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# Effect of steel slag on the mechanical behavior of surficial yellow marl of Tabriz

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Article

**Keywords**
High plastic fine-grained soil
Steel slag
CBR
Atterberg limits
Strength
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**Abstract**

Fine-grained soils usually have low shear strength and bearing capacity and high swelling potential in the wet state, therefore, they have often to be stabilized by additives. The main objective of this study is to determine the possible effects of ground-granulated blast-furnace slag on the physical and mechanical properties of fine-grained soil. For this purpose, a number of Atterberg, compaction, California bearing ratio (CBR), unconfined compression and freeze-thaw tests were conducted on fine-grained soil. Steel slag (SS) inclusion reduced plasticity index of soil from 44% to 20% when slag content increased from 0% to 55.0%. Moreover, the slag addition improved soil CBR with maximum improvement rate in the sample consists to 55% slag. This increment in CBR was about 140% and 154% for 2.54 mm and 5.08 mm penetration respectively. In addition, slag inclusion raised soil strength with a maximum increment of 132% for clay mixed with 55% slag. Water content and volume changes in freeze-thaw cycles also decreased with increasing percentage of SS, therefore mixtures durability increased.

## 1. Introduction

Soft depositional soils, in general, have very low strength and high compressibility and they may swell and shrink due to wetting and drying phenomenon. In permafrost regions, freeze-thaw phenomenon greatly affects characteristics of these soils. Thus, it is occasionally required to stabilize soft soils via mechanical or chemical techniques. In chemical techniques, additive materials such as lime, cement, etc. were added to soils (Sharma & Sivapullaiah, 2012), which is not reasonable since they release $CO_2$ into the environment (Sharma & Sivapullaiah, 2012), thus encouraging engineers to find alternatives for these stabilizers.

On the other hand, in the world, annually large volumes of iron used in the steel industry produces waste and garbage of an undesirable type, called steel slag (SS) or industrial waste (Yong-Feng et al., 2020). Several researchers suggested using blast furnace slag for various applications in civil engineering. Some researchers have been focused on compaction, unconfined compressive strength, consolidation, CBR and Atterberg limit properties of soil-slag mixtures (Wild et al., 1996; Manso et al., 2013; Yadu & Tripathi, 2013; Akinwumi, 2014; Goodarzi & Salimi, 2015; Sharma & Sivapullaiah, 2012, 2017; Chandra & Lavanya, 2017; Montenegro-Cooper et al., 2019; Mozejko & Francisca, 2020). Regarding compaction, SS inclusion increases maximum dry density and decreases optimum moisture of soils and the changes in these parameters are high as the slag amount increases (Yadu & Tripathi, 2013; Akinwumi, 2014; Chandra & Lavanya, 2017; Mozejko & Francisca, 2020).

Liquid and plastic limits of soils decrease by adding SS, and leads to reduce of plasticity index (Wild et al., 1996; Manso et al., 2013; Yadu & Tripathi, 2013; Akinwumi, 2014; Goodarzi & Salimi, 2015; Chandra & Lavanya, 2017).

Consolidation tests demonstrated that swelling pressure and free swelling index of soils reduce due to slag inclusion (Yadu & Tripathi, 2013; Sharma & Sivapullaiah, 2017; Afrasiabian et al., 2021) and their CBR values enhance (Yadu & Tripathi, 2013; Chandra & Lavanya, 2017; Bera et al., 2019). Moreover, adding SS to soils improves their unconfined compressive strength (Wild et al., 1996; Manso et al., 2013; Yadu & Tripathi, 2013; Akinwumi, 2014; Goodarzi & Salimi, 2015; Afrasiabian et al., 2021).

Previous researches revealed a lack of studies on the behavior of steel slag-stabilized soil under freeze-thaw cycles. The main objective of this research is to investigate the effect of SS on the physical properties including volume change, water absorption and durability of fine-grained soils due to freeze-thaw phenomenon. In addition to these tests, CBR

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and unconfined compressive strength tests were performed on the soil-slag mixtures.

## 2. Materials and Methods

### 2.1 Materials and sample preparation

A high plastic cohesive soil was retrieved from the north east of Tabriz city in East Azerbaijan province, Iran. At shallow depth, this yellow soil has low strength, bearing capacity and high compressibility, and it is often subjected to periodically freeze-thaw phenomenon. About 93% of soil particles are finer than 0.075 mm, as per ASTM D422 (ASTM, 2007), and its liquid limit and plasticity index are 87% and 43%, respectively. According to Unified Soil Classification System, the soil categorized as CH according to ASTM D2487 (ASTM, 2017).

Steel slag with mean grain particle of 0.24 mm used as a soil stabilizer. Chemical components of SS are $SiO_2$ (37.6%), $Al_2O_3$ (13.5%), CaO (38.23%), MgO (7.63%), $Fe_2O_3$ (0.6%), MnO (1.2%) and other (1.34%). Figure 1 presents the grain size distributions of Tabriz soil and steel slag.

