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Expansive clay subgrade soil improvement using municipal solid waste fly ash: Experimental and numerical approach

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ABSTRACT

The expansive soil under investigation has caused damage to lightweight structures due to its swelling and shrinkage characteristics in response to changing moisture content. The study aims to assess the impact of municipal solid waste (MSW) fly ash on the engineering properties of subgrade expansive soils and its influence on pavement structure deformation. The influence of municipal solid waste fly ash on expansive soils was evaluated using laboratory tests and finite element methods. The Abaqus software was used to investigate the effects of MSW fly ash on pavement structure deformation. The input parameters employed for this analysis were elastic modulus, Poisson ratio, load, contact area dimension, and pavement layer thickness. To mitigate this issue, MSW fly ash was used as a stabilizing agent at varying percentages (5 %, 10 %, 15 %, 20 %, 25 %, and 30 % of the dry mass of the soil sample).According to the AASHTO soil classification, the soil is classified as A-7, has a high free swell, a low soaked CBR value, and a high soaked CBR swell, and does not meet the ERA manual standard for subgrade materials. The laboratory tests shown several improvements in the engineering properties of expansive soil when MSW fly ash were mixed. These improvements included a reduction of soaked CBR swelling, free swell index, plasticity index, specific gravity, optimum moisture content. Additionally, the maximum dry density and soaked CBR values increased. Numerical analysis using Abaqus software focused on vertical deformation of the pavement structure. The results showed that as the percentage of MSW fly ash in form 0 % to 25 % of soil dry weight, the vertical deformation of the pavement structure decreased from 0.84 mm to 0.67 mm. This demonstrates that the addition of MSW fly ash reduced the deformation of expansive sub-grade soil and improved the engineering qualities of pavement structure. In conclusion, the study revealed that the use of MSW fly ash as stabilizing agent effectively reduced the deformation of expansive subgrade soil and improved the engineering qualities of pavement structure.

1. Introduction

The expansive soil a plastic clay soil and often known as black cotton soil. Volume of such types of soil fluctuates with changes in moisture content. The formation of expansive soils has been linked to two types of parent materials. These soils were formed at the end of the Cretaceous, Mesozoic era, to the Neocene or Quaternary of Tertiary era (Enkhtur and Dalai, 2011). The first category consists of volcanic sedimentary rocks found in North America, South Africa, and Israel, whereas the second group consists of volcanic igneous rocks found in India and the south-west USA (Murray, 2006; Yilmaz, 2004). As revealed by a previous study (Woldesenbet et al., 2023a), expansive soils disply water absorbing behavior and can trigger slope instability or landslides. This soil *contains* montmorillonite clay minerals that have been excessively expanded, which is typical in tropical areas. When exposed to water and air, clay minerals in expansive soil can cause excessive swelling and shrinking, respectively (Haile Fekadu et al., 2022; Beyene et al., 2022). The volume change characteristics of clay soils influenced the strength, consistency, and density parameters, which is enhanced by replacing the selected materials, stabilizing the soil, and using raft foundations (Barasa et al., 2015; Melese, 2022). In addition to this, fly ash and geo-polymer are used as stabilizers (e a Deepdarshan, 2020). The most common way to stabilize expansive soil is by adding cement. However, in Ethiopia, there is an insufficient supply of cement, and there are also number of

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alternative cements replacing cementitious materials (Abebe, 2020).

Because of the growing demand for construction materials, bottom ash has been utilized in various beneficial applications, particularly in civil engineering infrastructures such as road base layers, sub-base layers, road subgrades, and parking lots, because of the high demand for construction materials (Abhishek et al., 2016; Habtamu, 2015). Bottom ash can be successfully used for subgrade and embankment to produce mixtures for sub-base and base course as substitutes for gravel (Eden, 2017; Worku, 2019). Bottom ash, fly ash, and other materials are also used in construction as soil stabilizers due to their lower specific gravity, higher shear strength, and pozzolanic properties. The use of these ashes as stabilizing materials reduces both the disposal problem and the cost of stabilization (Barnat-Hunek et al., 2018; Ismaiel, 2013). According to (Kavish and Mehta, 2014), the strength and plastic characteristics of the materials are reduced and strengthened by the stabilization of geo-materials through the production of cohesive materials in the soil.

Municipal solid waste ash is produced as a by-product of a waste-to-energy (WTE) power plant. The waste-to-energy power plant produces waste ash as a by-product of bottom ash, which poses a major threat to the environment, society, and economy. Researchers have proven that wastes are widely used to treat subgrades of highways and railways (Roshan et al., 2022). Expansive soil stabilization with municipal solid waste fly ash used in the construction industry, such as road construction, would solve the pavement performance problem and reduce the volume of municipal solid waste ash at the WTE power plant, thereby protecting the environment from waste ash disposal. Fly ash is a byproduct utilized in the construction of geotechnical and infrastructure structures. The use of fly ash in soil stabilization to improve liquid limit, plastic limit, and CBR values to acceptable levels boosts strength and minimizes shrinkage strains in expansive soils. Fly ash is classified into two types based on the chemical composition: class C and class F fly ash (Wang et al., 2023; Russell et al., 2007). The amount of calcium oxide (CaO) found in the chemical composition of fly ash determines its classification. According to ASTM C-618–94a, fly ash of class C contains >20 % calcium oxide (CaO), and the sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ is <50 %, whereas fly ash of class F contains <20 % calcium oxide and the sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ is greater than 70 %. The plasticity index, clay size fraction, percent of swell, swell pressure, and volumetric water contents of the soil water characteristic curves are lowered by stabilization with class C fly ash, but the unconfined compressive strength is raised (Tanyıldızı et al., 2023; Sobczyk et al., 2023).

The finite element method (FEM) is widely used in engineering and mathematical modeling to numerically solve differential equations. With the FEM, the actual continuum or mass of matter, such as a solid, liquid, or gas, is represented by the FEM as an assemblage of subdivisions called elements (Woldesenbet et al., 2023a). Because of the advanced elements in the FEM software, FEM can be used in the disciplines of linear and non-linear analysis, heat transfer problems, bio-engineering, nuclear engineering, metallurgical engineering, and so on (Tsige et al., 2022). In engineering problems, not all terms must be understood to forecast the structure under investigation. In fact, the "modeling and computing" of an engineering system is the understanding and prediction of the system's response to a variety of stimuli and conceivable conditions and scenarios (with respect to both external stimuli and system parameters), which serves as the basis for a logical design. Abaqus is a software tool that is used to model and analyze mechanical components and assemblies (pre-processing) as well as to visualize the Finite Element Analysis (FEA) results. Abaqus is used in the automobile, aerospace, and industrial goods industries. The software is popular among academic and research institutes due to its ability to be customized and its comprehensive material modeling capability. Abaqus software has a powerful and easily extensible numerical tool for problems in geotechnical engineering due to the functionality available in Abaqus and the powerful mesh-to-mesh solution. One significant advantage of using Abaqus is the ability to switch between the implicit solver, which is commonly used for stress and strain, and the more dynamic explicit solver, allowing for seamless dynamic-static co-simulation. Abaqus software benefits comprise a reduction in a company's FEA toolset and training expenses, greater efficiency in model generation, and improved correlation between testing, and analysis (Gebretsadik et al., 2023; Yuan et al., 2021).

Municipal solid waste ash is a byproduct of incinerated waste, and this waste is an element of environmental pollution, leading to contamination of air, water, and soil with materials that can harm human health, quality of life, and nature. From this perspective, the excessive littering of municipal solid waste ash littering Addis Ababa, the capital city of Ethiopia, is one of the major areas of apprehension. Many studies recommend the use of MSW fly ash for construction purposes. However, there is no clear evidence, neither experimental nor numerical, proving its effectiveness for expansive subgrade soil in the study area. Therefore, this study aims to promote the use of municipal solid waste ash in order to reduce the excessive accumulation of this waste in the city. Consequently, the use of municipal solid waste ash can help to reduce construction material costs, as well as greenhouse emissions caused by municipal solid waste ash, while improving the strength of weak road payment subgrade.

2. Materials and methods

2.1. Characterization of materials

Expansive soil samples were collected using the non-probability sampling technique, known as the purposive sampling technique. The primary method was to identify an expansive soil site based on the previous investigation of the engineering properties of soils in Jimma Town. In addition to this, a free swell test was conducted on soil samples from selected test pits to check the degree of expansiveness. Thus, Bocho Bore Kebele and JIT sports field, in Jimma, Ethiopia, were selected as the sample collection sites because the free swell index results for Bocho Bore Kebele and JIT sports field were 165 % and 110 %, respectively. After this, the top organic soil was removed, and the disturbed and undisturbed soil samples were manually excavated and collected in plastic bags from both pits. Lastly, the collected samples were transported to the Jimma Institute of Technology for testing in a geotechnical laboratory.

