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Utilization of ladle furnace slag from a steelwork for stabilization of soil cement

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Abstract. Ladle furnace (LF) slag, waste from the steel-making process, was incorporated to improve the compressive strength of soil cement. LF slag was mixed to replace the cement in the soil-cement samples with wt% ratio 20:0, 15:5, and 10:10 of cement and slag, respectively. LF slag in the range of 5, 10, and 20 wt% was also separately added to the 20-wt% cement-treated soil samples. The soil-cement mixed LF slag samples were incubated in a plastic wrapping for 7, 14, and 28 days. The strength of soil cement was highly developed to be higher than the standard acceptable value (0.6 MPa) after incorporating slag into soil cement. The mixing of LF slag resulted in more hydration products for bonding soil particles, and hence improved the strength of soil cement. With the LF slag mixing either a replacement or additive materials in soil cement, the LF slag to cement ratio is considered to be less than 1, while the cement content should be more than 10 wt%. This is to promote a predominant effect of cement hydration by preventing the partially absorbed water on slag particles and keeping sufficient water content for the cement hydration in soil cement.

Keywords: LF slag; soil cement; soft clay; soil stabilization; strength

1. Introduction

Soil (Clay) is a natural material mainly composed of fine particles with plastic- and adhesive-like characteristics. When clay is exposed to excessive amounts of water, it tends to soften and turn into "Soft clay" (Obianigwe and Ngene 2018), which causes problems in construction including ground settlement, structural damage, unstable slopes, etc.

Soil cement is a kind of ground improvement technique to reduce plasticity and increase the strength of soft clay (Ma *et al.* 2014, Baghini *et al.* 2016, Lv *et al.* 2018). The strength of soil cement is directly proportional to the quantity of cement mixing. The strength of cement-stabilized soil increases due to the formation of a cement gel matrix mixed with the soil particles and the bonding of the surface-active particles (Crowley 1997, Minke 2006, Jun *et al.* 2018). At the actual construction area, cement, which is ordinary Portland cement, is mixed with soft clay by in situ deep mixing technique. The strength of soft clay in this area thus can be improved through a hydration reaction between the cement and water in the soil layer. This reaction forms calcium silicate hydrate (CSH) compounds acting as a binder between the adjacent soil granules resulting in more compaction, an increase of bearing capacity, and reduction of soil swelling (Ma *et al.* 2014, Niazi and Jalili 2009). To be used in the actual work, therefore, the Standards Australia (2002) has suggested the design soil-cement strength in the range of 0.4 to 0.6 MPa (400 to 600 kPa) as the accepted value for construction.

Besides the cement-treated soil, other waste materials have been attractive for use as additive and co-additive materials with the same purpose of improving soil or soil cement stiffness (Onal and Sariavci 2019, Moayyeri *et al.* 2019, Bozbey *et al.* 2021). Soft clay co-treated with recycled gypsum and cement and lime was studied by Aly and Usama (2014). A positive effect on the improvement of stability, strength, and durability was obtained for the tested soil in a wet environment within short curing times of 3 and 7 days. Songsuda and Runglawan (2013) reported the effect of blending calcium carbide residue and biomass ash in soft Bangkok clay. The strength development of treated clay at specific curing time and initial water content was the function of the calcium carbide residue content, the biomass ash content, and their combined effect. Also, the strength development ratio of treated clay with calcium carbide residue and biomass ash mixture was found to be higher than those of cemented clay with fly ash and cemented clay with biomass ash after 28 days of curing due to the progress of the pozzolanic reaction. Moreover, Salaheddin and Seyed (2018) have purposed to use epoxy resins as a new additive instead of the traditional additives such as cement and lime for increasing strength parameters of soft clay soils significantly. They claimed that epoxy resins have excellent physical and mechanical properties that can significantly increase the compressive strength, elastic modulus, and toughness of treated soils in any climatic zones.

White slag or a Ladle furnace (LF slag) (Fig. 1) is one of the wastes from the steelmaking industry, which is approximately 12%-20% of solid waste around the world (Mahoutian and Shao 2016, Maghool *et al.* 2016, Li *et al.* 2017, Yi *et al.* 2018). In the refining process after primary

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Fig. 1 Ladle furnace (LF) steel slag

steelmaking, both carbon and stainless steel can be performed in a ladle furnace, producing the LF slag. Due to the uses of fluxes such as calcium aluminate (CaF_2), lime (CaO), and dolomite limestone ($CaMg(CO_3)_2$ in the LF process, the compositions and properties of the produced LF slag are different from that of BOF and EAF slags (Yi *et al.* 2018). The components of LF slag are similar to those of cement. Dicalcium silicate compound (C_2S) is the primary mineral phase in LF slag. The chemical composition of LF slag is full of calcium oxide (CaO) as it occurs at the final stage of the steel melting, in which fluxes are added into the molten steel mixture (Yi *et al.* 2018, Chaiyaput and Ayawanna 2021a). Other oxides in the LF slag are SiO_2, MgO, and Al_2O_3, whereas the contents of the iron- compound are much lower than that in BOF and EAF slags. Compared to other additive waste materials mentioned above, the LF slag has been promptly used without any pre-treatment method. Hence, the LF slag has become an attractive waste material not only under the economic concept but also the eco-friendly materials and technologies in construction.