The slag was added to clay in a weight percentage of 15%, 25%, 35%, 45% and 55% and the mixtures were named MS15, MS25, MS35, MS45 and MS55, respectively. The specific gravity of the natural soil was 2.41 and the values corresponding to the mixtures were 2.47, 2.53, 2.58, 2.62 and 2.66, respectively (ASTM, 2014). For better moisture absorption, the mixtures were kept in plastic bags for 24 hours in 23 °C and, then, utilized to perform the tests. All samples for CBR, freeze-thaw and unconfined compressive strength (UCS) tests were prepared with 95% of maximum dry density (MDD) and at optimum moisture content (OMC).

### 2.2 Conducted tests

Plasticity characteristics of the samples were determined according to ASTM D4318 (ASTM, 2010) and Standard Proctor compaction tests were carried out on soil samples following ASTM D698 (ASTM, 2012) to obtain MDD and OMC. CBR of soaked samples was measured according to ASTM D1883 (ASTM, 2016a). Compressibility characteristics were evaluated in oedometer test on samples 75 mm in diameter and 21 mm in height, according to ASTM D2435 (ASTM, 2020). Cylindrical specimens with 50 mm in diameter and 100 mm in height were prepared for UCS tests, according to ASTM D2166/D2166M (ASTM, 2016b). Soil samples were compacted in four layers in a special mould, also scratching the interface of layers in a proper way to prevent the formation of weak planes.

Freeze-thaw tests were conducted on two similar compacted samples with 101.6 mm in diameter and 120.0 mm in height, according to ASTM D560 (ASTM, 2016c). After extraction, samples were placed on water saturated felt pads on the carrier. Both samples were kept in a freezer at a constant temperature of -23 °C for 24 h and, then, moved to a moisture room with the constant temperature of 23 °C for 23 h. Eight freeze-thaw cycles were performed. Some of the samples deteriorated after five cycles. One of the samples was used to determine the volume change and water absorption by measuring its height, diameter and weight. The loss of soil weight during freeze-thaw cycles was measured in the other one.

## 3. Results and Discussions

### 3.1 Consistency characteristics

Liquid Limit (LL), Plastic Limit (PL) and Plasticity Index (PI) values explain that all plasticity parameters decreased with an increase in SS content (Figure 2). Maximum decrease was observed in the mixture with 55% SS, in which LL, PL and PI values reduced from 87%, 43% and 44% to 45%, 25% and 20%, respectively; therefore, slag inclusion decreased these parameters about 42%, 18% and 24%, respectively.