The municipal solid waste fly ash samples were collected from the Waste to Energy Power Plant in Addis Ababa. The soil samples were designated as test pit 1 and test pit 2 for Bocho Bore Kebele and JIT sports field, respectively. The samples are expansive soil samples from two test pits and municipal solid waste fly ash. Undisturbed samples were used for natural moisture content determination, and disturbed samples were used for soil classification, compaction characteristics, CBR, specific gravity, Atterberg limit, shrinkage limit, free swell, and triaxial tests. The preparation of samples before and after stabilization is shown in Table 1.

2.2. Sample preparation

The sample preparation depends on the number of tests. For laboratory tests, disturbed samples of expansive soil and MSW fly ash were prepared. The sample was prepared according to AASHTO T87–86. The preparation procedures include air drying of samples, breaking up the soil aggregates with rubber, removing impurities, sieving the samples using different sieve sizes, and oven drying the samples based on types of laboratory tests. The municipal solid waste fly ash was collected from the Reppie (koshe) waste-to-energy facility in Addis Ababa Kolfie Keranio sub-city. The collected municipal solid waste fly ash was separated from impurity materials and sieved to find fine fly ash for laboratory tests, see Fig. 1.

Table 1
Preparation of expansive soil samples with waste fly ash for laboratory tests.

Test pits	Location/coordinates		Mixing percentage (%)		Expansive soil-MSW fly ash mixtures
	Latitude	**Longitude**	**Expansive soil**	**MSW fly ash**	
1	7.660423	36.849700	100	0	natural expansive soil
			95	5	95 % ES + 5 % MSW-FA
			90	10	90 % ES + 10 % MSW-FA
			85	15	85 % ES + 15 % MSW-FA
			80	20	80 % ES + 10 % MSW-FA
			75	25	75 % ES + 15 % MSW-FA
			70	30	70 % ES + 30 % MSW-FA
2	7.688990	36.815353	100	0	natural expansive soil

2.3. Test methods and standards

A laboratory test program was carried out to determine the engineering parameters of untreated and treated expansive soil, as well as the chemical characteristics of municipal solid waste fly ash. The laboratory test program is divided into two parts. Firstly, the engineering aspects of natural expansive soil and the mineral compositions of MSW fly ash and expansive soil were investigated. Wet sieve analysis, hydrometer analysis, Atterberg limit, moisture content, linear shrinkage, specific gravity, modified Proctor compaction, California bearing ratio, triaxial compression test, and X-ray diffraction (XRD) test was performed in the laboratory. Secondly, based on the degree of expansiveness, the expansive soil from the two test pits was selected. The selected test pit samples were mixed with municipal solid waste fly ash at specified amounts. Municipal solid waste fly ash was added in increments of 5 % from 0 % to 30 % of the soil's dry weight. Finally, the mixture of the samples was subjected to free swell, Atterberg limit, linear shrinkage limit, modified Proctor compaction, specific gravity, CBR, and triaxial compression tests. A laboratory test program for determining the engineering parameters of untreated and treated expansive soil, as well as the chemical characteristics of municipal solid waste fly ash, was presented in Table 2.

2.4. Engineering properties of natural expansive clay soil

2.4.1. Grain size distribution

Wet sieve analysis and hydrometer analysis were used to identify the grain size distribution of expansive soil in the study area. Grain size analysis aims to determine the relative properties of the different grain sizes that comprise a soil mass (Woldesenbet et al., 2024). According to laboratory tests, pit 1 contains 0.25 % gravel, 2.34 % sand, 35.11 % silt, and 62.30 % clay, whereas pit 2 contains 2.14 % gravel, 4.12 % sand, 42.89 % silt, and 50.81 % clay. These results indicate that the soil samples collected from pits 1 and 2 contain a higher proportion of fine-grained material. Therefore, soil samples from both pits are classified as fine-grained clay soil, as the percentage of fine material passing sieve No 200 is greater than 35 %, and the clay content is higher than the silt content according to the AASHTO soil classification system. Fig. 2 shows the grain size distribution curves of the expansive soil samples from Pit-1 and Pit-2.

2.5. Expansive soil engineering properties

The natural moisture content of test pits 1 and 2 is 39.90 % and 38.84 %, respectively. From these results, the soil samples from the two pits are soft clay soil, according to (Das, 2019). The percentage of soil samples passing the No 200 sieve in test pits 1 and 2 is 97.34 % and 93.74 %, respectively. This result indicates that the soil samples from the two pits are fine-grained since the percentage of soil passing the No 200 sieve is greater than 35 % of the total soil sample passing the No 200 sieve, as per the AASHTO classification system. The liquid limits of test pits 1 and 2 samples are 95.59 % and 90.75 %, respectively, and the plasticity indexes of test pits 1 and 2 soil samples are 58.41 % and 57.21

Table 2
Laboratory test name and standard procedure used.

No	Name of test conducted	Standard testing Used	
		ASTM	BS/IS
1	Moisture Content	ASTM D 2216	
2	Free Swell		IS 720
3	Wet Sieve Analysis	ASTM D422	
4	Hydrometer Analysis	ASTM D422	
5	Specific Gravity	ASTM D854	
6	Atterberg Limit	ASTM D4318	
7	Linear shrinkage limit		BS 1377–2
8	Modified Compaction test	ASTM D1557	
9	California Bearing Ratio (CBR)	ASTM D1883	
10	Triaxial Compression Test	ASTM D2850	

a) b)

Fig. 1. Sample preparation: a) Air dried soil sample b) Municipal solid waste fly ash.

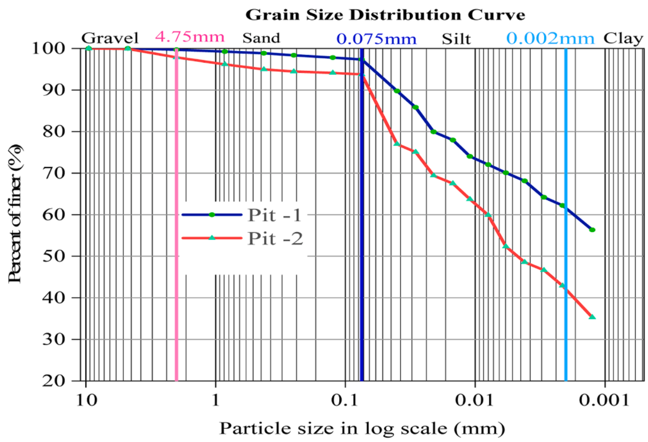

Fig. 2. Grain size distribution curve for soil sample of pits 1 and 2.

%, respectively. From these results, the soil has a very high swelling potential. The expansive soil sample of the study area of the two pits was classified as A-7–5 and high clay (CH) soil using the AASHTO and USCS soil classification systems, respectively. This indicates that the soil samples have a high expansive index and high clay content, according to (Prakash and S, 2004; Sridharan, 1985). The modified Proctor compaction test was conducted to determine the optimum moisture content and maximum dry density of the natural expansive soil. The results of these tests were 1.44 g/cc and 1.48 g/cc maximum dry density and 27.77 % and 21.6 % optimum moisture content of test pits 1 and 2, respectively. From the California bearing ratio test, the soaked CBR values of test pits 1 and 2 soil samples are 1.07 % and 1.29 %, respectively, and the soaked CBR swells of test pits 1 and 2 soil samples are 5.69 % and 4.49 %, respectively. As per the ERA manual's 2002 recommendation, the soil has a poor subgrade rating because the value of the soaked CBR is <3 % and the value of the soaked CBR swell is greater than 2 %. According to these findings, the natural expansive soil samples from both test pits have a very poor subgrade rating, high clay content, and a high plasticity index, making it difficult to work with as a subgrade material. Therefore, soil improvement will be required to use these soils as subgrade material in road construction. Table 3 describes all of the natural expansive soil properties of the two test pits.

2.6. Mineralogical composition of expansive soil

The mineralogical composition of the soil samples was determined using X-ray diffraction (XRD) analysis. The XRD analysis was conducted using the soil sample passing No 200 (0.075 mm) sieve size, and the intensity and the diffraction angle (2Θ) were obtained from the analysis. The mineral phases present in soil samples were identified using Match 3 software using data obtained from XRD analysis. According to the results, the soil samples contain silicon, aluminum, potassium, calcium, hydrogen, oxygen, and other elements. This soil contains exchangeable cations of Ca^{++}, Mg^{++}, H^{+}, K^{+}, and Na^{+}, which make the soil active. This means that when clay minerals contact water, they attract the hydrogen molecules from the water and react with oxygen ions that are found on the surface of clay soils. For this reason, the soils change volume during the wet and dry seasons because, during the wet season, they swell by absorbing moisture, whereas during the dry season, they shrink by losing moisture (Woldesenbet, 2023). Therefore, to use such a type of soil as subgrade material in road construction, soil improvement by different means will be necessary to reduce the movement or to achieve the appropriate subgrade strength as per the Ethiopian Road Authority (ERA) manual specifications. The detailed mineral and element compositions of both soil samples are presented in Table 4 and Fig. 3.

Table 3
Summary of expansive soil engineering properties.