The capability of by-product steel slags in stabilizing high-swelling soils has been previously reported by Shalabi *et al.* (2017), Manso *et al.* (2013) and Vanesa *et al.* (2014). An increase in the steel slag content enhanced the California bearing ratio and decreased the dry density, plasticity, and swelling index of the clayey soils. The capability of EAF slag and LF slag on strength improvement of lateritic soil was comparatively studied by Chaiyaput and Ayawanna (2021a). The California bearing ratio of lateritic soil was highly improved by LF slag due to the hydration reaction between water and excess lime in ladle furnace slag with free silica in lateritic soil. Meanwhile, the drawback effect was observed when the EAF slag was mixed in lateritic soil. Chaiyaput and Ayawanna (2021b) also showed that an increase in the California bearing ratio of the lateritic soil was positively correlated with an increase in the LF slag content. 10 wt% LF slag was recommended as a minimum admixture in the lateritic soil due to the highly improved plasticity and the mechanical properties of the lateritic soil.

This research, therefore, aimed to improve the mechanical properties of the cement-treated soft clay (soil-cement sample) by mixing the ladle furnace (LF) slag. The mixed LF was also investigated in two different roles, which were as the cement replacement material and as an extra additive material in the soil-cement samples for comparative study. It made this research completely different from many earlier studies in terms of the theoretical framework and principal research problem. This research not only discussed the performance of LF but also the appropriate application of LF in stabilizing soil-cement samples for further soil cement works. The ratio of cement in both studied roles was maximized at 20 wt% of total solid, meanwhile, the ratio of LF slag was varied in the range of 5 – 20 wt%. The effect of the LF slag content on the compressive strength improvement of the soft clay was investigated and reported in comparison to the acceptable value of soil-cement strength. Moreover, the chemical and mineral compositions of solely LF slag and soft clay, also the microstructures of the tested LF slag mixed soil-cement samples were examined and discussed concerning their strength values. In addition, the possibility of using low-cost industrial waste to improve ordinary construction materials without the environmental impact is going to be revealed by the outcome of this research.

2. Materials characterization

The ordinary Portland cement (OPC) type 1 was used to prepare soil-cement samples for improving the strength of soft clay. Ladle furnace (LF) slag (Fig. 1), which was produced in the stages of the steel-making process, was obtained from Siam Yamato Steel Company Limited at Rayong province, Thailand. The soft clay used in this study was collected from the real construction site in Samutprakarn province, Thailand. The chemical and mineral compositions of each Portland cement, LF slag, and soft clay used as raw materials in this work were characterized by Energy Dispersive X-ray Fluorescence (EDXRF Horiba XGT-5200) and X-ray diffraction (XRD Bruker D2 PHASER) with Cu-Kα radiation over the 2θ range of 10º-60º.

3. Sample preparation and testing conditions

3.1 Sample preparation

The soft clay was dried in an oven at 110 ºC and crushed to reduce the size with a jaw crusher and disc mill, respectively. The measured LL value of soft clay was about 88.00%. At the LL, soft clay changes from a liquid state to a plastic state with the minimum water content at which it flows when subjected to very light shear forces. As a result, it was simple to mix the soil samples to produce a homogeneous texture and color. Hence, to control the same amount of water in all mixing conditions, tap water at 88.00 % by weight of dried clay was added to the dried clay and soaked for 30 minutes. Then, the cement powder and LF slag were added to the soaked clay and continually agitated for 5 minutes until the uniform texture and color were obtained.

The mixtures samples were shaped in 50 mm x 50 mm x 50 mm stainless steel cubic mold (ASTM C-109/C 109M-05 2005) and covered by plastic wrapping. The cubic soil-cement-slag samples were kept under the plastic wrapping for 7, 14, and 28 days. The compressive strength and microstructures of the cubic soil-cement-slag samples with different curing times were tested by using the universal testing machine (UTM). The scanning electron microscopy (SEM, LV6010 JEOL) was used to examine the microstructures of the tested samples.

3.2 Testing conditions and procedures

The cubic soil-cement-slag samples with various LF slag contents were prepared and repeatedly tested in the laboratory. The effect of LF slag on the compressive strength of soil-cement samples was investigated under different curing times at 7 days, 14 days, and 28 days, respectively. To understand the effect of LF slag in the compressive strength development of soil-cement samples, this research was carried out under the conditions of LF slag replacement and LF slag addition as described below.

3.2.1 LF slag replacement

In this section, the replacement of cement by the LF slag was investigated to decrease the cement content in the soil-cement samples. Each cement powder and LF slag ratio were adjusted within the overall quantity of 20 by weight of dry soil sample. The compressive strength of soil-cement-slag samples was compared with the original soil-cement samples without LF slag. The conditions of LF slag replacement were studied by 3-testing conditions as given here and summarized in Table 1.

1. Soft clay was mixed with cement in the ratio of 20% by weight of dry soil sample (20C).
2. Soft clay was mixed with cement and LF slag in the ratios of 15% and 5% by weight of dry soil sample, respectively (15C-5SL).
3. Soft clay was mixed with cement and LF slag in the ratios of 10% and 10% by weight of dry soil sample, respectively (10C-10SL).