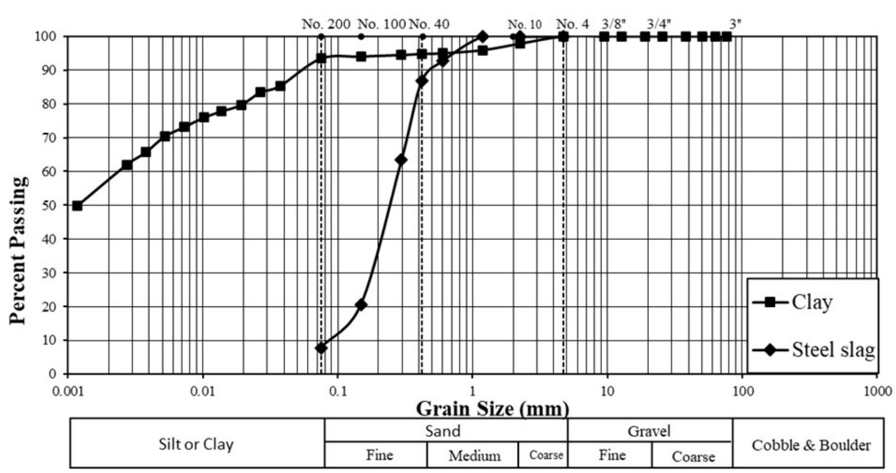


**Figure 1.** Grain size distributions of Tabriz soil and steel slag.

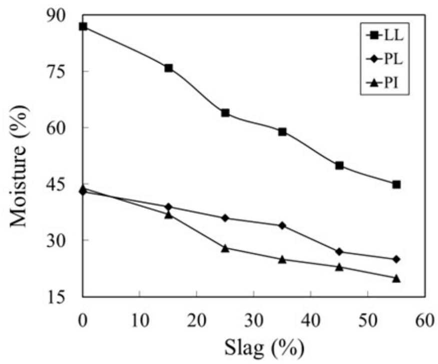


**Figure 2.** Effect of SS content on the Atterberg limits of the used soil.

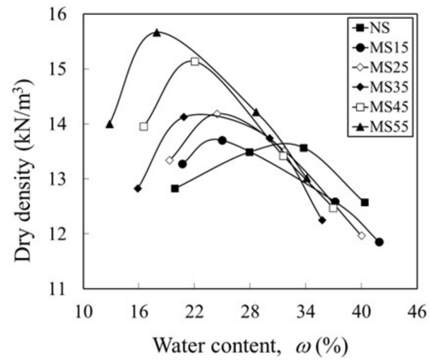


**Figure 3.** Effect of SS additive on the dry density-water content relation of soil.

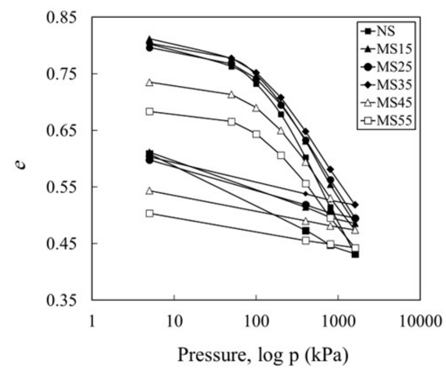


**Figure 4.** Void ratio versus stress curve.

In fact, adding SS increased the coarse-grained part of mixture, and in turn reduced the liquid and plastic limits and plasticity index of the soil. A similar trend was observed by Sivrikaya et al. (2014).

### 3.2 Compaction characteristics

Compaction curves of the mixtures revealed that adding SS led to an increase in MDD and a decrease in OMC (Figure 3). Maximum increment and decrement in MDD and OMC values are those of the mixture including 55% slag, which are about 15% and 56%, respectively. The increase in MDD by SS inclusion is mainly due to the higher specific gravity of the slag in comparison to the clay; on the other hand, coarse-grains need less water for compaction. The results reported on slag stabilized clay (Sivrikaya et al., 2014; Mozejko & Francisca, 2020) and on lime-slag treated black clay (Osinubi & Eberemu, 2006) are in agreement with those obtained in this research.

### 3.3 Consolidation test

Void ratio versus effective stress curves illustrate that the mixtures have different initial densities and void ratio at the end of loading step (Figure 4), implying that the samples exhibit different compressibility behaviour. Butterfield (1979) presented a method for interpreting the oedometer test result. So that one can be obtain the yielding point from the intersection of two straight lines from curve plotted as ln ν against log $p'$. In vertical axis ν is specific volume, which equals with 1 + *e;* in which *e* is void ratio.

The effect of slag was investigated using the intersection point of two lines, according to the method above (Figure 5a). It was observed that increasing slag content higher pressure was required to reach the yield point (Figure 5b). For example, by adding 55% slag the yielding point increased from 68 kPa to 98 kPa.

Both the values of the $C_C$ and $C_S$ decrease significantly when the percentage of SS varies from 0 to 55% (Figure 6a). This is due to the partial substitution of clay by the slag, which is less compressible.

Settlement of samples as a function of slag percentage under different stresses are seen in Figure 6b. In general, slag inclusion decreased the soil's compressibility, with the decreasing rate depending on the stress level. For example, at $p'$ = 50 kPa, adding 55% slag reduced the settlement from 0.461 mm to 0.221 mm. Similarly, the values at $p'$ = 1600 kPa reduced from 4.295 mm to 2.952 mm; therefore, 55% slag reduced the settlement about 52% and 31.2%, respectively. Since the slag particles have large stiffness as compared with the clay ones, thus by an increase in the slag content, total stiffness of the sample increased and consequently settlements reduced. Moreover, by raising the slag percentage, the mixture initial void ratio decreased (Figure 4). To explain the effect of slag on the compressibility of mixtures, the inter-granular void ratio ($e_s$), according to Monkul & Önal (2006), was computed using Equation 1:

$$e_s = \frac{e + \dfrac{G_{s(mix)} \times F_c}{G_{sc} \times 100}}{\dfrac{G_{s(mix)}}{G_{ss}} \times \left(1 - \dfrac{F_c}{100}\right)} \tag{1}$$

