.

3.1 The maximum dry density and the optimum moisture content

According to AASHTO T 180, the modified Proctor compaction is a function of the dry density and water content of the testing material. Thus, the maximum dry density ($\gamma_{d,max}$) and the optimum moisture content (OMC) of the lateritic soil with 0 wt%, 5 wt%, 10 wt%, and 12 wt% LF slag were determined to evaluate the compaction behavior of each lateritic soil sample.

In the modified Proctor compaction test, tap water was separately added into the mixed lateritic soil samples with 0 wt%, 5 wt%, 10 wt%, and 12 wt% LF slag. The soil slurry was gradually stirred until the homogeneous texture and color were obtained. The soil mixture was transferred into cylindrical molds of 152.40 mm-diameter in sequential order of five equal amounts of the soil sample up to the top surface of the mold. Each layer of the soil sample was compacted 56 blows. The compaction effort is equivalent to

Fig. 3 Ordinary lateritic soil with 10% LF slag

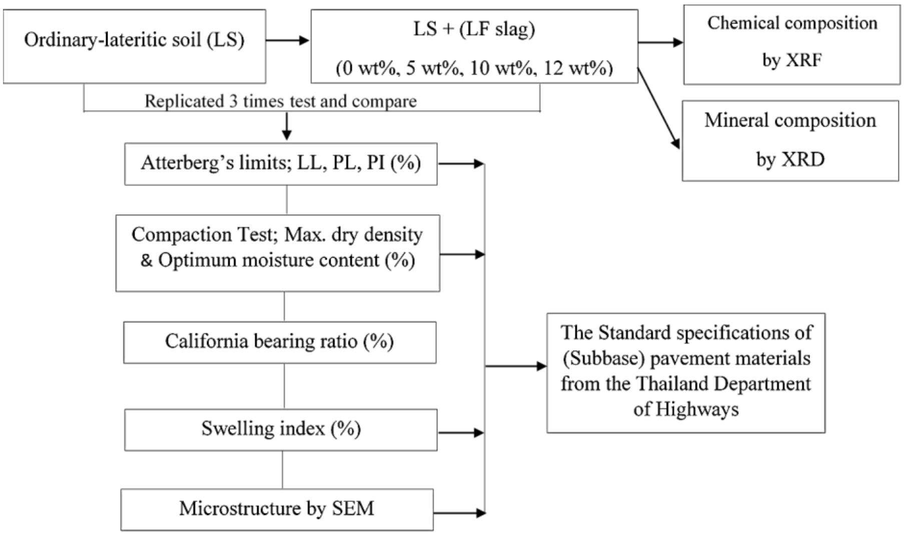

Fig. 4 Experimental diagram

2683 kJ/m^3, which is approximately 4.50 times the standard Proctor test, using a 44.48 N hammer pounding from a height of 457.20 mm. The molds containing compacted soil samples were weighed, and then the soil samples were ejected from the molds. The ejected soil samples were dried overnight in an oven before determining the optimum water content at the maximum dry density. In each LF slag content, three mixed soil samples were prepared and tested repeatedly to confirm the results.

3.2 The California bearing ratio and swelling index

According to AASHTO T 193, the California bearing ratio (CBR) under soaked conditions describes the strength of materials concerning the bearing capacity of well-graded crushed rock in which the CBR is 100% at the maximum dry density. The swelling behavior of lateritic soil containing different LF slag contents was also characterized under 96 h (4 days) soaked conditions before penetration test. The soaked condition was used to simulate the worst-case scenario of the fully saturated region after flooding.

In the CBR test under soaked conditions, the lateritic soil samples with 0 wt%, 5 wt%, 10 wt%, and 12 wt% LF slag after passing through a 40-mesh sieve were mixed homogeneously with the tap water determined by the OMC from the above compaction test. The soil samples were separately transferred into three cylindrical molds (152.40 mm inner diameter and 177.80 mm height) in sequential order of five equal amounts of soil sample up to the top surface of the mold. Each layer of transferring soil sample in those three molds was compacted 10, 25, and 56 blows, respectively. After soaking in water, the soaked samples of the lateritic soil with 0 wt%, 5 wt%, 10 wt%, and 12 wt% LF slag were removed from the water tank. The samples were dried for 15 min before subjecting to axial loading using the penetration test machine (CONTROLS Triaxial tester T400 Digital) with 50 kN maximum capacity and 1x10^{-5} to 6.00 mm/min speed.

