Geomechanics and Engineering, *Vol. 10, No. 5 (2016) 689-707*
DOI: http://dx.doi.org/10.12989/gae.2016.10.5.689

Effect of slag on stabilization of sewage sludge and organic soil

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(*Received January 23, 2015, Revised January 04, 2016, Accepted February 14, 2016*)

Abstract. Soil stabilization is one of the useful method of ground improvement for soil with low bearing capacity and high settlement and unrequired swelling potential. Generally, the stabilization is carried out by adding some solid materials. The main objective of this research was to investigate the feasibility of stabilization of organic soils and sewage sludge to obtain low cost alternative embankment material by the addition of two different slags. Slags were used as a replacement for weak soil at ratios of 0%, 25%, 50%, 75% and 100%, where sewage sludge and organic soil were blended with slags separately. The maximum dry unit weights and the optimum water contents for all soil mixtures were determined. In order to investigate the influence of the slags on the strength of sewage sludge and organic soil, and to obtain the optimal mix design; compaction tests, the California bearing ratio (CBR) test, unconfined compressive strength (UCS) test, hydraulic conductivity test (HCT) and pH tests were carried out on slag-soil specimens. Unconfined compressive tests were performed on non-cured samples and those cured at 7 days. The test results obtained from untreated specimens were compared to tests results obtained from soil samples treated with slag. Laboratory tests results indicated that blending slags with organic soil or sewage sludge improved the engineering properties of organic or sewage sludge. Therefore, it is concluded that slag can be potentially used as a stabilizer to improve the properties of organic soils and sewage sludge.

Keywords: organic soil; sewage sludge; slag; CBR; UCS; hydraulic conductivity; pH

1. Introduction

This paper presents a geotechnical investigation on the use of organic soil and industrial wastewater sludge with two different slags for soil stabilization purposes. The geotechnical characteristics of weak soils such as organic soils and wastewater sludge can be improved with soil stabilization techniques. The stabilization of soils offers technical, economical, ecological and environmental advantages to obtain stronger soil material for construction purposes (Malliou *et al*. 2007, Yadu and Tripathi 2013). Soil stabilization is used to make embankments, capping layers, and the base courses of transportation infrastructures such as roads, foundations, industrial and airport foundations (Singh *et al*. 2008).

On the other hand, the sludge from industrial wastewater treatment plants has become an increasing environmental problem (Güllü and Girisken 2013). Furthermore, from a management point of view, the sludge itself can be an environmental problem as a pollutant for the plant due to its huge quantity and toxicity in the management point of view, unless economical and safe techniques are available for the disposal of the sludge (Ohm *et al*. 2009, Soriano-Disla *et al*. 2010,

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

Ma *et al*. 2012).

It is known that sewage sludge management and disposal are major worldwide problems; current practices mainly include landfilling, whilst only a small amount is used in agriculture. Due to the vast amount produced daily, one of the best ways to utilize sewage sludge seems to be landfilling or burning. Burning seems to be costlier than landfilling. When sewage sludge is classified in terms of soil type, it falls into the peat or organic soil class with high fine content and organic matter with a lack of granular content. Peat or organic soils have low bearing capacity and high deformation problems are encountered when used foundation soils. Stabilization of these soils is required to avoid these problems. Organic soils traditionally have been more difficult to stabilize chemically than inorganic soils due to lower solids content, higher water content, lower pH, and chemical problems that occur in the cementing reactions (Janz and Johansson 2002). Except for mechanical compaction and soil reinforcement methods, fly ash, lime, cement, ground granulated blast furnace slag, rice husk ash etc. are commonly used to stabilize and improve the strength of the soil (Sharma and Sivapullaiah 2012, Kogbara and Al-Tabbaa 2011, Wild *et al*. 1999, Higgins 2005, James *et al*. 2008). These stabilizers can also be used to lower the water content of soils, reduce shrink-swell potential, improve workability, and increase soil strength and stiffness.

On the other hand, slag is waste or a by-product obtained from the manufacture of iron and other metals in a blast furnace; it is formed by the combination of metal ore with lime-stone flux (Singh *et al*. 2008, Yadu and Tripathi 2013, ASTM C989 2014). Slag can also be obtained from the manufacture of zinc and chrome. It is generally in granular form. When slag is classified in terms of soil type, it falls into well-graded sand with low silt (ASTM D2487 2011).

Sing *et al*. (2008) used the fly ash and granulated blast furnace slag (GGBS) and studied laboratory investigations on cement stabilized fly ash-GBFS mixes. This study showed that fly ash-GBFS-cement (52:40:8) mix can be successfully utilized for use in base and sub-base courses in highway pavements. Gupta and Seehra (1989) studied the effect of lime-GGBS on the strength of soil. They found that lime-GGBS mixtures with/without addition of gypsum revealed high UCS and CBR in comparison to untreated soil. Yadu and Tripathi (2013) studied to evaluate the usage of GBS to stabilize the soft soil. GGBS activated by cement and lime could effectively reduce the leachability of the contaminants. It has shown by Kogbara and Al-Tabbaa (2011) that improved mechanical and leaching properties were obtained with increasing binder dosage.

Papastergiadis *et al*. (2010, 2014) studied the examination of the stabilization of sewage sludge by the addition of the steelmaking slag. The addition of slag to sewage sludge is expected to contribute to its stabilization through the increase of pH towards highly alkaline values (> 11). Lin *et al*. (2005, 2007) suggested that the strength of soft cohesive subgrade soil can be improved by applying sewage sludge ash. A research was performed to investigate geotechnical performances of fine grained soil (silt) with sewage sludge by Güllü and Girisken (2013). This research showed that the sewage sludge can be used for improvement of engineering properties of silt. Chen *et al*. (2013) have studied the utilization of sewage sludge ashes as a substitute to cement and/or sand as cementitious construction materials.

The engineering properties of peat mixed with five types of binders as cement, pulverized fuel ash (PFA), lime, pelletized blast furnace slag, and gypsum were presented in a study performed by Hebib and Farrell (2003). They showed that mixing slag and cement with a peat increased the compressive strength of blended mixture approximately seven times when compared to untreated peat. Usage of sodium bentonite to generate maximum filler and pozzolanic effects on stabilized peat has been examined by Wong *et al*. (2013). Many researchers have studied that the effectiveness of fly ash use in the stabilization of organic soils and the factors that are likely to affect the degree of stabilization (Tastan *et al*. 2011, Edil *et al*. 2006). Some researchers have indicated that organic soils can be successfully stabilized using cementing products (Hoikkala *et al*. 1997, Den Haan 1998). Researchers measured the strength of peat stabilized using cement with a high gypsum content and a blast furnace slag cured at temperatures between -20°C and 20°C (Kido *et al*. 2009). Wong *et al*. (2008) have analyzed the unconfined compressive strength and initial permeability of peat soil stabilized by a mixture of cement, ground granulated blast furnace slag and siliceous sand.