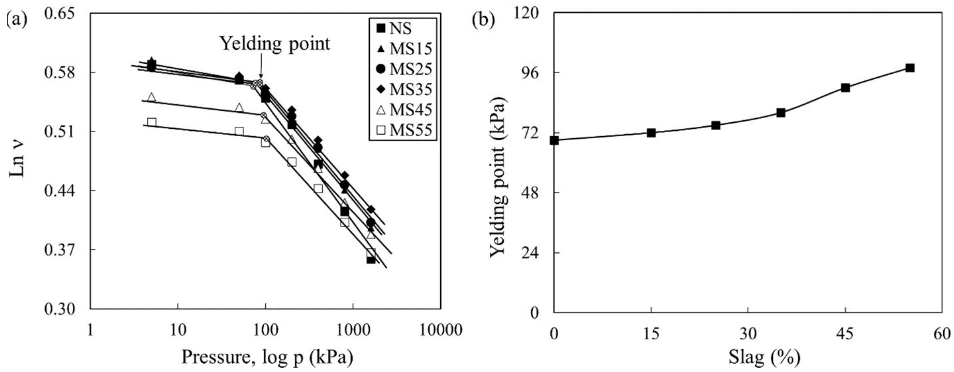


**Figure 5.** (a) ln ν versus log $p$’ of samples; (b) Consolidation yield stress versus slag content.

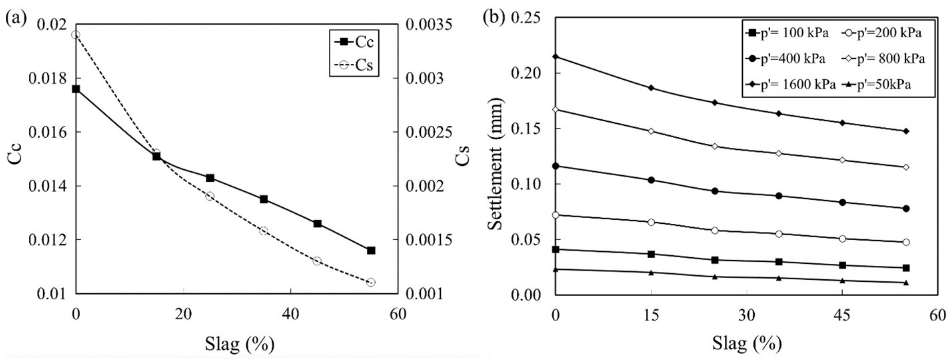


**Figure 6.** (a) Compression and swelling indices; (b) settlement values; versus slag content.

Figure 7 shows that by increasing the slag content the inter-granular void ratio decreases, which means that the slag grains tend to contact and the applied forces transform by the chain of slag grains, and as a result, the settlement decreased and strength improved.

In addition, due to adding 15% and 25% slag, free swelling of soil reduced about 58% and 92%, respectively, and samples with 35%, 45% and 55% slag did not show any swelling (Figure 8). The slag inclusion also diminished the soil’s swelling pressure. For example, adding 15% and 25% of slag reduced the swelling pressure from 19 kPa to 16 kPa and 6.9 kPa, respectively. In the other mixtures, the swelling pressure reduced to zero.

The decrease in compressibility and swelling characteristics of soil with an increase in SS content is due to replacing the clay particles by the *SS* material. This material has low compressibility and low water absorption, which has been led to mentioned results. These results are consistent with those reported for expansive soils by Rao et al. (2009).

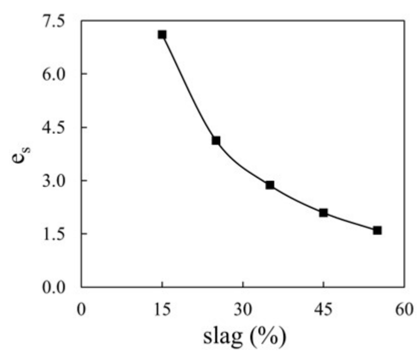


**Figure 7.** Effect of slag content on the inter-granular void ratio.

### 3.4 CBR

CBR is one of the most important tests to assess bearing capacity of sub-base and base layers. As shown in Figure 9, applied stress to samples versus penetration values indicate that by increasing slag percentage in the sample, the amount of suffered stress increased. Moreover, CBR values corresponding to penetrations of 2.54 mm and 5.08 mm indicated that slag addition improved the bearing capacity of the soil (Figure 9b). The highest improvement was observed for the mixture consisting of 55% SS, with values of 140% and 154%, respectively, for penetration of 2.54 mm and 5.08 mm. The reason for the CBR enhancement is due to increase in the maximum unit weight of the stabilized specimens and decrease in the void ratio of mixtures, due to the addition of slag to clay. These results are in agreement with results reported by Laxmikant & Tripathi (2013), which worked on stabilization of soft soil with slag and fly ash, and by Takhelmayum et al. (2013), who researched the soil stabilization using fine and coarse GGBS.

### 3.5 Unconfined compression tests

Stress-strain curves of samples displayed that adding steel slag to the soil improves the strength and changes the behavior pattern of mixtures from ductile to brittle (Figure 10). Therefore, in the MS55 mixture the UCS value increased about 132%. The failure pattern of this sample is completely brittle as compared to the ductile behavior of plain clay. In general, when the samples are subjected to freeze-thaw phenomenon, their strengths drop off suddenly (Figure 10b). This reduction is relatively low for samples with high slag content. Effect of slag inclusion is obvious in improvement of strength after freeze-thawing phenomenon. For plain clay, by applying one cycle freeze-thaw, the UCS value diminished from 175 kPa to 50 kPa, while for MS55, it reduced from 406 kPa to 194 kPa. The reduction in UCS due to freeze-thaw was 71% and 52% respectively for NS and MS55.