During the penetration test, a 4.54-kg surcharge weight containing two pieces of 2.27-kg circular discs was placed on top of the soil sample surface. A steel penetration piston with 49.63 mm-diameter (ASTM D 1883-07) connected to the proving ring was inserted through the central point, and then the penetration was performed at a rate of 1.27 mm/min. The load measurements corresponding to the deformation depth of 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. The soil samples were removed from the molds to determine the water content at the top layer of the soil sample. The load and the deformation at 5.08 mm-penetration depth under soaked conditions were converted into the CBR of the soil samples using Eq. (1). The resulting CBR was compared against the standard CBR (10.30 MPa) of the lateritic soil at the same penetration depth.

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

The swelling behavior of lateritic soil with 0 wt%, 5 wt%, 10 wt%, and 12 wt% LF slag were also examined to simulate flooding damage, whereby the soil samples in the mold loaded with 4.54-kg surcharge weight was submerged for 96 h (4 days) before penetration test. The swelling index after 96 h-submersion was calculated using Eq. (2), in which an initial height of the specimen is fixed as 4.584 inches.

$$\text{Swell (\%)} = (\text{Sample extension during soaking} / \text{Initial height of specimen}) \times 100 \quad (2)$$

4. Results and discussion

4.1 Compaction behavior

In Fig. 5, dry densities at different water contents are presented by the compaction curves of the lateritic soil with 0 wt%, 5 wt%, 10 wt%, and 12 wt% LF slag in comparison to the solely LF slag. The compaction behavior of the lateritic soil mixtures exhibited a bell-shaped trend similar to that of the pure LF slag, in which the top of the peak is

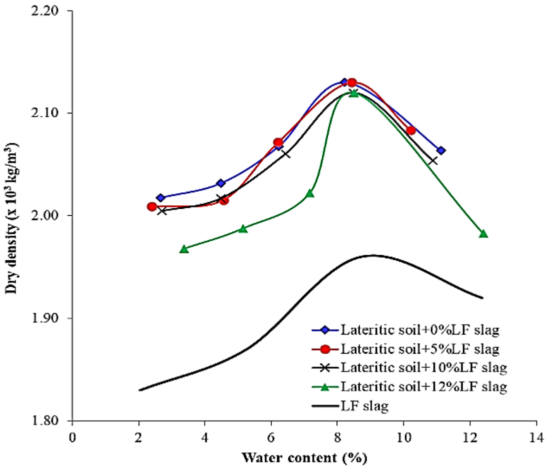

Fig. 5 Compaction curves of the mixed lateritic soil with LF slags in comparison to the pure LF slag

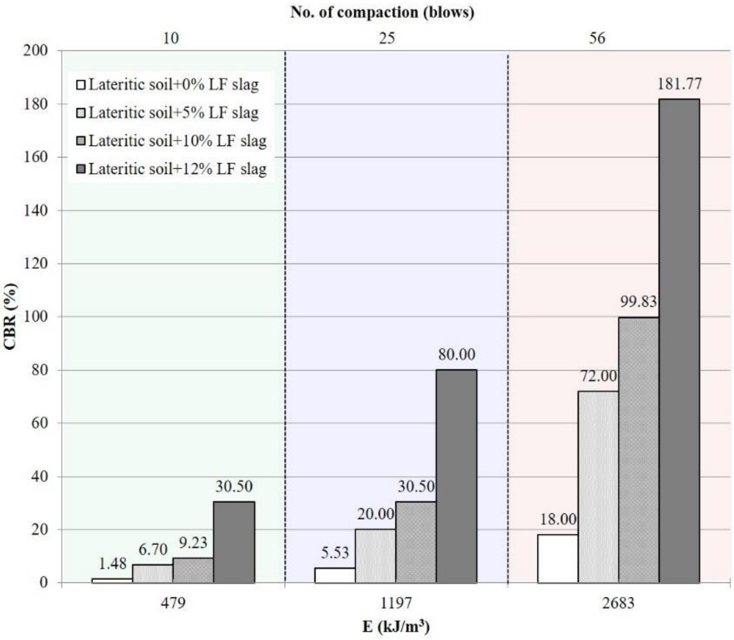

Fig. 6 Relationship between compaction energy (E) and CBR of lateritic soil at variable slag contents

the $\gamma_{d,max}$ at the OMC point (Horpibulsuk *et al*. 2009).