3.2.2 LF slag addition

In this section, the effect of LF slag addition on the compressive strength of soil-cement samples was investigated by varying the ratio of LF slag in the soil-cement samples. The dry soil sample and cement in the ratio of 20 wt% were fixed. The conditions of LF slag addition were studied by 3-testing conditions as given here and summarized in Table 1.

1. Soft clay with 20 wt% cement samples was mixed with LF slag in the ratio of 5% by weight of the total dry sample (20C-5SL).
2. Soft clay with 20 wt% cement samples was mixed with LF slag in the ratio of 10% by weight of the total dry sample (20C-10SL).
3. Soft clay with 20 wt% cement samples was mixed with LF slag in the ratio of 20% by weight of the total dry sample (20C-20SL).

Table 1 The conditions of testing samples

Condition names	Soft Clay (wt%)	Portland cement (wt%)	LF slag (wt%)
20C	80	20	-
15C-5SL	80	15	5
10C-10SL	80	10	10
20C-5SL	80	20	5
20C-10SL	80	20	10
20C-20SL	80	20	20

3.2.3 Testing procedure

The compressive strength was tested after different curing times at 7 days, 14 days, and 28 days. The precise dimensions of cubic samples were measured using Vernier caliper, and then taking into weight balance. The unconfined compressive strength (UCS) test of cubic soil-cement-slag samples was performed using a compressive strength test machine (UTM) with a shearing rate of 0.50 mm/min. The maximum load was recorded and calculate the compressive strength was calculated through the relation in Eq. (1). The samples after the strength test were examined the microstructures by SEM-EDS technique.

$$\text{Compressive strength} = \text{Maximum load} / \text{Area of load surface} \quad (1)$$

4. Results and discussion

4.1 Chemical and mineral compositions of raw materials

4.1.1 Ordinary Portland cement

From the XRF technique, the chemical composition of Portland cement was about 63 wt% lime or calcium oxide (CaO) as a major composition followed by 9 wt% silicon dioxide (SiO_2) as a minor component. The other trace oxide compounds belong to aluminum dioxide (Al_2O_3), magnesium oxide (MgO), sulfur trioxide (SO_3), potassium oxide (K_2O), and sodium oxide (Na_2O) as shown in Table 2. This is consistent with the mineral composition by the XRD technique shown in Fig. 2. The minerals in cement were identified by main mineralogical phases, which are dicalcium silicate (C_2S) and tricalcium silicate (C_3S), aluminate (C_3A), tetracalcium aluminoferrite (C_4AF), and gypsum ($CaSO_4{\bullet}2H_2O$) compounds. The C_2S, C_3S, C_3A, C_4AF compounds are well-known compositions to promote a hydration reaction between cement and water to form calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) in mixed cement samples (Kontoleontos *et al.* 2013).

4.1.2 Ladle finance slag

Compared to the cement powder, the major chemical composition of LF slag in Table 2 revealed approximately 90% CaO similar to the major eco-friendly composition in cement (Torres *et al.* 2020). The other trace compositions belong to Al_2O_3, SiO_2, MnO_2, and Fe_2O_3. Moreover, the heavy metal was not found in the LF slag that can confirm a

