An Environmentally Friendly Approach to Soil Improvement with by-Product of the Manufacture of Iron

İnan Keskin,[a] İbrahim Şentürk,[a] Halil İbrahim Yumrutaş,[a,]* Ermedin Totiç,[b] and Ali Ateş [c]

Blast furnace slag has been used for many years in various applications related to civil engineering. Many studies have created a wide variety of cost-effective and environmentally friendly solutions for this industrial by-product. This study aims to contribute to the performance evaluations of the usability of the blast furnace slag for soil improvement and the effects of the additive ratio and curing time. Bentonite samples were prepared with the addition of blast furnace slag at 5%, 10%, 15%, and 20% ratios by weight at optimum water content (w_{opt}). Results were evaluated using the liquid limit, plastic limit, unconfined compressive strength, and swelling tests performed after 1, 7, 14, and 28 days of curing time. Results revealed that the liquid limit value decreased, and the unconfined compressive strength increased with increasing curing time and blast furnace slag ratio in the mixture. Additionally, swelling pressure generally decreased with increasing slag contribution and curing time. The lowest values of the unconfined compressive strength were observed on the 7th day of curing time, and the minimum value was obtained at 10% mixing ratio. The highest unconfined compressive strength values were observed on the 28th days of curing time. The optimum mixing ratio was 5%.

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Contact information: a: Department of Civil Engineering, Karabuk University, Box 78050, Karabuk, Turkey; b: Department of Civil Engineering, Bartın University, Box 74110, Bartın, Turkey; c: Department of Civil Engineering, Abant İzzet Baysal University, Box 14030, Bolu, Turkey;
** Corresponding author: iyumrutas@karabuk.edu.tr*

INTRODUCTION

Waste material management and disposal are global environmental endeavors. Due to the rapid growth of the population, urbanization, economic growth, and increasing consumption patterns, the problem has attracted the attention of scientists, governments, institutes, and companies. Industrially developed countries have made significant efforts to overcome this matter. However, it is obvious that the problem is growing steadily, and more action needs to be implemented. The USA created 292.4 million tons of municipal solid waste in 2018. The corresponding number for 27 European countries is approximately 69 million tons. The amount of waste materials seems to be increasing incessantly. The generation of solid waste materials is predicted to increase by about 70% and to reach 3.4 billion metric tons all over the world according to various projections (EPA 2018; Eurostat 2018; Statista 2020; Van *et al.* 2021).

Blast furnace slag is a by-product of the manufacture of iron. This industrial by-product also has great potential to be used as a stabilizing agent in civil engineering. The world generated about 100 million tons of blast furnace slag (Mehta 1999). The global amount of slag generated in 2019 was 510 to 664 million tons, and it is predicted to increase considerably in the future (Recovery 2020). Waste management has become one of the most significant challenges being faced in the world. The European Union (EU) proposed implementation of waste management with the order "reduce, reuse, recycle, recover, and dispose" (EUR-Lex 2018). Increasing and diversifying the utilization areas of slag, therefore, may contribute to the global challenge to save natural resources.

Swellable soils cause significant damage to engineering structures. It is important to investigate the swelling behavior of the soils and make plans to minimize the damage that may occur in construction. When some soils absorb water, they undergo drastic volume changes. The improvement of such materials before embarking on building construction projects is very important in economic terms. Damage caused by such soils result in considerable economic losses (Chen and Ma 1987; Dif and Blumel 1991; Day 1994; Al-Homoud *et al.* 1995; Coduto 1999; Tripathy *et al.* 2002; Al-Rawas and Goosen 2006; Chen *et al.* 2007; Huang and Wu 2007; Langroudi and Shahaboddin 2009; Avsar *et al.* 2009; Ferber *et al.* 2009; Singh *et al.* 2016; Mohammadinia *et al.* 2018; Chittoori *et al.* 2018; Daraei *et al.* 2019).

The utilization of waste materials is an economical and environmentally friendly alternative for such aims. The swelling pressure and its magnitude are very significant due to deformations in expansive soils in locations where building foundations, highway pavements, tunnels, pipelines, dams, *etc*., are constructed. When the volume changes occur at different dimensions under a foundation, the structure also will experience problems. Because of the population growth and the rapid development of the construction industry, the engineering structure projecting on problematic soils has increased significantly (Moayedi and Nazir 2017; Rashid *et al*. 2018). The volume increase as a result of the change in water content and stress conditions on dry soils is called swelling. Many factors such as clay percentage, mineralogical structure of clay, dry unit weight, stress conditions, external loads, water content, climatic conditions can affect the swelling of clayey soils (Lambe 1960; Lambe and Withman 1979). Waste materials have an important place as additives in soil stabilization studies. Improvement of soils with additives is widely used because it is more economical than other improvement methods. Additives such as lime, fly ash, cement, asphalt, and chemicals are generally used in soil improvement. Besides, materials such as broken concrete, sawdust, bark, gravels, industrial wastes, chips, seashells, waste rice husk ash, burnt oil waste, volcanic ash, marble dust, and waste tires are also utilized for soil improvement (Kamon and Nontanandh 1991; Aksoy 1998; Tremblay *et al.* 2001; Çokça and Toktaş 2002; Hossain 2004; Phanikumar and Sharma 2007; Zha *et al.* 2008; Chauhan *et al.* 2008; Liu *et al.* 2011; Chore and Vaidya 2015; Abhishek *et al.* 2018; Gong *et al.* 2020; Sharo *et. al.* 2021; Keskin and Kahraman 2022).

The use of waste materials soil improvement is important for recycling the waste material and in the economic improvement of problematic soils. The reason why waste materials are preferred as additives in soil improvement is the decrease in storage costs, the desire to use the areas reserved for storage for another reason, and sometimes these resources are cheaper than other materials (Baykal *et al.* 2004). Storage of waste in urban areas is very expensive due to difficulties in finding suitable areas and storing them safely. The use of these materials in different areas reduces the amount of waste to be stored and enables the use of cheap stabilization materials. It is often seen that waste materials taken as by-products from different production sectors are evaluated as substitute materials, especially in the construction sector, rather than being disposed of or discarded.

Soil stabilization has been carried out with different waste materials such as bagasse ash (Muntohar 2002; Hasan *et al.* 2016; Jamsawang *et al.* 2017; Rajeswari *at al.* 2018), rice husk ash (Yadav *et al.* 2017), lime (Okagbue and Yakubu 2000), fly ash (Sezer *at al.* 2006, Phummiphan *at al.* 2018; Keramatikerman *et al.* 2018; Bhurtel and Eisazadeh 2020), cement (Basha *et al.* 2005; Jamsawang *et al.* 2017), coal ash (Rifa'i *et al.* 2009), fuel oil fly ash (Al-Malack *et al.* 2016) granulated blast furnace slag (Shalvati and Pozolo 2012; Sharma and Sivapullaiah 2012; Mujtaba *et al.* 2018; Sharma and Verma 2018; Wu *et al.* 2021), and cement kiln dust (Solanki *et al.* 2007; Mosa *et al.* 2017; Al-Homidy *et al.* 2017). With the developing technology, researchers continue to work with the intention of using different wastes in this context. Choosing the additives used in soil improvement from the materials considered as waste materials reduces their storage costs. According to the statistics of 1987 to 1989, 415 million tons of fly ash and 147 million tons of slag were produced in the world. 16% of the ash produced was used in the construction sector, most of which was used as cement, lightweight aggregate, brick, tile, ceramic, light construction elements, road stabilization, mine, and quarry fillings and 10% as chemical filling materials (Döven *et al.* 2003).

