

## ARTICLE

# Stabilization of Expansive Soil Using Biomedical Waste Incinerator Ash

Asefachew Belete Tseganeh<sup>1,2\*</sup> Henok Fikre Geberegiabher<sup>3</sup> Ayele Tesema Chala<sup>1,4</sup>

1. African Railway Center of Excellence (ARCE), Addis Ababa Institute of Technology (AAiT), Addis Ababa University (AAU), Addis Ababa, Ethiopia.
2. School of Civil and Water Resource Engineering, Woldia University Institute of Technology, Woldia, Ethiopia.
3. School of Civil and Environmental Engineering, Addis Ababa Institute of Technology (AAiT), Addis Ababa University (AAU), Addis Ababa, Ethiopia.
4. Department of Structural and Geotechnical Engineering, Széchenyi István University, Egyetem tér 1, Győr Hungary 9026.

### ARTICLE INFO

#### Article history

Received: 10 September 2021

Accepted: 26 September 2021

Published Online: 29 September 2021

#### Keywords:

Expansive soil

Stabilization

BWIA

Subgrade

CBR

### ABSTRACT

Expansive soils undergo high volume change due to cyclic swelling and shrinkage behavior during the wet and dry seasons. Thus, such problematic soils should be completely avoided or properly treated when encountered as subgrade materials. In the present study, the biomedical waste incinerator ash and lime combination was proposed to stabilize expansive soil. Particle size analysis, Atterberg limits, free-swell, compaction, unconfined compression strength, and California bearing ratio tests were conducted on the natural soil and blended with 3%, 5%, 7%, 9%, and 11% biomedical waste incinerator ash (BWIA). The optimum content of BWIA was determined based on the free-swell test results. To further investigate the relative effectiveness of the stabilizer, 2% and 3% lime were also added to the optimum soil-BWIA mixture and UCS and CBR tests were also conducted. In addition, scanning electron microscopy (SEM) tests for representative stabilized samples were also conducted to examine the changes in microfabrics and structural arrangements due to bonding. The addition of BWIA has a promising effect on the index properties and strength of the expansive soil. The strength of the expansive soil significantly increased when it was blended with the optimum content of BWIA amended by 2% and 3% lime.

## 1. Introduction

Expansive soils are problematic in nature and are not suitable for engineering. According to [1], engineering problems related to expansive soils have been investigated and reported in many countries, which comprise about 3% of the world's land area. Such kinds of soil are mostly found in the central part of Ethiopia following the major trunk roads from Addis Ababa-Ambo, Addis Ababa-Wol-

liso, Addis Ababa-Modjo, Addis Ababa-Gohatsion, and Addis Ababa-Debire Birhan [1]. Areas like Mekelle and Gambella are also covered by expansive soils [1]. These soils undergo high volume change due to the cyclic swelling and shrinkage behavior in wet and dry seasons. Hence, it is necessary to solve the problems posed by expansive soils and prevent cracking of civil infrastructure [2-8] such as roads, railways, airfields, etc. This swelling and shrinkage is mainly due to the presence of montmorillonite clay

\*Corresponding Author:

Asefachew Belete Tseganeh

1. African Railway Center of Excellence (ARCE), Addis Ababa Institute of Technology (AAiT), Addis Ababa University (AAU), Addis Ababa, Ethiopia.

2. School of Civil and Water Resource Engineering, Woldia University Institute of Technology, Woldia, Ethiopia.

Email: asefachew.belete@aait.edu.et; assfitibel2009@gmail.com

minerals<sup>[9-11]</sup>, which make the soil swell because of the infiltration of water during wet seasons and shrink due to the evaporation of water during dry seasons<sup>[12]</sup>. For this reason, civil infrastructure founded on it is no longer functional<sup>[9,12]</sup>, but such soils are suitable for agriculture. Hence, there is a need to be excavated and then replaced by selected materials having better swelling and shrinkage properties and bearing capacities as well<sup>[13]</sup>, or by modifying the properties of the raw expansive soil mechanically without any chemical additives<sup>[14]</sup>, or by blending with different pozzolanic additives<sup>[9]</sup>; called chemical stabilization. When expansive soils are encountered on highway, railway, and airfield projects where there is no appropriate backfill (granular) material nearby, treating with different pozzolanic or cementitious materials (chemical stabilization) is the most popular method used to enhance the physical, index, and mechanical properties of expansive clayey soils. It is also mostly considered to be the most economical alternative measure to be taken by engineers<sup>[14,15]</sup>.

Many researchers have conducted various studies on the stabilization of expansive soils using lime, cement, fly ash, etc.<sup>[6,9]</sup> to mitigate the problems behind expansive soils, and promising results have been obtained from the experimental results they conducted. Many researchers all over the world use lime and cement as traditional stabilizers<sup>[16]</sup>. But, in recent times, the focus of geotechnical engineers has shifted to the utilization of different industrial and agricultural solid wastes (bi-products) in combination with hydrated lime to gain improved performance and manage wastes that may cause environmental pollution<sup>[16,17]</sup> such as bagasse ash<sup>[8,16,18]</sup>, rice husk ash<sup>[19,20]</sup>, pumice<sup>[1]</sup>, etc. Based on the experimental results they obtained, those solid wastes blended with lime significantly improved the engineering properties of expansive soils. In addition to these waste materials, there is also abundantly

available solid waste generated from healthcare facilities which has an adverse impact on human beings and the environment as well; this is called biomedical waste.