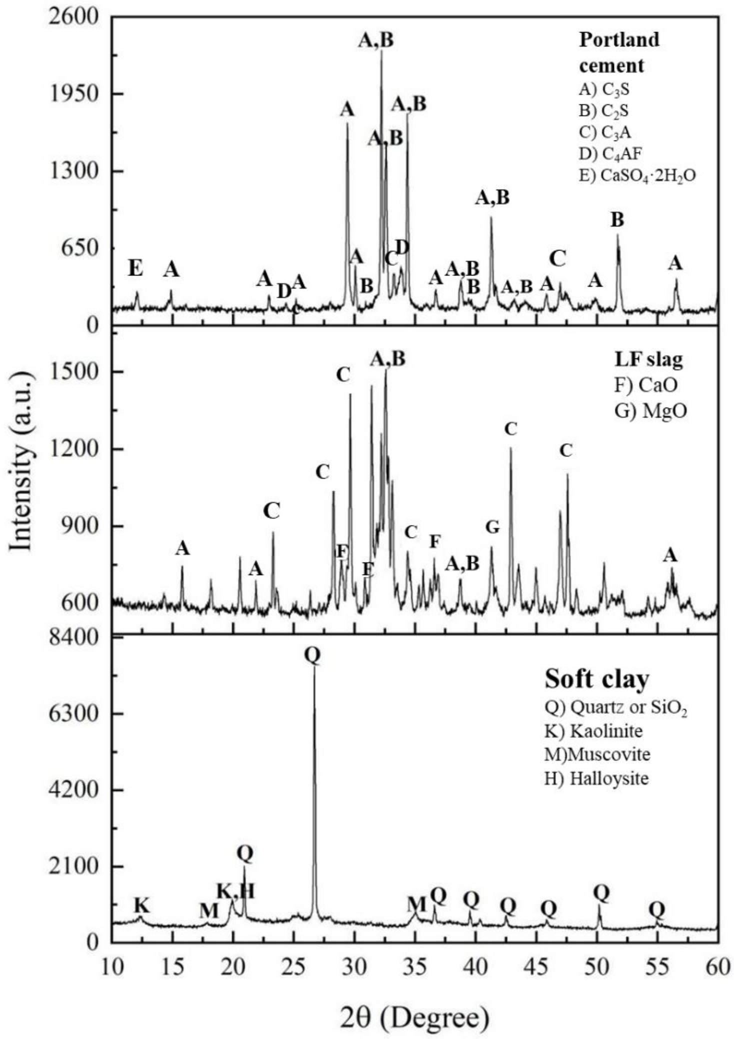


Fig. 2 XRD pattern of raw materials: Portland cement, LF slag and soft clay

non-toxic character of LF slag as reported previously by Maghool *et al.* (2017). The XRD was applied to present the diffraction pattern of LF slag as shown in Fig. 2. The minerals in LF slag were identified by the main mineralogical phases of C_2S, C_3S, and C_3A, which are the precursors of hydration reaction were similarly observed in cement. It also contains free lime (CaO) and MgO, which are different from cement powder.

4.1.3 Soft clay

The properties of soft clay were determined by the experimental program in the laboratory as follows: Atterberg's limits, density, XRD, and XRF. The Atterberg's limits were tested under ASTM D4318 (2005) to determine liquid limit (LL) and found to be 88.00%, while the density was approximately 2.18 g/cm^3. The chemical composition of soft clay in Table 2 revealed approximately 63 wt% SiO_2 and 19 wt% Al_2O_3 as major aluminosilicate compositions. Meanwhile, CaO, Fe_2O_3, TiO_2, MgO, SO_3, K_2O, and Na_2O are the other trace compositions found in soft clay. From Fig. 2, the quartz mineral or SiO_2 are predominantly detected in the soft clay following the chemical composition. An aluminosilicate clay minerals in form of kaolinite ($Al_2Si_2O_5(OH)_4$), muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$), and halloysite ($Al_2Si_2O_5(OH)_4$) were also presented in the soft clay.

Table 2 Chemical composition of Portland cement, LF slag, and soft clay

Compounds	Oxides (wt%)		
	Portland Cement	LF slag	Soft clay
Al_2O_3	1.60	1.88	19.18
SiO_2	9.45	4.74	63.43
CaO	62.70	90.73	0.92
MnO_2	-	0.33	-
Fe_2O_3	3.29	2.32	8.88
TiO_2	-	-	0.93
MgO, SO_3, K_2O, Na_2O	22.96	-	6.66

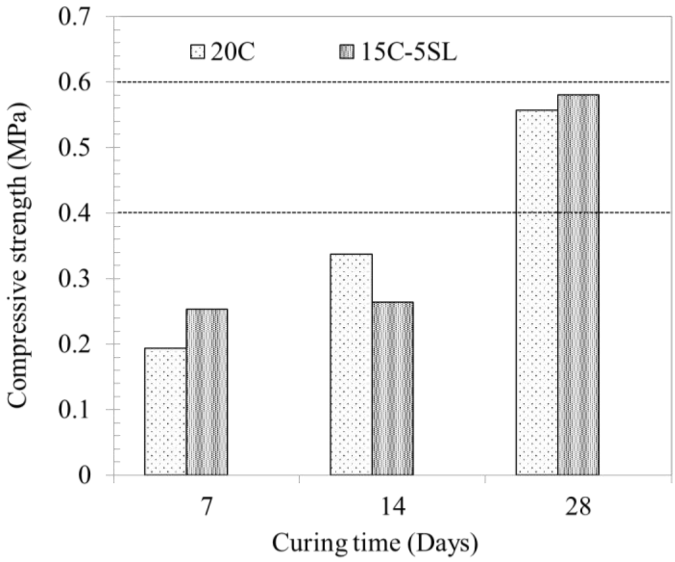


Fig. 3 Effect of LF slag replacement on the compressive strength of the 20-wt% cement-treated soil samples at different curing days

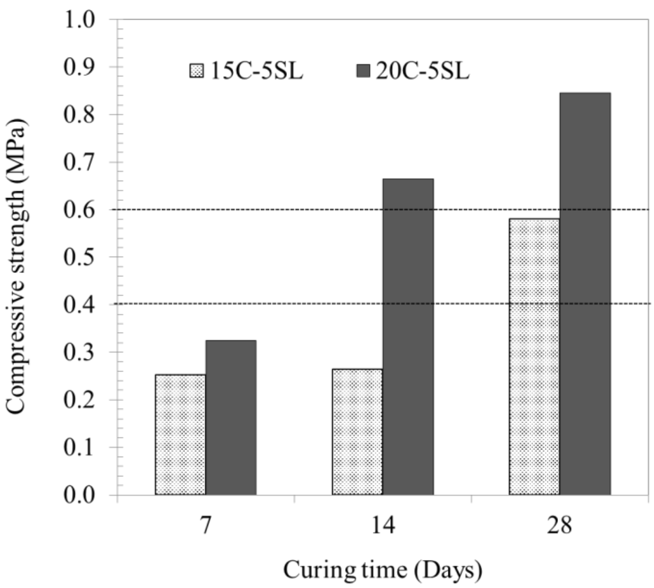


Fig. 4 Effect of 5-wt% LF slag mixing on the compressive strength of 15 wt% and 20 wt% cement-treated soil samples at different curing days

4.2 Compressive strength

4.2.1 LF slag replacement

Fig. 3 shows the compressive strength of LF slag replacement in the 20-wt% cement-treated soil samples at different curing days. The substitution of cement by LF slag was investigated to possibly reduce cement consumption and solve waste management. The compressive strength of 20C was 0.19 MPa, 0.34 MPa, and 0.56 MPa after curing for 7 days, 14 days, and 28 days, respectively. The compressive strength of 15C-5SL was 0.25 MPa, 0.26 MPa, and 0.58 MPa after curing for 7 days, 14 days, and 28 days, respectively. Meanwhile, the compressive strength of 10C-10SL cannot be presented because the samples are too soft to be tested by UCS.