The relationships of UCS, failure strain and secant deformation modulus of specimens with slag content for

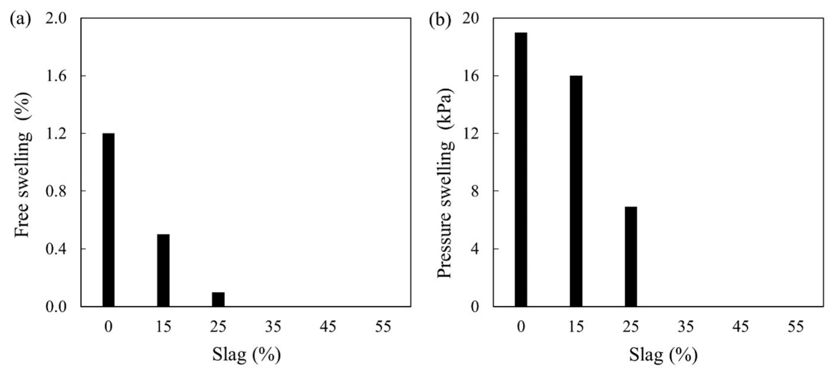


**Figure 8.** Effect of percentage of SS on: (a) the free swelling; (b) the pressure swelling.

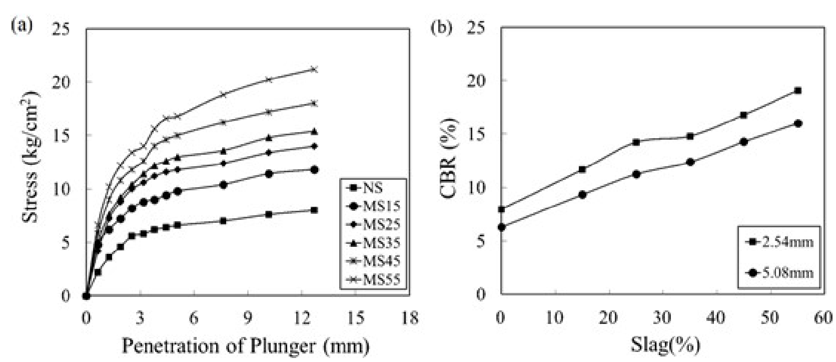


**Figure 9.** (a) Stress-penetration depth of samples; (b) CBR values versus slag content.

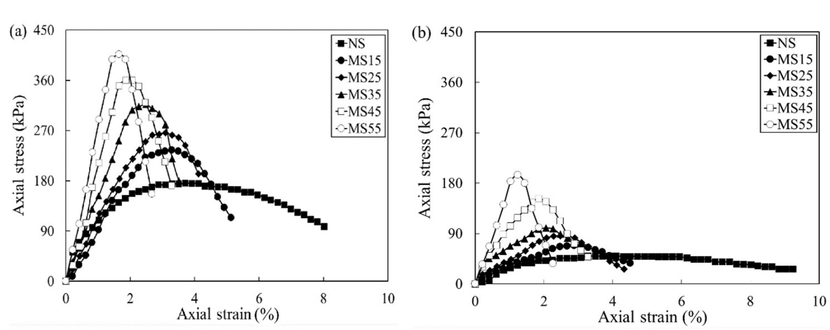


**Figure 10.** Effect of slag content on the stress-strain behavior of soils: (a) without freezing and thawing cycles; (b) after cycles.

unfrozen and frozen samples are presented in Figure 11. By use of a regression analysis, as listed in Table 1, linear functions suggested for UCS and failure strain parameters and a power function obtained for unconfined compression strength. $R^2$ shows that these models may use as a useful engineering tool to describe the relationship between geotechnical characteristic in terms of slag percentage for clayey soils.

By adding more slag to clay, like that described for clay-sand mixtures by Soroush & Soltani-Jigheh (2009), the soil structure becomes contact structure; in other word, when the slag content is high the slag particles are in contact together. In fact, as the slag percentage increases, the force applied to the soil mixture is sustained by the slag particles rather than clay particles. Therefore, the improvement in strength may be due to (i) decrease of fine-grained part of soil and increase of slag material with high friction and hardness, (ii) inducing soil cementation by pozzolanic compounds of soil and SS reaction (Yi et al., 2015; Yong-Feng et al., 2020; Mozejko & Francisca, 2020). It should be noted that the source of calcium is calcium hydroxide contributed by the slag.

The secant deformation modulus ($E_{50}$) increased as the slag content increased. This means that the deformation and flexibility of the specimens reduced. For example, by increasing the 55% slag to the soil, the $E_{50}$ value for unfrozen and frozen samples increased from 7.14 MPa to 27.1 MPa and 2.94 MPa to 16.37 MPa, respectively. Regression analysis provided exponential functions for frozen and unfrozen samples as seen in Table 1.