The literature review shows that SS or SS ash was used to stabilize soft soil, silty soil or granulated slag. Moreover, GGBS, fly ash, cement, lime, gypsum were also used to stabilize soft soil. In our study, the economic and ecological way of using slag in soil stabilization is chosen, since producing SS ash needs extra energy, as well as GGBS, fly ash, cement, lime, gypsum had economic value. In this study, the slags were directly used without any costly process in the investigation to stabilize soft soil.

When sewage sludge is used in landfilling purposes, it can cause bearing capacity and settlement problems due to its higher fine content and water content. Slag can also result in bonding problems due to lack of fine part. Mixing slag with sewage sludge or organic soil is one way to improve the lack of fine content in slag or to improve the lack of granular content in sewage sludge or organic soils. Mixing slag with sewage sludge or organic soil can also improve the low bearing capacity, high settlement, and swelling potential of sewage sludge or organic soil.

Although, the suitability of slag's has been studied as a primary load bearing structural component in pavement systems and soil stabilization, no significant research has been conducted on the effects of blending slag with organic soils and sewage sludge behavior. Therefore, a need is raised to investigate the properties of the mixtures of slag and sewage sludge or organic soil together and separately. Thus, the aim of this paper is to evaluate the influence of slag when blended with organic soils and sewage sludge for pavement subgrade/subbase application and soil stabilization.

To achieve this aim, a series of laboratory tests were performed on soil mixtures prepared with slags, organic soils and sewage sludge at different mixing ratios. The effects of slags on the properties of sewage sludge and organic soils were evaluated separately. The present study sought to compare the use of sewage sludge-slag and organic soil-slag mixtures for the stabilized treatment of blended materials.

As a result of the laboratory studies, it was found that generally the unconfined compressive strength, swelling behavior, and CBR values are improved for slag and weak soil mixtures when compared to weak soil properties.

2. Properties of materials used

2.1 Slags

Two slags, named as KA and EYC, were used in this study. The slags were provided from an industrial zinc production plant that is located in the city of Kayseri, Turkey. The slags were obtained from two different stockpiles. The chemical composition and physical properties of the slags are summarized in Table 1 and Table 2, respectively. X-ray fluorescence (XRF) technique was performed to determine the elemental compositions of the slags, organic soil, and sewage sludge. X-ray fluorescence spectrometry is a rapid, inexpensive, and non-destructive technique for the analysis of bulk specimens. Analyses can be performed on samples which are prepared as

Table 1 XRF analysis of materials used

	EYC (%)	KA (%)	Sewage sludge (%)	Organic soil (%)
LOI	10.47	25.35	53.15	24.78
CaO	33.43	39.45	9.26	2.69
Fe_2O_3	32.00	12.34	5.15	4.29
SiO_2	5.89	6.67	15.51	56.73
SO_3	4.00	2.04	2.29	2.72
ZnO	3.31	6.82	0.42	0.01
MnO	2.07	0.43	0.07	0.03
Al_2O_3	2.00	2.58	4.72	4.93
Na_2O	0.99	0.02	0.52	0.30
Cl	0.98	0.12	0.13	0.14
PbO	0.94	1.45	0.04	-
MgO	0.92	1.16	1.56	2.07
K_2O	0.89	0.54	1.39	0.66
I	0.52	-	0.02	-
CuO	0.40	0.08	0.06	-
Cr_2O_3	0.28	0.07	0.07	0.02
P_2O_5	0.19	0.07	4.95	0.10
F	0.17	-	-	-
TiO_2	0.16	0.19	0.45	0.32
BaO	0.14	0.45	0.07	0.04

compressed powder pellets or fused glass discs (Potts 1992). The examination indicated that EYC and KA mainly consist of calcium oxide (CaO), iron oxide (Fe_2O_3) and silicon oxide (SiO_2). The ratio of CaO/SiO_2, which is an indicator of cementing potential (Janz and Johansson 2002), varies between 5.7 and 5.9 and the loss on ignition content (LOI), which is an indicator of the amount of unburned coal in the ash, varies between 10.47% and 25.35%.

The slags exhibited no plasticity and did not include any organic matter as per ASTM D4318 (2010) and D2974 (2014), respectively. The gradation curves of the slags are presented in Fig. 1. The slags were sieved through U.S. No. 4 (4.75 mm) and No. 200 (75 m) sieves to obtain the coarse grain size distributions. The amount passing through the 75-mm sieve (i.e., fines content) was 9.0% and 5.7% for EYC and KA, respectively. The specific gravity (G_s) of EYC and KA, passing through the 4.75 mm sieve (ASTM D854 2014) was 2.91 and 2.39, respectively (Table 2). Finally, it is found that EYC and KA slags have similar particle size distributions, with the EYC slag being slightly finer than the KA slag. KA and EYC are classified as SW-SM (well-graded sand with silt) according to the United Soil Classification System (USCS, ASTM D2487 2011).

Additionally, the same slags were also classified into the A-1-b category according to another ASTM D3282 standard. The pH values of the EYC and KA were 12.71 and 12.63, respectively.

2.2 Sewage sludge

Sewage sludge (SS) is the waste that remains after the treatment process in municipal wastewater plants. SS was obtained from wastewater treatment plants in the city of Kayseri. The amount of sewage sludge produced by the wastewater treatment plants of Kayseri in Turkey is about 100000 tons per year. The XRF chemical examination analysis of sewage sludge soil is presented in Table 1. The sludge used in this study can be categorized as “Class B” biosolids in the classification of Environmental Protection Agency (EPA 1993).

It is evident from XRF examination of oven-dried sewage sludge that the SS contains 15.51% SiO_2, 4.71% Al_2O_3 and 5.15% Fe_2O_3. In addition, LOI is 53.15%, and the pH value of sewage sludge is 5.76. The physical properties of sewage sludge are presented in Table 2.

