Soft clay stabilization using ladle slag-ground granulated blastfurnace slag blend

Xu, Bo; Yi, Yaolin

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Corresponding Author: Dr. Yaolin Yi, Ph.D.

Corresponding Author's Institution: Nanyang Technological University

First Author: Bo Xu

Order of Authors: Bo Xu; Yaolin Yi, Ph.D.

Abstract: Ladle furnace basic slag (ladle slag, LS) is a by-product of the steel refining process. There is a great amount of LS generated worldwide every year and the current solution is simply landfilling it, which causes both economic and environmental issues. This study attempts to use LS to activate ground granulated blastfurnace slag (GGBS) for stabilization of soft clay, as well as immobilization of heavy metals in LS. The LS-GGBS-stabilized clays with different binder contents and LS:GGBS ratios were cured for different periods, and then subjected to unconfined compressive strength (UCS) test, leaching test, and X-ray diffraction (XRD). The results indicated that the LS-GGBS-stabilized clays with LS:GGBS ratio of 2:8-5:5 could achieve similar or higher UCS compared to ordinary Portland cement-stabilized clay after 56 days of curing. The leaching of potential heavy metals was not detected for the LS-GGBS stabilized clays. According to XRD analysis, the main hydration products of LS-GGBS-stabilized clay were calcium silicate hydrates (CSH) and ettringite, which were responsible for the strength development of LS-GGBS-stabilized clays.

Suggested Reviewers: İrem Zeynep Yıldırım PhD
Assistant Professor, MEF University
yildirimz@mef.edu.tr
Expert in this area

Ningjun Jiang PhD
Assistant Professor, University of Hawai'i at Manoa
jiangn@hawaii.edu
Expert in this area

Cheng Lin PhD
Assistant Professor, University of Victoria
chenglin918@uvic.ca
Expert in this area

Amelia Md Som PhD
Senior Lecturer, University Kuala Lumpur

ameliamds@unikl.edu.my
Expert in this area

Response to Reviewers: The authors sincerely appreciate the Editor's and Reviewers' comments. The responses to the comments are detailed below. The line numbers noted in the authors' responses correspond to those in the "Revised manuscript_changes marked", where the changes are made in revised manuscript (marked with red). A clean version of revised manuscript entitled "Revised manuscript_clean version" is also provided.

COMMENTS FROM EDITOR AND/OR REVIEWERS:

The conclusions have to stand alone. Hence, all the acronyms appearing should be explained again the first time they are mentioned in the Conclusions.

Response:

The acronyms in the Conclusions, including GGBS, LS, OPC, UCS, XRD and CSH, have all been explained in the revised manuscript, as follows:

"Ladle slag (LS) could provide a high pH environment to accelerate the ground granulated blastfurnace slag (GGBS) hydration for soft clay stabilization." (Lines 217-218).

"After 56 days, the LS-GGBS-stabilized clays with LS:GGBS ratio of 2:8-5:5 could achieve similar or higher unconfined compressive strength (UCS) compared to the corresponding ordinary Portland cement (OPC)-stabilized clay." (Lines 221-223).

"The X-ray diffraction analysis indicated that the Ca(OH)_2 in LS was the main mineral for activation of GGBS. The main hydration products of LS-GGBS-stabilized clay were calcium silicate hydrates (CSH) and ettringite." (Lines 229-231).

L228: XRD gives mineral composition, so please, do not refer to Ca(OH)_2 as a "chemical"

Response:

The "chemical" has been revised to "mineral" as suggested, as follows:

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The acronyms in the Highlights have to be explained

Response:

The acronyms in the Highlights have been explained as suggested.

Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:

Data will be made available on request

Cover letter

Dear Editor,

Please, find attached revised manuscript entitled “Soft clay stabilization using ladle slag-ground granulated blastfurnace slag blend” which I would like to submit to Applied Clay Science as a Technical Note on behalf of myself as well as the co-authors.

This manuscript is revised according to the Editor’ comments. Every comment has been addressed as detailed in the “Revision Notes” and “Revised manuscript_changes marked”. The authors would like to take the chance to sincerely thank the Editor’s hard work, which significantly improved the quality of the manuscript.

Should you need to contact me, please via e-mail at yiyaolin@ntu.edu.sg

Yours Sincerely

Yaolin Yi

Revision Notes

The authors sincerely appreciate the Editor’s and Reviewers’ comments. The responses to the comments are detailed below. The line numbers noted in the authors’ responses correspond to those in the “**Revised manuscript_changes marked**”, where the changes are made in revised manuscript (**marked with red**). A clean version of revised manuscript entitled “**Revised manuscript_clean version**” is also provided.

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1 **Soft clay stabilization using ladle slag-ground** 2 **granulated blastfurnace slag blend**

3 Bo Xu and Yaolin Yi*

4 School Civil and Environmental Engineering, Nanyang Technological University,
5 Singapore. *Corresponding: yiyaolin@ntu.edu.sg

6 **Abstract:** Ladle furnace basic slag (ladle slag, LS) is a by-product of the steel refining
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21 **Keywords:** Soft clay stabilization; Ladle slag; Ground granulated blastfurnace slag;
22 Strength; Heavy metal.

1 Introduction

The ladle furnace basic slag (ladle slag, LS), is a by-product produced in the stage of the steel refining process (Setién et al., 2009). There are around 30 million tons of LS produced worldwide per year (Mahoutian and Shao, 2016); the current solution is simply landfilling it, which is costly and not sustainable.