Previous studies have focused on the utilization of slag material as ballast, concrete aggregate, asphalt aggregate, road foundation, sub-base material, cement additives, brick aggregate, slag wool, and prefabricated elements (Motz and Geiseler 2001; Omer *et al.* 2007; Monshi and Asgarani 1999; Maslehuddin *et al.* 2003; Beshr *et al.* 2003; Shih *et al.* 2004; Kang *et al.* 2004). The soil improvement potential of this industrial by-product has been researched in the literature for decades. However, unlike general applications, this study examines especially swelling pressure the influence of improvement performance of slag in the context of as well as other physical and mechanical properties considering curing and additive ratio. The experiments were conducted on the samples prepared at optimum water content by adding 5%, 10%, 15%, and 20% of slag based on the dry weight of the bentonite soil, which was equilibrated (cured) for 1, 7, 14, and 28 days. Considering various curing times, the effect of the slag on swelling and strength properties of bentonite soils was observed. To conduct the experiments under similar conditions, compaction tests were performed on each mixture. The optimum water content and maximum dry unit weight were determined within the scope of the study, and all experiments were performed on the samples prepared with these water contents. Thus, probable sample differences due to sample properties were eliminated in the swelling and strength tests to be performed in clay-slag mixtures at different ratios. The data obtained indicated that slag waste can be applied to soil improvement. This study will inspire diversification of utilization of waste materials for various engineering solutions.

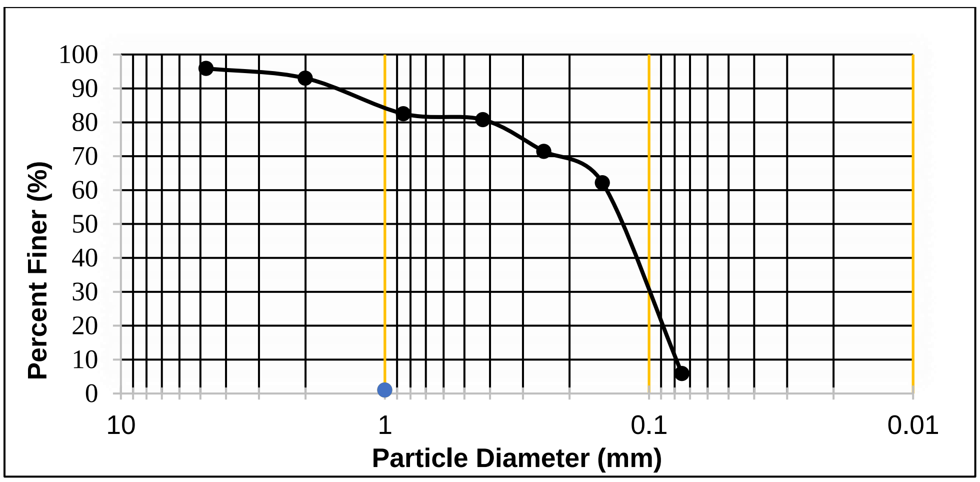
EXPERIMENTAL

Materials

The blast furnace slag (Fig. 1a) used in this study was provided from Kardemir steel and iron factory in Karabuk province, Türkiye. The material supplied from the factory was sieved through a 4.75 mm sieve, and the material passed under this sieve was used in this study. 95% of the material supplied from the factory is less than 4.75 mm in size. The chemical properties of blast furnace slag defined by XRF are given in Table 1. The swellable soil used in this study was bentonite clay, and it was mixed with slag at different ratios (Fig. 1b). The bentonite soil sample was provided from a big bentonite field in Tokat province, Türkiye. The bentonite consisted of 75% montmorillonite with other components such as silica and feldspar. Montmorillonite has a higher swelling percentage compared to other types of clay. Thus, the montmorillonites were used in this study to be able to observe the effect on swelling more clearly (Fig. 2, Table 2). All experiments were conducted with distilled water.

(a)

(b)



(c)

Fig. 1. (a) Crushed blast furnace slag, (b) bentonite, (c) particle size distribution, blast furnace slag

Table 1. Chemical Composition of the Blast Furnace Slag Used, as Determined by X-ray Fluorescence (XRF)

Analysis	Measured Values (%)
SiO_2	8.96
Al_2O_3	1.12
Fe_2O_3	40.33
MnO	2.88
CaO	37.89
MgO	7.11
S	0.35
P_2O_5	0.75
K_2O	0.02
TiO_2	0.44
Na_2O	0.03
Baz	4.462

Table 2. Chemical Composition of the Bentonite Used, as Determined by XRF

Definition	Bentonite
>75 µm	2.5% (by weight)
E (Methylene blue concentration (0.01N))	310 ml
Montmorillonite content	75%
SiO_2	61.28%
Al_2O_3	17.79%
Fe_2O_3	3.01%
CaO	4.54%
MgO	2.10%
K_2O	1.24%
Na_2O	2.70%
Liquid Limit	230%
Plastic Limit	476%

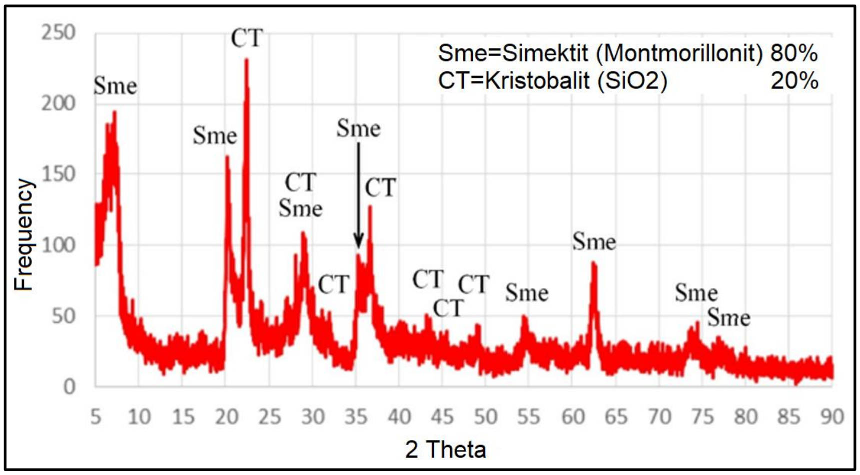


Fig. 2. XRD diffraction trace of %75-%25 bentonite-sand mixture

Experimental Process

The test samples were prepared at optimum water content and mixed manually in a large bowl for at least 5 min for each mixing ratio. The mixtures were then left to cure and stored in large plastic bags to prevent rapid moisture loss. Experiments were conducted after the curing periods. The blast furnace slag was added at levels of 5%, 10%, 15%, and 20% of the weight of bentonite sample, and five different experiments were conducted after 1, 7, 14, and 28 days. Liquid limit and plastic limit tests were performed to observe the effect of blast furnace slag on consistency limits. The unconfined compressive strength test (Fig. 3) was performed to observe the changes in shear strength, and swelling tests were performed to obtain the swelling amounts. The mixtures used in the experiments, curing times, and the details of the experiments are summarized in Table 3.

The first step was to determine the optimum water content of all mixtures. The optimum water content and maximum dry density ($\gamma_{d\max}$) of the whole test were determined by conducting proctor tests in laboratory following ASTM D698 (2012) standard. Distilled water was used for all the tests. Atterberg limits (w_L, w_P) are defined as the limiting water content between liquid and plastic states (Sridharan and Prakesg 1998). There are two standardized methods for determining the Atterberg limits (w_L, w_P) of fine-grained soils:

the Casagrande cup method and the cone penetrometer method. In this study, liquid limits and plastic limit were determined by the cone penetrometer method following ASTM D3441 (1998), ASTM D4318-17 (2017) standards, respectively.

Fig. 3. Unconfined compression test snapshot

Table 3. Experiment Matrix

Experiment Matrix		Curing Times (Days)			
		1	7	14	28
	Compaction Tests and Determination of Optimum Water Content				
Bentonite		X			
	Atterberg Limits				
Bentonite		X	X	X	X
Bentonite + %5 Blast Furnace Slag		X	X	X	X
Bentonite + %10 Blast Furnace Slag		X	X	X	X
Bentonite + %15 Blast Furnace Slag		X	X	X	X
Bentonite + %20 Blast Furnace Slag		X	X	X	X
	Unconfined Compressive Strength Tests				
Bentonite		X			
Bentonite + %5 Blast Furnace Slag		X	X	X	X
Bentonite + %10 Blast Furnace Slag		X	X	X	X
Bentonite + %15 Blast Furnace Slag		X	X	X	X
Bentonite + %20 Blast Furnace Slag		X	X	X	X
	Swelling Pressure Tests				
Bentonite		X			
Bentonite + %5 Blast Furnace Slag		X	X	X	X
Bentonite + %10 Blast Furnace Slag		X	X	X	X
Bentonite + %15 Blast Furnace Slag		X	X	X	X
Bentonite + %20 Blast Furnace Slag		X	X	X	X

To perform unconfined compression tests as outlined in ASTM D2166 (2013), all mixtures prepared under w_{opt} and γ_{dmax} conditions were sampled with a steel cylindrical mold of 38 mm diameter and 80 mm height. Test samples had a saturation degree of 80 to 85%. Using a standard steel piston, the samples were removed from the steel cylinders, placed in the loading device, and loaded axially with a speed of 0.01 mm/min. The axial load and deformation values were recorded, and the tests were continued until the axial load values started to decrease with the increase of axial deformations. The recorded maximum axial load was divided by the mean cross-sectional area of the sample, and the unconfined compressive strength (q_u) of the soil sample was obtained.