2.3 Organic soil

Organic soils were obtained from the Kayseri Free Zone and Kayseri Organized Industrial Zone in Turkey. Samples were collected at a depth of 1.50-3.0 m. The depth of the organic soils ranging from 1 to 3 m implies that the soil can be categorized as moderately deep peat according to the definition made by Lim (1989). The chemical analysis and physical properties of organic soil are presented in Table 1 and Table 3, respectively.

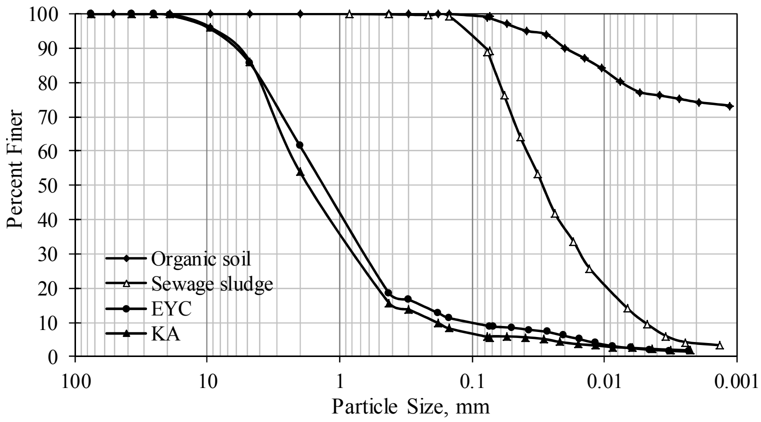


Fig. 1 Grain size distributions of the materials used

Table 2 Index properties of SS, EYC and KA materials

Property	Sewage sludge	EYC	KA
Passing No. 4 sieve (%)	100	85.6	86.2
Passing No. 200 sieve (%)	89.1	9.0	5.7
Classification of soil (USCS)	-	SW-SM	SW-SM
Natural moisture content (%)	Sun dried	Sun dried	Sun dried
Specific gravity (G_s)	1.72	2.91	2.39
Plasticity index (%)	-	NP	NP
pH	5.76	12.71	12.63
Maximum dry unit weight (kN/m^3)	9.1	18.0	15.9
Optimum water content (%)	45.0	16.0	17.5

XRF examination of oven-dried organic soil showed that organic soil contains 56.73% SiO_2, 4.93% Al_2O_3 and 4.29% Fe_2O_3. The organic soil sample was classified as belonging to the organic silt (OH) group according to USCS. The natural water content of organic soil was found to be in the range of 90%-220.0% depending on seasonal weather condition. The gradation curve of the organic soil is shown in Fig. 1. The color of the organic soil was observed to vary between brown and dark brown.

The ash content of the organic soil sample in this study was determined by igniting the oven-dried sample in a muffle furnace at 440°C (Method C) according to ASTM D2974 (2014). The ash percent of organic soil was found to be in the range of 75%-81.4% and, organic matter content was in the range of 18.6%-25%. Considering the results obtained, the present soil obtained from the Kayseri Organized Industrial Region can be classified as organic soil (organic silt-OH), since Huat *et al*. (2014) state that "if the organic content of soil exceeds 20% of its dry mass", then, these soils can be defined as "organic soil".

3. Experimental methods

The specimens of mixture were prepared by adding 0%, 25%, 50%, 75% and 100% (in weight) of EYC and KA slags to organic soils and sewage sludge. The slags and organic soil mixtures or slags and sewage sludge mixtures were prepared according to the above specified ratios. Mixing was carried out until the mix appeared to be homogeneous. After mixing and prior to compaction, the mixture was allowed to mellow for one hour in accordance with Kalinski and Yerra (2005). In

Table 4 OMC, MDD, CBR (unsoaked and soaked condition) and swell value for mix

Material designation	OMC (%)	$\gamma_{d\max}$ (kN/m^3)	CBR (%)		Swell (%)
			Unsoaked	Soaked	
Sewage sludge	45.0	9.05	4.25	1.29	2.18
Organic soil	75.0	6.82	0.90	0.79	1.63
EYC	16.0	18.0	117.19	108.52	0.04
KA	17.5	15.9	121.13	120.99	0.03
25:75% Blend of KA and SS	37.0	9.75	6.33	5.98	1.70
50:50% Blend of KA and SS	34.0	11.22	10.39	8.46	0.88
75:25% Blend of KA and SS	28.5	12.90	12.96	8.80	0.59
25:75% Blend of KA and OS	50.0	9.82	5.03	4.85	0.64
50:50% Blend of KA and OS	40.0	11.45	5.59	5.09	0.50
75:25% Blend of KA and OS	36.0	11.65	7.00	6.43	0.21
25:75% Blend of EYC and SS	34.5	10.25	8.06	6.13	1.92
50:50% Blend of EYC and SS	27.5	12.15	9.05	7.86	1.57
75:25% Blend of EYC and SS	25.0	14.2	11.33	11.03	0.23
25:75% Blend of EYC and OS	68.0	8.6	9.05	8.71	0.94
50:50% Blend of EYC and OS	50.0	9.45	12.89	11.53	0.64
75:25% Blend of EYC and OS	30.0	13.70	17.31	16.29	0.30

Note: OMC = Optimum moisture content. $\gamma_{d\max}$ = Maximum dry density order to investigate the effects of two different slag materials on the geomechanical and hydraulic behavior of organic soil and sewage sludge materials, compaction tests, CBR tests, the UCS test, HCT, and pH test were carried out on slag-soil specimens that were prepared at the maximum dry density (MDD) with optimum moisture content (OMC), determined according to ASTM D698 (2012) for each mixture. The mixture proportions are presented in Table 4 for each slag-soil mixture. The test specimens were prepared for each mixture combination.

3.1 Compaction tests

In order to determine the optimum water content and maximum dry unit weight of raw and mixing specimens, compaction tests (Standard Proctor method) on samples with a diameter of 101.6 mm and a height of 116.4 mm were carried out according to ASTM D698 (2012). All materials were oven-dried at 105°C and sieved through a U.S. 19-mm sieve before compaction. The maximum dry density and optimum moisture content were determined for each mixture combination.

The OMC and MDD values determined from the Standard Proctor tests were later used as target values for preparing the soaked/unsoaked CBR test, UCS test and hydraulic conductivity test specimens. At least four data points were collected to develop the moisture-density curve for each mixture.