Soil Properties	Test Pits	
	1	2
Natural moisture content	39.9	38.44
Free swelling index (%)	165	110
Free Swelling Ratio (%)	2.65	2.1
Specific gravity	1.7	1.68
Liquid limit (%)	95.59	90.75
Plasticity Limit (%)	37.17	33.54
Plastic Index (%)	58.42	57.21
Linear shrinkage (%)	22.03	20.11
Percentage of passing #200 sieve size (%)	97.34	93.74
AASHTO soil classification system	A-7–5	A-7–5
Unified soil classification system	CH	CH
Maximum dry density (g/cc)	1.44	1.48
Optimum Moisture Content (%)	27.77	21.6
Soaked CBR values (%)	1.07	1.29
Soaked CBR Swell (%)	5.69	4.49

2.7. Mineral composition of MSW fly ash

The crystalline phases of MSW fly ash were characterized using the X-ray diffraction (XRD) instrumental technique. The mineralogical composition of the MSW fly ash was determined by matching the X-ray diffractogram with the database of the Match 3 software package (Woldesenbet, 2022).Fig. 4 shows the three main chemical compounds found in MSW fly ash. The strongest peaks for silica oxide (SiO_2) are found at 25.83°, 28.71°, 32.05°, 40.90°, and 62.52°, while the strongest peaks for aluminum oxide (Al_2O_3) are found at 23.31°, and 45.8° The peaks for calcium oxide (CaO) are found at 50.54°, 59.03°, and 66.76° A previous study (He Xinghua, 2016) revealed that the predominant elements in the fly ash particles are Cl, Ca, K, Na, Si, Al, O, and S, and the primary heavy metal elements are Zn, Pb, Cr, and Cu. It was observed that the fly ash particles have a tendency to be highly alkaline, with a pH level of ≥ 11.

2.8. Finite element analysis

The finite element analysis was conducted to determine the impact of MSW fly ash on pavement deformation on expansive subgrade soil. The software program used for this simulation was Abaqus 6.14–5 software program. The input parameters for the software included elastic modulus, Poison's ratio, pavement layer thickness, and dynamic load. These parameters were utilized to model and analyze pavement deformation. The essential information for the finite element analysis using Abaqus software includes material properties, model geometry, finite element meshing , boundary conditions, loading conditions, and contact area.

2.9. Materials and sections properties

The materials and section properties are important information for analyzing the pavement deformation using the Abaqus software. Mate-

Table 4
Elemental composition of the soil sample.

Symbol	Element Name	Element composition (%)	
		TP-1	TP-1
Si	Silicon	7.8	17.4
Al	Aluminum	11.7	8.5
Fe	Iron	10	7.9
H	Hydrogen	1.9	1
Mg	Magnesium	1.6	1.5
Na	Sodium	1.9	1.3
Ca	Calcium	1.1	1.5
K	Potassium	3.9	3.1
O	Oxygen	56	53.9

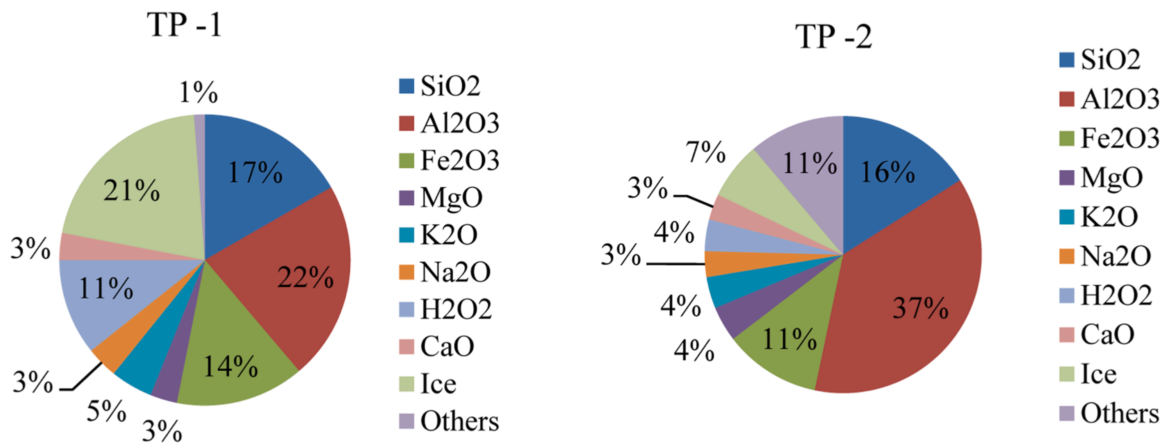

Fig. 3. Mineral composition of the soil sample.

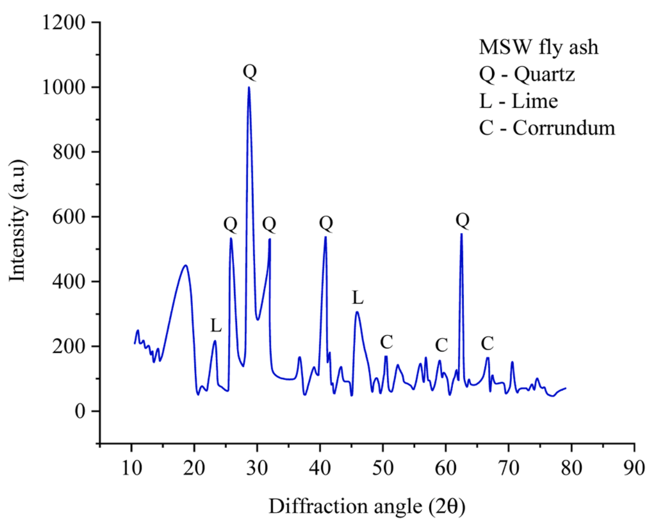

Fig. 4. X-ray diffraction pattern of MSW fly ash.

rial properties, such as elastic modulus, are obtained through laboratory tests or correlation. Studies have shown that the CBR depends on Young's modulus, yield stresses in compression and the permeability of the soil (Mendoza and Caicedo, 2019). The elastic modulus was obtained by correlating it with CBR values from the Georgia Department of Transportation (DOT) for some fine-grained subgrade soils (Webb and Campbell, 1986), as follows: (Webb and Campbell, 1986)

$$Mr = 3116 * (CBR)^{0.4779707} \quad (1)$$

Where, CBR in (%) and resilient modulus in (psi) where (1 psi = 6.9 kPa).

The CBR values of the granular road base and granular sub-base were taken from the ERA manual specifications; however, the CBR values for the subgrade were obtained from laboratory tests. The pavement layer thickness was taken from the selected design chart. The design chart was selected based on subgrade strength. In this study, the subgrade strength of stabilized expansive soil at the optimum percentage of MSW fly ash was subgrade class-three (S3). Depending on this subgrade strength, S3, the stabilized expansive soil was used only for design charts B and C1 because other design charts required additional selected fill or capping layers. However, when comparing design charts B and C1 from an economic point of view, design chart C1 is uneconomical because the asphalt concrete surface thickness was 100 mm, whereas chart D has a 50 mm asphalt concrete surface thickness. Therefore, in this finite element analysis, design chart D with the maximum traffic volume six (T6) of this design chart was used. The materials and section properties of the selected design chart are shown in Tables 5 and 6.

The pavement materials used in this study are asphalt concrete surface, granular road base, granular sub-base, and subgrade (natural expansive soil & stabilized expansive soil), as shown in Fig. 5. For the sake of simplicity, material properties of the granular road base, granular sub-base, and subgrade are assumed to be temperature-independent and linear elastic, while the asphalt layer is also represented by linear elastic behavior.

2.10. Model geometry

To check the key fundamental issues in pavement application, three-dimensional finite element analysis tools appeared to be the best choice. To simulate the finite element analysis, a model of flexible pavement is created. An asphalt concrete surface with a granular road base, granular sub-base, and subgrade (natural and stabilized soil) materials was used in this simulation. To simulate the finite element analysis, the geometry of the model having 5 m lengths (along the longitudinal direction), 3.5 m width (along the transverse direction), and the thickness of each pavement layer listed in Tables 5 and 6 are used as parameters in the simulation of the finite element analysis. Fig. 6 shows the pavement layer 3D cross-section.

2.11. Meshing of finite element analysis

The meshing of the model is in the way of getting more accurate results. The model is built using the 8-node continuum three-dimensional brick element (C3D8R) with reduced-order numerical integration. In finite element analysis, the 8-node continuum three-dimensional brick element serves as a reduced-integration linear element. In this particular model, each node possesses three degrees of freedom. By utilizing a smaller mesh, the accuracy of the finite element

Table 5
Materials properties of stabilized subgrade soil.

Materials		Lab. CBR values	Elastic modulus	Poisson ratio
Expansive soil	MSW fly ash	%	MPa	
100	0	1.07	22.21	0.4
95	5	1.73	27.94	0.4
90	10	2.04	30.23	0.4
85	15	2.98	36.23	0.4
80	20	3.68	40.08	0.4
75	25	6.96	54.35	0.4
70	30	6.64	53.14	0.4

The subgrade layer thickness used for all these stabilized materials is 750 mm

Table 6
Materials properties of other pavement layers.