Eight high-temperature medical waste incinerators are constructed in Ethiopia to incinerate (burn) biomedical wastes generated from different healthcare facilities. The one built-in Adama city has a burning capacity of 1000 kg per hour. Similar facilities constructed in Bahir Dar, Dessie, Jimma, Nekemte, Dire Dawa, Hawassa, and Mekelle have a burning capacity of 500 kg per hour. Those incineration plants can burn the waste up to 1200 °C and also use disinfectants to completely sterilize the toxic elements. Therefore, the incinerated medical waste ash is abundantly available and has no side effects for human beings and the environment. Since the technology is being adopted very soon, there is no research conducted by utilizing the incinerated ash for concrete production or as an expansive soil stabilizer. However, many researchers in other countries have investigated the effects of biomedical waste incinerator ash on the physical and mechanical properties of concrete<sup>[21-23]</sup>, and also<sup>[24]</sup> studied the effect of incinerator ash on the properties of expansive soil and found that there is a reduction in swelling potential & cohesion (C), and an increase in angle of internal friction ( $\phi$ ) with an increase incinerator ash for concrete. The effect of incinerator ash on the swelling potential, cohesion and angle of internal friction were studied, but other properties such as unconfined compressive strength and California bearing ratio were not addressed by the study. Because the strength of subgrade soil is represented by its California bearing ratio value, which is an important design parameter for flexible pavement. Similarly, this study aims at investigating the effect of biomedical waste incinerator ash (BWIA) on the engineering properties of expansive soil, and also to investigate its relative effectiveness on the strength and microstructural properties with amendment of hydrated lime.



**Figure 1.** Materials used in the Study (a) soil, (b) BWIA and (c) lime

## 2. Materials and Methods

### 2.1 Materials

The materials used for the present study are Expansive Soil, Biomedical Waste Incinerator Ash (BWIA) and Hydrated lime (Figure 1).

The expansive soil was obtained from the Kaliti-Meshualekiya road stretch, Akaki Kaliti sub-city, Addis Ababa, Ethiopia. The properties of this dark grey soil under investigation, are summarized in Table 1. The BWIA utilized for the study was obtained from Adama modern health-care waste incineration center, which is located in the rift valley region of Ethiopia, while the lime was obtained from the Senkelie lime factory. The properties of BWIA and lime are listed in Table 2 and 3 respectively.

### 2.2 Methods

The research aims were achieved basically by performing classification tests following the usual procedure mentioned in Table 1. Brief definitions of these tests are described hereunder.

#### Liquid Limit (LL)

The water content at which a soil specimen starts to behave as liquid, or it can also be defined as the moisture content at which a cohesive (clayey) soil changes from plastic to semi-liquid states. The liquid limit was determined in the laboratory by using the Casagrande apparatus following the clear procedure stated in [25].

#### Plastic Limit (PL)

The percentage of water content in a soil specimen at the interface between the plastic and semi-solid states. The plastic limit was determined by following the procedure clearly stated in [25].

#### Plasticity Index (PI)

The percentage of moisture at which a soil behaves plastically. It is determined as the difference between the liquid limit and the plastic limit as shown below.

$$PI = LL - PL \tag{1}$$

Where:

PI = Plasticity index of a soil (%)

LL = Liquid limit (%)

PL = Plastic limit (%)

#### Shrinkage Limit (SL)

The smallest moisture content at which a soil can still be saturated, or the water content at which a soil specimen

changes from semi-solid to solid states. It is calculated as the change in length divided by the initial length of the specimen when the water content is reduced to the shrinkage limit.

$$S_l = \frac{L_i - L_f}{L_i} \times 100 \tag{2}$$

Where:

$L_i$  = The initial length of the specimen (mm)

$L_f$  = The final length of the specimen after the water content is reduced to the shrinkage limit (mm)

$S_l$  = Linear shrinkage (%)

#### Free-Swell Index (FSI)

The increase (expansion) in volume of a soil submerged in water without the application of external loads. It is calculated as the ratio of the difference in volume of the soil submerged in water and kerosene to that of the volume of the soil in kerosene as shown in Equation 3.

$$FSI (\%) = \left[ \frac{V_w - V_k}{V_k} \right] \times 100 \tag{3}$$

Where:

FSI = Free-swell index of the soil (%)

$V_w$  = Volume of a soil in distilled water after 24 hours (ml)

$V_k$  = Volume of a soil after 24 hours submerged in kerosene (ml)

The area where the soil sample has been taken is known for its expansiveness as has been investigated earlier [1]. Consequently, a single test pit has been used for the purpose of investigating the effectiveness of the proposed stabilizer, namely, the biomedical waste incinerator ash on the index and engineering properties of the original soil.

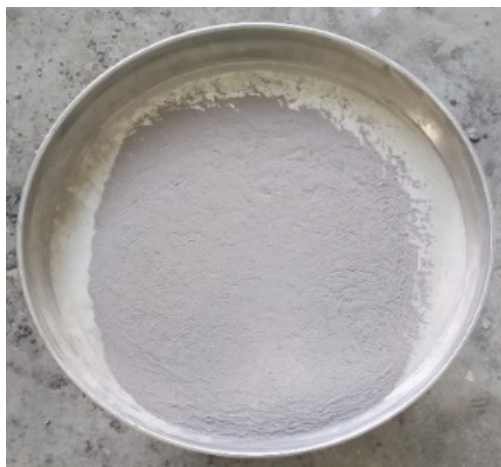
The following laboratory tests were conducted on the raw expansive soil, blended with 3%, 5%, 7%, 9%, and 11% of BWIA, and the optimum soil-BWIA mixture (soil + 9% BWIA) amended with 2% and 3% of hydrated lime. All the tests were conducted as per the corresponding standards listed and references (cited) in Table 1.