The properties of LS vary with the steel refining procedure to obtain the desired steel grade, but the main chemical and mineral compositions are similar. The LS is constituted of CaO, SiO₂, Al₂O₃, and MgO. The main minerals of LS are portlandite (Ca(OH)₂), fluorite (CaF₂), calcite (CaCO₃), mayenite (Ca₁₂Al₁₄O₃₃, C₁₂A₇), merwinite (CaMg(SiO₃)₂), brucite (Mg(OH)₂), larnite (β-Ca₂SiO₄, β-C₂S), and belite (γ-Ca₂SiO₄, γ-C₂S) (Shi, 2002; Monkman et al., 2009; Tossavainen et al., 2007; Yildirim and Prezzi, 2011; Adolfsson et al., 2011; Bignozzi et al., 2013). Due to the presence of γ-C₂S, LS was reported as a weak cementitious material (Shi and Hu, 2003). Another concern is the potential leaching of heavy metals from LS. Some elements, such as Cr, Mn, Cd, Zn, Cu, and Pb, were detected in LS by previous studies (Setién et al., 2009; Yildirim and Prezzi, 2011; Adolfsson et al., 2011), which may be leached out from LS and causes environmental pollution. Hence, it is difficult to directly use LS as a binding material in civil engineering.

Nevertheless, some scholars attempted to recycle LS into soil stabilization. Manso et al. (2005, 2013) blended LS with electric arc furnaces (EAF) slag and lime as binders for soil stabilization and achieved acceptable strength. But it was not clear whether LS played the key role for hydration reaction. Kanagawa and Kuwayama (1997) found

that using LS alone for treating soft clay could improve soil behavior, indicating the high cementitious properties of LS. However, Ortega-López et al. (2014) pointed out that the hydration properties of LS depended on the chemical compositions which varied with the steelmaking process.

Hence, it is necessary to find alternative ways to exert the chemical and mineral properties of LS for soil stabilization and reduce the leaching of heavy metals from LS. It is worth noting that the presence of lime (CaO and Ca(OH)_2) and magnesia (MgO) in LS may enable it as an alkali activator to activate other binding materials, e.g. ground granulated blastfurnace slag (GGBS), for soil stabilization. GGBS is a by-product produced from the blast furnace ironmaking and well known as a ‘green binder’, in terms of low energy consumption and low emission of CO_2 (Higgins, 2007). GGBS was proved to be efficient for soil stabilization when activated by lime, magnesia, and carbide slag (Yi et al., 2015a, 2015b, 2016a).

This study investigated the utilization of LS-GGBS blend for soft clay stabilization, where the LS was intended to activate the GGBS for stabilization of soft clay, as well as immobilization of heavy metals in LS. The stabilized clays with different binder contents and LS:GGBS ratios were cured at different periods and tested for UCS and leaching of heavy metals. The mineral properties of stabilized clays were also studied using X-ray diffraction (XRD).

2 Materials and methods

The LS used was generated in Singapore, and the GGBS was purchased from EnGro Corporation Limited, Singapore. Ordinary Portland cement (OPC), grade 42.5, was

used as the control binder, which was also purchased from EnGro Corporation Limited. A kaolin clay, with a liquid limit of 58% and plastic limit of 23% (ASTM, 2017), was used as an artificial soft clay, which was obtained from International Scientific Private Limited, Singapore. The chemical properties were analyzed by X-ray fluorescence (XRF), as shown in Table 1. The mineral compositions of LS, GGBS, and kaolin clay determined by XRD were provided in Fig. 1. Due to different types of steel scrapes were recycled as raw materials for steelmaking (Varga et al., 2016), heavy metals such as Zn, Pb, Mn, Cr, and Cu in LS were all detected. Thus, the leaching of these heavy metals needs to be concerned when using LS in soil stabilization.

LS was firstly dried in an oven at 105°C and passed a 300 µm sieve. The water content, defined as the mass of water over the mass of dry clay, of natural soft clay below ground water table is usually close to its liquid limit (Bergado et al., 1996; Kitazume and Terashi, 2013); hence, a water content of 60% was used in this study, which was close to the liquid limit of the kaolin (58%). The binders were added into clay without additional water to simulate the dry jet mixing method for soft clay stabilization. The testing program was shown in Table 2. Two binder contents, mass of binder over dry clay of 20% and 30% or mass of binder over volume of saturated clay of 203 kg/m³ and 305 kg/m³, were selected in this study, which was based on the practical application in Singapore (Tan et al., 2002; Xiao and Lee, 2008), where cement content used were from 10% to 30%. Different LS:GGBS ratios (by mass), including 0:10 (pure GGBS), 2:8, 3:7, 4:6, 5:5, 6:4, 7:3, 10:0 (pure LS), were studied.