3.2 Strength tests

Generally, CBR tests are used for the assessment of strength of soil for road construction. Also, the UCS test as an alternative approach to the CBR test was used to evaluate the strength of soil to be used for the purpose of road works by Thomas (2002). In the current study both CBR and UCS tests were performed to assess the strength properties of each compacted mixture.

3.2.1 California Bearing Ratio (CBR)

CBR tests were performed on each soil mixture sample after compaction with and without soaking, following the methods outlined in AASHTO T-193 and ASTM D1883 (2007). Tests were performed with a 1.27 mm/min strain rate using a loading frame. Samples were immersed in a water tank for 96 hours at a temperature of about 20°C and the amount of swell was checked before testing. At the end of four days, a final dial reading on the soaked specimens was taken and the amount of swell were determined as a percentage of the initial sample length. The equipment had a maximum loading capacity of 50 kN. Two specimens were tested for CBR tests as quality control, and the averages of these two tests were reported as the CBR value results.

3.2.2 Unconfined Compressive Strength (q_u)

Specimens of each mixture were compacted according to ASTM D698 (2012) Method B, and samples with a height of 116.4 mm and a diameter of 101.6 mm were prepared in compaction molds for UCS tests following the guidelines in ASTM D5102 (2009) Method B or ASTM D1633 Method A. This test method covers procedures for preparing, curing, and testing laboratory-compacted specimens of soil-lime and other lime treated materials to determine unconfined compressive strength. Specimens were removed from the mold after compaction. The specimens were wrapped, sealed using stretch film, and cured in a climatic cabinet capable of maintaining a temperature of 23°C ± 2.0 for seven days before testing.

To assess the effect of curing time on q_u, the unconfined compression strength of the blended specimens was also measured after a curing period of seven days. Two replicate specimens of each material were subjected to UCS tests immediately (within one hour after compaction) and at 7 days after compaction to assess the strength gain in time.

The specimens were subjected to UCS test at a constant strain rate of 1.0 mm per minute until failure or 5% axial displacements were reached. The standard specifies that the axial deformation rate should be approximately between 0.5 to 2.0 % per min (ASTM D5102 2009). The axial strain rates used in this study also comply with the published literature: Singh *et al*. (2008) and Obuzor *et al*. (2011) used strain rate values in the range of 1.0 to 2.0 mm/min.

3.3 Hydraulic conductivity tests

Hydraulic conductivity tests were performed to assess the effects of slag content on the permeability of compacted organic soil and sewage sludge stabilized with slag. In the vertical hydraulic conductivity testing, the constant head compaction permeameter or falling-head tests (whichever is appropriate) were carried out depending on the level of the permeability coefficient. Permeability tests were conducted on specimens of each material compacted according to ASTM D698 (2012). The applied hydraulic gradient was maintained at ~1 during the hydraulic conductivity tests. Finally, the vertical hydraulic conductivities were calculated using Darcy's law. The samples' sizes were the same as used in the UCS test.

3.4 pH tests

The pH testing on soil samples was carried out according to ASTM D4972 (2013) and D2976 (1998), which cover the measurement of the pH of soils. Such measurements are used in the agricultural, environmental, and natural resources fields. This measurement determines the degree of acidity or alkalinity of soil materials suspended in water and a 0.01 M calcium chloride solution. This variable is useful in determining the solubility of soil minerals and the mobility of ions in the soil and in assessing the viability of the soil-plant environment.

It is known that hydration and secondary pozzolanic reactions occur in high alkaline conditions. Thus, it was necessary to perform pH tests (BS1377: 1990, Test 11 (A)) using a pH meter to investigate the degree of alkalinity of the stabilized soil mixtures immediately after mixing (Wong *et al*. 2013). For effective organic soil stabilization, the pH value of the stabilized soil admixture must exceed 9. Test specimens with organic acids producing a pH value lower than 9 in the pore solution strongly affect the development of cementing products. Tremblay *et al*. (2002) noted no strength gain at such a pH value. The pH values of stabilized organic soil and sewage sludge admixtures were compared to those of untreated organic soil and sewage sludge.

pH measurements were made in a calcium chloride solution because the calcium displaces some of the exchangeable aluminum. The liquid-to-solid ratio (0.01 M $CaCl_2$ solution/soil admixture: 20 mL/20 g) was kept at 1:1 in the pH value tests, and samples were allowed to stand for 1 hr in this study (ASTM D4972 2013).

4. Results

4.1 Compaction tests

Compaction tests were carried out for different moisture content to obtain the moisture content and density curves. Fig. 2 shows the effect of slag mixture with organic soil and sewage sludge through the compaction tests (Standard Proctor) on the raw KA, EYC slags and KA+SS, KA+OS, EYC+SS, and EYC+OS mixtures for a range of slag dosage changes from 0 to 100%. The compaction test result data, including OMC and MDD, are presented in Table 4 for each mixture. Also, the zero air void curves (S = 100% curve) are obtained for all mixtures by substituting for a fully saturated soil (i.e., S = 100%) and plotted alongside the compaction curve.

It can be seen from Table 4 that the OMC and MDD of the mixture containing only KA are 17.5% and 15.9 kN/m³, respectively. In the same manner, the OMC and MDD of the mixture containing only EYC are 16% and 18 kN/m³. They are 45% and 9.05 kN/m³, and 75% and 6.82 kN/m³ for the mixture containing only SS and OS, respectively.

When KA or EYC slag are mixed with SS, OMC value is reduced, and MDD value is increased when compared to mixture containing only SS. The more the replacement of slag with SS result with lower OMC and higher MDD value, regardless of slag type.

When KA or EYC slag are mixed with OS, OMC value is reduced, and MDD value is increased when compared to mixture containing only OS. The more the replacement of slag with OS result with lower OMC and higher MDD value, regardless of slag type.