Properties of Pavement layers					
Name	Materials	Layer thickness (mm)	CBR values, (%)	Elastic modulus, (MPa)	Poisson ratio
Wearing surface	Asphalt concrete	50		3000	0.35
Road base	Granular road base, GB1	200	85	179.74	0.3
Road sub-base	Granular sub-base, GS	350	30	109.26	0.3

method is enhanced, but at the cost of increased model complexity. Therefore, the mesh in model was designed with an estimated global size of 100 mm for all layers, as depicted in Fig. 7.

2.12. Boundary condition

The specification of boundary conditions is used to control the displacement of the pavement structure. In this model, the two sides have roller supports, so the finite element model is not allowed to move horizontally but is allowed to move vertically. The bottom of the finite element model has fixed support and is not allowed to move either horizontally or vertically (see Fig. 8). As stated in the previous study (Jawad et al., 2020), boundary conditions are chosen to minimize the influence of stress distribution. Asphalt surfaces are permitted for vertical displacement.

2.13. Modeling interaction method

The interaction modeling method was used to merge the two adjacent surfaces of pavement structures in the simulation of the Abaqus software program. The interaction method is used to reduce the sliding between two adjacent surfaces, because the interaction qualities between them are assumed to be perfectly bonded. The interaction between the road surface-road base, road base-road sub-base, and road sub-base-road subgrade are shown in Fig. 9. The surface, binder, base course, subbase, and subgrade, all of which can be thought of as closed systems with multiple layers, were all modeled using Abaqus The Abaqus interaction module models how the tire contact interacts with several pavement layers, including the surface and binder, binder and base, base and subbase, and subgrade and base (Hadi and Al-Sherrawi, 2021).

2.14. Moving load and contact area

In order to calculate damages for each pass of the wheel load on the pavement, the appropriate contact area must be determined. The PCA

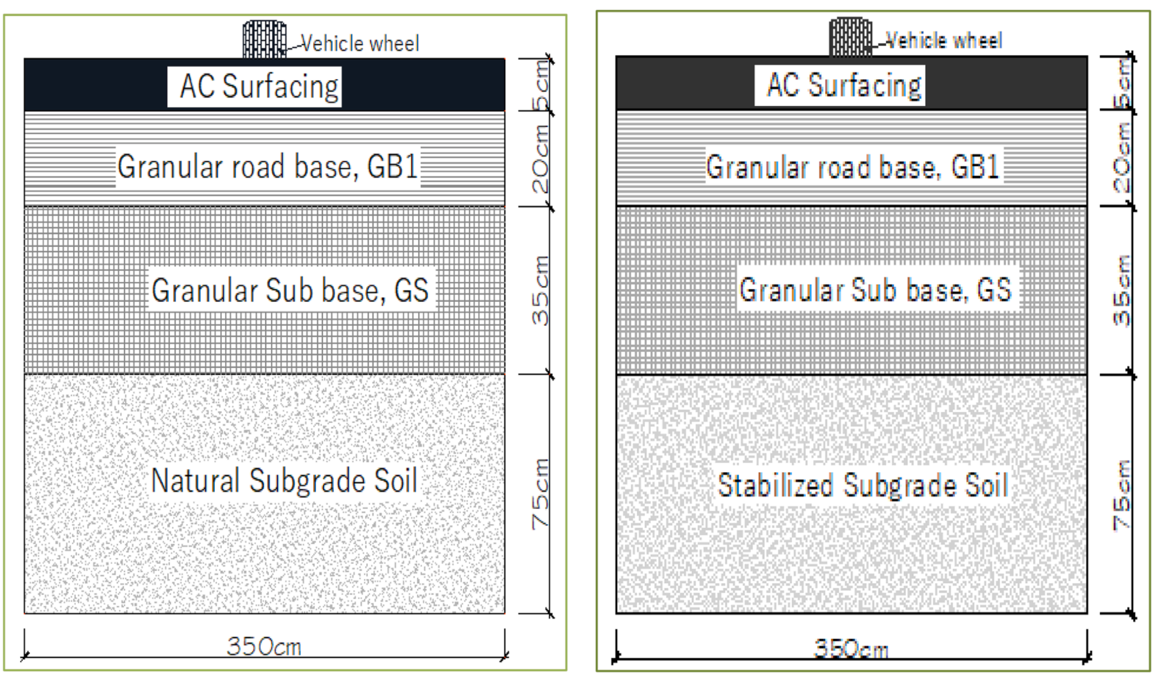

Fig. 5. Pavement structure cross-sections.

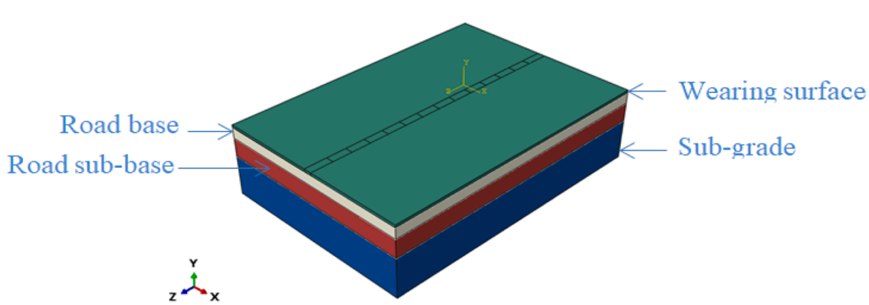

Fig. 6. Model geometry.

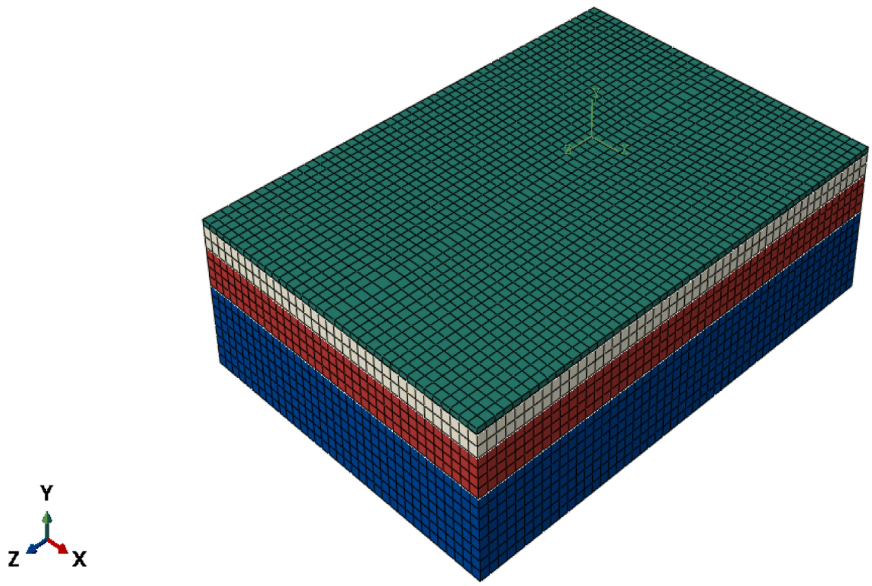

Fig. 7. Meshing of finite element.

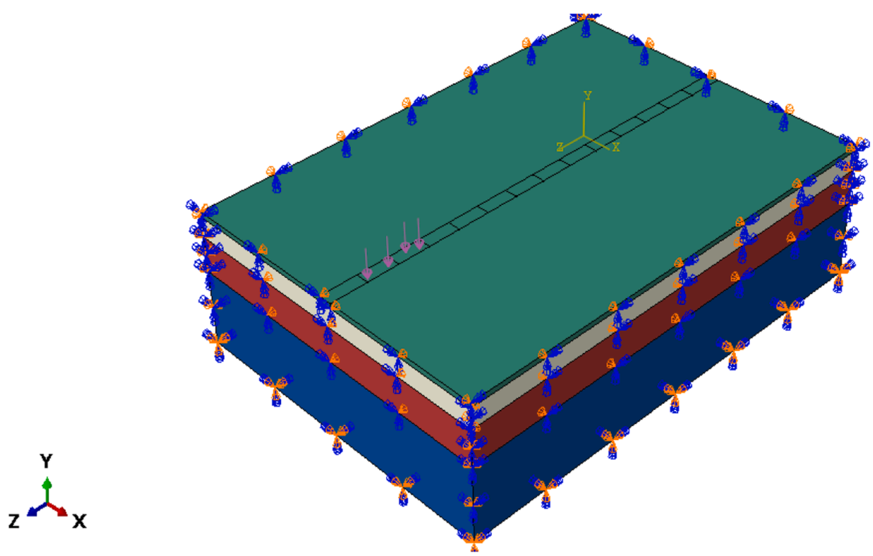

Fig. 8. Boundary Condition of Modeling.