When the swelling of the soil is not allowed to increase or when the volume of the soil is stable, the pressure it exerts is known as the swelling pressure of the soil. Swelling pressure can be determined by applying the constant volume method. For this purpose, a new device operating in accordance with the ASTM D 4546 standard has been designed in our laboratory. The device consists of an S type load cell and oedometer cell. This swelling pressure tester can record data automatically for four samples at the same time with a 4-channel data collector. In addition, this device can instantly create all swelling pressure time graphs by means of software by recording the data instantly during the swelling process (Fig. 4.)

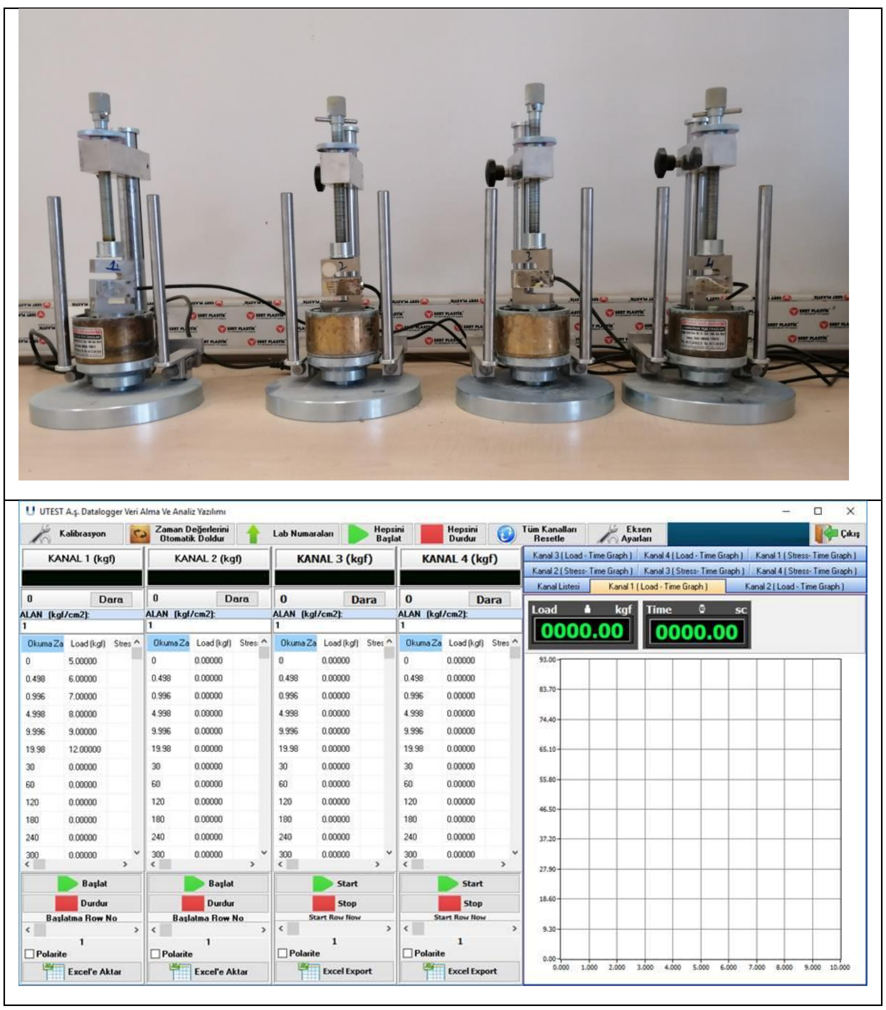


Fig. 4. Swelling pressure device snapshot

RESULTS AND DISCUSSION

The maximum dry unit weight (γ_{dmax}) and the optimum water content (w_{opt}) of the bentonite were measured as 12 kN/m^3 and 40%, respectively (ASTM D698 2012). To determine the optimum water content of mixtures to be used at the tests, the procedure was performed again, and the values are shown in Table 4 and Fig. 5. All test samples were prepared at the rate of optimum water content and were subjected to curing in a specific time. During the curing process, the samples were wrapped strictly to prevent water loss.

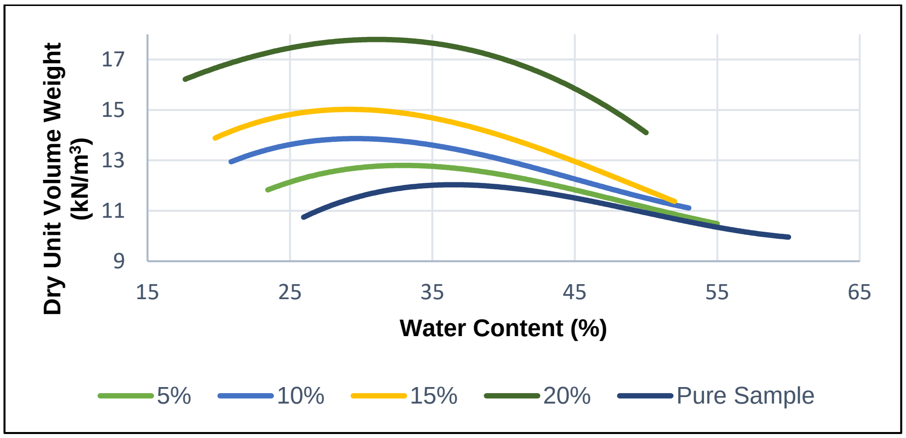


Fig. 5. The results of compaction test for different mixtures

The liquid limit and plastic limit results of the pure bentonite and the mixed samples (prepared by adding blast furnace slag in the specified ratios) are presented in Fig. 6. It is known that significant changes occur in the index properties of the soil with the addition of pozzolanic materials such as slag and ash, which reduce the dispersed double layer thickness and cause flocculation of clay particles (Sivapullaiah *et al.* 1996; Sharma and Sivapullaiah 2016). In this study, the liquid limit values decreased in all mixed samples as the ratio of blast furnace slag increased and as the curing time increased due to similar particle foliation. The opposite effect was observed for the plastic limit results.

The effect of curing time on the unconfined compressive strength was investigated. In this context, 1st day, 7th day, 14th day, and 28th day unconfined compressive strength tests following ASTM D2166 were performed for samples prepared by adding blast furnace slag at 5%, 10% 15%, and 20% by weight of bentonite in specified curing times. The total test results for 38 mm diameter samples are presented in Table 4. Figure 7 indicates the changes of unconfined compressive strength values depending on the curing times considering the blast furnace slag ratios in the mixture. Although it has been stated in the literature that slag, as an additive material, increases the strength of the soil, the additive material ratios and curing times were studied in detail in this study. The addition of slag increased the pozzolanic reaction by providing an increased effect on the soil and binder association due to the formation of a cementitious matrix. Therefore also, the unconfined compressive strengths increased depending on the curing times. The unconfined compressive strength of the sample which was prepared by adding blast furnace slag at the level of 5% was higher than the others after 28-days of curing time. At the end of the curing days 1, 7, and 14, similar unconfined compressive strength values were gained. Unconfined compressive strength values increased dramatically after 14 days of curing time.