**Table 1.** Laboratory tests conducted for the study

Laboratory tests	Standards Used	Reference (cited)
(i) Particle size Analysis	ASTM D 422 - 63	[26]
(ii) Specific Gravity	ASTM D 854 - 98	[27]
(iii) Free-Swell Index	IS: 2720 (Part XL)	[28]
(iv) Atterberg Limits	ASTM D 4318 - 98	[25]
(v) Compaction	ASTM D 698 - 91	[29]
(vi) UCS	ASTM D 2166 - 98a	[30]
(vii) CBR	ASTM D 1883 - 99	[31]

### Scanning Electron Microscopy (SEM) test

The morphology and bonding (interlocking) of clay minerals as a result of a chemical reaction with other materials (stabilizers) can be more readily seen using scanning electron microscopy than with any other technique. The microstructural properties of the raw expansive soil and the optimum mixture (soil + 9% BWIA) blended with 3% lime cured for seven days were investigated using SEM at the microbiology laboratory of Adama Science and Technology University, Adama, Ethiopia. The failed UCS samples for both mixtures were powdered and sieved to get a sample passing 150  $\mu\text{m}$  sieve, which can be easily investigated by the SEM machine. A JCM-6000 PLUS Bench Top SEM JEOL machine was used to conduct the test.



(a)



(b)

**Figure 2.** (a) Powdered sample for the SEM test finer than 150 microns, (b) SEM Machine

### 3. Discussion of Results

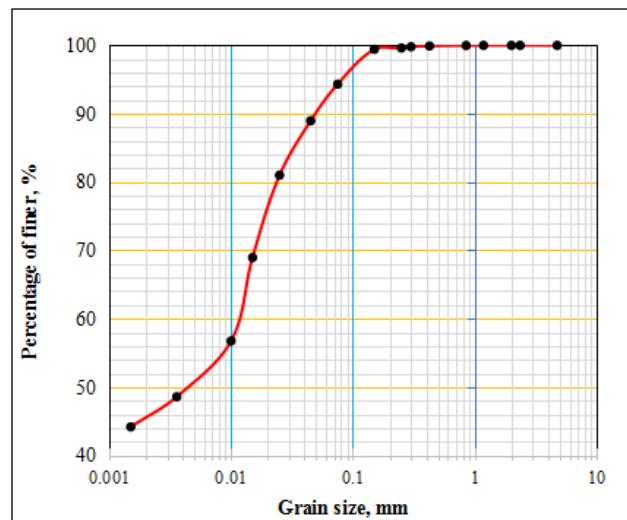
The results (findings) of the study are promising and will be used as an indication to develop a guideline for the field application. It is recommended that a standard for the

BWIA stabilization of expansive soils should be developed by taking representative samples (greater number) at different locations where such types of soil exist and conducting extensive laboratory and field tests.

A summary of the results of the laboratory investigations performed on the natural soil are summarized in Table 2. It is thus clearly visible that the soil is highly expansive and weak.

**Table 2.** Characteristics of the expansive soil

Properties	Soil Sample
Natural Moisture Content (%)	46.22
Specific gravity	2.7
% Passing No.200 sieve	94.32
LL (%)	103.74
PL (%)	45.57
Plasticity Index (%)	58.18
Shrinkage Limit (%)	26
USCS	CH
AASHTO classification	A-7-5 (20)
OMC (%)	33
MDD (g/cc)	1.52
Free-Swell Index (%)	100
Activity (A)	1.28 active
UCS (kPa)	27.31
CBR-Swell (%)	9.33
Soaked CBR (%)	2.3



**Figure 3.** Particle size distribution curve

The complete silicate laboratory results (chemical compositions) of biomedical waste incinerator ash and lime are summarized in Table 3 and 4, respectively.

**Table 3.** Chemical compositions of BWIA

Compound	Present (%)	Compound	Present (%)
SiO <sub>2</sub>	37.96	K <sub>2</sub> O	1.02
Al <sub>2</sub> O <sub>3</sub>	14.11	MnO	0.08
Fe <sub>2</sub> O <sub>3</sub>	1.12	P <sub>2</sub> O <sub>5</sub>	0.75
CaO	28.86	TiO <sub>2</sub>	0.49
MgO	4.1	H <sub>2</sub> O	2.61
Na <sub>2</sub> O	1.94	L.O. I	6.93

**Table 4.** Chemical compositions of lime

Compound	Present (%)	Compound	Present (%)
SiO <sub>2</sub>	6.21	K <sub>2</sub> O	0.79
Al <sub>2</sub> O <sub>3</sub>	2.18	MnO	0.28
Fe <sub>2</sub> O <sub>3</sub>	3.57	P <sub>2</sub> O <sub>5</sub>	0.21
CaO	59.47	TiO <sub>2</sub>	0.33
MgO	3.91	L.O. I	0.58
Na <sub>2</sub> O	0.61		

BWIA is an intermediate material that has a good percentage of both oxides of silicon and calcium. According to the [32] specification of the chemical composition of fly ash, the material’s major oxide composition (SiO<sub>2</sub> + Fe<sub>2</sub>O<sub>3</sub> + Al<sub>2</sub>O<sub>3</sub>) is equal to 53.19%, which is greater than the minimum requirement of 50%. Thus, BWIA satisfies the criteria of class C fly ash pozzolanic material. So, it can enhance the strength of the soil by forming the compounds of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These compounds flocculate the clay particles in a soil mass by creating a bond with each other.