Moreover, it was observed from both Fig. 2 and Table 4 that when the amounts of SS or OS are increased in the mixture, the OMC was increased (see Fig. 2, peak point of compaction curves shifts to right side) and the MDD was decreased. This was attributed to the high amount of fine content with high water absorption capacity of SS and OS. It was also observed that there was a

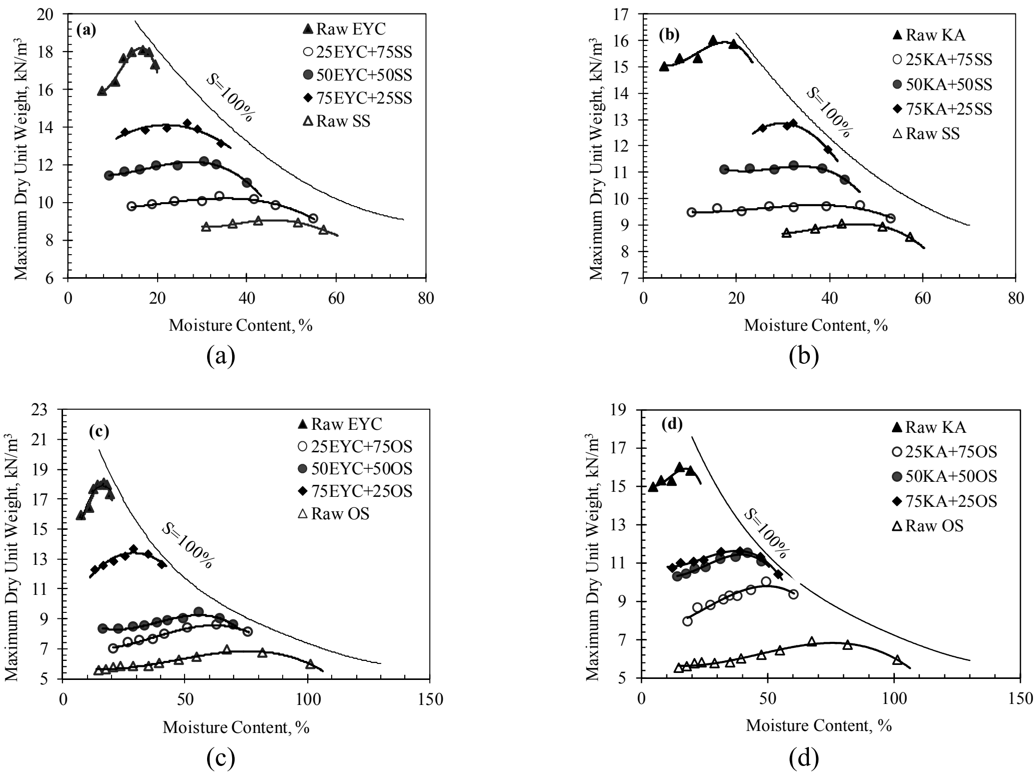


Fig. 2 The moisture-density relationship for all mixtures

decrease in MDD with an increase in OMC, which is consistent with observations reported by Yadu and Tripathi (2013); this is natural since specific gravity of water is lower than the other materials in the mixture.

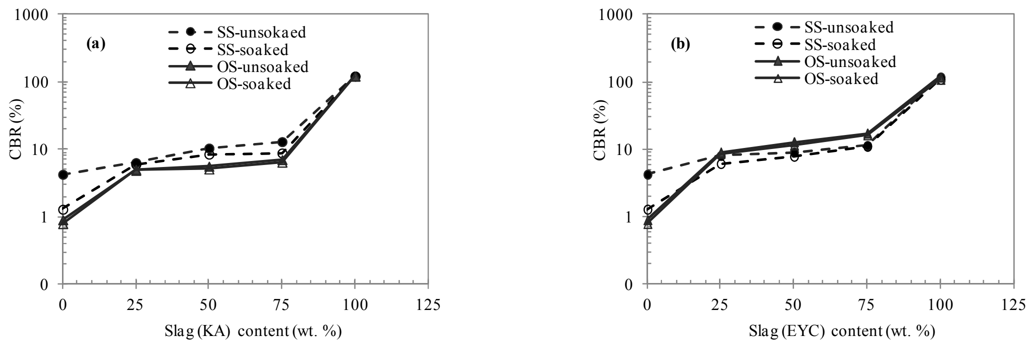
It is concluded that inclusion of KA and EYC slag with SS or OS reduced OMC and increased MDD value. It is known that OS is finer than SS. Also, OS and SS are finer than both KA and EYC. When a coarse material is mixed with a fine material, fineness of resultant mixture is lower than that of fine material, and it is higher than that of coarse material. Furthermore, fine material had larger specific value than that of coarse material. Finer material absorbs more water when compared to coarse material (Güllü and Girisken 2013). This is the reason for reduced the OMC value and, thus, increased MDD value when mixing EYC or KA with SS or OS.

4.2 CBR tests

The curves of variation of CBR with slag content under soaked and unsoaked conditions for (a) KA and SS, or, KA and OS mixtures; and (b) EYC and SS, or, EYC and OS mixtures at different ratios are plotted in Fig. 3. These CBR data are also presented in Table 4. It can be seen from both Table 4 and Fig. 3 that when the amounts of EYC or KA content are increased in the mixture, the CBR values of the mixtures are improved for both the SS and OS cases. Similar comments can be made for both unsoaked and soaked CBR values.

When SS or OS materials were compared with each other in the case of KA slag, the SS and KA mixture gave a higher CBR than that of the counterpart OS and KA mixture. When SS or OS materials were compared with each other in the case of EYC slag, the OS and EYC mixture gave a higher CBR than that of the counterpart SS and EYC mixture. It can be concluded that use of KA with SS and the use of EYC with OS were more appropriate than KA with OS and EYC with SS in the mixture.

It can also be seen from Fig. 3 that mixing slag in weak soil material improves, the CBR values; however, the improvement was not found to be at the expected rate. Mixing 25% KA slag with SS or OS increased the unsoaked CBR value approximately 1.5 times and 5.4 times when compared to the mixtures containing only SS or OS, respectively. Mixing 25% EYC slag with SS or OS increased the unsoaked CBR value approximately 2 times and 9 times when compared to mixture containing only SS or OS, respectively. The same is valid for the soaked CBR values. A higher than 25% slag amount in the mixture did not improve the CBR value when compared to 25%



(a) (b)

Fig. 3 CBR value relationship with slag amount

amount of slag. Therefore, the use of 25% slag replacement with weak soil material (SS or OS) is suggested, since slag material is more valuable than SS and OS.