The specimen preparation procedure attempted to simulate the mixing effect of in-situ dry jet mixing method by using a laboratory mixer. In order to achieve homogeneous clay-binder mixture to reasonably compare the effectiveness of different binders, the dry kaolin and binders were homogenized in a mixer for 10 minutes, and then the water was added, and the mixture was subjected to mixing for another 10 minutes. The mixture was filled in the cylindrical mold with a height of 10 cm and a diameter of 5 cm in three layers. The molds were tapped against a table by hand for 50 times for each layer to remove air bubbles. Because the soft clay used in this study has a high water content of 60%, higher than its liquid limit (58%), so the clay-binder mixture is very soft and the compaction would not affect much on the sample density except for the air pocket removal. The specimens were then cured in a moist room with temperature of 26°C and relative humidity of 100% for 14, 28, 56, and 112 days. Song et al. (2000) suggested that GGBS was primarily activated in the early stage and its strength could be developed rapidly when the initial pH was higher than 11.5; hence, the initial pH of binder-soil mixture was measured in this study according to ASTM D4972-18 (2018). 10 g dry sample was prepared by mixing kaolin with different ratios of LS and GGBS. 10 mL water was added into the dry sample, which was mixed and then rested for 1 hour before measured by the Laqua pH 1100 meter. The UCS was tested in triplicate with the vertical load applied at a constant displacement rate of 1 mm/min until failure. The crushed specimens were then grounded to pass 2 mm sieve and then soaked into alcohol to stop hydration reactions. These samples were also dried in the vacuum freeze-drying machine for 48 hours,

which were tested for XRD. XRD was performed on Bruker D8 X-ray diffractometer using Cu K α radiation, the 2 θ started at 5° and stopped at 60°. The dwelling time is 2 s/step with a step size of 0.05° and slit width is 0.49. The leaching test was conducted for 14- and 112-day stabilized clays according to one stage batch test (BS EN12447-22002). The crushed specimens and distilled water, with a liquid to solid ratio of 10 L/kg, were placed in a polypropylene bottle. The bottle was rotated with a tumbler (10 rpm) for 24 h. The leachate was then filtered by a vacuum filtration device. As Cr, Mn, Zn, Cu, and Pb are the main heavy metal elements, the leachates of these elements were then analyzed by the inductively coupled plasma optical emission spectrometer (ICP), PerkinElmer Optima 8300 ICP-OES.

3 Results and Discussion

3.1 Initial pH

The initial pH of LS-GGBS-stabilized clay was presented in Table 3. The pH of pure LS was 12.5, which was close to the pH of saturated Ca(OH)₂ (Ma and Brown 1997). The initial pH of pure LS-stabilized clay was also 12.5 for both 20% and 30% binder contents, although the pH of clay was 4.39. This indicated that LS could provide a strong alkaline environment in the soil. According to Song et al. (2000), when the initial pH was above 11.5, GGBS was activated in the early stage and its strength could be developed rapidly; the alkaline environment would lead to the breaking of Si-O and Al-O bond of GGBS, facilitating the formation of hydration products (Ouf, 2001; Ouhadi and Yong, 2003). Hence, Table 3 implied that the addition of LS could accelerate the hydration of GGBS and strength development of stabilized clay. From

Table 3, the initial pH of the stabilized clays could be higher than 11.5 when the LS:GGBS ratios were higher than 5:5 and 3:7 for 20% and 30% binder contents, respectively.

3.2 Unconfined Compressive Strength

The UCS of LS-GGBS-stabilized clay was plotted against the LS:GGBS ratio in Fig. 2 and Fig.3. The pure LS-stabilized clays showed negligible strength at the four ages, confirming that LS was a weak hydration material. The pure GGBS-stabilized clays also yielded negligible strength at 14 days, but achieved considerable strength after 28 days for 30% binder content or 56 days for 20% binder content, confirming GGBS had certain hydration property. LS could increase the strength development rate of GGBS, e.g. stabilized clays with LS:GGBS ratios of 2:8-5:5 all yielded higher UCS than the pure GGBS-stabilized clay with the same binder content at 14, 28, and 56 days.

At 14, 28, and 56 days, the UCS of LS-GGBS-stabilized clay first increased with the increase of LS:GGBS ratio, and then decreased (Fig. 2 and Fig. 3). This was because a high LS:GGBS ratio facilitated the strength development of stabilized clay, but also reduced the GGBS content, which dominated the total quantity of hydration products. This trend was similar to those of marine clay stabilized by GGBS activated by lime and MgO with lime:GGBS or MgO:GGBS from 0.05 to 0.4 at 7, 28, and 90 days (Yi et al., 2015b, 2016a). At the early age, the effect of LS, like lime and MgO, was more pronounced, as suggested by Song et al (2000), the initial pH needed to be above 11.5 to effectively activate the GGBS. From Fig. 2 and Fig. 3, the optimum LS:GGBS

ratios for the highest 14-, 28-, and 56-day UCS were 5:5, 4:6, and 4:6 for 20% and 30% binder contents, which were close to the LS:GGBS ratios (5:5 and 3:7) to achieve initial pH higher than 11.5 as shown in Table 3. However, the optimum lime:GGBS and MgO:GGBS ratios at all ages in previous studies (Yi et al., 2015b, 2016a) were far lower than the optimum LS:GGBS ratio in this study, indicating that LS had lower activating efficacy than lime or MgO. This was because the Ca(OH)_2 and MgO content in LS was not very high. In Yi et al. (2015b, 2016a), the highest UCS of lime-GGBS- and MgO-GGBS-stabilized clays with 30% binder content both yielded around 1700 kPa at 28 days, which was lower than the highest UCS (2483 kPa) of LS-GGBS stabilized clay. The strength difference should be mainly due to the different soil types; the soils used in previous studies (Yi et al., 2015b, 2016a) were natural marine sediments which had different mineral compositions, although the liquid limit and water content were similar as those in this study. At 112 days, the UCS of LS-GGBS-stabilized clay did not change when LS:GGBS ratio increased from 0:10 to 2:8, and then decreased when LS:GGBS ratio further increased, indicating the GGBS itself could hydrate adequately to produce high strength in the long term.