The complete silicate laboratory results confirmed that the two materials BWIA and lime have good compositions of the two oxides (an indicator of their stabilizing potential) needed for the stabilization of expansive soil for engineering purposes. This was verified by the following test results and especially by the Scanning Electron Microscopy (SEM) test results in which the effect is well demonstrated as shown by the micrographs in Figure 10.

### 3.1 Effect of BWIA on Atterberg Limits

The addition of BWIA has a promising result on the Atterberg limits of the highly expansive soil.

As can be seen from Table 5, with every 2% increment of BWIA stabilizer, a significant decrease in liquid limit and hence plasticity index is observed to decrease significantly, indicating the stabilizing potential of the industrial waste. The main reason behind the decrease in the liquid limit and plasticity index is due to the percentage replacement of clay particles in the highly expansive soil by the BWIA, which reduces the water affinity of clay particles. Thus, the plasticity index kept on decreasing for all mixtures. Since BWIA has a linear shrinkage of 0%, the ad-

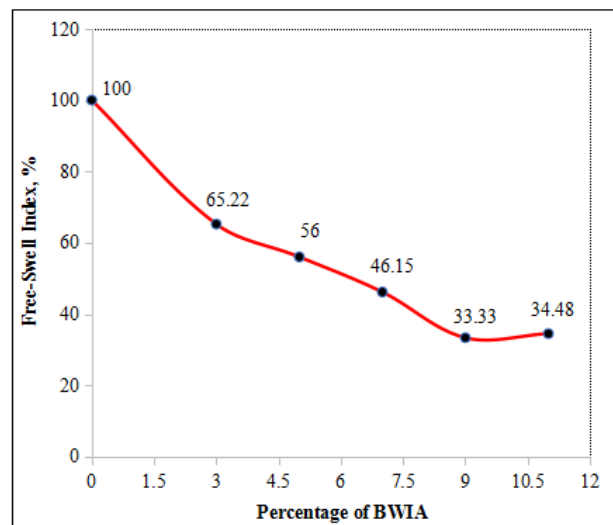
dition of 11% BWIA reduced the shrinkage of the highly expansive soil by 50%. The BWIA sample didn’t show any shrinkage after it was kept for 24 hours in an oven. The BWIA sample didn’t show any shrinkage after it was kept for 24 hours in an oven.

**Table 5.** Effect of BWIA on Atterberg limits

BWIA (%)	Variation of liquid limit (LL)	Variation of plastic limit (PL)	Variation of plasticity index (PI)	Variation of Shrinkage limit (SL)
0	103.74	45.57	58.18	26
3	100.11	47.84	52.27	21
5	93.92	48.62	45.30	20
7	90.63	52.06	38.57	18
9	86.6	58.88	27.72	16
11	84.92	60.06	24.86	13

### 3.2 Effect of BWIA on Swelling Potential

The stabilizing potential of the BWIA is further demonstrated by the significant reduction of the free - swell index test results, that are summarized in Figure 4.



**Figure 4.** Variation of free-swell index

Figure 4 shows the free swell-well index (FSI) is kept on decreasing up to 9% BWIA and a little bit increasing (nearly constant) for the last percentage (11%) of BWIA. Therefore, 9% BWIA could be the optimum content to stabilize the highly expansive soil. The addition of 9% BWIA reduces the FSI by 66.67%.

### 3.3 Effect of BWIA on the Moisture-Density Relationship

The variation of optimum moisture content and maximum dry density with the addition of BWIA are shown in

Figure 5 (a) and (b) respectively. The addition of BWIA has increased the optimum moisture content and decreased the maximum dry density. The increase in moisture content is obviously due to the pozzolanic reaction process and percentage replacement of clay particles by the BWIA (finer mater) that the soil-BWIA mixture needs more water to get the desired dry density. Thus, the dry density kept on decreasing. The decrease in density is because the density of BWIA (2.44) is lower than the density of the soil (2.7).

### 3.4 Effect of BWIA and Lime on UCS

The potential effectiveness of the BWIA is also demonstrated by the significant improvement in the unconfined compressive strength test results of both uncured and 7 days cured specimens, that shown in Figure 6, 7 and 8.

As can be inferred from Figure 6, the unconfined com-

pressive strength of the soil is kept on increasing up to 9% of BWIA, but for the BWIA content greater than 9%, it is slightly reduced, Therefore, 9% BWIA could be the optimum percentage that can achieve the highest compressive strength of the highly expansive soil. In order to further investigate the strength of the soil, a hydrated lime of 2% and 3% were added to the optimum uncured and 7 days cured expansive soil + 9% BWIA mixture and the results are shown in Figure 7 and 8.

Figure 7 shows the UCS of the stabilized expansive soil with the optimum content of BWIA (9%) was slightly increased for both dosages of lime. The UCS was increased by 13.5% and 16.7% when there was an amendment of 2% and 3% hydrated lime, respectively. The increment is not significant because the hydration process needs more curing time to gain the desired strength. This was verified when the specimen was cured for seven days and the results are as shown in Figure 8.