The dry density of the lateritic soil mixtures was much higher than the pure LF slag. It also tended to increase with increasing the water content until the $\gamma_{d,max}$ was achieved at the OMC point. This can be attributed to the water lubrication resulting in the minimized surface tension and space between the adjacent soil particles. The rearrangement of the soil particles simultaneously took place and increased the density of the lateritic soil mixtures. At the OMC point (the top of the peak), the maximum dry density was obtained in certain water content, indicating that the adjacent particles become closer leaving a space as small as possible. Once the $\gamma_{d,\,max}$ of the soil mixtures was achieved, the excess water or the further added water did not affect the increasing density. On the contrary, the water over the OMC point penetrated to the remaining space between the soil particles leading to swelling and decreasing density of the lateritic soil mixtures.

From Fig. 5, the compaction experiments were carried out three-time repeatedly on the randomized soil samples. The average OMC of the lateritic soil without LF slag was 8.21% corresponding to 2130 kg/m^3 of $\gamma_{d,max}$. Meanwhile, the average OMC of the mixed lateritic soil with 5 wt%, 10 wt%, and 12 wt% LF slag was 8.43%, 8.48%, and 8.50% at the $\gamma_{d,max}$ of 2130 kg/m^3, 2120 kg/m^3, and 2120 kg/m^3, respectively. The $\gamma_{d,max}$, and the OMC values were independent of LF slag content in the range of 0 wt% to 12 wt%. These values suggest that with an increase of the LF slag content, the optimum moisture to achieve the maximum dry density is very slightly increased possibly because of the high absorption capacity of the finer LF slag (Alexander *et al*. 2020). However, the maximum dry density was observed to slightly decrease with growing LF slag content up to 10wt%. This probably due to the LF slag having a similar specific gravity to the lateritic soil but the slag particle is finer than lateritic soil (Marco 2020).

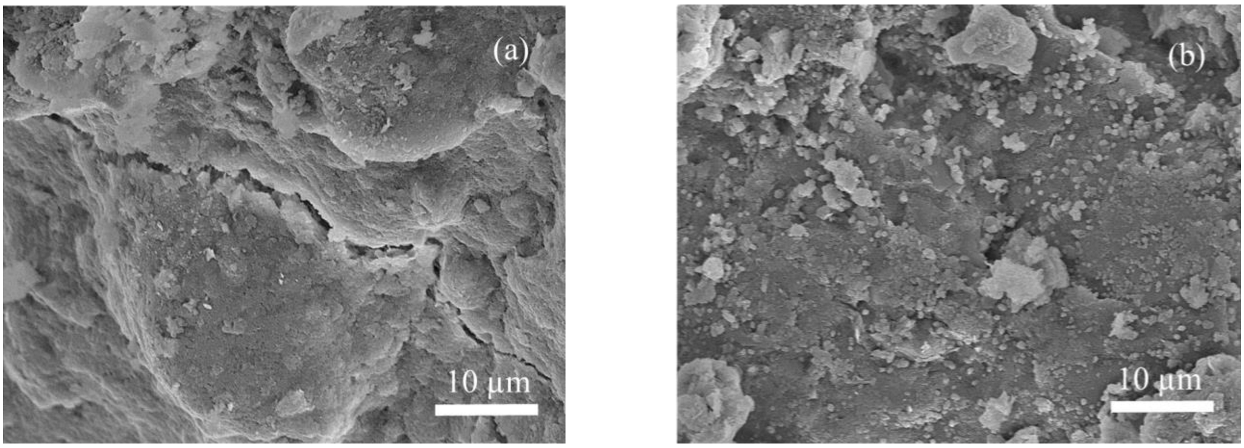

Fig. 7 SEM images showed a compacted surface of (a) the lateritic soil sample and (b) the lateritic soil mixed with LF slag

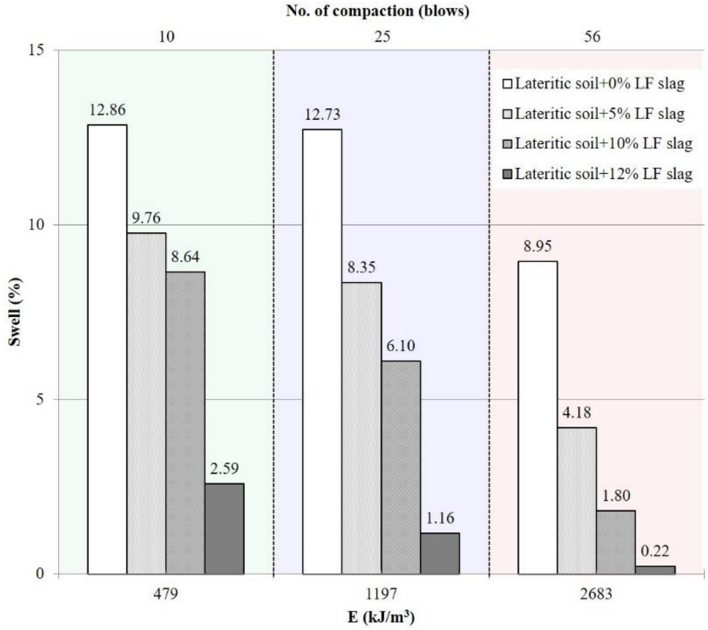

Fig. 8 Relationship between compaction energy (E) and swelling index of lateritic soil with different slag contents