From Fig. 3, the compressive strength of 20C and 15C-5SL samples increased with increasing curing time. The compressive strength development of the 20C samples continually increased with aging time. On the contrary, the compressive strength of 15C-5SL samples, in which cement was replaced by 5-wt% LF slag, was not much increased even the curing time went through 14-curing days. However, after 14-curing days, the compressive strength of 15C-5SL samples highly increased and become slightly higher than that of the 20C in 28-days curing. The difference in strength development within the first 14 curing days of 20C and 15C-5SL samples was explained by the difference in cement content, which was related to the early stage of hydration reaction. When the cement was replaced by LF slag in 15C-5SL, the very early stage of hydration become less powerful

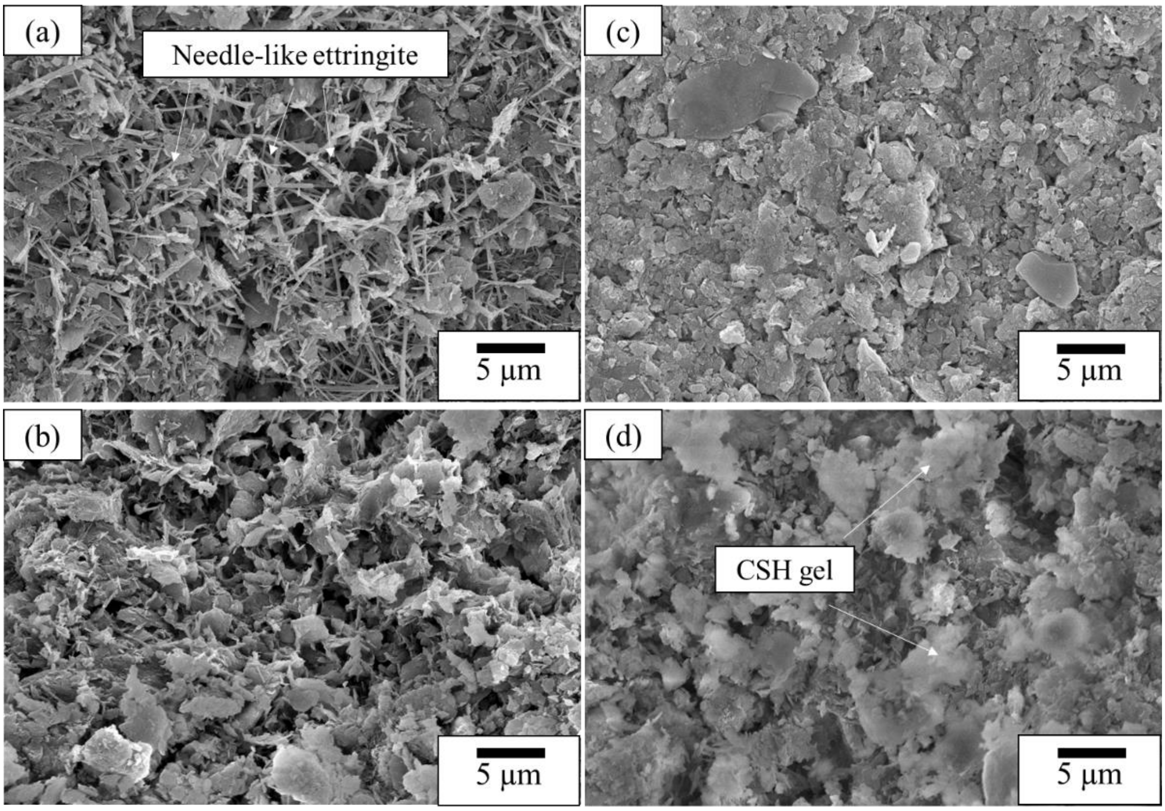


Fig. 5 Microstructures of 15C-5SL and 20C-5SL samples at 7 and 28 days of incubation: (a) 15C-5SL/7 days, (b) 20C-5SL/7 days, (c) 15C-5SL/28 days and (d) 20C-5SL/28 days

due to the reduction in active cementitious phases (C_3S, C_2S) in cement (Termkhajornkit *et al.* 2014). Although the LF slag contained both C_3S and C_2S phases, the amount of these active phases was still less than those in cement powder as can be seen from the lower C_3S and C_2S peak intensities in LF slag (Fig. 2). Hence, the strength of 15C-5SL samples was not much changed in 14-days of curing compared to that of 20C samples. The strength of 15C-5SL samples increased quickly after 14-curing days due to the cement hydration followed by the hydration in LF slag to form the cementitious products (CSH and CAH) (Termkhajornkit *et al.* 2014).