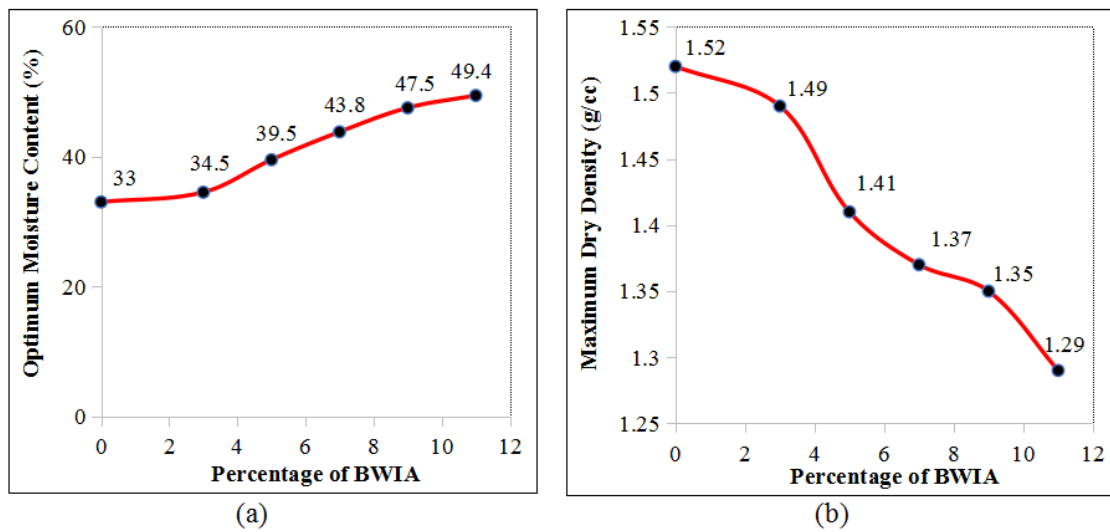


Figure 5. Effect of BWIA on (a) OMC and (b) MDD

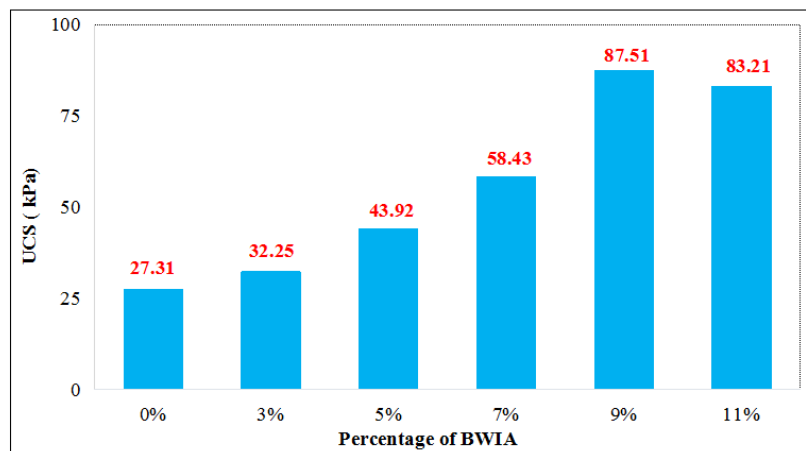


Figure 6. Effect of BWIA on UCS

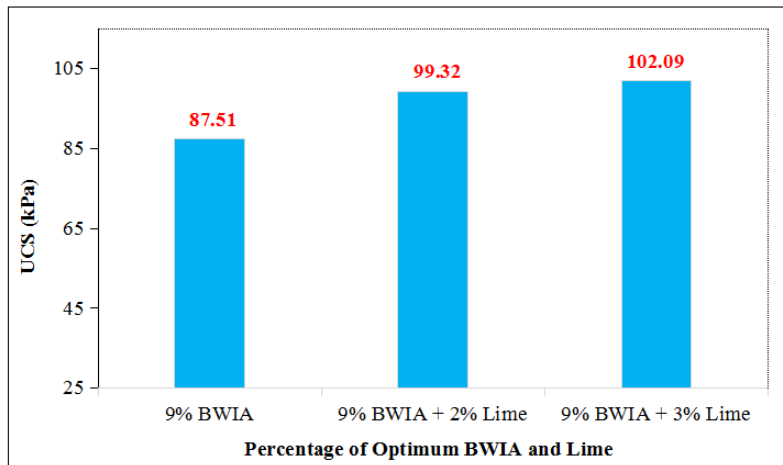


Figure 7. Effect of BWIA and lime on UCS

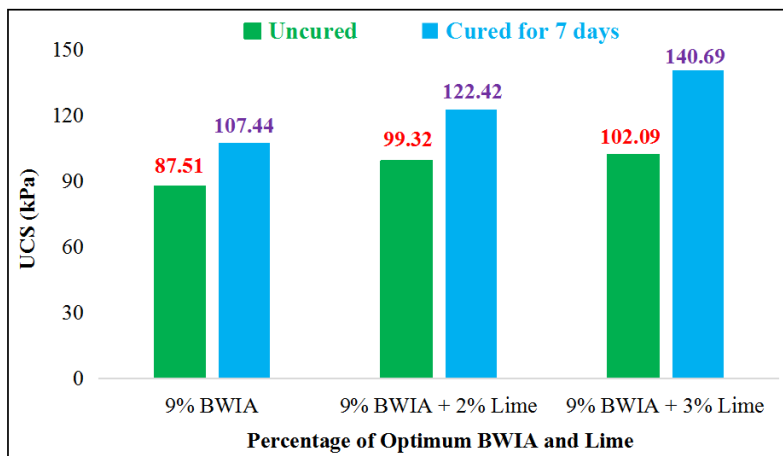


Figure 8. Variation of UCS for uncured and 7 days cured specimens

In Figure 8, the seven-day cured UCS of the BWIA-lime stabilized soil was significantly increased by 22.77%, 32.26%, and 37.81% for 9% BWIA, 9% BWIA + 2% lime, and 9% BWIA + 3% lime mixtures, respectively. The strength of the soil significantly increased from 27.31 kPa UCS of the untreated soil to 140.69 kPa of the soil treated with 9% BWIA and 3% lime cured for seven days. This is mainly due to the silica and calcium oxides contained in the BWIA and lime can produce compounds such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) which are responsible for the strength improvement of the soil.