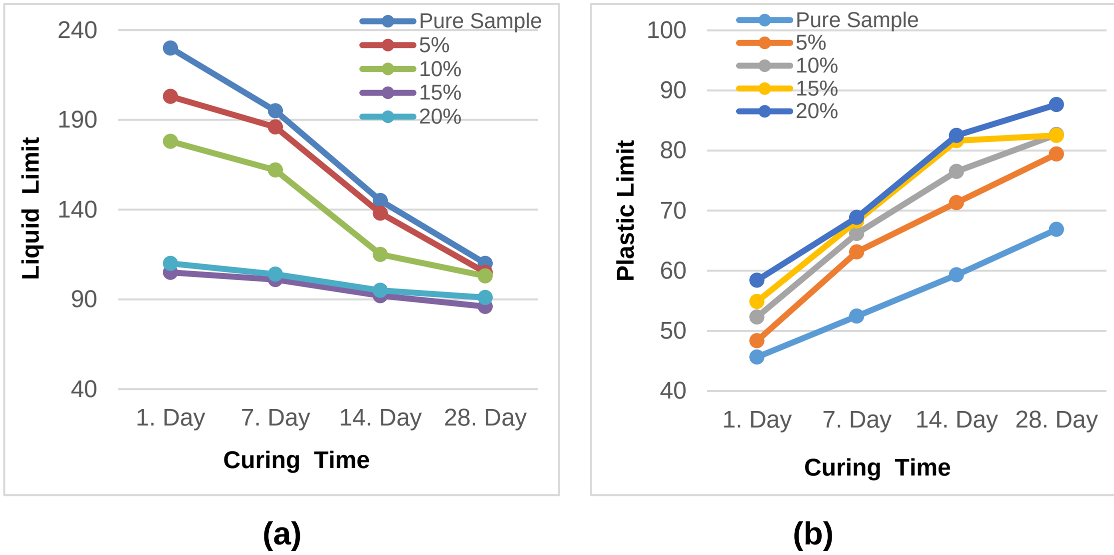


Fig. 6. Liquid limit test results (a), Plastic limit test results (b)

Table 4. Unconfined Compressive Strength Test Results by Curing Time

	1. Day (kPa)	**7. Day** (kPa)	**14. Day** (kPa)	**28. Day** (kPa)
Pure Sample	17.2±0.015	17.2±0.15	17.2±0.15	17.2±0.15
5%	7.4±0.011	10.1±0.020	24.7±0.001	75.4±0.185
10%	13±0.013	17.5±0.013	19±0.029	29±0.050
15%	11±0.015	15±0.010	16.8±0.029	30.1±0.038
20%	9.6±0.019	13.2±0.022	22.9±0.020	46.6±0.079

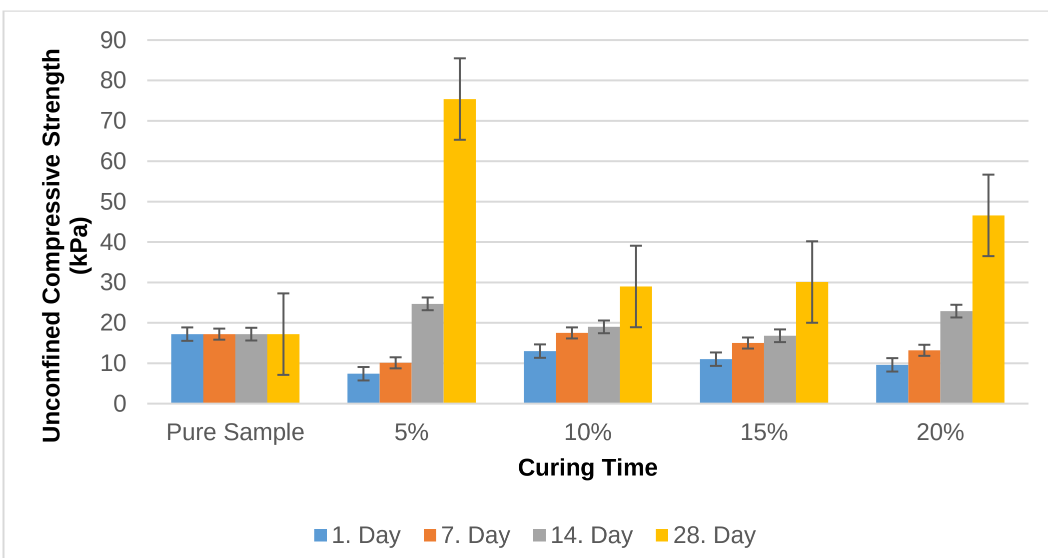


Fig. 7. Unconfined compressive strength values

The soil improvement mechanism is realized by flocculation and agglomeration, cementitious hydration, and pozzolanic reaction, especially cation exchange, as explained by many researchers (Prusinski and Bahttacharja 1999; Chew *et al*. 2004; Sargent 2015). The calcium aluminates/silicates of the additive materials react with water to form hydration products including calcium silicate hydrates and calcium aluminate hydrates. The swelling of the clay involves the balancing of the interaction forces between the clay surface, ions, and water (McBride 1989). At the same time, expansive clays swell according to crystalline swelling and osmotic/double-layer swelling mechanisms. Sposito (1973) stated that the swelling pressure is related to the osmotic pressures exerted by the cations and therefore to the bilayer theory. However, Low and Marqheim (1979) suggested that the swelling pressure is mainly due to the reduction in the potential energy of interlayer water due to its interaction with the surfaces of the adjacent clay layer and that the effect of osmotic pressures is low. Swellable clays cause significant damage to engineering structures such as building foundations, highway pavements, tunnels, pipelines, dams, *etc*. It is a great deal for engineers to determine the swelling pressures and swelling potential of soils. Therefore, in this study, a series of experiments were carried out to determine how the swelling pressures of bentonite, a swellable soil, changes with the addition of slag. In the literature several empirical formulas have been established in order to predict the swelling potential and the swelling pressure using simple physical parameters (Thomas *et al.* 2000; Gray and Allbrook 2002; Kariuki *et al.* 2004; Yılmaz 2006; Ferber *et al.* 2009; Erzin and Gunes 2013; Vanapalli *et al.* 2014). In this study the swelling pressure was determined directly. The swelling pressure of the pure sample was determined, and the swelling pressure curve over time is obtained as presented in Fig. 8. Accordingly, the swelling pressure of the pure bentonite sample reached the value of 63 kPa after 7 days.

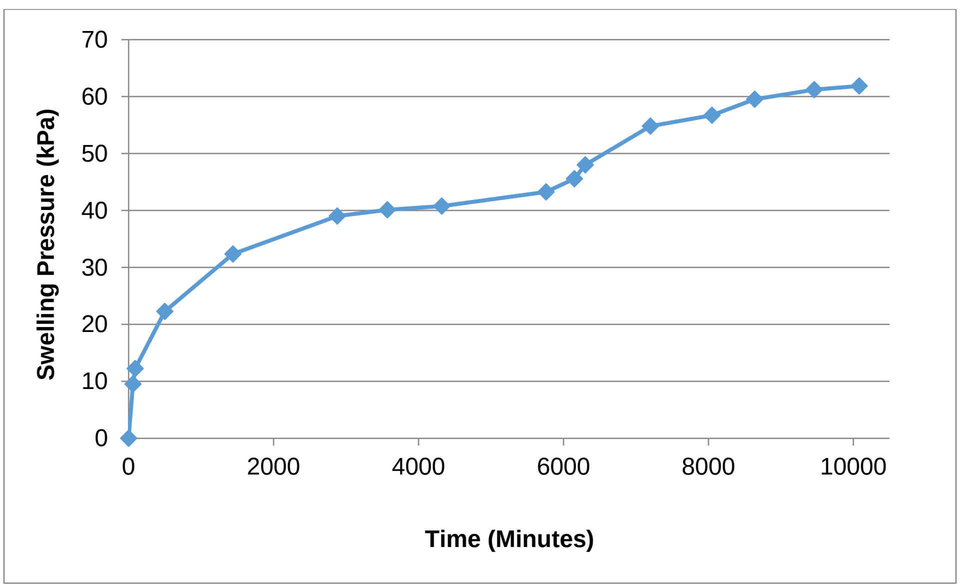


Fig. 8. Experimental results of the swelling pressure of the pure sample

In order to demonstrate the effect of slag additive on the swelling pressure of bentonite, samples prepared with 5%, 10%, 15%, and 20% additives considering the curing at the 1st, 7th, 14th, and 28th days underwent swelling pressure tests, and the results were compared to pure bentonite samples.