Compared to OPC, the optimum LS-GGBS produced lower strength at 14 and 28 days, as shown in Fig. 2 and Fig. 3. This should be due to that the Ca(OH)_2 content in LS was not very high. Additionally, the Zn and Pb in LS might also retard the strength development of stabilized clay (Komonweeraket et al., 2015). Nevertheless, after 56 days, the LS-GGBS-stabilized clays with LS:GGBS ratio of 5:5-2:8 achieved higher

UCS than that of OPC; this was still useful for practical applications, e.g. deep mixing for soft ground improvement, for which 56-day UCS could be used as the design strength (Kitazume and Terashi, 2013). If the LS:GGBS with a ratio of 5:5 is used to replace OPC for soft clay stabilization, it will reduce at least half of the binder cost, while achieves similar or higher design strength.

3.3 Leaching Test

The leaching test results of LS-GGBS-stabilized clays at 14 and 112 days were presented in Table 4, expressed as mg/L. Only Zn and Pb with relatively low concentrations were leached out as shown in Table 4. The leaching of Zn from raw LS was 2.12 mg/L, which was lower than the stand limit of non-hazardous wastes (5 mg/L) according to the Council Decision 2003/33/EC (EUR-Lex, 2003). The leaching of Pb (3.62 mg/L) lightly exceeded the non-hazardous wastes limit (1 mg/L). Generally, if more LS was added, the more quantities of heavy metal could be leached out. For instance, the leaching of Zn was 0.11 mg/L for 30% pure LS-stabilized clay at 14 days, which was larger than 0.02 mg/L for 20% pure LS-stabilized clay at 14 days (Table 4). However, the leaching of possible heavy metals was not detected in any of the LS-GGBS-stabilized clays, including the one with 30% LS:GGBS=7:3, which had a high LS content of 21%. This should be due to that LS-GGBS produced cementitious hydration products, such as calcium silicate hydrates (CSH), which could further immobilize the heavy metals by adsorption or co-precipitation, i.e. heavy metals substituted Ca^{2+} at CSH surface (Taylor, 1993; Andersen et al., 2003; Chen et al., 2009). Over all, the leaching test results confirmed that the leaching of

heavy metals was not a concern when LS-GGBS is used for soft clay stabilization.

3.4 X-ray Diffraction

The XRD patterns of 30% stabilized clay with LS:GGBS ratio of 5:5 at 0 and 112 days were shown in Fig. 4. The 0-day sample referred to the mixture of dry LS, GGBS, and clay without water (before hydration). Compared to the 0-day sample, it was evident that the intensity of Ca(OH)_2 decreased after curing for 112 days, indicating that the Ca(OH)_2 was consumed due to activation of GGBS. The mechanisms of LS for GGBS activation was based on the alkali activation, which was similar to that of lime (Yi et al., 2016a). A strong alkaline environment was provided in the soil (Table 3), which led to the breaking of Si-O and Al-O bond of GGBS, facilitating the formation of hydration products (Ouf, 2001; Ouhadi and Yong, 2003). It was found that CSH and ettringite were produced from the LS-GGBS hydration, which was commonly detected in Ca(OH)_2 -GGBS-stabilized clays (Nidzam and Kinuthia, 2010; Yi et al., 2014a, 2015c, 2015d). Additionally, a reflection of Ca(OH)_2 was still detected at 112 days, indicating that the Ca(OH)_2 content in LS-GGBS stabilized clay (LS:GGBS=5:5) was excessive for activation of GGBS.

4 Concluding Remarks

The following conclusions can be obtained based on the analysis above.

1. **Ladle slag (LS)** could provide a high pH environment to accelerate the **ground granulated blastfurnace slag (GGBS)** hydration for soft clay stabilization. The addition of LS could increase the strength development rate of GGBS-stabilized

clay; however, excess high LS:GGBS ratio also decreased the final strength of stabilized clay. After 56 days, the LS-GGBS-stabilized clays with LS:GGBS ratio of 2:8-5:5 could achieve similar or higher **unconfined compressive strength (UCS)** compared to the corresponding **ordinary Portland cement (OPC)**-stabilized clay.

2. The leaching of potential heavy metals was not detected for the LS-GGBS stabilized clays. These results indicated that the LS-GGBS blend could potentially replace OPC for soft clay stabilization applications (e.g. deep mixing for soft ground improvement), which could reduce the cost for both soft clay stabilization and landfilling LS.

3. The **X-ray diffraction** analysis indicated that the $\text{Ca}(\text{OH})_2$ in LS was the main **mineral** for activation of GGBS. The main hydration products of LS-GGBS-stabilized clay were **calcium silicate hydrates (CSH)** and ettringite.

4. It should be emphasized that natural soft clays have different properties (e.g. water content and minerals) compared to the artificial kaolin clay used in this study. Hence, it is necessary to experimentally determine the exact design parameters (e.g. LS:GGBS ratio and UCS) for a specific soft clay, for which the results in this study can be used as references.