### 3.5 Effect of BWIA and Lime on CBR

In addition to the above parameters, the BWIA effect is also demonstrated by the improvement of the CBR test results. The CBR value of the soil improved when it was blended with the optimum content of BWIA. Also, there was a significant improvement when 2% and 3% lime were amended.

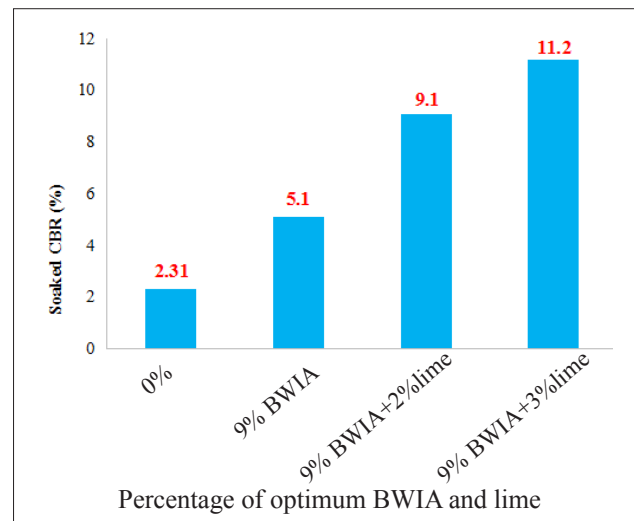
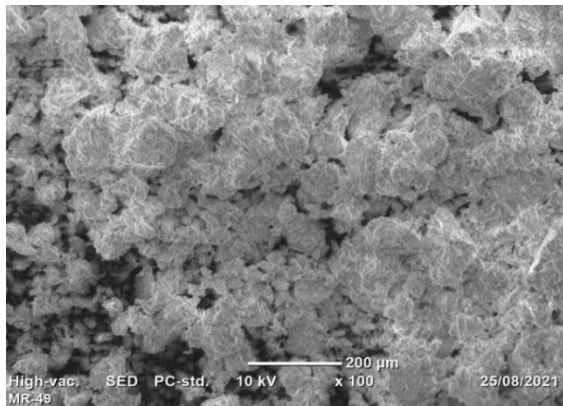
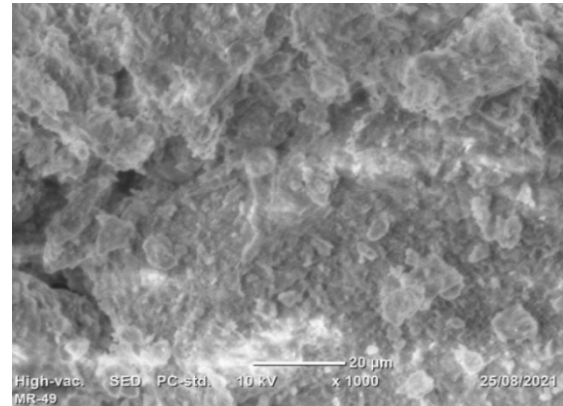


Figure 9. Variation of CBR

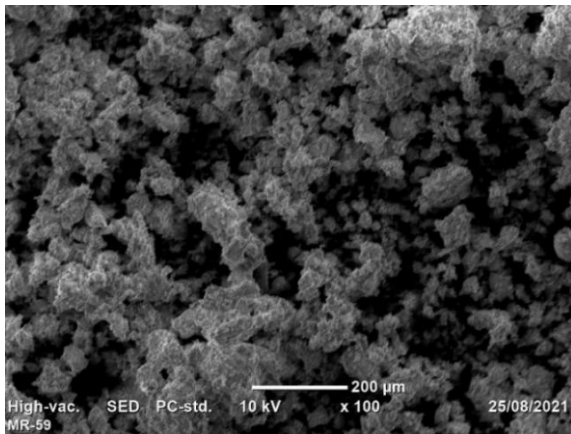
Figure 9 shows the CBR of the soil is increased by 121.74%, 295.65%, and 386.96% when it was treated



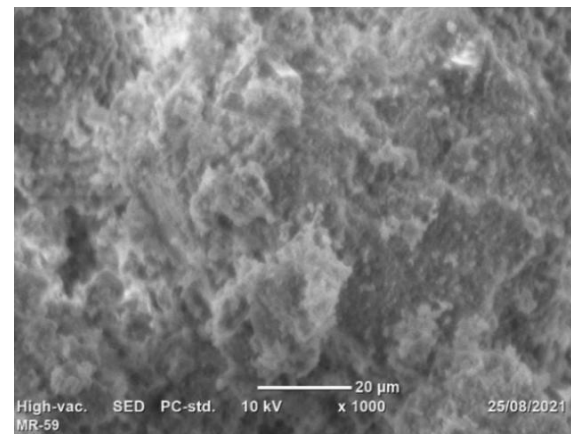
(a) 200  $\mu\text{m}$ , x100



(b) 20  $\mu\text{m}$ , x1000



(c) 200  $\mu\text{m}$ , x100



(d) 20  $\mu\text{m}$ , x1000

**Figure 10.** Scanning Electron micrographs of (a&b) raw expansive soil, (c&d) expansive soil blended with 9 % BWIA and 3 % lime at different size and magnification rates

