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RESILIENT MODULUS PROPERTIES OF MINE OVERBURDEN TREATED WITH FLY ASH-BASED GEOPOLYMER

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ABSTRACT: Due to the global need for mineral resources and the large increase in population, mining activity has increased significantly. The growing need for sustainable growth in the mining industry highlights the importance of waste management throughout the whole mining process. The main objective of the study is to utilize the mine overburden (OB) soil in pavement subgrade applications. According to the mechanistic empirical pavement design guidelines, the fundamental input parameters include the resilient modulus (M_R) characteristics of the pavement layers. Mine OB soil typically exhibits relatively low resilient modulus and strength properties. The addition of fly ash (FA) based geopolymer additive is one of the solutions to enhance these properties. This study examines the effect of the addition of 0% to 50% fly ash-based geopolymer to mine OB soil that was sourced from open-pit coal mines in the State of Telangana, India. An alkaline activator solution consisting of sodium hydroxide with 3M concentration and sodium silicate mixed in a ratio of 1.0 is used. The cyclic triaxial tests are conducted as per AASHTO T-307-99 to determine the resilient modulus model as a function of deviator and radial stresses. The addition of fly ash-based geopolymer to mine OB soil significantly increased the resilient modulus. From the results, the study identified the 70OB:30FA mixture as the optimal mixture.

Keywords: Mine Overburden, Resilient Modulus, Geopolymer, Fly ash, Sustainable Pavements

1. INTRODUCTION

Coal is one of the most abundant fossil fuels globally. According to the Energy Institute Statistical Review of World Energy 2024 [1], fossil fuels remained the dominant source for power generation in 2023, collectively contributing to 60% of global electricity production. Global coal production reached an all-time high of 179 exajoules, surpassing the previous year's record. The Asia-Pacific region accounted for nearly 80% of the world's coal output, with significant production concentrated in four countries, viz., Australia, China, India, and Indonesia. Together, these countries produced 97% of the region's coal output. Coal extraction is expected to continue as long as the demand for electricity generation persists. Open-cast mining is steadily growing in its share of coal production. In India, more than 90% of coal is produced through open-cast mining [2]. Along with the coal, the earth material (rocks and soils) that the coal mining industries remove in order to reach the coal seam is referred to as coal mine overburden (OB). In open-cast mining, the stripping ratio refers to the amount of overburden that must be removed to extract a certain quantity of coal. Over the last few decades, the average stripping ratio in Indian coal mines has been approximately 1.97 m^3/t [3]. Overburden (OB) materials lack typical soil characteristics, consisting of loosely adhering particles of shale, boulders, stones, cobbles, and other nutrient-poor materials. Due to the high concentrations of trace metals in mine overburden (OB) soils, these soils do not support potential plant growth. Consequently, the natural recovery process for mine-overburdened land to restore its original soil properties takes a long time. It typically takes at least 50 to 100 years for advanced plant species to establish themselves on ground that has been mined and filled with OB [4]. On the other hand, the processing of extracted coal in thermal power plants to generate electricity produces significant amounts of processing waste, like fly ash. Effective management or disposal of these waste materials from the mining industry is crucial for preserving land and protecting the environment. Stabilizing the generated OB waste with fly ash is one effective method for their utilization [5]. Since traditional materials like cement and lime are detrimental to natural resources when used for chemical stabilization, the concept of using non-traditional materials has been proposed. These waste materials can be chemically activated to produce highly compact, well-cemented composites from glassy structures that are partially or completely amorphous and/or metastable [6]. When these materials are used in road construction, the amount of overburden waste materials consumption increases, but at the same time, green and sustainable growth accelerates.