### 3.6 Freeze-Thaw tests

The freezing-thaw cycle is a weathering process that significantly alters the geotechnical properties of the soil. This phonemonon changes the volume, strength, bearing capacities and microstructure of clays (Eigenbrod, 1996; Czurda & Hohmann, 1997). In this study, the water content of soil samples was measured during the freeze–thaw cycles (Figure 12a). The amount of water absorption during the tests decreased with increasing the amount of SS. Figure 12b shows that the soil samples volume also decreased with increasing number of freeze–thaw cycles. The highest reduction in volume change was obtained in the sample stabilized with 55% SS content. Also it was observed that with increasing slag percentage freezing-thaw cycles has less effect on the volume changes and water absorption of the samples. Since water absorption of slag is less than that of the clay, *SS* behaves like sand and reduces water content and volume changes of mixtures.

Moreover, the weight loss of soil due to freeze-thaw was determined by weighing the specimen before and after brushing process for each cycle. The samples with a higher amount of slag are more resistant to brushing and lose less weight. Also with increasing slag the weight loss of samples decreases, so that, the weight loss in NS (natural soil) and MS55 is 68% and 26%, respectively. It should be noted that the pure sample and MS15 were destroyed in cycle 4 (Figure 13).

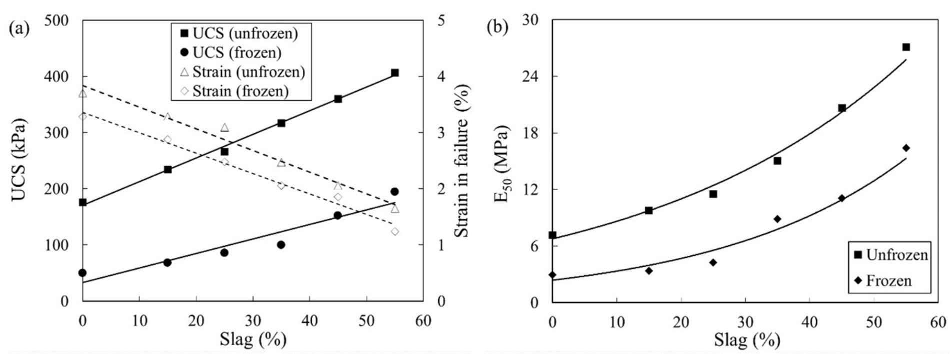


**Figure 11.** Relationship between slag content and: (a) *UCS* and failure strain; (b) $E_{50}$.

**Table 1.** Linear regression of UCS and failure strain and $E_{50}$ with SS content.

| Samples | *y* Parameter | Correlation with SS (%)* | Coefficient $R^2$ |
|---|---|---|---|
| Unfrozen | *UCS* | $y = 4.2088\ SS\ (\%) + 170.6$ | 0.996 |
| | Failure strain | $y = -0.0386\ SS\ (\%) + 3.8384$ | 0.9764 |
| | $E_{50}$ | $y = 6.7704e^{0.0243\ SS\ (\%)}$ | 0.9878 |
| Frozen | *UCS* | $y = 2.5873\ SS\ (\%) + 32.942$ | 0.9093 |
| | Failure strain | $y = -0.0364\ SS\ (\%) + 3.362$ | 0.9843 |
| | $E_{50}$ | $y = 2.3881e^{0.0338\ SS\ (\%)}$ | 0.9352 |

**SS* (%) refers to steel slage percentage.

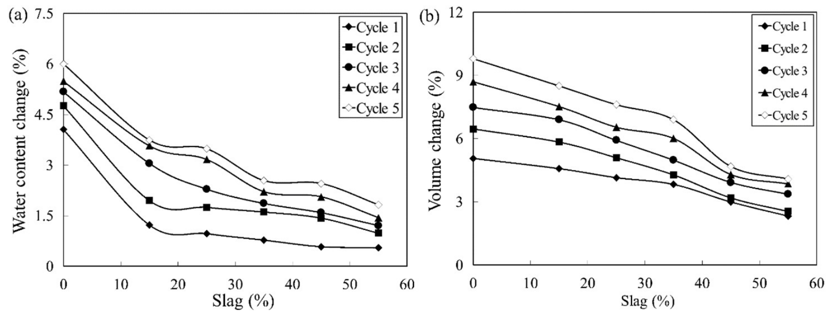


**Figure 12.** Effect of freeze-thaw cycles on: (a) water content change; (b) volume change.

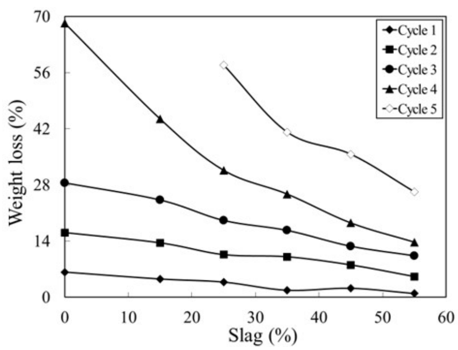


**Figure 13.** Effect of freeze-thaw cycles on soil loss weight of stabilized soil *SS*.

# 4. Conclusion

In this paper, a comprehensive experimental study conducted to know the stabilizing effect of steel slag on the properties plastic, strength and durability of fine-grained soils and the obtained main results are the following:

- By adding slag content from 0 to 55%, the liquid limit and plasticity index reduced 42% and 24%, respectively. Moreover, the addition of slag increased the MDD and decreased the OMC of the soil;
- In low stresses, the effect of steel slag on the settlement reduction was very high and by increasing of the stress level, its effect diminished. The compressibility and swelling indices of clay decreased by adding 55% slag about 34% and 67%, respectively;
- Adding 15% and 25% slag content, free swelling of soil reduced about 58% and 92%, respectively and clay mixtures with slag amount more than 25% did not show swelling;
- With increasing slag from 0 to 55% in clay, CBR values enhanced;
- The unconfined strength of clay increased from 175 kPa to 406 kPa by adding 55% slag. Under frozen condition, the *UCS* values reduced to 50 kPa and 194 kPa, respectively;
- The amount of water absorption and volume changes in freeze-thaw cycles decreased with increasing SS content; thus, the mixtures' durability increased;
- Due to slag inclusion, the freeze-thaw induced weight loss of soil decreased, so that this parameter diminished from 68% to 26% by adding 55% slag to the clay.

To avoid accumulation of steel slag in the environment and solving the technical problems of the soil, the use of soil-slag mixture was developed as a way to stabilize the soil. Therefore, the use of slag as soil stabilizing materials to increase bearing capacity and strength as an appropriate method is suggested.

# Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

# Authors' contributions

Hossein Soltani-Jigheh: data curation, writing – review & editing. Hamed Golmohammadi: writing – original draft preparation. Manouchehr Tajrostami: investigation.

# List of symbols

| | |
|---|---|
| CBR | California bearing ratio |
| *Cc* | Compression index |
| CH | Fat clay |
| *Cs* | Swell index |
| *e* | Void ratio |
| $e_0$ | Initial void ratio |
| $e_s$ | inter-granular void ratio |
| $E_{50}$ | Secant deformation modulus |
| $F_c$ | clay content in the mixture |
| *Gs* | Specific gravity |
| $Gs_{(mix)}$ | specific gravities of the mixture |
| *Gss* | Specific gravity of the clay |
| *Gsc* | Specific gravity of the slag |
| LL | Liquid limit |
| PI | Plasticity index |
| PL | Plastic limit |

## References


Afrasiabian, A., Salimi, M., Movahedrad, M., & Vakili, A.H. (2021). Assessing the impact of GBFS on mechanical behaviour and microstructure of soft clay. *International Journal of Geotechnical Engineeringg*, 15(3), 327-337. http://dx.doi.org/10.1080/19386362.2019.1565393.

Akinwumi, I. (2014). Soil modification by the application of SS. *Periodica Polytechnica. Civil Engineering*, 58(4), 371-377. http://dx.doi.org/10.3311/PPci.7239.

ASTM D422. (2007). *Standard Test Method for Particle-Size Analysis of Soils.* ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D0422-63R07E02.

ASTM D4318-10. (2010). *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.* ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D4318-17E01.

ASTM D698. (2012). *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12400 ft-lbf/ft3 (600 kN-m/m3)).* ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D0698-12E02.

ASTM D854. (2014). *Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer.* ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D0854-14.

ASTM D1883-16. (2016a). *Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils.* ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D1883-16.

ASTM D2166/D2166M-16. (2016b). *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil.* ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D2166_D2166M-16.

ASTM D560/D560M-16. (2016c). *Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures.* ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D0560_D0560M-16.

ASTM D2487-17. (2017). *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).* ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D2487-17E01.

ASTM D2435/D2435M-11. (2020). *Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading.* ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D2435_D2435M-11R20.

Bera, A.K., Das, A., & Patra, S. (2019). Influence of granulated blast furnace slag contents on California bearing ratio value of clay GBFS mixture. In *Proceedings of the Ground Improvement Techniques and Geosynthetics* (pp. 277-284). Singapore. Springer. http://dx.doi.org/10.1007/978-981-13-0559-7_31.

Butterfield, R. (1979). A natural compression law for soils (an advance on e–logp′). *Geotechnique*, 29(4), 469-480. http://dx.doi.org/10.1680/geot.1979.29.4.469.

Chandra, J.V., & Lavanya, P.M. (2017). Effect of granulated blast furnace slag in the stabilization of expansive soil for the pavement sub-grades. *International Research Journal of Engineering and Technology*, 4(5), 1735-1739.

Czurda, K.A., & Hohmann, M. (1997). Freezing effect on shear strength of clayey soils. *Applied Clay Science*, 12(1-2), 165-187. http://dx.doi.org/10.1016/S0169-1317(97)00005-7.