However, the strength development in 15C-5SL samples was predominantly promoted by cement hydration. This was also confirmed by a non-rigid body after 28 curing days of 10C-10SL samples, in which the cement ratio was reduced to be equal to the LF slag ratio. These results could be implied that the cement content in the soil-cement mixed slag samples should be more than the slag content. Fig. 4 also confirmed the predominant effect of the cement hydration on the strength of the soil-cement mixed slag samples with the same LF slag content (5 wt%). An increase of cement content from 15 wt% to 20 wt% resulted in highly improved compressive strength of the soil-cement mixed 5 wt% slag samples to be higher than 0.4-0.6 MPa, which are the acceptable compressive strength values of soil cement reported by Standards Australia (2002). Thus, the cement content of about 20 wt% was strongly proposed to use in the soil-cement mixed slag samples.

Fig. 5 shows microstructures of 15C-5SL and 20C-5SL samples at 7 and 28 days of incubation. The ettringite with a needle-like shape is generally formed at the early ages (≤ 7 days) of hydration and normally disappeared as the cement hydration continues beyond 7 days (Wu *et al.* 2020). However, the full of ettringite was observed in the 15C-5SL samples at 7 days of incubation, (Fig. 5(a)), and remained at ages 28 days together with the CSH phase (Fig. 5(b)). On the contrary, there was no needle-like ettringite product in the 20C-5SL samples at 7 days of curing (Fig. 5(c)). Meanwhile, the CSH was the predominant cementitious product for 20C-5SL samples at 28 days of incubation (Fig. 5(d)). This result confirms the higher strength of the 20C-5SL samples than that of 15C-5SL at ages 28 days.

4.2.2 LF slag addition

Effect of LF slag addition was performed by adding the LF slag to the original soil-cement sample (20C) in the quantity range of 5wt% (20C-5SL), 10wt% (20C-10SL), and 20 wt% (20C-20SL). The curing in the plastic wrapping was carried out on these samples for 7, 14, and 28 days. The development of compressive strength of these soil-cement added slag samples is shown in Fig. 6. The compressive strength of soil-cement added slag samples was increased as the time of incubation increased. The compressive strength of 20C samples was 0.19 MPa, 0.34 MPa, and 0.56 MPa for 7 days, 14 days, and 28 days of curing, respectively. The compressive strength of 20C-5SL was 0.39 MPa, 0.66 MPa, and 0.85 MPa for 7 days, 14 days and, 28 days, respectively. The compressive strength of 20C-10SL was 0.47 MPa, 0.61 MPa, and 0.80 MPa, meanwhile the compressive strength of 20C-20SL was 0.24 MPa, 0.36

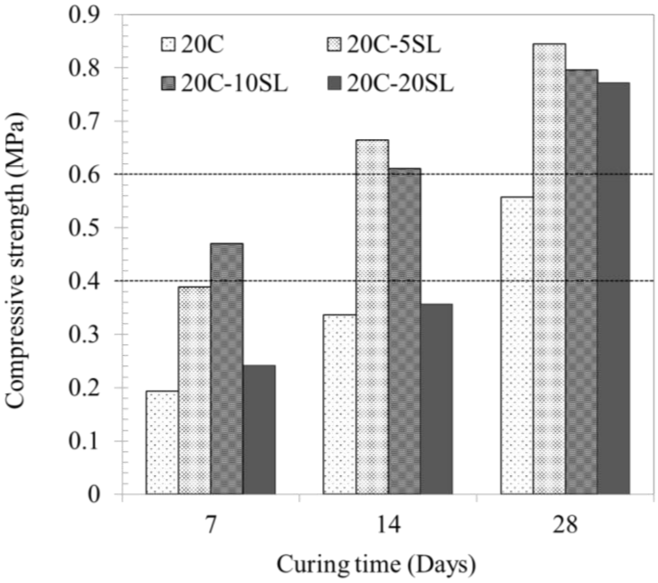


Fig. 6 Effect of LF slag addition on the compressive strength of the 20-wt% cement-treated soil samples at different curing days