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333

334 **Figure captions**

335 Fig. 1 X-ray diffraction (XRD) of kaolin, ladle slag (LS), and ground granulated
336 blastfurnace slag (GGBS)

337 Fig. 2 Unconfined compressive strength (UCS) of stabilized clay with 20% binder
338 content

339 Fig. 3 Unconfined compressive strength (UCS) of stabilized clay with 30% binder
340 content

341 Fig. 4 X-ray diffraction (XRD) of 30% ladle slag (LS):ground granulated blastfurnace
342 slag (GGBS)=5:5-stabilized clay at 0 and 112 days

1 **Soft clay stabilization using ladle slag-ground**
2 **granulated blastfurnace slag blend**

3 Bo Xu and Yaolin Yi*

4 School Civil and Environmental Engineering, Nanyang Technological University,
5 Singapore. *Corresponding: yiyaolin@ntu.edu.sg

6 **Abstract:** Ladle furnace basic slag (ladle slag, LS) is a by-product of the steel refining
7 process. There is a great amount of LS generated worldwide every year and the
8 current solution is simply landfilling it, which causes both economic and
9 environmental issues. This study attempts to use LS to activate ground granulated
10 blastfurnace slag (GGBS) for stabilization of soft clay, as well as immobilization of
11 heavy metals in LS. The LS-GGBS-stabilized clays with different binder contents and
12 LS:GGBS ratios were cured for different periods, and then subjected to unconfined
13 compressive strength (UCS) test, leaching test, and X-ray diffraction (XRD). The
14 results indicated that the LS-GGBS-stabilized clays with LS:GGBS ratio of 2:8-5:5
15 could achieve similar or higher UCS compared to ordinary Portland cement-stabilized
16 clay after 56 days of curing. The leaching of potential heavy metals was not detected
17 for the LS-GGBS stabilized clays. According to XRD analysis, the main hydration
18 products of LS-GGBS-stabilized clay were calcium silicate hydrates (CSH) and
19 ettringite, which were responsible for the strength development of
20 LS-GGBS-stabilized clays.

21 **Keywords:** Soft clay stabilization; Ladle slag; Ground granulated blastfurnace slag;
22 Strength; Heavy metal.

1 Introduction

The ladle furnace basic slag (ladle slag, LS), is a by-product produced in the stage of the steel refining process (Setién et al., 2009). There are around 30 million tons of LS produced worldwide per year (Mahoutian and Shao, 2016); the current solution is simply landfilling it, which is costly and not sustainable.

The properties of LS vary with the steel refining procedure to obtain the desired steel grade, but the main chemical and mineral compositions are similar. The LS is constituted of CaO, SiO₂, Al₂O₃, and MgO. The main minerals of LS are portlandite (Ca(OH)₂), fluorite (CaF₂), calcite (CaCO₃), mayenite (Ca₁₂Al₁₄O₃₃, C₁₂A₇), merwinite (CaMg(SiO₃)₂), brucite (Mg(OH)₂), larnite (β-Ca₂SiO₄, β-C₂S), and belite (γ-Ca₂SiO₄, γ-C₂S) (Shi, 2002; Monkman et al., 2009; Tossavainen et al., 2007; Yildirim and Prezzi, 2011; Adolfsson et al., 2011; Bignozzi et al., 2013). Due to the presence of γ-C₂S, LS was reported as a weak cementitious material (Shi and Hu, 2003). Another concern is the potential leaching of heavy metals from LS. Some elements, such as Cr, Mn, Cd, Zn, Cu, and Pb, were detected in LS by previous studies (Setién et al., 2009; Yildirim and Prezzi, 2011; Adolfsson et al., 2011), which may be leached out from LS and causes environmental pollution. Hence, it is difficult to directly use LS as a binding material in civil engineering.

Nevertheless, some scholars attempted to recycle LS into soil stabilization. Manso et al. (2005, 2013) blended LS with electric arc furnaces (EAF) slag and lime as binders for soil stabilization and achieved acceptable strength. But it was not clear whether LS played the key role for hydration reaction. Kanagawa and Kuwayama (1997) found

that using LS alone for treating soft clay could improve soil behavior, indicating the high cementitious properties of LS. However, Ortega-López et al. (2014) pointed out that the hydration properties of LS depended on the chemical compositions which varied with the steelmaking process.

Hence, it is necessary to find alternative ways to exert the chemical and mineral properties of LS for soil stabilization and reduce the leaching of heavy metals from LS. It is worth noting that the presence of lime (CaO and Ca(OH)_2) and magnesia (MgO) in LS may enable it as an alkali activator to activate other binding materials, e.g. ground granulated blastfurnace slag (GGBS), for soil stabilization. GGBS is a by-product produced from the blast furnace ironmaking and well known as a ‘green binder’, in terms of low energy consumption and low emission of CO_2 (Higgins, 2007). GGBS was proved to be efficient for soil stabilization when activated by lime, magnesia, and carbide slag (Yi et al., 2015a, 2015b, 2016a).

This study investigated the utilization of LS-GGBS blend for soft clay stabilization, where the LS was intended to activate the GGBS for stabilization of soft clay, as well as immobilization of heavy metals in LS. The stabilized clays with different binder contents and LS:GGBS ratios were cured at different periods and tested for UCS and leaching of heavy metals. The mineral properties of stabilized clays were also studied using X-ray diffraction (XRD).