Eigenbrod, K.D. (1996). Effects of cyclic freezing and thawing on volume changes and permeabilities of soft fine-gained soils. *Canadian Geotechnical Journal*, 33(4), 529-537. http://dx.doi.org/10.1139/t96-079-301.

Goodarzi, A., & Salimi, M. (2015). Stabilization treatment of a dispersive clayey soil using granulated blast furnace slag and basic oxygen furnace slag. *Applied Clay Science*, 108, 61-69. http://dx.doi.org/10.1016/j.clay.2015.02.024.

Laxmikant, Y., & Tripathi, R. (2013). Stabilization of soft soil with granulated blast furnace slag (GBS) and fly ash (FA). *International Journal of Research in Engineering and Technology*, 2(2), 115-119. http://dx.doi.org/10.15623/ijret.2013.0202005.

Manso, J.M., Ortega-López, V., Polanco, J.A., & Setién, J. (2013). The use of ladle furnace slag in soil stabilization. *Construction & Building Materials*, 40, 126-134. http://dx.doi.org/10.1016/j.conbuildmat.2012.09.079.

Monkul, M.M., & Önal, O. (2006). A visual basic program for analyzing oedometer test results and evaluating intergranular void ratio. *Computers & Geosciences*, 32(5), 696-703. http://dx.doi.org/10.1016/j.cageo.2005.09.005.

Montenegro-Cooper, J.M., Celemín-Matachana, M., Cañizal, J., & González, J.J. (2019). Study of the expansive behavior of ladle furnace slag and its mixture with low quality natural soils. *Construction & Building Materials*, 203, 201-209. http://dx.doi.org/10.1016/j.conbuildmat.2019.01.040.

Mozejko, C.A., & Francisca, F.M. (2020). Enhanced mechanical behavior of compacted clayey silts stabilized by reusing steel slag. *Construction & Building Materials*, 239, 117901. http://dx.doi.org/10.1016/j.conbuildmat.2019.117901.

Osinubi, K.J., & Eberemu, O.A. (2006). Hydraulic conductivity of compacted lateritic soil treated with blast furnace slag. *The Electronic Journal of Geotechnical Engineering*, 11, 1-16. http://dx.doi.org/10.1504/IJEWM.2013.050522.

Rao, A.S., Sridevi, G., & Rao, M.R. (2009). Heave studies on expansive clays with stabilized granulated blast furnace slag cushion. In *Proceedings of the Indian Geotechnical Conference 2009* (pp. 109-113). New Delhi: Allied Publishers.

Sharma, A.K., & Sivapullaiah, P. (2012). Improvement of strength of expansive soil with waste granulated blast furnace slag. In *Proceedings of the GeoCongress* (pp. 15-17). Oakland: ASCE. http://dx.doi.org/10.1061/9780784412121.402.

Sharma, A.K., & Sivapullaiah, P. (2017). Swelling behaviour of expansive soil treated with fly ash–GGBS based binder. *Geomechanics and Geoengineering*, 12(3), 191-200. http://dx.doi.org/10.1080/17486025.2016.1215548.

Sivrikaya, O., Yavascan, S. & Cecen, E. (2014). Effects of ground granulated blastfurnace slag on the index and compaction parameters of clayey soils. *Acta geotechnica Slovenica*, 11(1), 19-27.

Soroush, A., & Soltani-Jigheh, H. (2009). Pre-and post-cyclic behavior of mixed clayey soils. *Canadian Geotechnical Journal*, 46(2), 115-128. http://dx.doi.org/10.1139/T08-109.

Takhelmayum, G., Savitha, A.L., & Gudi, K. (2013). Experimental studies on soil stabilization using fine and coarse GGBS. *International Journal of Emerging Technology and Advanced Engineering*, 3(3), 919-921. http://dx.doi.org/10.1007/s12594-018-1019-2.

Wild, S., Kinuthia, J., Robinson, R., & Humphreys, I. (1996). Effects of ground granulated blast furnace slag (GGBS) on the strength and swelling properties of lime-stabilized kaolinite in the presence of sulphates. *Clay Minerals*, 31(3), 423-433. http://dx.doi.org/10.1180/claymin.1996.031.3.12.

Yadu, L., & Tripathi, R. (2013). Effects of granulated blast furnace slag in the engineering behaviour of stabilized soft soil. *Procedia Engineering*, 51, 125-131. http://dx.doi.org/10.1016/j.proeng.2013.01.019.

Yi, Y., Li, Ch., & Liu, S. (2015). Alkali-Activated Ground-Granulated Blast Furnace Slag for Stabilization of Marine Soft Clay. J*ournal of Materials in Civil Engineering*, 27(4):04014146. http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001100.

Yong-Feng, D., Tong-Wei, Z., Yu, Z., Qian-Wen, L., & Qiong, W. (2020). Mechanical behaviour and microstructure of SS-based composite and its application for soft clay stabilisation. *European Journal of Environmental and Civil Engineering*, 10(22), 8210. http://dx.doi.org/10.3390/app10228210.