Accordingly, the swelling compressive curves versus the time obtained from the swelling compressive tests for the 1-day of curing time are depicted in Fig. 9. The final swelling value of the sample with 15% slag addition is close to that of the pure sample. The swelling pressure increases over time for all samples, but the final swelling values are less than the swelling value of the pure sample (bentonite). The swelling pressure is stabilized at about 7-days of curing time for all samples.

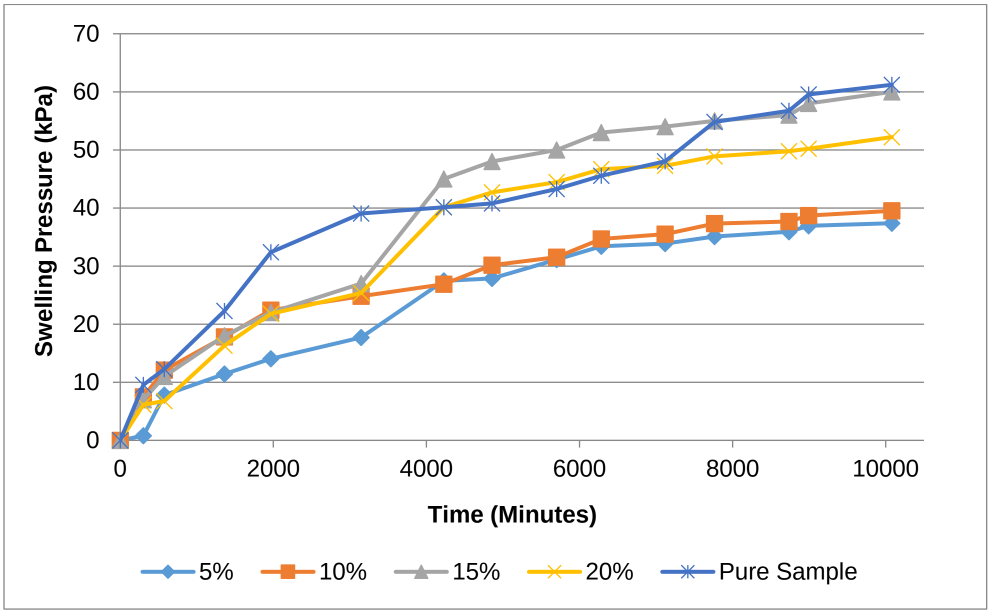


Fig. 9. Change in swelling pressure after 1-day of curing time

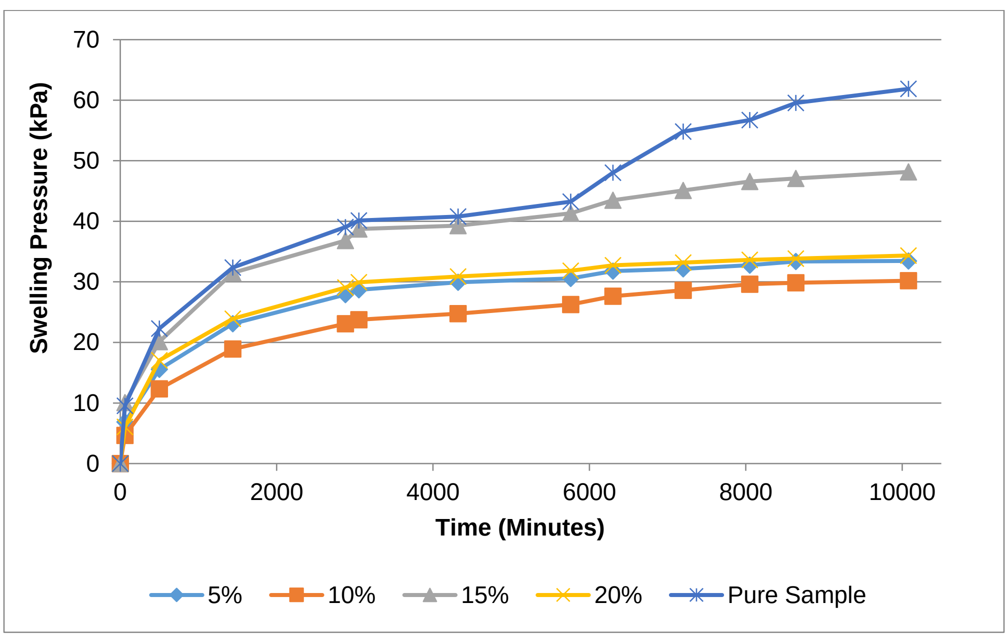


Fig. 10. Change in swelling pressure after 7 days of curing time

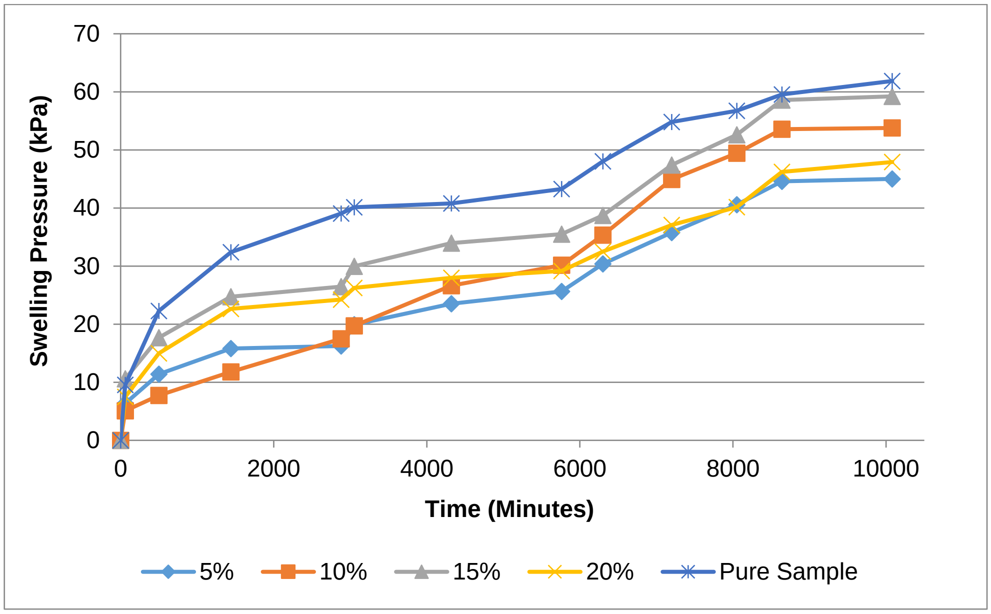


Fig. 11. Change in swelling pressure after 14-days of curing time

The swelling pressure test was repeated after 7-days of curing time on the test samples, and the time response swelling compressive change graphs obtained from the experiments are given in Fig. 10. Although swelling was observed in all mixtures, maximum swelling was observed in the mixture prepared with 15% blast furnace slag. Also, it was observed that 5% and 20% mixtures formed a similar curve. The least swelling occurred at the ratio of 10 %.