With regard to the pavement design specification, AIIS-181, regulated by the Asphalt Institute, Lin *et al*. (2007) suggests that subgrade soil can be categorized into three groups by CBR values: if the CBR value is less than or equal to 3, the material is classified as poor subgrade soil; if the CBR value is higher than 3 and less than or equal to 8, material is classified as medium subgrade soils; and if CBR value is higher than 8, the material is classified as good-to-excellent subgrade soil. Thus, many of the mixtures produced in this study fall within the good-to-excellent subgrade soils category. However, some of the mixtures made with KA and OS are categorized as medium subgrade soils. Mixtures which contain only SS and OS are categorized as poor subgrade and medium subgrade soils, respectively. This study proved that weak soil materials (SS or OS), which can be mostly classified as poor subgrade soils, can be improved to medium subgrade soil or good-to-excellent subgrade soil by adding slag materials (KA or EYC) into the weak soil mixture.

It was reported by Lin *et al*. (2005) that the swelling characteristic of soil is important; it was defined as a phenomenon of moistured soil body volume change and was generally related to organic matter in soil, types and quantities of clay mineral. Water is the main factor in the swelling behavior mechanism of soil. The Design Procedures for Soil Modification or Stabilization (2008) state that the allowed swell amount is no more than 3% in modified soils.

The swelling results of the mixture prepared in this study are given in Table 4. The swell potentials of all mixtures are found to be lower than 3%. The swell potentials of only SS and OS containing mixtures are 2.18 and 1.63%, respectively. When KA or EYC slag is added to weak SS or OS materials, the swelling value decreased when compared to only SS or OS containing mixtures.

Table 4 also illustrates that slag addition could lessen the swelling of SS and OS, and the original expanded volume could be reduced up to 7.3 times and 5.4 times, respectively. In general, the volumetric swellings of CBR samples for all slag-SS/OS samples were found to be smaller when compared to the untreated soil. The swelling behavior of weak soils (SS or OS) was observed clearly. It was found that the swelling potential improved greatly after slag was added to untreated soil.

4.3 UCS tests

UCS tests were conducted under the specifications of ASTM D5102 (2009) Method B. The unconfined compressive strength (q_u) of mixtures containing slag (EYC or KA) and weak soil (SS or OS) was measured. The mixtures were prepared at the OMC and MDD.

Mixtures prepared with only KA or EYC or SS or OS or a blend of them was allowed to mellow for only one hour. Then, they were subjected to UCS testing; these mixtures were considered to be uncured. Equivalent samples were also subjected to UCS testing at 7 days, to evaluate the self-cementing properties of slags. It is known that some slags can have either self-cementing or pozzolonic properties, while others cannot have self-cementing properties but can have pozzolonic properties (ASTM C618 2005 and C989 2014).

The results obtained from the laboratory study are presented in Table 5, Figs. 4, 5 and 6 which show that SS, OS and EYC do not have self-cementing properties since their UCS test results were found to be similar at no curing and at 7 days curing. However, KA showed good cementing properties, because its UCS value changed from 34.81 to 120.71 kPa, when curing time changed from one hour to 7 days curing time.

When KA or EYC slags were mixed with SS or OS, the UCS value of the mixture improved. A higher amount of slag in mixtures results in higher UCS values when compared to mixtures made without slag. However, mixtures containing slag and OS gave higher UCS values than those containing slag and SS, regardless of slag (EYC or KA) type. Curing time influenced the UCS value regardless of blended mixtures. The UCS values were improved with longer curing time,

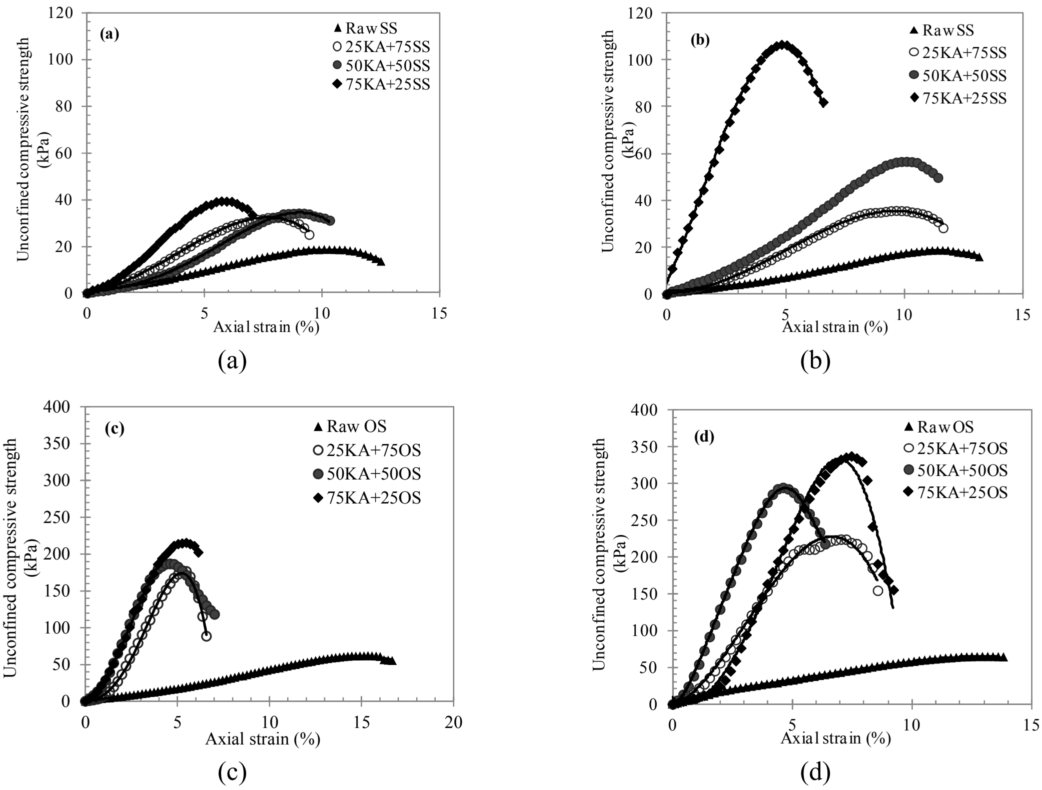


Fig. 4 UCS vs. axial strain for KA containing mixtures (right sides belong to 7 day cured samples)