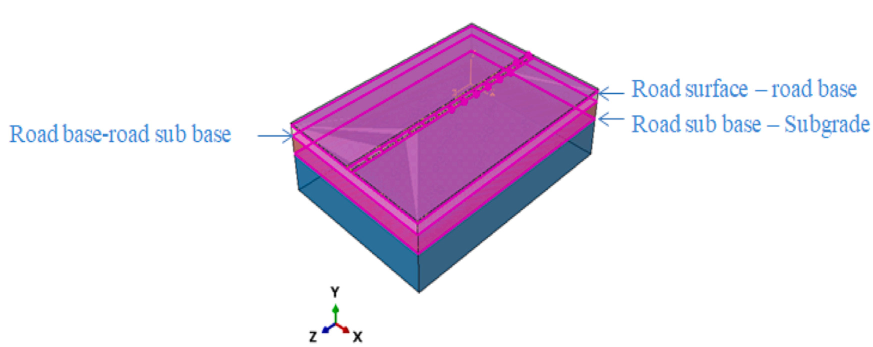

Fig. 9. Boundary condition of modeling the pavement layers.

(P, 1966) provides the most commonly used method for calculating the wheel contact area, which has a length of 0.8712 L and a width of 0.6 L, as shown in Fig. 10. The contact area is formed from two semicircles and a rectangle as shown in Fig. 11 (H, 2004). The wheel contact area is computed under a standard single axle load of 80 kN and a contact pressure of 480 kPa. This is done using a single seat of a wheel with a rectangular contact area of 0.5227 L^2. From a wheel load of 40 kN and contact pressure 480 kPa, contact area dimensions of 350 mm length and 240 mm width were determined. This is the method used to obtain the equivalent contact area dimensions from the wheel load and contact pressure.

The traffic load was used to simulate the moving load. The applied load was specified as pressure to simulate the pavement model. When the FEM was modeled, the wheel pressure of the vehicle had a uniform distribution load on the contact area of the vehicle wheel, as shown in Fig. 12.

3. Results and discussion

3.1. Effect of MSW fly ash on specific gravity

The effects of waste fly ash on specific gravity were checked by mixing expansive soil with a waste fly ash amount ranging from 0 % to 30 % of the soil's dry weight. The natural specific gravity of expansive soil was 2.70, and when different percentages of waste fly ash were added, the specific gravity of expansive soil decreased from 2.70 to 2.47. This decrease in specific gravity can be attributed to the lower density of municipal solid waste fly ash compared to that of expansive clay soil. A similar study also observed a reduction in specific gravity (Alrubaye et al., 2016). The effect of MSW fly ash on the specific gravity of the expansive soil test is shown in Fig. 13.

3.2. Effects of MSW fly ash on free swell

A free swell test is used to determine the expansiveness of soil by measuring the volume of soil that has been soaked and settled in water for one day (24 h). When the MSW fly ash percentage blended changed from 0 % to 30 % of the dry weight of the soil, the expansive soil free swell index and free swell ratio decreased from 165 % to 33.33 % and from 2.65 to 1.33, respectively (see Table 7). The results showed that the degree of the expansiveness of the soil sample significantly changed from highly expansive to low expansive clay soil (Chen, 1988). Free swelling index values showed a decrease due to high alkaline Fly Ash (Binal, 2016).

3.3. Effects of MSW fly ash on Atterberg limit

MSW fly ash affects the liquid limit and plasticity index when stabilized with expansive soil. In order to check the effects, laboratory tests are conducted using 0 % to 30 % municipal solid waste fly ash. The results of the liquid limit, plastic limit, and plasticity index decreased from 95.59 % to 57.99 %, 37.17 % to 30.05 %, and 58.42 % to 27.94 %, respectively. The results might suggest that the liquid limit and plastic limit decreased as MSW fly ash amounts increased. This is related to cation exchange reactions that result in the flocculation and agglomeration of the soil particles, with a consequent reduction in the amount of clay-size materials, and hence the soil surface area to volume ratio was reduced, which certainly accounts for the reduction in plasticity (Woldesenbet, 2022). Therefore, the stabilization of expansive soil was used as subgrade material because it fulfilled the requirement for subgrade material since the plasticity index of 29.50 % is <30 %, which the ERA manual recommended. The test results for Atterberg limits are shown in Fig. 14.

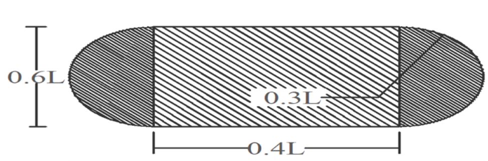

Fig. 10. Actual contact area between pavement surface and tire.

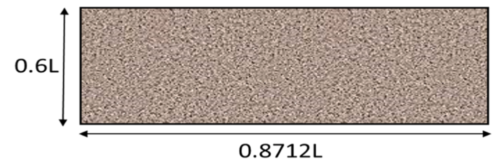

Fig. 11. Equivalent contact area between pavement surface and tire.

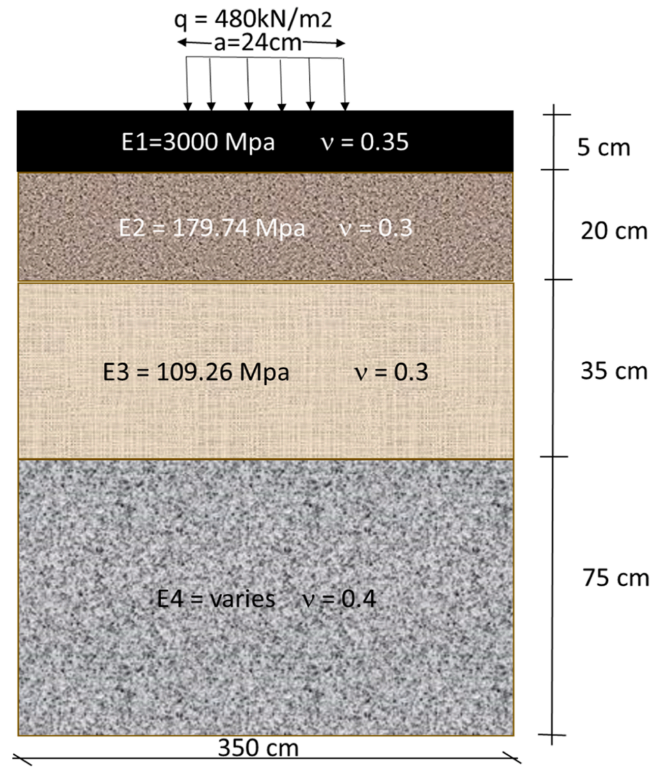

Fig. 12. Wheel Load applied on pavement and section properties.

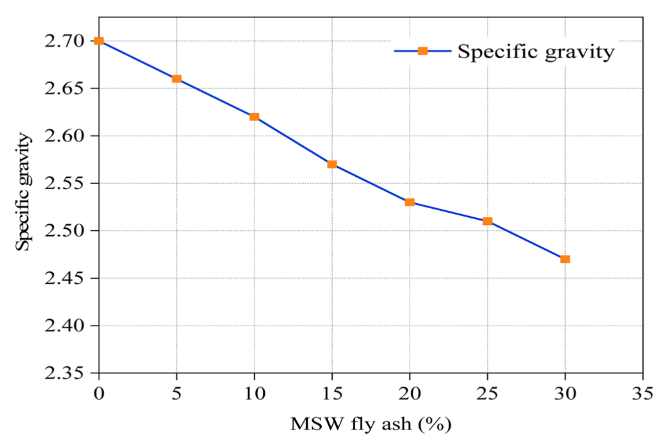

Fig. 13. Municipal solid waste fly ash effects on Specific gravity results.

3.4. Effects of MSW fly ash on linear shrinkage limit

The linear shrinkage limit test was conducted to determine the shrinkage of the length of the soils. The test involved blending expansive soils with the samples municipal solid waste fly ash. The results of the linear shrinkage limit test showed a reduction from 20.60 % to 12.12 % when increasing the MSW fly ash content from 0 % to 30 %. Based on

Table 7
MSW fly ash effects on expansive soil free swell index and free swell ratio.

Material mixed in,%	Free swell index, FSI (%)	Free swell ratio, FSR
Natural Expansive soil	165	2.65
95 % Expansive soil + 5 % MSW fly ash	137.62	2.38
90 % Expansive soil + 10 % MSW fly ash	121.67	2.22
85 % Expansive soil + 15 % MSW fly ash	86.27	1.86
80 % Expansive soil + 20 % MSW fly ash	65.05	1.65
75 % Expansive soil + 25 % MSW fly ash	44.23	1.44
70 % Expansive soil + 30 % MSW fly ash	33.33	1.33

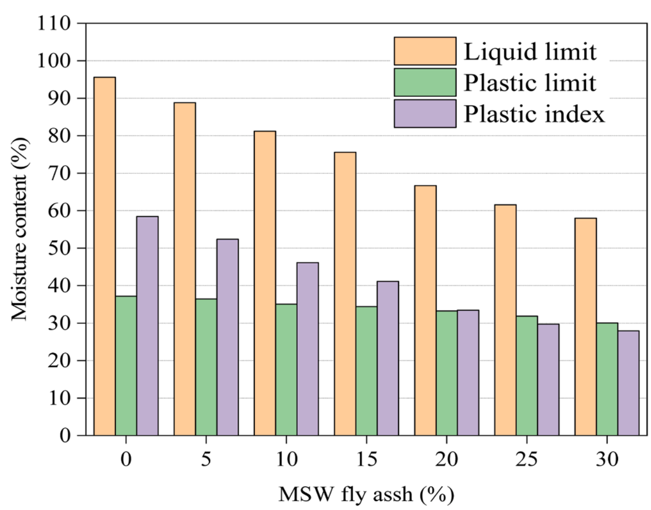

Fig. 14. Effect of municipal solid waste fly ash on Atterberg limits results.

this findings, the decrease in the linear shrinkage limit can be attributed to the non-plastic characteristics of MSW fly ash and the reduction of fine particles in the clay soil caused by the addition of MSW fly ash (see Fig. 15).

