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Soil stabilization with Basic Oxygen Furnace (BOF) slag

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ABSTRACT: The number of problems regarding the weak foundation and subgrade profile to support overlaying weight addresses mainly clay soils. Clay soils usually tend to be problematic and exhibit unsustainable infrastructure due to their low stiffness, strength, and high compressibility. In this study, the stabilization of kaolin clay with an iron by-product called Basic Oxygen Furnace (BOF) slag is considered. The aim of this study is to treat the problematic soil and promote the waste disposal of steel waste material. Soil treatment with BOF slag content of 10, 20, and 30% was assessed by an unconfined compressive strength test (UCS) for soil samples cured for 3, 7, 14, and 28 days. This technique would contribute to a sustainable and green environment in road construction.

1 INTRODUCTION

One of the essential aspects of geotechnical engineering is lying on soil stabilization. Soil stabilization means improving soil properties to make it suitable for further application. Soft soils represent weak soil with low stiffness, high compressibility, and inefficient bearing capacity. BOF slag is a steel by-product produced during pig iron transformation in a basic oxygen furnace (Fisher & Barron 2019; O'Connor et al. 2021). There is a tremendous amount of steel production worldwide because it is one of the most demanded materials in the engineering industry.

The chemical binders such as lime, ordinary Portland cement (OPC), and calcium sulfoaluminate cement (CSA) has been generally used as a soil stabilizer due to its high bonding properties when added to the soil (Bazarbekova et al. 2021; Jumassultan et al. 2021; Moon et al. 2020; Ocheme et al. 2023; Sagidullina et al. 2022; Subramanian et al. 2018; Subramanian et al. 2023). However, processing BOF slag to powder-form cementitious material would take only about 10% of the energy needed to produce OPC, releasing a substantial amount of CO_2 (O'Connor et al. 2021; Shi & Qian 2000). Furthermore, because of the similar mineralogical composition of BOF slag and OPC, BOF slag is considered a weak OPC by several researchers (Poh et al. 2006; Shi & Qian 2000). However, BOF slag contains mainly slowly hydrating C_2S, and OPC contains specifically faster hydrating C_3S (Poh et al. 2006). Additionally, it was reported that even a small share of fines (<5%) cannot be ignored in cement-treated sand (Vinoth et al. 2018). Thus, higher BOF content and longer curing time would be recommended for clay soil stabilization with BOF slag (Cikmit et al. 2019; Goodarzi & Salimi 2015; Kang et al. 2019; Poh et al. 2006; Salimi & Ghorbani 2020).

BOF slag has already been used as a primary stabilizing agent for soft clays such as dredged marine clay, English China clay, Mercia Mudstone, dispersive smectite clay, and in combination with Ground granulated blast furnace slag (GGBFS) for kaolin clay. (Cikmit 2019; Cikmit et al. 2019; Goodarzi & Salimi 2015; Kang et al. 2019; Poh et al. 2006). However, the stabilization of kaolin clay with BOF slag as a primary stabilizer has not been researched yet. Therefore, this study examines the stabilization of kaolin clay with BOF slag.

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2 EXPERIMENTAL PROGRAM

2.1 *Materials*

The soil used in this study is kaolin clay. It has white color and powder texture. According to the Unified Soil Classification System, this soil has been classified as MH. Basic soil characteristics of kaolin clay are shown in Table 1, specified with corresponding ASTM standards. The soil was dried in the oven before conducting any tests. Particle size distribution (PSD) analysis was performed using the QICPIC (M7) particle size and shape analyzer tool. Fresh BOF slag obtained from a steel company near Karaganda in Kazakhstan is evaluated in grain size, unit weight, chemical composition, and mineralogical composition, which define its basic properties (Table 2).

Table 1. Basic characteristics of kaolin clay.

Property	Value	Standard
Plastic Limit, %	33.1	ASTM D4318
Liquid Limit, %	53.6	ASTM D4318
Plasticity Index, %	20.5	ASTM D4318
Fine, %	> 80	QICPIC
USCS classification	MH	ASTM D1921
Specific gravity	2.4	ASTM D854
Optimum Moisture Content, %	19.3	ASTM D698
Maximum Dry Density, kN/m^3	12.1	ASTM D698

Table 2. Basic characteristics of BOF slag.

Property	Value	Standard
Specific gravity of fine aggregate	3.14	ASTM C188
Absorption rate of fine aggregate, %	3.05	ASTM C128
Free CaO, %	4.51	XRD analysis
Coarse aggregate (>0.075mm), %	99.5%	ASTM C136
Fine aggregate (<0.075mm), %	0.5%	ASTM C136

2.2 *Mixture design and sample preparation*

The standard proctor compaction test (ASTM D698) was used to define the optimum moisture content (OMC) and maximum dry density (MDD) of the future samples. There were three different mixtures according to BOF addition rate. Table 3 demonstrate how OMC and MDD increase with the increase of BOF content. However, the difference in OMC-MDD between BOF content of 10, 20, and 30% is not substantially huge.

Table 3. MDD-OMC of the BOF-stabilized soil.