with 9% BWIA, 9% BWIA + 2% lime, and 9% BWIA + 3% lime, respectively. Thus, a small amount of lime has a significant role in the strength of the expansive soil blended with the optimum content of BWIA. The results of the experiments showed and confirmed that the soil stabilized with the optimum content of BWIA and with an amendment of 2% and 3% lime is suitable for road subgrade material as per the specifications of the Ethiopian Roads Authority (ERA) pavement design manual (2013).

### 3.6 Scanning Electron Microscopy (SEM) Results

The codes MR-49 and MR-59 at the left bottom of the pictures represent the raw expansive soil and the soil blended with BWIA and lime. As can be inferred in Figure 10 (a and b), the raw expansive soil shows a dispersed and scattered type of fabric and less interlock and bond between particles having an opened (floated) arrangement of layered structure. But, when it was blended with BWIA and lime, the negatively charged clay surface attracted the cations in the additives and a more flocculated and aggre-

gated structure is shown in Figure 10 (c and d), and the particles act as a homogeneous mass with no holes in between. This is mainly due to the formation of cementitious compounds.

### 4. Conclusions

The present study has focused on the stabilization of expansive soils using industrial waste called biomedical waste incinerator ash (BWIA). The soil is classified as CH and A-7-5 (20) as per the USCS and AASHTO classification systems respectively, which is a typical indicator of highly expansive soil that is of poor quality to be used as a road subgrade material. The stabilizing behavior of the BWIA was demonstrated by the significant reduction of the free-swell index; a 66.7% decrease was obtained when the subgrade was blended with 9% of BWIA. The addition of BWIA has also significantly increased the UCS and CBR of the soil. This is because of the formation of flocculated structures as a result of bonding between the negatively charged clay surfaces with cations present in the



BWIA and lime. The UCS increased significantly with the addition of BWIA, up to about 9% by weight. Doubling and tripling the strength of the original subgrade material was observed for uncured and 7 days cured specimens at this optimal addition of the stabilizer. Thus, 9% BWIA is said to be the optimum content required to stabilize the expansive soil. Likewise, the CBR value also increased by 121.74% when it was treated with the optimum content of the stabilizer.

A significant improvement in the UCS (7 days cured) and CBR were demonstrated when the soil was treated with 9% of BWIA amended by 2% and 3% hydrated lime. The UCS and CBR were increased from 27.31 kPa and 2.3% to 140.69 kPa (cured for 7 days) and 11.2%, respectively when the optimum BWIA was amended by 3% lime.

The morphology and fabric of the control specimen were changed when the soil was blended with BWIA and lime. The raw expansive soil is dispersed (non-flocculated) fine particles with an open arrangement, but it became a homogeneous and flocculated structure when it was treated with 9% BWIA and 3% lime.

### Conflict of Interest

The authors declares that there are no conflict of interest concerning with the publication.

### Acknowledgment

The authors would like to acknowledge the microbiology laboratory technicians of Adama Science and Technology University for their cooperation to conduct the scanning electron microscopy (SEM) test.

### References

- [1] P. E. T. Q. Robel Tewelde Mesfun, Anteneh Geremew “Experimental Study of Stabilized Expansive Soil using Pumice Mixed with Lime for Subgrade Road Construction,” *International Journal of Research -GRANTHAALAYAH*, vol. 7, 2019.
- [2] J. S. Trivedi, S. Nair, and C. Iyyunni, “Optimum Utilization of Fly Ash for Stabilization of Sub-Grade Soil using Genetic Algorithm,” *Procedia Engineering*, vol. 51, pp. 250-258, 2013.
- [3] I. K. Suwantara, S. P. R. Wardani, and Y. A. Priastiwati, “Expansive Clay Soil Stabilization Using White Soil Material and Sulfuric Acid Solution (H<sub>2</sub>SO<sub>4</sub>) For Subgrade in Godong Area - Grobogan District,” *IOP Conference Series: Earth and Environmental Science*, vol. 328, p. 012022, 2019.
- [4] F. Zhang, L. Zhang, and W. Hong, “Stabilization of Expansive Soil with Polyvinyl Alcohol and Potassium Carbonate,” *Advances in Civil Engineering*, vol. 2019, pp. 1-11, 2019.
- [5] S. Asuri and P. Keshavamurthy, “Expansive Soil Characterisation: an Appraisal,” *INAE Letters*, vol. 1, pp. 29-33, 2016.
- [6] S. He, X. Yu, A. Banerjee, and A. J. Puppala, “Expansive Soil Treatment with Liquid Ionic Soil Stabilizer,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2672, pp. 185-194, 2018.
- [7] F. E. Jalal, Y. Xu, B. Jamhiri, and S. A. Memon, “On the Recent Trends in Expansive Soil Stabilization Using Calcium-Based Stabilizer Materials (CSMs): A Comprehensive Review,” *Advances in Materials Science and Engineering*, vol. 2020, pp. 1-23, 2020.
- [8] H. H. Liet Chi Dang, Behzad Fatahi, Robert Jones and Hadi Khabbaz, “Enhancing the Engineering Properties of Expansive soil Using Bagasse Ash and Hydrated Lime,” *International Journal of GEOMATE*, vol. 11, pp. 2447-2454, 2016.
- [9] S. Srikanth Reddy, A. C. S. V. Prasad, and N. Vamsi Krishna, “Lime-Stabilized Black Cotton Soil and Brick Powder Mixture as Subbase Material,” *Advances in Civil Engineering*, vol. 2018, pp. 1-5, 2018.
- [10] C. C. Ikeagwuani, J. C. Agunwamba, C. M. Nwankwo, and M. Eneh, “Additives optimization for expansive soil subgrade modification based on Taguchi grey relational analysis,” *International Journal of Pavement Research and Technology*, vol. 14, pp. 138-152, 2020.
- [11] A. Soltani, R. Raeesi, and B. C. O’Kelly, “Cyclic Swell–Shrink Behavior of an Expansive Soil Treated with a Sulfonated Oil,” *Proceedings of the Institution of Civil Engineers - Ground Improvement*, pp. 1-27, 2020.
- [12] B. R. Phanikumar, J. R. m, and R. R. e, “Silica fume stabilization of an expansive clay subgrade and the effect of silica fume-stabilised soil cushion on its CBR,” *Geomechanics and Geoengineering*, vol. 15, pp. 64-77, 2019.
- [13] C. C. Ikeagwuani and D. C. Nwonu, “Emerging trends in expansive soil stabilisation: A review,” *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, pp. 423-440, 2019.
- [14] N. S. Surjandari, N. Djarwanti, and N. U. Ukoi, “Enhancing the engineering properties of expansive soil using bagasse ash,” *Journal of Physics: Conference Series*, vol. 909, p. 012068, 2017.
- [15] R. A. Blayi, A. F. H. Sherwani, H. H. Ibrahim, R. H. Faraj, and A. Daraei, “Strength improvement of ex-