3.5. Effects of MSW fly ash on modified proctor compaction

A modified Proctor compaction test was performed to determine the MDD and OMC of the natural expansive soil and expansive soil–MSW fly ash. The MDD and OMC of the expansive soil changed from 1.44 to 1.53 g/cm3 and 27.77 % to 21.5 %, respectively. The results showed that the OMC decreased from 27.77 % to 21.5 % and the MDD increased from 1.44 g/cm3 to 1.53 g/cm3 as the MSW fly ash percentage increased from 0 % to 25 %, as shown in Table 8. This change in MDD and OMC is because the clay particles act as a binding medium between the fly ash particles when used as a stabilizing agent. Furthermore, fly ash requires less moisture content to achieve MDD since its surface area is smaller than that of clay particles. Studies have revealed that binding additives may increase the MDD and reduce the OMC (Woldesenbet, 2022).

The curve shifted to the top-left position when the expansive soil was stabilized with MSW fly ash ranging from 0 % to 30 % with a 5 % increment, as shown in Fig. 16. It showed that as the percentage of MSW fly ash increased beyond 25 %, the optimum moisture content increased and the maximum dry density decreased. However, adding >25 % MSW fly ash caused the curve to shift to the bottom-right position.

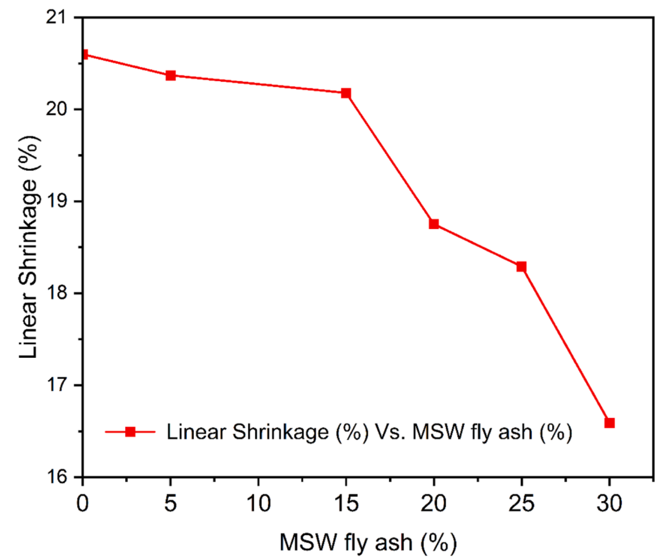

Fig. 15. Municipal solid waste fly ash effects on linear shrinkage limit.

Table 8
MSW fly ash effects on dry density and moisture content.

Material mixed	Optimum moisture content, %	Maximum dry density, %
Natural Expansive soil	27.77	1.44
95 % Expansive soil + 5 % MSW fly ash	24.5	1.45
90 % Expansive soil + 10 % MSW fly ash	23.5	1.49
85 % Expansive soil + 15 % MSW fly ash	23	1.51
80 % Expansive soil + 20 % MSW fly ash	22	1.51
75 % Expansive soil + 25 % MSW fly ash	21.5	1.53
70 % Expansive soil + 30 % MSW fly ash	24	1.44

3.6. Effects of MSW fly ash on California bearing ratio, CBR

The soaked CBR value and soaked CBR swell of the natural expansive soil with MSW fly ash mixtures compacted in the mold of CBR at OMC

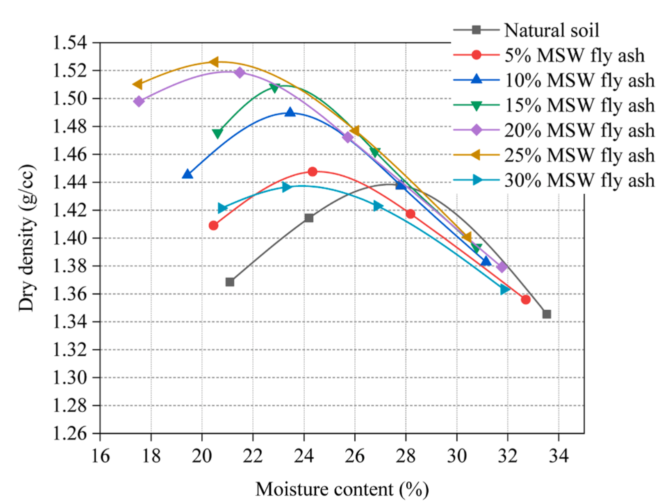

Fig. 16. Effects of MSW fly ash on dry density-moisture content of expansive soil.

and MDD were measured after four days of soaking. The results of the soaked CBR swell and soaked CBR value decreased from 5.69 % to 1.34 % and increased from 1.07 % to 6.69 %, respectively, as the MSW fly ash percentage increased from 0 to 30 %. The results show that increasing the MSW fly ash percentage from 0 to 25 % for a 4-day soaking period raised the soaked the CBR of expansive clay soil from 1.07 % to 6.69 %. The soaked CBR value dropped when the MSW fly ash content increased by >25 %. As the results indicated in Table 9, using MSW fly ash as a stabilizing agent for expansive clay soil improved the value of CBR of weak subgrade soil in the study area. Similar studies have shown improvements in CBR of residual soil modified by lime, activated carbon, and coir fiber on the subgrade soils in road construction (Tamassoki et al., 2023). According to the ERA manual's 2002 recommendation, the value of CBR is greater than 3 % and the swell percent is <2 % at the optimum percentage (25 %) value. With increased stabilizer content, reinforced soil becomes stronger and more rigid; as a result, reinforced soil's CBR value is higher than that of unreinforced soil (Singh and Bagra, 2013).

3.7. Effects of MSW fly ash on shear strength of soil

The triaxial compression test was conducted to find shear strength parameters (internal friction angle and cohesion), shear stress, and normal stress. The triaxial compression test results showed that the angles of internal friction increased from 7.36 to 10.42, and cohesion decreased from 30.16 kPa to 19.68 kPa, respectively, when the MSW fly ash percentage increased from 0 to 30 %. The angle of internal friction increased from 7.36 to 10.42, and the cohesion value decreased from 30.16 kPa to 19.68 kPa as the fly ash amount increased from 0 % to 30 % (see Table 10). These phenomena occurred due to the behavior of the additive material in the samples. In previous study by (Kalhor et al., 2022), it was found that the addition of Nano Silica to the soil resulted in increased internal friction angle and cohesion of the treated samples. The strength differences caused by the different cationic stabilizers can be best explained by examining both the physicochemical changes occurring in the peat and the mineralogical composition (Moayedi et al., 2013).

3.8. Effects of MSW ash on deformation of pavement structure on expansive subgrade soil

3.8.1. Validation of finite element analysis

Finite element analysis is a powerful modeling and analysis technique that offers many advantages over laboratory and field testing. However, finite element analysis is an approximate method for idealizing real-world events. Therefore, either laboratory or field tests should be used to verify the results of finite element analysis. To verify the applicability of the assumed material model, we first compared the results of the finite element analysis with the results of laboratory or field tests. Researchers reported validation of finite element methods using laboratory experiments and field-testing approaches and employed the 3D finite element method for laboratory testing and determination where he used the Abaqus software approach (Ibrahim et al., 2014). The models used have the same material and cross-sectional properties for both approaches. This report shows that the results of the Abaqus software program are very similar to the clinical test results, as shown in Fig. 17.

Table 9
The California bearing ratio value of stabilized expansive soil.

Sample mixing ratio	Soaked	Soaked CBR Swell,%	Subgrade strength rate as per ERA manual	Use as subgrade material as per ERA manual specification
Expansive soil	1.07	5.69	S1	Insufficient
5 % MSW fly ash	1.73	3.35	S1	Insufficient
10 % MSW fly ash	2.04	2.7	S1	Insufficient
15 % MSW fly ash	2.98	2.18	S1	Insufficient
20 % MSW fly ash	3.68	1.67	S2	Sufficient
25 % MSW fly ash	6.96	1.34	S3	Sufficient
30 % MSW fly ash	6.64	1.32	S3	Sufficient

Table 10
Municipal solid waste fly ash effects on triaxial compression test.