2 Materials and methods

The LS used was generated in Singapore, and the GGBS was purchased from EnGro Corporation Limited, Singapore. Ordinary Portland cement (OPC), grade 42.5, was

used as the control binder, which was also purchased from EnGro Corporation Limited. A kaolin clay, with a liquid limit of 58% and plastic limit of 23% (ASTM, 2017), was used as an artificial soft clay, which was obtained from International Scientific Private Limited, Singapore. The chemical properties were analyzed by X-ray fluorescence (XRF), as shown in Table 1. The mineral compositions of LS, GGBS, and kaolin clay determined by XRD were provided in Fig. 1. Due to different types of steel scrapes were recycled as raw materials for steelmaking (Varga et al., 2016), heavy metals such as Zn, Pb, Mn, Cr, and Cu in LS were all detected. Thus, the leaching of these heavy metals needs to be concerned when using LS in soil stabilization.

LS was firstly dried in an oven at 105°C and passed a 300 μm sieve. The water content, defined as the mass of water over the mass of dry clay, of natural soft clay below ground water table is usually close to its liquid limit (Bergado et al., 1996; Kitazume and Terashi, 2013); hence, a water content of 60% was used in this study, which was close to the liquid limit of the kaolin (58%). The binders were added into clay without additional water to simulate the dry jet mixing method for soft clay stabilization. The testing program was shown in Table 2. Two binder contents, mass of binder over dry clay of 20% and 30% or mass of binder over volume of saturated clay of 203 kg/m^3 and 305 kg/m^3 , were selected in this study, which was based on the practical application in Singapore (Tan et al., 2002; Xiao and Lee, 2008), where cement content used were from 10% to 30%. Different LS:GGBS ratios (by mass), including 0:10 (pure GGBS), 2:8, 3:7, 4:6, 5:5, 6:4, 7:3, 10:0 (pure LS), were studied.

The specimen preparation procedure attempted to simulate the mixing effect of in-situ dry jet mixing method by using a laboratory mixer. In order to achieve homogeneous clay-binder mixture to reasonably compare the effectiveness of different binders, the dry kaolin and binders were homogenized in a mixer for 10 minutes, and then the water was added, and the mixture was subjected to mixing for another 10 minutes. The mixture was filled in the cylindrical mold with a height of 10 cm and a diameter of 5 cm in three layers. The molds were tapped against a table by hand for 50 times for each layer to remove air bubbles. Because the soft clay used in this study has a high water content of 60%, higher than its liquid limit (58%), so the clay-binder mixture is very soft and the compaction would not affect much on the sample density except for the air pocket removal. The specimens were then cured in a moist room with temperature of 26°C and relative humidity of 100% for 14, 28, 56, and 112 days. Song et al. (2000) suggested that GGBS was primarily activated in the early stage and its strength could be developed rapidly when the initial pH was higher than 11.5; hence, the initial pH of binder-soil mixture was measured in this study according to ASTM D4972-18 (2018). 10 g dry sample was prepared by mixing kaolin with different ratios of LS and GGBS. 10 mL water was added into the dry sample, which was mixed and then rested for 1 hour before measured by the Laqua pH 1100 meter. The UCS was tested in triplicate with the vertical load applied at a constant displacement rate of 1 mm/min until failure. The crushed specimens were then grounded to pass 2 mm sieve and then soaked into alcohol to stop hydration reactions. These samples were also dried in the vacuum freeze-drying machine for 48 hours,

which were tested for XRD. XRD was performed on Bruker D8 X-ray diffractometer using Cu K α radiation, the 2 θ started at 5° and stopped at 60°. The dwelling time is 2 s/step with a step size of 0.05° and slit width is 0.49. The leaching test was conducted for 14- and 112-day stabilized clays according to one stage batch test (BS EN12447-22002). The crushed specimens and distilled water, with a liquid to solid ratio of 10 L/kg, were placed in a polypropylene bottle. The bottle was rotated with a tumbler (10 rpm) for 24 h. The leachate was then filtered by a vacuum filtration device. As Cr, Mn, Zn, Cu, and Pb are the main heavy metal elements, the leachates of these elements were then analyzed by the inductively coupled plasma optical emission spectrometer (ICP), PerkinElmer Optima 8300 ICP-OES.

3 Results and Discussion

3.1 Initial pH

The initial pH of LS-GGBS-stabilized clay was presented in Table 3. The pH of pure LS was 12.5, which was close to the pH of saturated Ca(OH)₂ (Ma and Brown 1997). The initial pH of pure LS-stabilized clay was also 12.5 for both 20% and 30% binder contents, although the pH of clay was 4.39. This indicated that LS could provide a strong alkaline environment in the soil. According to Song et al. (2000), when the initial pH was above 11.5, GGBS was activated in the early stage and its strength could be developed rapidly; the alkaline environment would lead to the breaking of Si-O and Al-O bond of GGBS, facilitating the formation of hydration products (Ouf, 2001; Ouhadi and Yong, 2003). Hence, Table 3 implied that the addition of LS could accelerate the hydration of GGBS and strength development of stabilized clay. From

Table 3, the initial pH of the stabilized clays could be higher than 11.5 when the LS:GGBS ratios were higher than 5:5 and 3:7 for 20% and 30% binder contents, respectively.