Therefore, the above-average water contents were used to prepare the samples of lateritic soil containing LF slag for the CBR test.

4.2 California bearing ratio and swelling index

The CBR and swelling index are governed by the particle size and material strength. The high content of fine particles typically resulted in high water absorption, leading to a swelling and low CBR of the soil samples. Since the OMC point at the $\gamma_{d,max}$ values were not different among the mixed lateritic soil samples containing different LF slag contents, the number of compaction was varied for the CBR test of the mixed lateritic soil samples.

Fig. 6 shows the CBR values under the soaked condition and the number of compactions at 10, 25, and 56 blows of the lateritic soil with 0 wt%, 5 wt%, 10 wt%, and 12 wt % LF slag. The CBR values increased with increasing LF slag as well as the number of compactions. The compaction energy (E) was subsequently evaluated using the values of hammer weight, the height of hammer drop, the number of blows per layer, the number of layers, and the volume of mold as shown in Eq. (3). Therefore, the 10, 25 and 56 compaction blows were respectively equal to 479, 1197, and 2683 kJ/m^3 of the compaction energy.

The relationship between the compaction energy (E) and the CBR of lateritic soil at variable slag contents is also shown in Fig. 6. In each compaction energy applied to the lateritic soil mixtures, an increase of the CBR values was observed with increasing the LF slag contents. This confirmed the strong positive correlation between the CBR under the soaked condition and the increase of E with the LF slag content. The CBR values were significantly improved more than 10 times for the mixed lateritic soil with > 10% LF slag. Thus, the highest CBR under the soaked condition for all E values was obtained in the lateritic soil samples containing 12-wt% LF slag.

$$E = \frac{\text{Hammer weight x Height of hammer drop x (No. of blows /layer) x No. of layers}}{\text{Volume of mold}} \tag{3}$$

Table 4 The properties of lateritic soil (grade E) with 0%, 5%, 10%, and 12% LF slag compared to the standard specifications of (subbase) pavement materials from the Thailand Department of Highways

Properties	Subbase Material	LF slag in lateritic soil			
		0%	5%	10%	12%
Compaction (modified): $\gamma_{d,,max}$ (x10^3 kg/m^3)	-	2.13	2.13	2.12	2.12
Compaction (modified): OMC (%)	-	8.21	8.43	8.48	8.50
95% Modified Proctor: CBR (soaked 4 days) (%)	≥ 25	10.84	61.32	72.65	103.69
Swell (soaked 4 days) (%)	≤ 4	11.06	4.98	3.51	1.36
LL (%)	≤ 35	36.29	34.37	28.98	24.98
PL (%)	-	14.31	15.94	19.31	20.68
PI (%)	≤ 11	21.89	18.42	9.67	4.30

An enhancement of the CBR value was associated with the size and stiffness of the lateritic soil as well as the angularity and roughness of LF slag particles. The result showed that the stiffness of the LF slag was higher than that of the lateritic soil. Thus, the addition of LF slag minimized the particle damage and promoted the strength of the compacted lateritic soil samples. The increase of E values also generated higher energy in the lateritic soil samples containing LF slag, and therefore the samples were in a denser state with higher CBR values. The improvement of the CBR in the lateritic soil sample containing LF slag was confirmed by SEM images of the compacted surfaces as shown in Fig. 7. A highly compacted surface was observed in the mixed lateritic soil sample with LF slag, meanwhile, the compacted surface of the solely lateritic soil was much easily broken during the compaction.