One of the primary expenses in mine operations is haulage, which becomes more costly when substandard and deteriorated haul roads are utilized. A typical surface coal mining operation includes approximately 4 to 5 kilometers of permanent haul roads, along with an additional 10 to 12 kilometers of branch roads. The hauling truck typically operates with tire pressures between 600 and 700 kPa, but its gross vehicle weight can occasionally reach 4000 kN [5]. Typically, overburden soil is used to construct mine haul roads due to its availability. Mine haul roads consist of multiple layers, with the subgrade serving as the foundational layer made of compacted overburden soil, modified materials, or stabilized soil. The subgrade is crucial for providing support and load-bearing capacity, ensuring the road can withstand heavy mining equipment. Above the subgrade, aggregate base layers and a granular surface add strength and durability. Proper compaction and stabilization of the subgrade are key to the overall performance of the road. This study primarily focuses on the utilization and improvement of overburden soil for pavement subgrade applications.

Resilient modulus (M_R) of the subgrade soil is a crucial parameter in the design of the subgrade structure of a pavement. Under repeated load testing, the ratio of dynamic deviatoric stress to recoverable strain, known as the resilient modulus, serves as a measure of material stiffness. For both coarse- and fine-grained soils, M_R is influenced by confining pressure and deviatoric stress. One of the most effective ways to assess pavement stabilization outcomes is by investigating variations in M_R [7]. As a result, to assess the stabilizing impact of traditional materials such as cement [8] and lime [9], etc., especially on the subgrade soil, it has been used in numerous research studies. Zain [10] investigated the addition of fly ash and an alkaline activator and its impact on the resilient modulus properties of peat soil. The mine OB soil typically has a relatively low resilient modulus and bearing capacity, making it unsuitable for direct use in pavement subgrade applications.

Hence, enhancing the mechanical properties of OB soil is crucial for its effective utilization. Current cement-based materials have slow strength development, durability issues, and environmental concerns due to the energy-intensive and environmentally polluting nature of cement production. Alkali-activated materials, such as fly ash and metakaolin, offer a promising alternative. These inorganic polymers provide superior strength, corrosion resistance, fire resistance, and durability, making them a more environmentally friendly option to replace Portland cement in construction applications. Geopolymer technology, which uses aluminosilicate raw materials activated by a high-alkaline solution (sodium or potassium), can reduce emissions by up to 80%. Through a fast chemical reaction in alkaline conditions, the Si-Al minerals polymerize into a three-dimensional network of Si-O-Al-O bonds [11], offering a sustainable solution with enhanced performance for pavement subgrade applications.

In this context, the subsequent sections of this paper first highlight the research significance, followed by a description of the materials used in the current study. The geotechnical properties of the materials are then discussed, followed by the experimental methodology and results. Finally, the paper concludes with key findings and their implications for sustainable infrastructure development.

2. RESEARCH SIGNIFICANCE

This study investigates the effectiveness of fly ash-based geopolymer in enhancing the unconfined compressive strength (UCS) and resilient modulus (M_R) of mine overburden soil. Stabilization of overburden soil with geopolymer renders it suitable for haul road construction in mine sites, reducing the need for expensive natural materials and minimizing transportation costs. By providing a sustainable and eco-friendly solution for pavement construction, the findings foster sustainable growth in mining regions through greener infrastructure development, improved waste management practices, and adherence to environmental regulations.

3. MATERIALS

Mine overburden (OB) soil was sourced from open-pit coal mines in Tadicherla coal mines, Bhupalapally, Telangana, India, located 250 km from the laboratory at IIT Hyderabad (IITH). Fig. 1 depicts the mine site from which the material was sourced.

Fig. 1 Tadicherla open-cast mine site

Fly ash was collected from the National Thermal Power Corporation (NTPC) in Ramagundam, Telangana, India, situated 200 km from IIT Hyderabad laboratory. The material was transported in bulk to the laboratory, ensuring no contamination or loss during transit. Both materials were oven-dried, pulverized, and stored in bags for further analysis.