3.2 Unconfined Compressive Strength

The UCS of LS-GGBS-stabilized clay was plotted against the LS:GGBS ratio in Fig. 2 and Fig.3. The pure LS-stabilized clays showed negligible strength at the four ages, confirming that LS was a weak hydration material. The pure GGBS-stabilized clays also yielded negligible strength at 14 days, but achieved considerable strength after 28 days for 30% binder content or 56 days for 20% binder content, confirming GGBS had certain hydration property. LS could increase the strength development rate of GGBS, e.g. stabilized clays with LS:GGBS ratios of 2:8-5:5 all yielded higher UCS than the pure GGBS-stabilized clay with the same binder content at 14, 28, and 56 days.

At 14, 28, and 56 days, the UCS of LS-GGBS-stabilized clay first increased with the increase of LS:GGBS ratio, and then decreased (Fig. 2 and Fig. 3). This was because a high LS:GGBS ratio facilitated the strength development of stabilized clay, but also reduced the GGBS content, which dominated the total quantity of hydration products. This trend was similar to those of marine clay stabilized by GGBS activated by lime and MgO with lime:GGBS or MgO:GGBS from 0.05 to 0.4 at 7, 28, and 90 days (Yi et al., 2015b, 2016a). At the early age, the effect of LS, like lime and MgO, was more pronounced, as suggested by Song et al (2000), the initial pH needed to be above 11.5 to effectively activate the GGBS. From Fig. 2 and Fig. 3, the optimum LS:GGBS

ratios for the highest 14-, 28-, and 56-day UCS were 5:5, 4:6, and 4:6 for 20% and 30% binder contents, which were close to the LS:GGBS ratios (5:5 and 3:7) to achieve initial pH higher than 11.5 as shown in Table 3. However, the optimum lime:GGBS and MgO:GGBS ratios at all ages in previous studies (Yi et al., 2015b, 2016a) were far lower than the optimum LS:GGBS ratio in this study, indicating that LS had lower activating efficacy than lime or MgO. This was because the Ca(OH)_2 and MgO content in LS was not very high. In Yi et al. (2015b, 2016a), the highest UCS of lime-GGBS- and MgO-GGBS-stabilized clays with 30% binder content both yielded around 1700 kPa at 28 days, which was lower than the highest UCS (2483 kPa) of LS-GGBS stabilized clay. The strength difference should be mainly due to the different soil types; the soils used in previous studies (Yi et al., 2015b, 2016a) were natural marine sediments which had different mineral compositions, although the liquid limit and water content were similar as those in this study. At 112 days, the UCS of LS-GGBS-stabilized clay did not change when LS:GGBS ratio increased from 0:10 to 2:8, and then decreased when LS:GGBS ratio further increased, indicating the GGBS itself could hydrate adequately to produce high strength in the long term.

Compared to OPC, the optimum LS-GGBS produced lower strength at 14 and 28 days, as shown in Fig. 2 and Fig. 3. This should be due to that the Ca(OH)_2 content in LS was not very high. Additionally, the Zn and Pb in LS might also retard the strength development of stabilized clay (Komonweeraket et al., 2015). Nevertheless, after 56 days, the LS-GGBS-stabilized clays with LS:GGBS ratio of 5:5-2:8 achieved higher

UCS than that of OPC; this was still useful for practical applications, e.g. deep mixing for soft ground improvement, for which 56-day UCS could be used as the design strength (Kitazume and Terashi, 2013). If the LS:GGBS with a ratio of 5:5 is used to replace OPC for soft clay stabilization, it will reduce at least half of the binder cost, while achieves similar or higher design strength.

3.3 Leaching Test

The leaching test results of LS-GGBS-stabilized clays at 14 and 112 days were presented in Table 4, expressed as mg/L. Only Zn and Pb with relatively low concentrations were leached out as shown in Table 4. The leaching of Zn from raw LS was 2.12 mg/L, which was lower than the stand limit of non-hazardous wastes (5 mg/L) according to the Council Decision 2003/33/EC (EUR-Lex, 2003). The leaching of Pb (3.62 mg/L) lightly exceeded the non-hazardous wastes limit (1 mg/L). Generally, if more LS was added, the more quantities of heavy metal could be leached out. For instance, the leaching of Zn was 0.11 mg/L for 30% pure LS-stabilized clay at 14 days, which was larger than 0.02 mg/L for 20% pure LS-stabilized clay at 14 days (Table 4). However, the leaching of possible heavy metals was not detected in any of the LS-GGBS-stabilized clays, including the one with 30% LS:GGBS=7:3, which had a high LS content of 21%. This should be due to that LS-GGBS produced cementitious hydration products, such as calcium silicate hydrates (CSH), which could further immobilize the heavy metals by adsorption or co-precipitation, i.e. heavy metals substituted Ca^{2+} at CSH surface (Taylor, 1993; Andersen et al., 2003; Chen et al., 2009). Over all, the leaching test results confirmed that the leaching of

heavy metals was not a concern when LS-GGBS is used for soft clay stabilization.