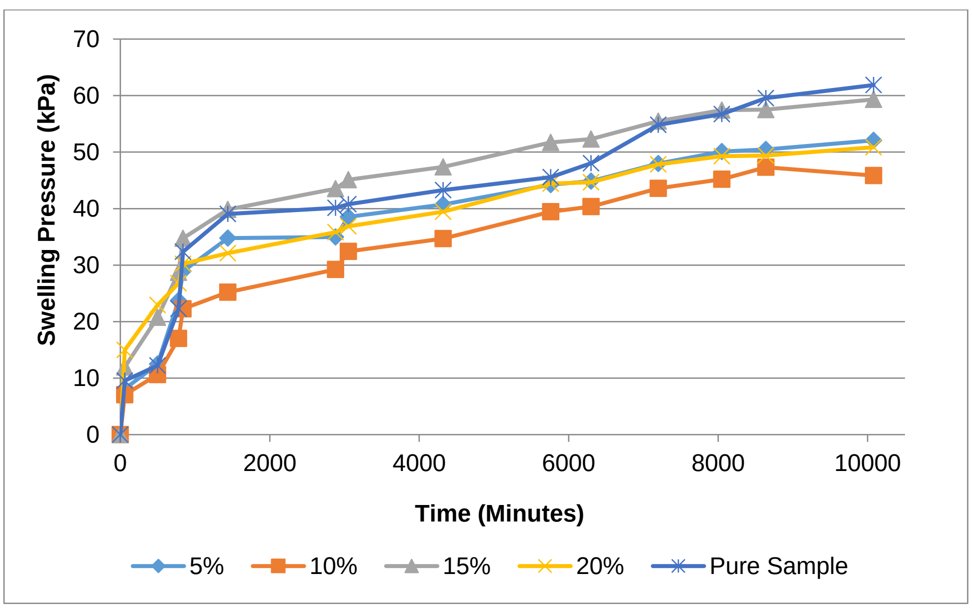


Fig. 12. Change in swelling pressure after 28-days of curing time

The swelling pressure curves generally flattened in other mixtures except 15% after the 14-days of curing time. Furthermore, it was observed that the swelling pressures of the samples in all mixing ratios were lower than the swelling pressure of the pure sample. At the end of 14-days of curing time, the swelling pressure test was repeated for all samples. The swelling pressure curves as a function of time are presented in Fig. 11. Accordingly, the swelling pressure of the sample prepared by adding 15% blast furnace slag increased more than the other mixtures; however, it was lower than the swelling pressure value of pure sample.

The swelling pressure test results for the samples after the 28-days of curing time, *i.e.* the maximum curing period, are presented in Fig. 12. The mixture prepared by adding 15% blast furnace slag reached the highest swelling pressure value. The mixture prepared with blast furnace slag at 5% and 20% presented similar results. The lowest swelling pressure value was obtained for the sample with 10% of the slag. The results of the swelling pressure test results after various curing times on the soil samples prepared by adding blast furnace slag in different ratios are summarized in Fig. 13. The blast furnace slag generally decreased the swelling pressure of bentonite. When the effect of the curing time on the swelling pressure was considered, a decrease was observed until the 7th day, but there was no decrease in the swelling pressure afterwards. It can be inferred from this result that the effect of slag additive on swelling pressure did not change with curing.

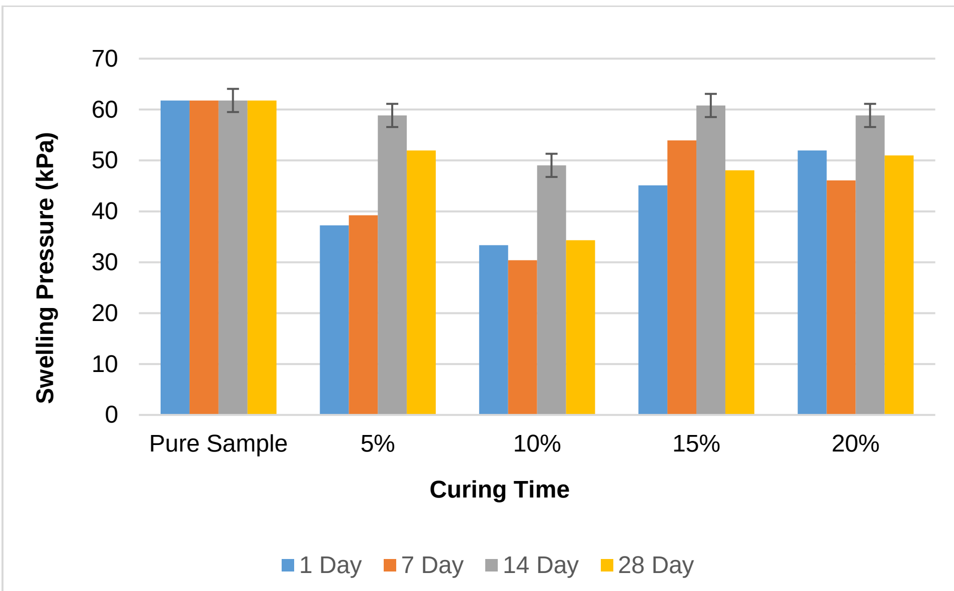


Fig. 13. Final strength at swelling pressure due to additive ratios and curing times

CONCLUSIONS

The following conclusions can be drawn from the analysis of the results obtained in this study made for the purpose of the conditions of use and performance of slag as a soil improvement tool to improve problems and weak soils.

1. Results revealed that in the compaction test, as the amount of blast furnace slag in the mixture increased, the dry unit weight increased, and the optimum water content decreased. Also, the liquid limit value decreased, and the unconfined compressive strength generally increased in response to increases in the curing time and blast furnace slag ratio in the mixture. However, the lowest values of the unconfined compressive strength were observed in the 7 days of curing time, and the minimum

value was obtained at 10% mixing ratio. The highest unconfined compressive strength values were observed in the 28 days of curing time and the optimum mixing ratio was 5%.

2. The swelling pressure is regarded as one of the most important parameters of clayey soils. The samples prepared by adding blast furnace slag at various ratios generally reduced the swelling pressure of the soil. Experiments showed that the highest increase occurred in the sample with 15% slag, while the least swelling was in the sample with 5% slag. In addition, according to the data obtained, the final swelling value of the sample with 15% slag was close to that of the pure sample. It is thought that the reason for this situation is that 15% slag additive increases the permeability of bentonite. According to the test results, it was observed that the swelling pressure increased with time in other mixing ratios, but the final swelling values were less than the swelling value of the pure sample.
3. When the swelling graphs prepared for 1-day of curing time were examined, it was observed that the biggest increase was in 15% slag doped sample and the least swelling was in 5% slag doped sample. Furthermore, according to the obtained data, it was observed that the final swelling value of the sample with 15% slag doping was close to the swelling value of the pure sample. It was observed that the swelling pressure increased over time in other mixing ratios for 1-day of curing time, but the final swelling values were less than the swelling value of the pure sample. When the 7-days of curing time was examined, although the swelling was observed in all mixtures, the maximum swelling was observed in the mixture prepared with 15% blast furnace slag.
4. According to the 14-days of curing time, 15% of blast furnace slag was added to the mixture and the mixture was increased more than other mixing ratios, but it was lower than the swelling pressure value of the pure sample. At the end of the 28-days of curing time test results, it was seen that the mixture prepared by adding 15% blast furnace slag reached the highest swelling pressure value. When the 28-days of curing time was examined, it is seen that the mixture prepared with blast furnace slag at 5% and 20% showed a similar course. According to the results of this curing time at the test, the minimum swelling was in the sample with 10% slag mixture.
5. When the effect of curing time on swelling pressure was examined, although a decrease was observed until the 7-days of curing time, there was no decrease in swelling pressure afterward. Therefore, it is appreciated that the effect of slag additives on swelling pressure did not change with curing.
6. This kind of soil improvement methods especially should be applied to for specific construction projects such as highways, tunnels, dams, bridges, *etc*., as an environmentally friendly solution.

ACKNOWLEDGEMENTS

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REFERENCES CITED

ASTM D698 (2012). "Standard test methods for laboratory compaction characteristics of soil using standard effort," ASTM International, West Conshohocken, PA, USA.

ASTM D2166 (2013). "Standard test method for unconfined compressive strength of cohesive soil," ASTM International, West Conshohocken, PA, USA.

ASTM D3441 (1998). Standard test method for mechanical cone penetration tests of soil," ASTM International, West Conshohocken, PA, USA

ASTM D4318-17 (2017). "Standard test methods for liquid limit, plastic limit, and plasticity index of soils," ASTM International, West Conshohocken, PA, USA.

Aksoy, I. H. (1998). "Hafif dolgu malzemeleri ve geoteknikte kullanımı," in: *Zemin Mekaniği ve Temel Mühendisliği 7. Ulusal Kongresi*, Türkiye, Cilt 2, p.p 428-437.

Al-Homoud, A. S., Basma, A. A., Malkavi, A. I. H., Al-Bashabshah, M. A. (1995). "Cyclic swelling behavior of clays," *Journal of Geotechnical Engineering* 121, 562-565.

Al-Homidy, A. A., Dahim, M. H., El Aal, A. K. A. (2017). "Improvement of geotechnical properties of sabkha soil utilizing cement kiln dust," *J. Rock Mechanics and Geotechnical Engineering* 9 (4), 749-760. DOI: 10.1016/j.jrmge.2016.11.012.