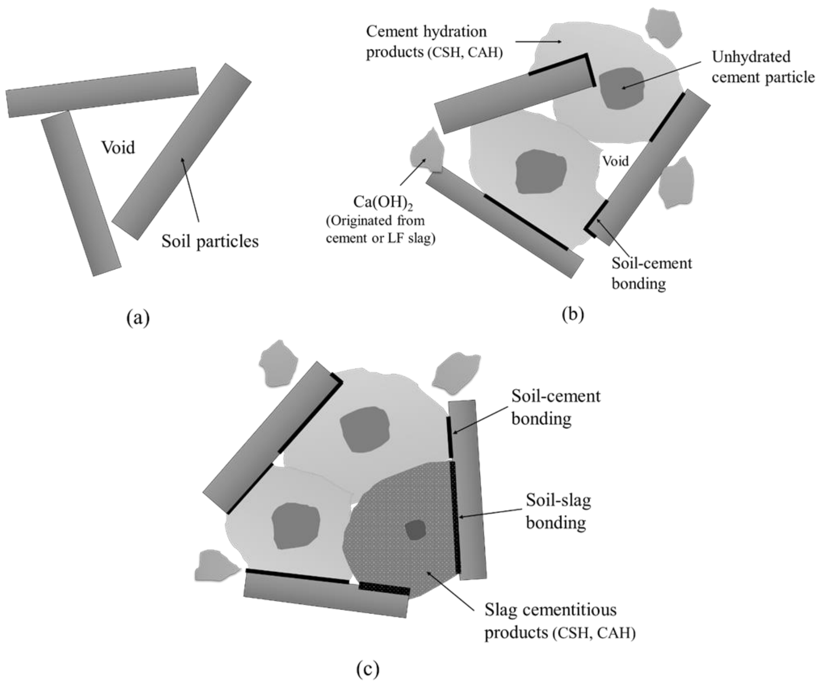
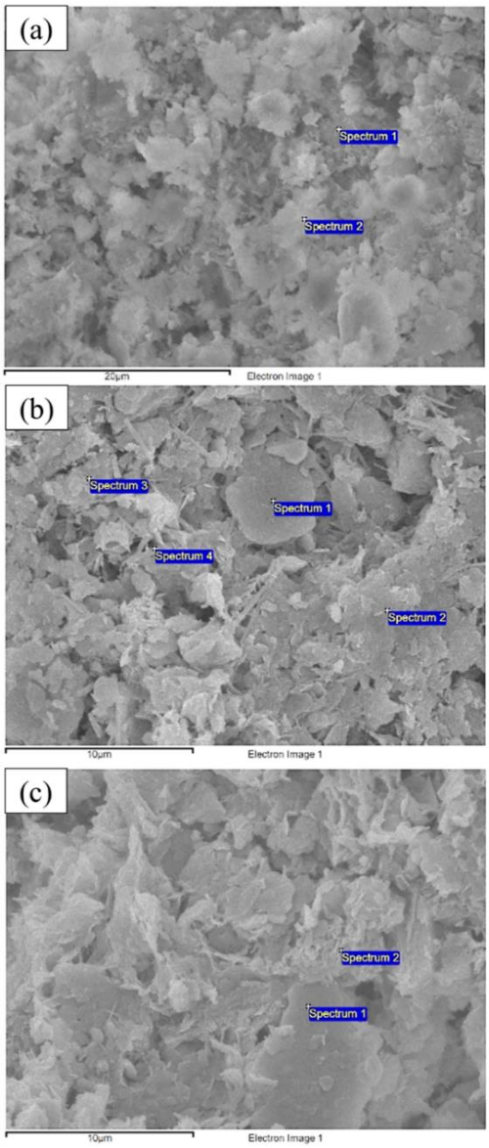


Fig. 7 Schematic models showed possible hydration reaction in soil samples: (a) without any additives, (b) with cement, and (c) with cement and LF slag

MPa, and 0.77 MPa for 7 days, 14 days and, 28 days, respectively.

In comparison to the 20C samples, the strength of all soil-cement samples was enhanced with the addition of LF slag (Fig. 6). The compressive strength of soil-cement samples increased more quickly in the period of 7 to 14 days incubation when 5 wt% and 10 wt% LF slag were added to the soil-cement samples. The compressive strength of the 20C-10SL samples touched the acceptable range of strength (0.4-0.6 MPa) within 7 days of incubation. Both compressive strength of 20C-5SL and 20C-10SL samples got beyond the acceptable practical values to ~0.8 MPa in 28 days of incubation (Standards Australia 2002).

From Fig. 6, however, the tendency of compressive strength was found to be reduced with LF slag content. Especially when the hydration shifted to the stage after 7-days of incubation. This can be seen that the strength development rate in 20C-20SL samples was relatively low compared to that of 20C-5SL and 20C-10SL samples. Lin and Meyer (2009) were previously reported that the water



(d)

Processing option : All elements analysed (Normalised)

Spectrum	In stats.	O	Al	Si	Ca	Au	Total
Spectrum 1	Yes	32.64	9.46	16.78		41.12	100.00
Spectrum 2	Yes	52.19	5.82	12.82	10.49	18.69	100.00

(e)

Processing option : All elements analysed (Normalised)

Spectrum	In stats.	O	Al	Si	Ca	Au	Total
Spectrum 1	Yes	30.18	10.49	15.69	1.49	42.15	100.00
Spectrum 2	Yes	39.14	6.64	14.65	2.98	36.61	100.00
Spectrum 3	Yes	30.35	2.10	25.68	3.37	38.49	100.00
Spectrum 4	Yes	30.68	9.17	14.37	12.78	32.99	100.00

(f)

Processing option : All elements analysed (Normalised)

Spectrum	In stats.	O	Al	Si	Ca	Au	Total
Spectrum 1	Yes	15.96	9.37	11.42	2.13	61.12	100.00
Spectrum 2	Yes	22.94	4.87	7.53	9.79	54.87	100.00

Fig. 8 SEM-EDS analysis on the soil-cement samples with different LF slag additions at 28 days of incubation: (a) 20C-5SL, (b) 20C-10SL and (c) 20C-20SL

to cement ratio has a small effect on the early stage of hydration rate, but after the middle period of hydration, the lower water to cement ratio could lead to a lower hydration rate. The addition of 20-wt% LF slag thus resulted in lower compressive strength of soil-cement samples. This was also similar to the study by Bo *et al.* (2019) that revealed the decrease of soil-cement strength with the increase of LF slag. When the content of fine slag particles was as high as the same of cement particles, the mixed water was partially absorbed by slag particles, and therefore the remained water was not enough for the hydration reaction with cement.