The relationship between the E value and swelling index of the lateritic soil mixtures under the variation of the LF slag contents is presented in Fig. 8. At E=479 kJ/m^3, the swelling index of the lateritic soil with 0 wt%, 5 wt%, 10 wt%, and 12 wt% LF slag were 12.86%, 9.76%, 8.63%, and 2.59%, respectively. At E=1197 kJ/m^3, the swelling index of the lateritic soil with 0 wt%, 5 wt%, 10 wt%, and 12 wt% LF slag were 12.73%, 8.35%, 6.10%, and 1.16%, respectively. At E=2683 kJ/m^3, the swelling index of lateritic soil with 0 wt%, 5 wt%, 10 wt%, and 12 wt% LF slag were 8.95%, 4.18%, 1.80%, and 0.22%, respectively. An enhancement of the LF slag and E values resulted in a reduction of the swelling index of the lateritic soil samples. Especially at above 10-wt% LF slag with a high E value (2683 kJ/m^3), the swelling index was almost 0% under the highest CBR value as shown previously in Fig. 6. The swelling index is typically involved with the water attraction and coating as a film on the particle surface. The degree of the swelling index is thus controlled by the particle size and the specific surface area of the soil in the excessive water under soaking conditions. The fine particles with a high specific surface area can easily get a high level of swelling compared to the coarse particles. Therefore, a decrease in swelling index of the lateritic soil when increased the LF slag was due to a reduction of the total fine particle ratio for a water attraction in the lateritic soil samples by adding a unimodal size of LF slag.

Table 4 shows the $\gamma_{d,max}$, OMC, CBR (95% Modified Proctor), and swelling index values of the lateritic soil with 0 wt%, 5 wt%, 10 wt%, and 12 wt% LF slag. Without the LF slag, the mechanical properties and the plasticity of the natural lateritic soil were below the standard requirement of the subbase course material. An increase of LF slag much improved in the soaked CBR values of the lateritic soil samples from 11% to 104%. In contrast, the swelling index was effectively reduced from 11% to 1.4%, and the PI values of the natural lateritic soil were also reduced from 22% to 4.3% when the LF slag was enhanced in the mixed lateritic soil.

From the above results, the lateritic soil and LF slag mixture produced improvement in the plasticity index, the swelling, and the CBR of the original soil. The CBR index for bearing capacity reached values of 61.32 % with 5 wt%-LF slag addition. This value is above the standard specifications of subbase pavement materials from the Thailand Department of Highways (>25%). However, the plasticity index and the swelling are admissible under the standard specifications of subbase pavement materials when the LF slag was higher than 10 wt% (Table 4). The effects of the lateritic soil and LF slag mixtures under an improvement in bearing capacity, swelling properties and plasticity index may be attributed to the presence of high CaO with reaction capacity with lateritic soil, which enhances its Proctor compaction and reduces swelling in the presence of water. Hydration of calcium aluminates (mainly C_3A) and slight hydration of certain calcium silicates (C_3S and C_2S) in the LF slag as shown in Fig. 2 are also possible for the mechanical improvement of the lateritic soil and LF slag mixtures.

Moreover, the earlier report on the utilization of steel slag in stabilizing high-plastic subgrade soil by Aldeeky and Hattamleh (2017) was used to verify the observation in this work. A similar effect of using steel slag on the soil properties was observed, although the soil type was different. This can be explained by a non-plastic behavior of the steel slag that can reduce the plasticity of the soil mixtures. From Table 4, therefore, a decrease in the LL, and PI values were observed when the LF slag was increased from 0 wt% to 12 wt%. Also, it can be observed that the properties including CBR, swelling index, LL, and PI values of the mixed lateritic soil with 10 wt% and 12 wt% LF slag get over the minimum requirement of the subbase course according to the standard specifications of pavement materials from the Thailand Department of Highways. Therefore, in practical use, a 10-wt% LF slag was strongly proposed as the minimum LF slag content to improve the mechanical properties of the natural lateritic soil for use as a pavement subbase course material in the road constructions. Meanwhile, a 12-wt% LF slag with lateritic soil, in which the CBR is above the minimum standard of subbase materials, was suggested to further develop as a base course material instead of the current crush rock base course material in the pavement structure.

5. Conclusions

The ladle furnace (LF) slag was studied as a stabilizing material to improve the mechanical properties of the lateritic soil subbase course material for pavement structure. The natural lateritic soil studied in this research did not meet the minimum standard requirements in terms of the mechanical properties and plasticity of the subbase course material. The addition of LF slag effectively improved the natural lateritic soil properties. An increase of the LF slag resulted in a lower fine-particle ratio in the lateritic soil mixtures, contributing to the high degree of compaction and swelling tolerance in the lateritic soil mixture. The 10-wt% LF slag was found to be a minimum content that can effectively adjust the plasticity and enhance the mechanical properties of the natural lateritic soil to get the standard requirement for selecting the subbase course material in the pavement structure.

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