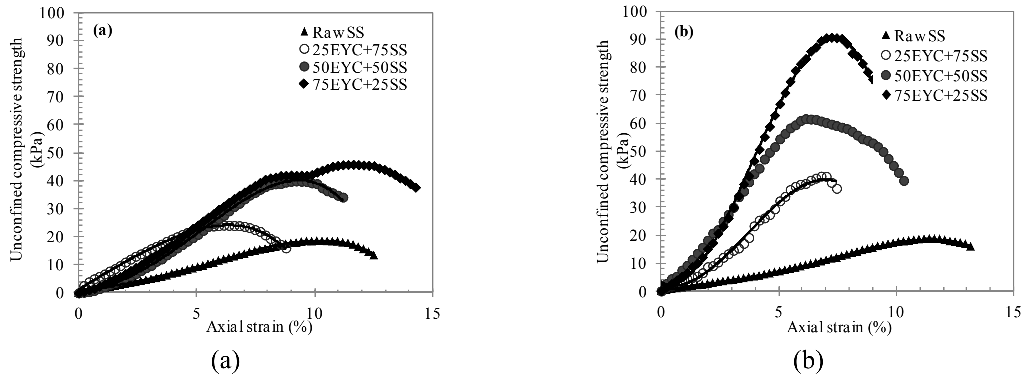
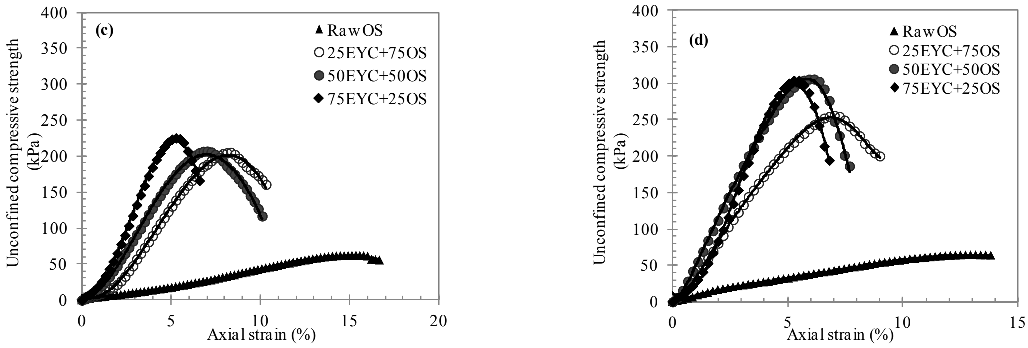
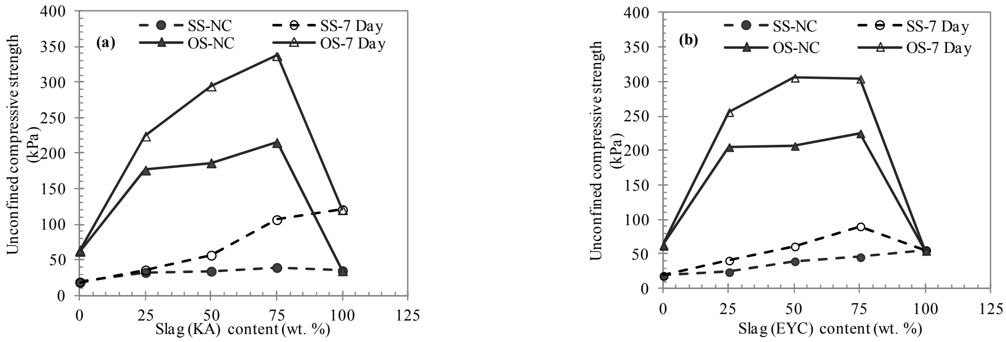


Fig. 5 UCS versus axial strain for EYC containing mixtures (right sides belong to 7 day cured samples)



(c) (d)

Fig. 5 Continued



(a) NC:non-cured (b)

Fig. 6 Fig. 6 Variation of UCS with slag content with and without curing

they were also improved by increasing slag content. Higher slag content results in higher UCS values at 7 days curing time. The improvement in UCS values at 7 days is attributed to the self-cementing properties or pozzolonic properties of the slags used.

Tastan *et al*. (2011) stabilized soft soil using cement and fly ash. While soft soil had 57 kPa UCS value, this value is increased to 140-395 kPa by using cement and fly ash as a stabilizer. Hebib and Farrell (2003) studied to improve the engineering properties of peat. They reported that UCS value of peat increased from 5-10 kPa to 70 kPa for a blended mixture of peat, cement and blast furnace slag. Lin *et al*. (2005, 2007) have studied to stabilize soft soil by using sludge ash. They found that stabilized soil reached up to 70 kPa UCS value. Yadu and Tripathi (2013) stabilized soft soil by treating it 12% GBS. They obtained up to 150 kPa UCS value from treated soil.

In this study, while organic soil had originally 62 kPa UCS value which is improved up to 225.0 kPa by mixing slag with organic soil. In similar manner, the sewage sludge had 18.91 kPa UCS value which is improved to 45.82 kPa UCS value by mixing with it slag. The results of UCS value obtained from this study in agreement or better (for organic soil case) when compared with the published literature.

Table 5 UCS values for the mixtures

Material designation	UCS (kPa)	
	Non-cured	7 days cured
Sewage sludge	18.91	18.57
Organic soil	62.11	63.42
EYC	56.00	55.00
KA	34.81	120.71
25:75% Blend of KA and SS	32.37	35.73
50:50% Blend of KA and SS	34.19	56.69
75:25% Blend of KA and SS	39.36	106.63
25:75% Blend of KA and OS	176.49	224.28
50:50% Blend of KA and OS	186.51	294.64
75:25% Blend of KA and OS	215.11	337.47
25:75% Blend of EYC and SS	24.12	40.95
50:50% Blend of EYC and SS	39.89	61.44
75:25% Blend of EYC and SS	45.82	90.48
25:75% Blend of EYC and OS	205.40	256.14
50:50% Blend of EYC and OS	207.12	305.98
75:25% Blend of EYC and OS	225.39	304.39

Note: UCS: Unconfined compressive strength

4.4 Hydraulic Conductivity Tests (HCT)

The constant-head test and falling head tests were employed in this study. The samples were prepared according to ASTM D698 (2012) using Standard Proctor compaction effort underwent hydraulic conductivity testing. The hydraulic conductivity testing results are presented in Table 6 which shows that the permeability values obtained from samples were between 5.94×10^{-4} and 5.05×10^{-9} cm/sec; the difference between the permeability margins of the samples was found to be very large. The lowest permeability of 5.05×10^{-9} cm/sec belongs to the mixture containing SS, while the highest permeability of 5.94×10^{-4} cm/sec belongs to the mixture containing only EYC slag. It can be observed from Table 6 that the mixtures containing only SS and OS showed lower permeability when compared to the mixtures containing only KA and EYC slag. Blending KA or EYC slag with SS or OS increased the permeability coefficient depending on mixing ratio when compared to the mixture containing only SS or OS. When more slag was introduced into the mixture (KA or EYC), the permeability increased. In other words, the higher the fines content of the mixtures, the lower the permeability coefficient. This is consistent with the published literature. It is well known that increased fines content in the granular highway base/subbase layers reduces the hydraulic conductivity of the base materials (Berthelot *et al*. 2009).