4.3 Possible mechanism of compressive strength improvement in soil-cement mixed slag

Soil or clay is generally defined as the natural loose surface material that possesses small voids to retain water causing expansion and shrinkage (Fig. 7(a)). It tends to soften and liquefy when exposed to water in high quantity that makes construction difficult due to its low strength and stiffness (Obianigwe and Ngene 2018). When cement is deeply mixed into the soft clay layer, the soil strength in the construction area can be improved through a hydration reaction between the cement and water in the soft clay layer (Fig. 7(b)). This reaction forms calcium silicate hydrate (CSH) compounds and calcium aluminate hydrate (CAH) as cementitious products, which act as the "glue" between adjacent clay or soil particles to make them more compact and reduce voids for the permeability of water and soil swelling, leading to an increase of compressive strength (Sargent 2015, Chaiyaput and Ayawanna 2021b). Moreover, when LF slag was added to the soil-cement of Samutprakarn soft clay, the strength of soft clay was further improved to be higher than the acceptable value (0.6 MPa) of the soil cement. This is because the addition of LF slag having similar compositions compared to cement leads to more reaction with water to form CSH and CAH (Wu *et al.* 2020). This can increase bonding between soil particles and increase the strength of the soil-cement samples (Fig. 7(c)). However, the hydration reaction with LF slag is not as fast as in cement due to the main precursors of hydration reaction (C_3S, C_2S, C_3A) in LF slag is less than in cement (Yishun *et al.* 2020). Therefore, the development of compressive strength in soil-cement mixed slag samples was rapidly enhanced in the curing period of 14 to 28 days. The result showed that the compressive strength of the soil-cement of soft clay in the Samutprakarn area is 796 kPa after 28 days, which shows the possibility of using steel slag waste in the construction of soil cement.

SEM analysis of the soil-cement samples with different LF slag additions at 28 days of incubation is shown in Fig. 8. The microstructures from SEM analysis showed that the 28 days of curing samples were mostly connected into a whole by the CSH gel, especially in the 20C-5SL samples (Fig. 8(a)). There were some white particles of unequal size and irregular shape on the surface. The existence of needle-like ettringite and flake Ca(OH)2 cannot be found in 20C-5SL samples, but there were remained some in the 20C-10SL (Fig. 8(b)) and 20C-20SL samples (Fig. 8(c)). The 20C-5SL samples thus showed relatively high compactness accompanied by high strength compared to those of 20C-10SL and 20C-20SL samples.

The above hydration products were confirmed by the SEM-EDS in Figs. 8(d)-8(f). From Fig. 8(d), the main substance in the area of spectrum 2 was CSH (CAH) gel compared to a nearby area. The Ca/Si of the CSH gel of the hydration 20C-5SL sample for 28 days was about 0.82. In Fig. 8(e), the loose accumulated flake Ca(OH)2 grew into a thick and dense block and was closely bound to the CSH (CAH) gel. Acicular ettringite grew in a small number of voids. As shown in the EDS spectrum and morphology, there were still reactive residues in samples after curing for 28 days. The EDS energy spectrum 4 was the hydration product in the CSH (CAH) gel, and its Ca/Si was about 0.89. In the SEM-EDS of 20C-20SL in Fig. 8f, there were evident traces of reactive dissolution in spectrum 1, which was mainly composed of CSH gel and unhydrated aluminosilicate minerals. Spectrum 2 was flocculent CSH (CAH), and the Ca/Si was about 1.30. It can be seen that with the increment of LF slag content, the Ca/Si ratio increased possibly due to the high CaO content from LF slag, and late increased hydration activity at age of 28 days (Yongjia et al. 2013). The development of compressive strength in 20C-20SL samples was thus rapidly enhanced in the age after 14 days, and finally got beyond the acceptable strength value (0.6 MPa) at the age 28 days of curing. Therefore, there is possible to use LF slag waste up to 20 wt% in the construction of soil cement with the 28-days of incubation.

5. Conclusions

The ladle furnace (LF) slag was studied as a stabilizing material to improve the compressive strength of the original soil cement. The conditions of LF slag replacement were investigated to reduce the cement consumption by replacing LF slag waste. LF slag addition was investigated to compare the strength development of original soil cement. The finding from this research showed that incorporating slag into cement could improve the strength of soil cement to be much higher than the standard acceptable value (0.6 MPa). This is because the mixing of LF slag leads to forming slag-cementitious material from more reaction and hence increase bonding between soil particles, and further increase the strength of the soil-cement. However, the incorporation of LF slag either as a replacement material or an additive material in soil cement, the ratio of LF slag to cement should be less than 1, while the cement content should be more than 10 wt% in the soil-cement samples. This is to prevent the partially absorbed water on slag particles and remain enough water content for serving a predominant effect of the cement hydration. This research offers the possibility to carry steel slag, which is an industrial waste to be used in the construction of soil cement.

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