Material mixing proportion	Shear strength parameters	
	Cohesive (C)	Internal friction angle (Ø)
(%)	(Kpa)	(degree)
100 % Expansive soil	30.16	7.34
90 % ES + 10 % MSW Fly Ash	25.34	8.51
80 % ES + 20 % MSW Fly Ash	23.18	10.59
75 % ES + 25 % MSW Fly Ash	21.97	12.35
70 % ES + 30 % MSW Fly Ash	19.68	10.42

The validation of a three-dimensional finite element model using the Abaqus software program and field testing using the Pennsylvania field test was reported in a previous study (Shafabakhsh et al., 2013). Field-measured pavement reactions and the output of the finite element model were compared. The results showed a close relationship between the field measurements and the results of Abaqus software model. Consequently, the impact of MSW fly ash on the deformation of pavement structures on expansive subgrade soil was assessed with complete confidence using the Abaqus software program to simulate a finite element model.

3.8.2. Deformation of pavement structure on expansive soil using finite element method

Pavement deformation is the visible distress of pavement in the surfacing layers that occurs along the wheel path. It results from the accumulation of load-induced stresses. The finite element Abaqus software program was used to evaluate the effects of MSW fly ash on the vertical deformation of flexible pavement. The displacement result of FEA using Abaqus software was 0.84 mm when the subgrade material was naturally expansive soil, and 0.67 mm when the soil was improved by 30 % MSW fly ash. The displacement values showed a reduction for each increment of stabilizers, as shown in Fig. 18 (a-g). However, the vertical deformation of pavement structures decreased from 0.84 mm to

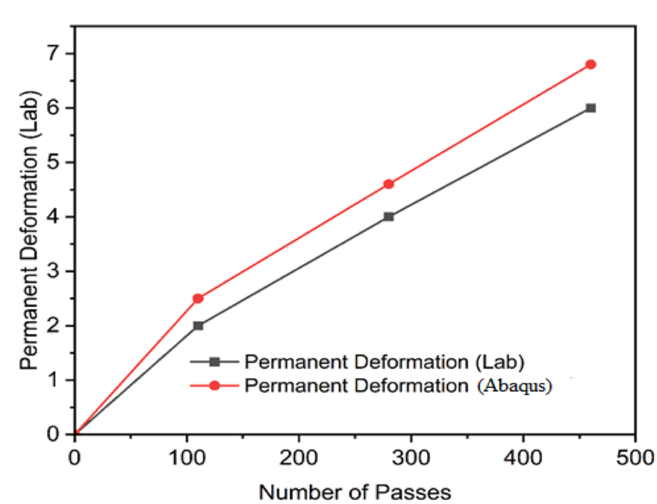

Fig. 17. Deformation results of Abaqus software and laboratory tests (Ibrahim et al., 2014).

0.67 mm as the percentage of MSW fly ash increased from 0 % to 25 % of the dry weight of the soil (see Fig. 19). This is because; MSW fly ash comprises fine articles that seal in the voids between soil particles, resulting in increased cohesion within the soil matrix. This improved cohesion helps to bind the soil particles together, reducing their susceptibility to deformation. The addition of MSW fly ash can reduce the plasticity and compressibility of soil. This ensued the soil becomes less prone to excessive deformation under applied loads, resulting in reduced vertical deformation of the pavement structure. The decrease in deformation observed from 0 % to 25 % MSW fly ash content attributed to the beneficial effects of flash on soil stabilization. Therefore, the typical an optimum content of fly ash in this study is 25 %, which used to achieve the best engineering properties. Beyond this optimum content, the beneficial effects may diminish, leading to a decrease in performance and an increase in deformation. At higher fly ash contents, the particle size distribution may become more skewed, leading to a less compacted and less stable mixture. This can result in increased deformation under loading.

The result indicated that the deformation of pavement structures depends on the properties of the subgrade material, even if the section properties and other parameters are the same. From this analysis, it can be concluded that the stabilization of expansive subgrade soils with MSW fly ash improves the deformation of pavement structures when used as subgrade materials in road construction in the study area. A similar study on the improvement of black cotton soil showed a decrease in deformation on FEA due to an improvement in the strength of the subgrade soil (Melese et al., 2023). The findings indicate that the expansive clay sub-grade exhibits elastoplastic hardening behavior, whereas the pavement displays elastoplastic non-linear behavior with variable moduli of deformation along different pavement sections (Djellali et al., 2012). As revealed in a previous study (Zaika and Suryo, 2019), improved soil embankment could reduce total displacement, avoid cracks in the pavement structure, and change from tensile to compressive strain.

3.9. Result comparison, cost-benefit analysis and long term effect

MSW significantly improved the mechanical strength expansive subgrade soil. The CBR increased by 625.23 %. The result obtained is nearly similar to soil stabilized by plastic bottle, that was 673 % (Woldesenbet, 2023) . Again the CBR value showed better performance with MSW than fly ash, 274 % (Z. Zimar et al., 2022). Besides its engineering use, using MSW enhance the development of sustainable green environment. The use of such Environmental waste is economical. However it's applicable for low traffic volume roads, such as collectors and feeder roads. Since the MSW is converted to ash its doesn't contain organic matter. That assures MSW is free from decay and sustainable for long time. According to Mir A. and E. Ravi C. (Hussain and Chahal, 2024) MSW is waste it is economical in engineering use when compared to the common methods of stabilization. The study by Z. Zimar et al., (Z. Zimar et al., 2022) on the use of MSW for stabilizing expansive clay soils and revealed that MSW raises the ten-day soaked CBR to roughly 80 % and decreases swelling potential. Microlevel study revealed that the important stages of MSW fly ash stabilization are hydration reaction, cationic exchange, flocculation, and agglomeration are the key phases in fly ash stabilization

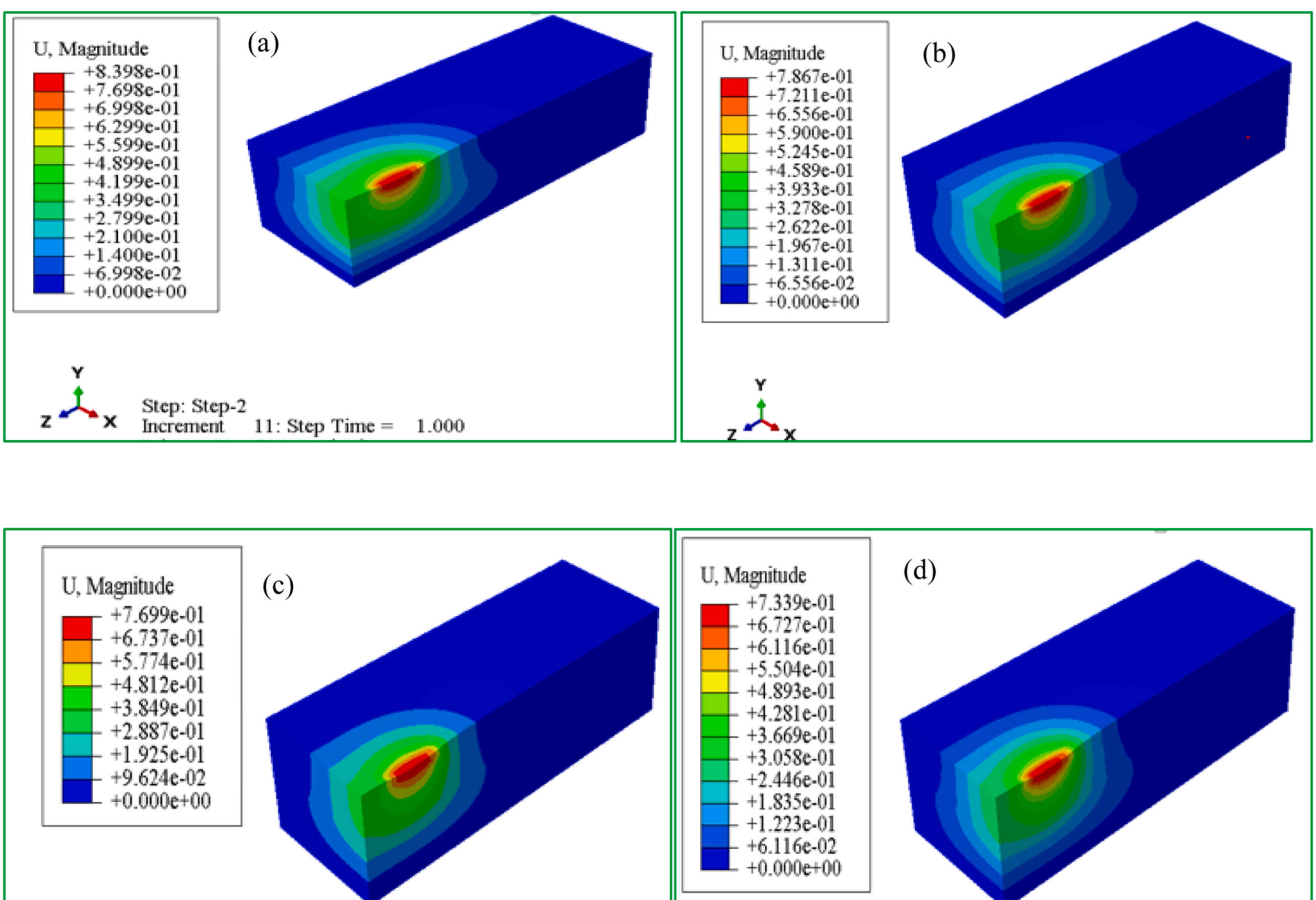

Fig. 18. Vertical deformation of pavement on natural expansive subgrade soil for (a) Natural soil, (b) 5 % MSW fly ash, (c) 10 % MSW fly ash, (d) 15 % MSW fly ash, (e) 20 % MSW fly ash, (f) 25 % MSW fly ash, (g) 30 % MSW fly ash.