Al-Malack, M. H., Abdullah, G. M., Al-Amoudi, O. S. B., Bukhari, A. A. (2016). "Stabilization of indigenous Saudi Arabian soils using fuel oil fly ash," *Journal of King Saud University Engineering Sci.* 28(2), 165-173. DOI: 10.1016/j.jksues.2014.04.005

Al-Rawas, A. A., Goosen, M. F. A. (2006). *Expansive Soils: Recent Advances in Characterization and Treatment,* Taylor and Francis Group, London.

Avsar, E., Ulusay, R., and Sonmez, H. (2009). *"Assessments of swelling anisotropy of Ankara clay," Engineering Geology* 105(1–2), 24-31 DOI: 10.1016/j.enggeo.2008.12.012

Basha, E., Hashim, R., Mahmud, H., Muntohar, A. (2005). "Stabilization of residual soil with rice husk ash and cement," *Construction and Building Materials* 19(6), 448-453. DOI: 10.1016/j.conbuildmat.2004.08.001

Beshr, H., Almusallam, A. A., and Maslehuddin, M. (2003). "Effect of coarse aggregate quality on the mechanical properties of high strength concrete," *Construction and Building Materials* 17, 97-103. DOI: 10.1016/S0950-0618(02)00097-1

Bhurtel, A., and Eisazadeh, A. (2020). "Strength and durability of bottom ash and lime stabilized Bangkok clay," *KSCE Journal of Civil Engineering* 24, 404-411. DOI:10.1007/s12205-019-0850-3

Chen, F. H., and Ma, G. S. (1987). "Swelling and shrinkage behavior of expansive clays," in: *6th International Conference Expansive Soils,* New Delhi, pp. 127-129.

Chen, L., Yin, Z., and Zhang, P. (2007). "Relationship of resistivity with water content and fissures of unsaturated expansive soils," *Journal of China University Mining and Technol*ogy 17(4), 537-540. DOI: 10.1016/S1006-1266(07)60141-2

Chew, S. H., Kamruzzaman, A. H. M., and Lee, F. H. (2004). "Physico-chemical and engineering behavior of cement treated clays," *Journal of Geotechnical and Geoenvironmental Engineering* 130(7), 696-706.

Chittoori, B. C. S., Mishra, D., and Islam, K. M. (2018). "Forensic investigations into recurrent pavement heave from underlying expansive soil deposits," *Transportation Research Record* 2672, 118-128. DOI: 10.1177/0361198118758625

Coduto, D. P. (1999). *Geotechnical engineering. Principles and Practices,* Prentice Hall, New Jersey, USA, pp. 759.

Çokça, E., and Toktaş, F. (2002). "Dispersif bir kilin C tipi ucucu kül ile stabilizasyonu," in: *Zemin Mekaniği ve Temel Muhendisliği 9. Ulusal Kongresi*, Türkiye, Cilt 2, pp. 659-668.

Day, R. W. (1994). "Day swell-shrink behaviour of expansive compacted clay," *Journal of Geotechnical Engineering* 120(3), 618-623.

Daraei, A., Sherwani, A. F. H., Faraj, R. H., Mohammad, S., Kurdo, S., Zare, S., and Mahmoodzadeh, A. (2019). "Stabilization of problematic soil by utilizing cementitious materials," *Innovative Infrastructure Solutions* 4(33). DOI: 10.1007/s41062-019-0220-5

Dif, A. F., and Blumel, W. F. (1991). "Blumel expansive soils under cyclic drying and wetting," *Geotechnical Testing Journal* 14(1), 96-102.

Döven, A. T., Tümay, M. T., Çelik, T., Güçbilmez, E., Pekrioğlu, A., Aydın, E., Uygar, E., and Atak, C. E. (2003). *Fiber Donatılı Uçucu Kül Çimento Hamurunun İnşaat Mühendisliği Uygulama Alanlarında Kullanım Olanakları* (Project No. 199I027 İNTAG-650, TUBITAK, Türkiye.

EPA. (2018). "National Overview: Facts and Figures on Materials, Wastes and Recycling Facts and Figures about Materials, Waste and Recycling," (https://www.epa.gov/facts-and-figures-about-materials-waste-andrecycling/national-overview-facts-and-figures-materials), Accessed 02 March 2021.

Erzin, Y., and Gunes, N. (2013). "The unique relationship between swell percent and swell pressure of compacted clays," *Bulletin of Engineering Geology and Environment* 72, 71-80. DOI: 10.1007/s10064-013-0461-z

EUR-Lex. (2021). "Directive (Eu) 2018/851 of the European Parliament and of the Council," (https://eur-lex.europa.eu/eli/dir/2018/851/oj), Accessed 08 March 2021. Eurostat. (2018). "Waste statistics," (https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics), Accessed 02 March 2021.

Ferber, V., Auriol, J. C., Cui, Y. J., and Magnan, J. P. (2009). "On the swelling potential of compacted high plasticity clays," *Engineering Geology Journal* 104(3), 200-210.

Gray, C. W., and Allbrook, R. (2002). "Relationships between shrinkage indices and soil properties in some New Zealand soils," *Geoderma* 108(3–4), 287-299.

Hasan, H., Dang, L, Khabbaz, H., Fatahi, B., and Terzaghi, S. (2016). "Remediation of expansive soils using agricultural waste bagasse ash," *Procedia Engineering* 143, 1368-1375. DOI: 10.1016/j.proeng.2016.06.161

Hossain, K. M. A. (2004). "Potential use of volcanic pumice as a construction material," *Journal of Materials in Civil Engineering* 573-577.

Huang, R., and Wu, L. (2007). "Stability analysis of unsaturated expansive soil slope," *Earth Sci. Front.* 14(6), 129-133.

Jamsawang, P., Poorahong, H., Yoobanpot, N., Songpiriyakij, S., and Jongpradist, P. (2017). "Improvement of soft clay with cement and bagasse ash waste," *Construction and Building Materials* 154, 61-71. DOI: 10.1016/j.conbuildmat.2017.07.188

Keramati, K. M., Chegenizadeh, A., Nikraz, H., and Sabbar, A. S. (2018). "Effect of fly ash on liquefaction behaviour of sand-bentonite mixture," *Soils Found.* 58(5), 1288-1296. DOI: 10.1016/j.sandf.2018.07.004

Kamon, M., and Nontanandh, S. (1991). "Combining industrial wastes with lime for soil stabilization," *Journal of Geotechnical Engineering* 117, 1-17.

Kang, H. J., An, K. G., and Kim, D. S. (2004). "Utilization of steel slag as an adsorbent of ionic lead in wastewater." *Journal of Environmental Science and Health Part A-Toxic/Hazardous Substances and Environmental Engineering* 39(11–12), 3015-3028.

Kariuki, P. C., and Van der Meer, F. D. (2004). "A unified swelling potential index for expansive soils," *Engineering Geology* 72(1–2), 1-8.

Lambe, T. W. (1960). "A mechanistic picture of shear strength in clay", in: *Proceeding Research Conference on Shear Strength of Cohesive Soils*, ASCE, Boulder, Colorado, pp. 555-580.

Lambe, T. W., and Whitman, R. W. (1979). *Soil Mechanics*, John Wiley and Sons, New York, pp. 553.

Langroudi, A. A., and Shahaboddin, S. (2009). "A micro-mechanical approach to swelling behavior of unsaturated expansive clays under controlled drainage conditions," *Applied Clay Science* 45(1–2), 8-19.

Low, P. F., and Margheim, J. F. (1979). "The swelling of clay: I. Basic concepts and empirical equations," *Soil Science Society of America Journal* 43(3), 473-481.

Maslehuddin, M., Sharif, A. M., and Shameem, M. (2003). "Comparison of properties of steel slag and crushed limestone aggregate concretes," *Construction and Building Materials* 17, 105-112.

McBride, M. B. (1989). *Surface Chemistry of Soil Minerals*, *Minerals in Soil Environments*, Soil Science Society of America, Inc. Madison, the USA.

Mehta, P. K. (1999). "Advancements in concrete technology" *Concrete International* 21(6), 69-76.