BOF	Maximum Dry Density, kN/m^3	Optimum Moisture Content, %
BOF D 10%	14.27	27.7
BOF D 20%	14.35	28.9
BOF D 30%	14.48	29.0

Samples were prepared using the ratio of BOF slag mass to the mass of dry soil, and water content was taken as the ratio of water to the total mass of solids (mass of kaolin clay and slag). Initially, dry ingredients were mixed thoroughly, and then water was added. After manually mixing for about 5 minutes, the mixture was mixed with Hobart mixer for another 5 minutes to make a uniformly mixed texture. Cylindrical molds with dimensions 50x100mm, greased with oil inside, were used to prepare specimens. Samples were prepared with manual compaction of 3 layers with 25 blows. Samples were extruded from the mold on the third day of curing to obtain enough hardening without breaking the specimen. After extrusion, the diameter and height of samples for further testing were recorded. Then, samples were carefully wrapped into polyethylene and rubber bands to avoid moisture loss. The curing period for all samples is 3, 7, 14, and 28 days. Five samples were prepared for each curing day and mix design.

2.3 *Unconfined compressive strength (UCS) and Bender element (BE) tests*

One of the critical parameters of the stabilized soil is increasing the resistance to compressive forces. An unconfined compressive strength test (UCS) was conducted to see the stabilization effect on strength gain. Test was performed according to ASTM D2166 with a standard compressive speed of 1mm/min.

Bender Element (BE) test was conducted according to ASTM D8295, using a peak-to-peak method to determine shear wave velocity at small strains. Two piezoelectric materials are placed on the top and bottom of the tested sample. The height of the sample is measured and input into the GDS Bender Element software. By the signal transmitted from the source (top) and receiver (bottom) of the specimen, the shear wave velocity can be calculated using the wave travel time through the length of the specimen.

It was reported that the maximum stress of the cemented sand has a direct relationship with the shear strength of its particles (Bisserik et al. 2021). This means that with increasing the UCS, the BE also should increase.

3 RESULTS AND DISCUSSION

3.1 *Unconfined Compressive Strength (UCS)*

Figure 1 (a) shows the impact of BOF content on the strength of stabilized soil with 10, 20, and 30% fine BOF particles (i.e., BOF 10%, BOF 20%, and BOF 30%). At an early age, there was no strength development (3 and 7 days), which means that 3-7 days are not enough for strength improvement. The increase in strength occurs only after seven days. Moreover, BOF 30% shows a considerable strength gain compared to BOF 20% and BOF 10%. However, BOF 10% was consistent throughout the whole curing period. BOF 20% has a moderate rate of strength improvement. Furthermore, the difference is also insignificant in regard to 14 and 28 curing days. Consequently, BOF 30% replacement tends to be the most prominent one.

3.2 *Shear wave velocity (Vs)*

According to Figure 1 (b), shear wave velocity starts to gradually increase only after the 7 days. BOF 10% and BOF 20% did not show any substantial difference throughout 28 days. Only BOF 30% started to rise apparently after 7 days. The highest Vs increase is obtained with BOF 30% for approximately 100m/s during the whole curing period. Hence, with an increasing curing period, the shear wave velocity also increases due to the prevalence of fine BOF slag rate. It was reported that with the increasing of curing days the stiffness of the soil is also increasing (Di Sante et al. 2022). It means that Vs increases with the increasing of the soil stiffness.

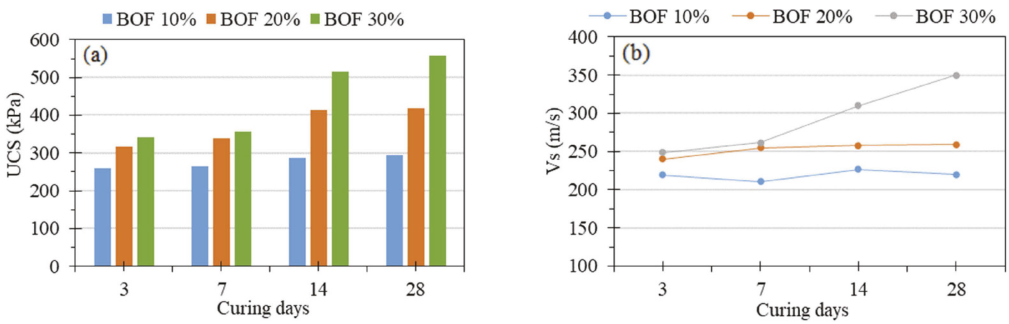

Figure 1. UCS (a) and BE (b) test results of BOF 10%, BOF 20%, and BOF 30%.

4 CONCLUSION

This research's main aim is to stabilize kaolin clay with BOF slag. A considerable strength increase is acquired for BOF 30% after seven days of curing. On the other hand, BOF 10% saved a consistent trend throughout 28 days. Compared to BOF 30% and BOF 10%, BOF 20% showed a moderate strength improvement. However, 3-7 days are insufficient to improve the soil properties in all cases. The highest strength increase is seen in the transition from 7 to 14 days. Bender Element test showed a similar trend with UCS test. BOF 10% and BOF 20% did not increase substantially from 3 to 28 days. Only BOF 30% showed the maximum strength increase after 7 days. It is assumed that shear wave velocity is linked with the soil stiffness, as well as with the strength of the soil sample. To sum up, BOF slag has excellent potential to be used as a stabilizing agent. Although there is a strength development to the maximum value of 557 kPa on the 28th day of curing with 30% of BOF D, it is not enough to stabilize kaolin clay. Therefore, long-term stabilization is needed to see the stabilization behavior of BOF slag. If the results from long-term stabilization (56 and 112 days) will be the same as 28 days, then other calcium-based materials should be added to improve the stabilization effect of BOF slag.

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