Sodium hydroxide and sodium silicate were sourced from a local manufacturer. The sodium silicate had a composition of 27.8% SiO_2, 8.5% Na_2O, and 63.5% H_2O, with a SiO_2/Na_2O ratio of 3.3 and a specific gravity of 1.35 at 20°C. The NaOH pellets had 99% purity and appeared white and deliquescent. To prepare the alkaline liquid, NaOH was dissolved in water to create a 3M solution. The solution was stirred for one hour using a magnetic stirrer, and then left for 24 hours to ensure complete dissolution of all ions. The weight ratio between sodium hydroxide and sodium silicate was maintained at 1.0 throughout the study. This ratio and concentration were selected based on the literature [12]. When the Na_2SiO_3 and NaOH solutions were added to the fly ash (FA), an excess of reactive silica was released, which accelerated the pozzolanic reactions and maintained an alkaline environment throughout the process [12].

4. GEOTECHNICAL CHARACTERIZATION OF MATERIALS

4.1. Gradation Analysis

Gradation analysis was initially conducted using sieve and hydrometer methods on both materials, in accordance with ASTM D6913-04 [13] and ASTM 7928 [14] guidelines. Mechanical particle-size analysis involved vibrating soil samples through a series of sieves, with sieve sizes decreasing from top to bottom. This test was used for soils with particle diameters larger than 75 microns, while particles smaller than 75 microns were analyzed using hydrometer analysis. Fig. 2 shows the resulting gradation curves of mine OB soil and fly ash. Based on the grain-size distribution, it is evident that most of the particles in the mine OB soil fall under the sandy type, while the fly ash consists predominantly of silty particles. The mine overburden soil is categorized as poorly graded sand (SP), and the fly ash as non-plastic silty sand (SM) according to the Unified Soil Classification System (USCS).

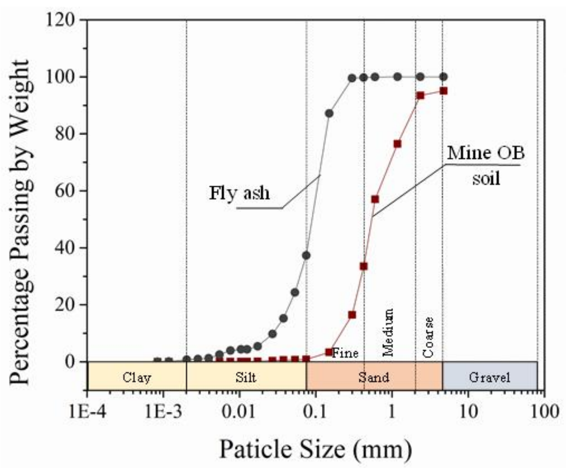


Fig. 2 Particle size analysis of mine OB soil and fly ash

4.2. Chemical Composition

X-Ray flouroscence analysis was performed on the mine OB soil and fly ash to determine their chemical oxide compositions in the previous study [3]. Table 1 gives the chemical composition of both materials. Fly ash was classified as Class F based on its chemical composition.

Table 1 Chemical oxide composition of mine OB and fly ash [3]

Compound	Mine OB (percentage by weight)	Fly ash (percent by weight)
SiO_2	51.43	52.47
Al_2O_3	29.25	23.04
Fe_2O_3	3.26	6.47
CaO	0.41	4.93
TiO_2	2.11	1.92
K_2O	6.01	2.70
MgO	1.96	2.59
Na_2O	3.40	3.47
Others	2.17	2.41

4.3. Specific Gravity

The specific gravity of mine OB soil and fly ash was determined as per ASTM D854-10 [15]. The results showed that the specific gravity of mine OB soil is 2.2, while fly ash has a specific gravity of 1.92. These results indicate that OB soil is denser than fly ash.

4.4. Compaction Properties

The sensitivity of density changes to variations in moisture content is indicated by the compaction curve. A material with a flat curve can withstand changes in moisture content without significantly losing its compacted density. In contrast, materials with steep curves are highly sensitive to changes in moisture content, and even small variations can affect the ideal compaction value.