However, the permeability coefficients of the specimens, except for 25KA+75SS and 25 EYC+75 SS mixtures, measured during this study are not adequate with respect to the criterion of 1×10^{-7} cm/sec which is often used for waste containment layers, but these materials may be suitable for other geotechnical applications such as highway subbase and subgrade courses as reported by Kalinski and Yerra (2005).

Table 6 Permeability values of mixtures0

Material designation	OMC (%)	$\gamma_{d\max}$ (kN/m^3)	Hydraulic conductivity (cm/s)
Sewage sludge	45.0	9.05	5.05E-09
Organic soil	75.0	6.82	1.73E-07
EYC	16.0	18.0	5.94E-04
KA	17.5	15.9	4.54E-05
25:75% Blend of KA and SS	37.0	9.75	3.37E-07
50:50% Blend of KA and SS	34.0	11.22	1.50E-05
75:25% Blend of KA and SS	28.5	12.90	2.04E-05
25:75% Blend of KA and OS	50.0	9.82	1.26E-06
50:50% Blend of KA and OS	40.0	11.45	6.07E-06
75:25% Blend of KA and OS	36.0	11.65	8.38E-06
25:75% Blend of EYC and SS	34.5	10.25	8.47E-09
50:50% Blend of EYC and SS	27.5	12.15	1.05E-04
75:25% Blend of EYC and SS	25.0	14.2	1.76E-04
25:75% Blend of EYC and OS	68.0	8.6	1.22E-06
50:50% Blend of EYC and OS	50.0	9.45	1.67E-06
75:25% Blend of EYC and OS	30.0	13.70	3.51E-06

Table 7 pH values of mixtures

Material designation	OMC (%)	$\gamma_{d\max}$ (kN/m^3)	pH values with benchtop pH meter
Sewage sludge	45.0	9.05	5.76
Organic soil	75.0	6.82	7.85
EYC	16.0	18.0	12.71
KA	17.5	15.9	12.63
25:75% Blend of KA and SS	37.0	9.75	8.83
50:50% Blend of KA and SS	34.0	11.22	10.84
75:25% Blend of KA and SS	28.5	12.90	12.49
25:75% Blend of KA and OS	50.0	9.82	9.21
50:50% Blend of KA and OS	40.0	11.45	10.72
75:25% Blend of KA and OS	36.0	11.65	12.75
25:75% Blend of EYC and SS	34.5	10.25	7.94
50:50% Blend of EYC and SS	27.5	12.15	9.84
75:25% Blend of EYC and SS	25.0	14.2	10.14
25:75% Blend of EYC and OS	68.0	8.6	10.04
50:50% Blend of EYC and OS	50.0	9.45	11.87
75:25% Blend of EYC and OS	30.0	13.70	12.64

4.5 pH Values for all each mixtures

The pH values of slag soil mixtures prepared in this study measured according to ASTM D4972

(2013) are presented in Table 7. It can be seen from Table 7 that the pHs of mixtures containing only SS and OS are 5.76 and 7.85, respectively.

When KA slag was introduced into the SS mixture, the pH value increased from 5.76 to 12.49. Similarly, KA slag increased the pH value of OS mixtures from 7.85 to 12.75. When EYC slag was introduced into the SS mixture, the pH value increased from 5.76 to 10.14. Similarly, EYC slag increased the pH value of OS mixtures from 7.85 to 12.64. In general, introducing both slags into weak soil (SS and OS) increased the pH value, which is attributed to the high amount of calcium oxide (alkaline material) content of the slags. A similar conclusion was made by Hoyt and Nielsen (1985), who reported that high pH of the soil was usually associated with high calcium content.

5. Conclusions

The following conclusions were made from the laboratory investigation.

- When the amounts of EYC or KA slag in a blend are increased, the MDD value is also increased and the OMC value is decreased. The largest MDD and the smallest OMC are determined as 14.2 kN/m³ and 25% for the mixture containing 75% EYC slag and 25% SS.
- Introducing EYC or KA slags improved the CBR values of blended mixtures, when compared to the mixture made with only SS or OS. No difference was found between the unsoaked and soaked CBR values. Mixing 25% EYC slag with OS increased the CBR value approximately 9 times, when compared to mixture containing only OS.
- Although the swelling potential of OS or SS is within the allowable limits, blending slags with OS or SS decreased the swelling when compared to untreated soils. The swell potentials of only SS and OS containing mixtures are 2.18 and 1.63%, while slag blended mixtures with SS and OS gave 0.23 and 0.21 swelling potential, respectively.
- Blending slag with OS and SS increased the UCS value of blended mixtures when compared to non-blended mixtures. KA and EYC slags improved the UCS values of blended mixtures through their cementing and pozzolonic properties at 7 days curing time. KA showed good cementing properties, because its UCS value changed from 34.81 to 120.71 kPa, when curing time changed from one hour to 7 days.
- The permeability coefficients of mixtures containing slag were increased when compared to the mixture made with only SS or OS. A higher the amount of slags in blended mixtures results in a higher the permeability coefficient.
- Blending KA or EYC in the mixture results in a higher pH value, which explains the improvement in UCS values at 7 days since the pozzolonic reaction is associated with high pH values.
- As a result of the study, mixing a 25% amount of KA or EYC slag is recommended with SS or OS material, since mixing more than a 25% amount of slag did not relatively much improve the mechanical properties of the blended mixtures.
- The laboratory results showed that sewage sludge and organic soil can potentially be used in subbase/subgrade applications when they are blended with the proper amount of EYC and KA slags (i.e., 25-50%).
- Blending slag with OS allows the reuse of waste slag in soil improvement. Blending waste slag with SS provides the reuse of both waste slag and waste SS, and it recycles waste materials into a valuable embankment material to be used in subgrade applications. This can be considered as a better solution from a waste management point of view.

Acknowledgments

This study was supported by Research Fund of the Erciyes University (ERU), Kayseri, Turkey. Project Number: FBA-12-3921.

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