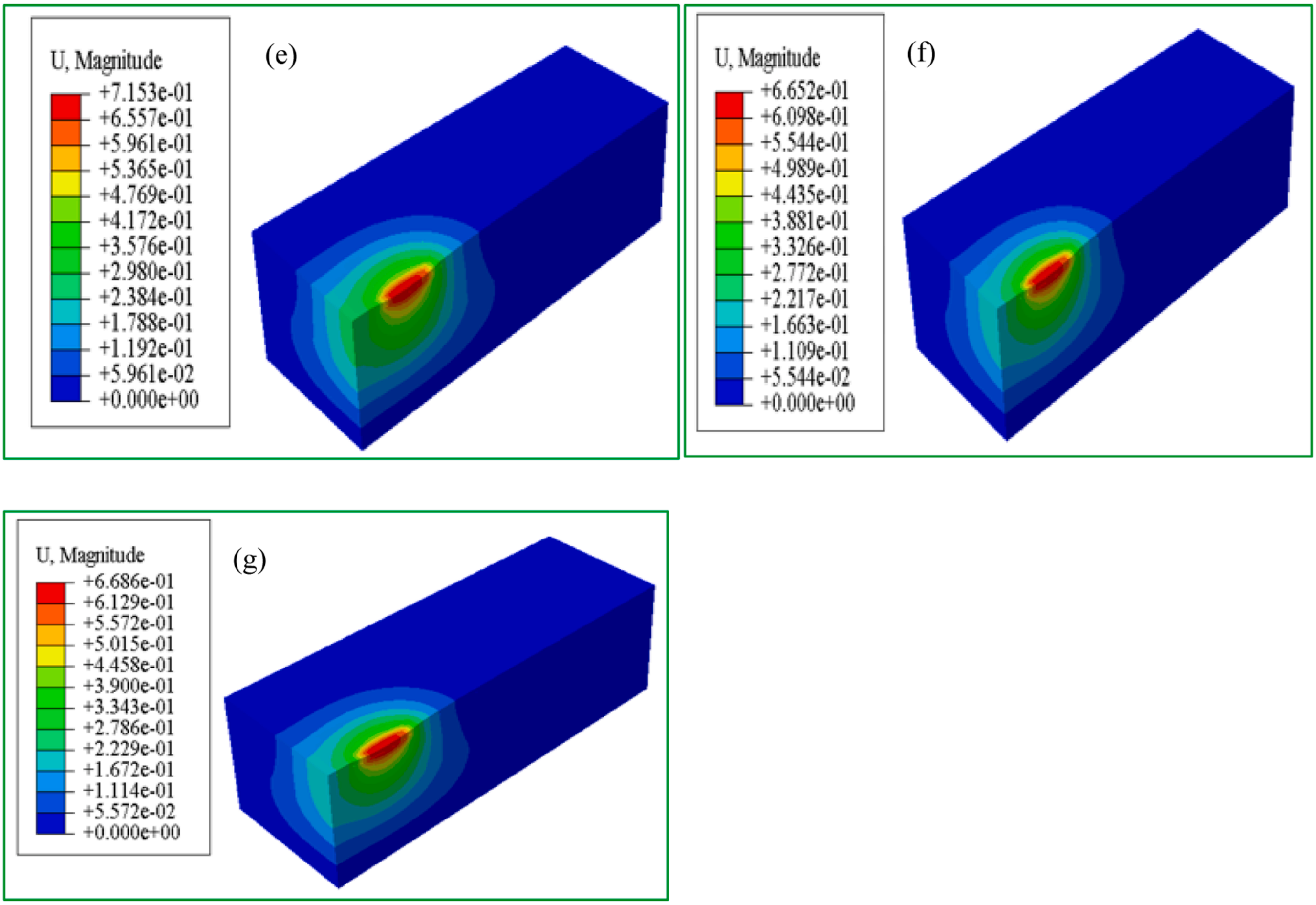

Fig. 18. (*continued*).

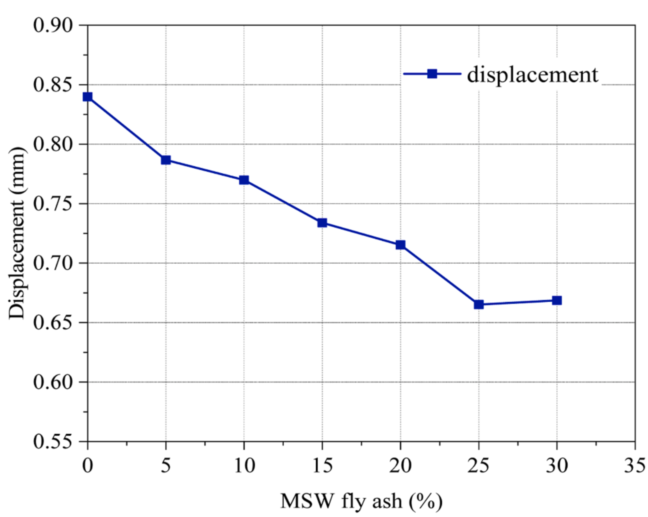

Fig. 19. Effects of MSW fly ash on vertical deformation of pavement.

4. Conclusion

This study aims to evaluate the effects of municipal solid waste fly ash on the engineering properties of expansive soil and the deformation of pavement structures. The laboratory tests conducted were natural moisture content, grain size analysis, modified proctor compaction test, Atterberg limit, CBR, specific gravity, triaxial test, and X-ray diffraction test based on ASTM, AASHTO, IS, and BS test standards. Also, a numerical analysis is performed to analyze the deformation of the pavement structure. Based on the laboratory test results and numerical analysis results, the following conclusions were drawn:

The results showed that the natural expansive soil samples from both pits for this study have A-7–5 as per the AASHTO and high clay (CH) as per the USCS classification system. The free swell ratio was 2.65 and 2.10, specific gravity was 2.70 and 2.68, plasticity index was 58.41 % and 56.59%, MDD was 1.44 g/cc and 1.48 g/cc, and OMC was 27.77% and 22.60%, soaked CBR was 1.07 % and 1.29%, and soaked CBR was 5.69 % and 4.49% for pits 1 and 2, respectively. Therefore, depending on these results; the soil samples from both test pits were categorized as fine-grained soil with high clay content, high expansive potential, high swelling potential, and poor subgrade strength.

The soil sample liquid limit and plasticity index decreased from 95.59% to 57.99% and 58.41 to 27.94%, respectively, when the MSW fly ash percentage added increased from 0% to 30% dry weight of soil.

The soil sample free swell index decreased from 165% to 33.33%, and the free swell ratio decreased from 2.65 to 1.33 as the waste fly ash percentage increased from 0% to 30% dry weight of soil.

The specific gravity decreased from 2.70 to 2.47 as the municipal solid waste fly ash increased from 0 % to 30 % of the dry weight of the soil.

The MDD increased from 1.44 g/cc to 1.53 g/cc, and the OMC decreased from 27.77% to 21.50% as the MSW fly ash percentage increased from 0 % to 25 % dry weight of soil. But by further increasing the MSW fly ash beyond 25%, the OMC increased and the MDD decreased.

The soaked CBR value increased from 1.07% to 6.96%, and the soaked CBR swell decreased from 5.69% to 1.33% as the MSW fly ash percentage increased from 0% to 25% dry weight of soil. However, with an increase in MSW fly ash beyond 25%, the soaked CBR swell increased and the soaked CBR decreased.

The FEA results indicated that the vertical deformation of the pavement structure decreased from 0.84 mm to 0.67 mm as the percentage of stabilizer increased from 0% to 25%.

Generally, the stabilization of expansive soil with municipal solid waste fly ash improved the engineering properties and the deformation of the pavement structure. Thus, the stabilized expansive soil with municipal solid waste fly ash at an optimum percentage was used as subgrade material in road construction, because it fulfilled the requirement for subgrade materials according to the ERA manual specification.

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CRediT authorship contribution statement

Damtew Tsige Melese: Methodology, Conceptualization. **Guta Jida:** Writing – original draft, Software, Resources, Formal analysis. **Ruhama Beyene:** Methodology, Data curation. **Tewodros Tsegaye Woldesenbet:** Writing – review & editing, Methodology, Conceptualization. **Abebe Eshetu Meshesha:** Validation, Supervision. **Wondwosen Sime Geleta:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

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

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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