- pansive soil by utilizing waste glass powder,” *Case Studies in Construction Materials*, vol. 13, p. e00427, 2020.
- [16] J. James and P. K. Pandian, “Bagasse Ash as an Auxiliary Additive to Lime Stabilization of an Expansive Soil: Strength and Microstructural Investigation,” *Advances in Civil Engineering*, vol. 2018, pp. 1-16, 2018.
- [17] I. Zorluer and S. Gucek, “The usability of industrial wastes on soil stabilization,” *Revista de la construcción*, pp. 80-89, 2020.
- [18] M. W. a. S. Tadesse, “STABILIZATION OF EXPANSIVE SOIL USING BAGASSE ASH & LIME,” MSc. Thesis, Department of Civil Engineering, Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa, 2014.
- [19] Y. Liu, Y. Su, A. Namdar, G. Zhou, Y. She, and Q. Yang, “Utilization of Cementitious Material from Residual Rice Husk Ash and Lime in Stabilization of Expansive Soil,” *Advances in Civil Engineering*, vol. 2019, pp. 1-17, 2019.
- [20] C. Admas, “POTENTIAL USE OF RICE HUSK ASH AS WORETA EXPANSIVE SOIL STABILIZER,” MSc. Thesis, Civil Engineering Department, Addis Ababa University, Addis Ababa 2020.
- [21] A. Elinwa, “Hospital Ash Waste-Ordinary Portland Cement Concrete,” *Science Research*, vol. 4, p. 72, 2016.
- [22] H. Kaur, R. Siddique, and A. Rajor, “Influence of incinerated biomedical waste ash on the properties of concrete,” *Construction and Building Materials*, vol. 226, pp. 428-441, 2019.
- [23] M. Rahman, R. Chowdhury, and T. Ahmed, “Stabilization of medical waste incineration fly ash in cement mortar matrix,” *Bangladesh Journal of Scientific and Industrial Research*, vol. 55, pp. 131-138, 2020.
- [24] A. Al Rawas, “Characterisation of incinerator ash treated expansive soils,” *Proceedings of the Institution of Civil Engineers-Ground Improvement*, vol. 8, pp. 127-135, 2004.
- [25] “ASTM D 4318-98. Standard Test Methods for Liquid Limit, Plastic limit and Plasticity Index of Soils. Reprinted from the Annual Book of ASTM Standards. Copyright ASTM.
- [26] “ASTM D 422-63 (Reapproved 1998). Standard Test Method for Particle-Size Analysis of Soils. Reprinted from the Annual Book of ASTM Standards. Copyright ASTM.
- [27] “ASTM D 854-98. Standard Test Method for Specific Gravity of Soils. Reprinted from the Annual Book of ASTM Standards. Copyright ASTM. ,” ASTM D 854-98.
- [28] IS, “IS : 2720 ( Part XL ). Indian Standard. Methods of Test for Soils Determination of Free-Swell Index of Soils. ,” ed. Manak Bhavan, 9 Bahadur Shah Zafar Marg, Newdelhi., 1977.
- [29] “ASTM D 698-91 (Reapproved 1998). Standard Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort. Reprinted from the Annual Book of ASTM Standards. Copyright ASTM.
- [30] “ASTM D 2166-98a. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. Reprinted from the Annual Book of ASTM Standards. Copyright ASTM.,” ASTM D 2166-98a.
- [31] “ASTM D 1883-99. Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils. Reprinted from the Annual Book of ASTM Standards. Copyright ASTM.
- [32] “ASTM C 618-08a. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. Reprinted from the Annual Book of ASTM Standard. Copyright ASTM.