Moayedi, H., and Nazir, R. (2017). "Malaysian experiences of peat stabilization, state of the art," *Geotech Geol Eng* 36(1), 1–11. DOI: 10.1007/s10706-017-0321-x

Mohammadinia, A., Arulrajah, A., D'Amico A., and Horpibulsuk, S. (2018). "Alkali-activation of fly ash and cement kiln dust mixtures for stabilization of demolition aggregates," *Construction and Building Materials* 186, 71-78. DOI: 10.1016/j.conbuildmat.2018.07.103

Mosa, A. M., Taher, A. H., and Al-Jaberi, L. A. (2017). "Improvement of poor subgrade soils using cement kiln dust," *Case Studies in Construction Materials* 7, 138-143. DOI: 10.1016/j.cscm.2017.06.005

Monshi, A., and Asgarani, M. K. (1999). "Producing Portland cement from iron and steel slags and limestone," *Cement and Concrete Research* 29, 1373-1377.

Motz, H., and Geiseler, J. (2001). "Products of steel slags an opportunity to save natural resources," *Journal of Waste Management* 21(3), 285-293.

Mujtaba, H., Aziz, T., Farooq, K., Sivakugan, N., and Das, B. M. (2018). "Improvement in engineering properties of expansive soils using ground granulated blast furnace slag," *Journal Geological Society of India* 92, 357-362.

Muntohar, A. S. (2002). "Utilization of uncontrolled burnt rice husk ash in soil improvement," *Civil Engineering Dimension* 4(2) 100-105.

Okagbue, C., and Yakubu, J. (2000). "Limestone ash waste as a substitute for lime in soil improvement for engineering construction," *Bulletin of Engineering Geology and Environment* 58(2), 107-113.

Omer, O., Isa, Y., and Ozgur, M. (2007). "Strength properties of concrete incorporating coal bottom ash and granulated blast furnace slag," *Journal of Waste Management* 27(2), 161-167.

Phanikumar, B. R., and Sharma, R. S. (2007). "Volume change behavior of fly-ash stabilized clays," *Journal of Materials in Civil Engineering* 19(1), 67-74. DOI:

10.1061/(ASCE)0899-1561(2007)19:1(67)
Phummiphan, I., Horpibulsuk, S., Rachan, R., Arulrajah, A., Shen, S. L., and Chindaprasirt, P. (2018). "High calcium fly ash geopolymer stabilized lateritic soil and granulated blast furnace slag blends as a pavement base material," *Journal of Hazardous Materials* 341, 257-267. DOI: 10.1016/j.jhazmat.2017.07.067
Prusinski, J. R., and Bhattacharja, S., (1999). "Effectiveness of Portland cement and lime in stabilizing clay soils," *Transportation Research Record* 1652(1), 215-227.
Rajeswari, K., Naidu, C. D., Rao, K. B., and Kumari, G. H. (2018). "Study of soil stabilization on subgrade using bagasse ash and phosphogypsum," *Int. J. Technol. Res. Eng.* 5(6), 3133-3142.
Rashid, A. S. A., Kueh, A. B. H., and Mohamad, H. (2018). "Behaviour of soft soil improved by floating soil-cement columns," *Int. J. Phys. Model Geotech.* 18(2), 95-116.
Recovery. (2020). "Slag recycling - recovery," (https://www.recovery-worldwide.com/en/artikel/slag-recycling_3528047.html), Accessed 08 March 2021.
Rifa'i, A., Yasufuku, N., and Tsuji, K. (2009). "Characterization and effective utilization of coal ash as soil stabilization on road application," in: *International Symposium on Ground Improvement Technologies and Case Histories*, ISGI'09, Singapore, pp. 469-474.
Sargent, P. (2015). *Handbook of Alkali-Activated Cements, Mortars and Concretes*, AECOM, Altrincham, England.
Sezer, A., Inan, G., Yılmaz, H. R., and Ramyar, K. (2006). "Utilization of a very high lime fly ash for improvement of Izmir clay," *Building and Environment* 41(2), 150-155.
Sharma, A. K., and Sivapullaiah, P. (2016). "Ground granulated blast furnace slag amended fly ash as an expansive soil stabilizer," *Soils Found*. 56(2), 205-212.
Sharma, K. A., and Sivapullaiah, P. (2012). "Improvement of strength of expansive soil with waste granulated blast furnace slag," in: *GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering*, pp. 3920-3928.
Sharo, A. A., Shaqour, F. M., and Ayyad, J. M. (2021). "Maximizing strength of CKD stabilized expansive clayey soil using natural zeolite," *KSCE Journal of Civil Engineering* 25, 1204-1213. DOI: /10.1007/s12205-021-0786-2
Shih, P. H., Wu, Z. Z., and Chiang, H. L. (2004). "Characteristics of bricks made from waste steel slag," *Waste Management* 24(10), 1043-1047.
Singh, V. K., Bommireddy, D., and Phanikumar, B. (2016). "Innovative techniques in road and rail construction on expansive soils," *International Journal of Civil Engineering* 3, 119-126.
Sivapullaiah, P. V., Prasshanth, J., and Sridharan, A. (1996). "Effect of fly ash on the index properties of black cotton soil," *Soils and Foundations* 36(1), 97-103.
Solanki, P., Khoury, N., and Zaman, M. (2007). "Engineering behavior and microstructure of soil stabilized with cement kiln dust," in: *Soil İmprovement*, Denver, Colorado, United States, pp. 1-10.
Sposito, G. (1973). "Volume changes in swelling soils," *Soil Science* 115, 315-320.
Sridharan, A., and Prakash, K. (1998). "Characteristic water contents of a fine-grained soil-water system," *Géotechnique* 48(3), 337-346. DOI: 10.1680/geot.1998.48.3.337
Statista. (2021). "Global Waste Generation - Statistics & Facts," (https://www.statista.com/topics/4983/waste-generation-worldwide/), Accessed 02 March 2021.

Thomas, P. J., Baker, J. C., and Zelazny, L. W. (2000). "An expansive soil index for predicting shrink-swell potential," *Soil Science Society of America Journal* 64, 268-274.

Tremblay, H., Leroueil, S., and Locat, J. (2001). "Mechanical improvement and vertical yield stress prediction of clayey soils from eastern Canada treated with lime or cement," *Canadian Geotechnical Journal* 38(3), 567-579.

Tripathy, S., Rao, K. S. S., and Fredlund, D. G. (2002). "Water content - Void ratio swell-shrink paths of compacted expansive soils," *Canadian Geotechnical Journal* 39(4), 938-959. DOI: 10.1139/t02-022

Van, L., Hamid, N. A., Ahmad, M. F., Ahmad, A. N. A., Ruslan, R., and Tamyez, P. F M. (2021). "Factors of single use plastic reduction behavioral intention," *Emerging Sciences Journal* 5(3), 269-278. DOI: 10.28991/esj-2021-01275

Vanapalli, S. K., Tu, H., and Oh, W. T. (2014). "Soil-water characteristic curve-based methods for predicting the swelling pressure and ground heave in expansive soils," in: *Indian Geotechnical Conference*, IGC-2014, Kakinada, India.

Yadav, A. K., Gaurav, K., Kishor, R., and Suman, S. (2017). "Stabilization of alluvial soil for subgrade using rice husk ash, sugarcane bagasse ash and cow dung ash for rural roads," *International Journal of Pavement Research and Technology* 10(3), 254-261. DOI: 10.1016/j.ijprt.2017.02.001

Yılmaz, I. (2006). "Indirect estimation of the swelling percent and a new classification of soils depending on liquid limit and cation exchange capacity," *Engineering Geology* 85, 295-301.

Wu, Y., Qiao, X., Yu, X., Yu, J., and Deng, Y. (2021). "Study on properties of expansive soil improved by steel slag powder and cement under freeze-thaw cycles," *KSCE Journal of Civil Engineering* 25, 417-428. DOI: /10.1007/s12205-020-0341-6

Zha, F., Liu, S., Du, Y., and Cui, K. (2008). "Behavior of expansive soils stabilized with fly ash, natural hazards," 47, 509-523. DOI: 10.1007/s11069-008-9236-4

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