3.4 X-ray Diffraction

The XRD patterns of 30% stabilized clay with LS:GGBS ratio of 5:5 at 0 and 112 days were shown in Fig. 4. The 0-day sample referred to the mixture of dry LS, GGBS, and clay without water (before hydration). Compared to the 0-day sample, it was evident that the intensity of Ca(OH)_2 decreased after curing for 112 days, indicating that the Ca(OH)_2 was consumed due to activation of GGBS. The mechanisms of LS for GGBS activation was based on the alkali activation, which was similar to that of lime (Yi et al., 2016a). A strong alkaline environment was provided in the soil (Table 3), which led to the breaking of Si-O and Al-O bond of GGBS, facilitating the formation of hydration products (Ouf, 2001; Ouhadi and Yong, 2003). It was found that CSH and ettringite were produced from the LS-GGBS hydration, which was commonly detected in Ca(OH)_2 -GGBS-stabilized clays (Nidzam and Kinuthia, 2010; Yi et al., 2014a, 2015c, 2015d). Additionally, a reflection of Ca(OH)_2 was still detected at 112 days, indicating that the Ca(OH)_2 content in LS-GGBS stabilized clay (LS:GGBS=5:5) was excessive for activation of GGBS.

4 Concluding Remarks

The following conclusions can be obtained based on the analysis above.

1. Ladle slag (LS) could provide a high pH environment to accelerate the ground granulated blastfurnace slag (GGBS) hydration for soft clay stabilization. The addition of LS could increase the strength development rate of GGBS-stabilized

clay; however, excess high LS:GGBS ratio also decreased the final strength of stabilized clay. After 56 days, the LS-GGBS-stabilized clays with LS:GGBS ratio of 2:8-5:5 could achieve similar or higher unconfined compressive strength (UCS) compared to the corresponding ordinary Portland cement (OPC)-stabilized clay.

2. The leaching of potential heavy metals was not detected for the LS-GGBS stabilized clays. These results indicated that the LS-GGBS blend could potentially replace OPC for soft clay stabilization applications (e.g. deep mixing for soft ground improvement), which could reduce the cost for both soft clay stabilization and landfilling LS.

3. The X-ray diffraction analysis indicated that the $\text{Ca}(\text{OH})_2$ in LS was the main mineral for activation of GGBS. The main hydration products of LS-GGBS-stabilized clay were calcium silicate hydrates (CSH) and ettringite.

4. It should be emphasized that natural soft clays have different properties (e.g. water content and minerals) compared to the artificial kaolin clay used in this study. Hence, it is necessary to experimentally determine the exact design parameters (e.g. LS:GGBS ratio and UCS) for a specific soft clay, for which the results in this study can be used as references.

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335 **Figure captions**

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- Ladle slag (LS)-ground granulated blastfurnace slag (GGBS) for clay stabilization
- Ca(OH)_2 in LS activates GGBS for strength gain
- Heavy metals in LS are immobilized in stabilized clay

Table 1 Main chemical composition (by % mass) of LS, GGBS, and kaolin

Material	LS	GGBS	Kaolin
CaO	40.20	37.02	0.06
SiO ₂	18.74	32.74	64.70
MgO	14.81	8.08	0.80
Al ₂ O ₃	4.94	15.33	30.17
Fe ₂ O ₃	3.64	ND	ND
SO ₃	1.06	4.67	0.05
TiO ₂	0.43	1.05	0.50
K ₂ O	0.09	0.49	3.57
MnO	0.66	ND	ND
ZnO	1.21	ND	0.01
PbO	0.06	ND	0.01
Cr ₂ O ₃	0.06	ND	ND
CuO	0.02	ND	ND
Other	0.60	1.11	0.63
Loss on ignition	13.48	0.00	0.00

ND-Not detected

Table 2 Testing Program

Binder	Binder content	Curing period	Testing
LS:GGBS=0:10 (pure GGBS), 2:8, 3:7, 4:6, 5:5, 6:4, 7:3, 10:0 (pure LS)	20%, 30%	14, 28, 56, and 112 days	Initial pH UCS at all curing periods Leaching of Zn, Pb, Mn, Cr, and Cu at 14 and 112 days XRD for 30% LS:GGBS=5:5 at 0 and 112 days
OPC	20%, 30%	14, 28, 56, and 112 days	UCS at all curing periods

Table 3 Initial pH of LS-GGBS-stabilized clay

LS:GGBS	0:10	2:8	3:7	4:6	5:5	6:4	7:3	10:0
pH	9.14	10.33	11.03	11.43	11.76	11.93	12.16	12.54
	9.83	11.19	11.72	12.05	12.21	12.29	12.33	12.57

Table 4 Leaching results of raw LS and LS-GGBS-stabilized clays (unit: mg/L)

Element	Raw LS	14-day LS:GGBS=10:0 (pure LS)		14-day LS:GGBS= 2:8, 3:7, 4:6, 5:5, 6:4, 7:3		112-day LS:GGBS = 10:0 to 0:10		Inert wastes	Non-hazardous wastes
		20%	30%	20%	30%	20%	30%		
Cr	ND	ND	ND	ND	ND	ND	ND	0.05	1.00
Cu	ND	ND	ND	ND	ND	ND	ND	0.20	5.00
Mn	ND	ND	ND	ND	ND	ND	ND	NM	NM
Zn	2.12	0.02	0.11	ND	ND	ND	ND	0.40	5.00
Pb	3.62	ND	ND	ND	ND	ND	ND	0.05	1.00

ND-Not detected, NM-Not mentioned (EUR-Lex (2003) does not mention the limit of inert waste or non-hazardous waste for Mn)

Fig.1

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Fig.2

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Fig.3

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Fig.4

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