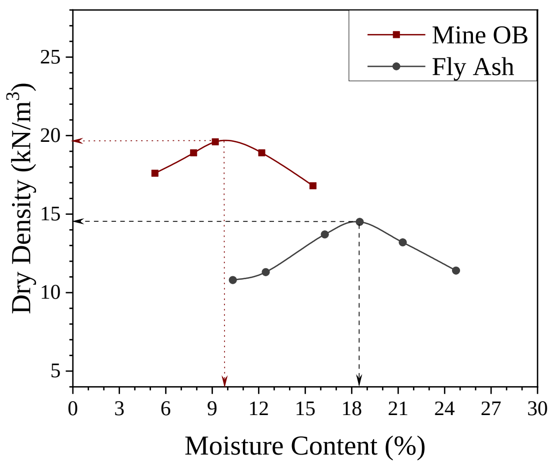


Fig. 3 Compaction curves for mine OB and fly ash

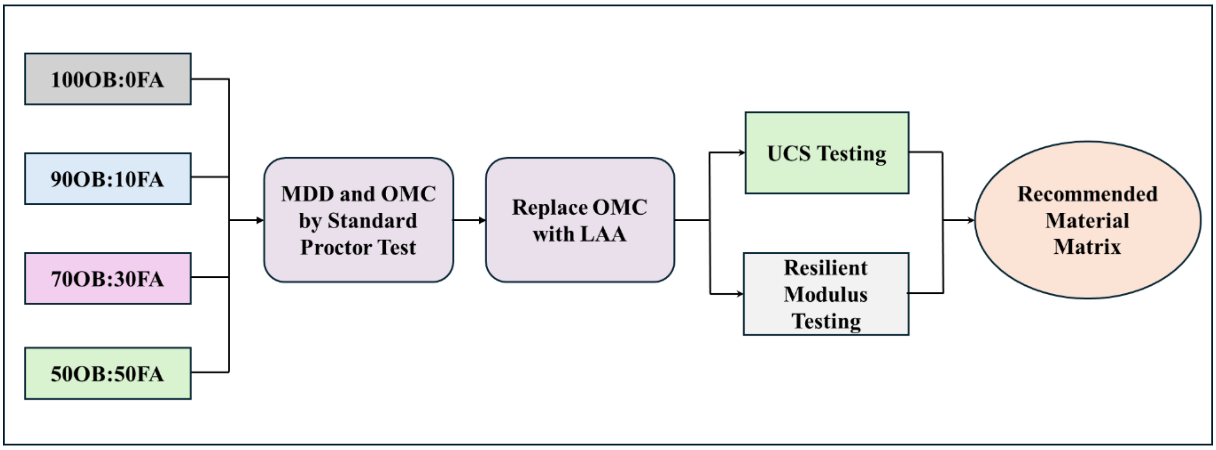


Fig. 4 Experimental flow chart of the current study

The Standard Proctor compaction test was conducted in accordance with ASTM D698-12 [16] on mine OB soil and fly ash to obtain the compaction curve and determine the maximum dry density (MDD) and optimum moisture content (OMC) of the materials. Fig. 3 presents the results of the Proctor compaction test. From the compaction curves, it was observed that the MDD and OMC of the mine OB soil are 19.7 kN/m³ and 9.8%, respectively, while for fly ash, the MDD and OMC are 14.5 kN/m³ and 18.45%,

5. EXPERIMENTAL METHODOLOGY AND RESULTS

The main objective of this study is to stabilize mine overburden soil with fly ash-based geopolymer, thereby enhancing its suitability for pavement subgrade applications. To achieve this, four distinct material mixtures were prepared, incorporating varying proportions of mine OB soil and fly ash: 100% mine OB (100OB:0FA), 90% mine OB and 10% fly ash (90OB:10FA), 70% mine OB and 30% fly ash (70OB:30FA), and 50% mine OB and 50% fly ash (50OB:50FA). The materials were mixed carefully in the specified proportions by weight to ensure consistency across the mixtures.

To evaluate the compaction characteristics of the material mixtures, a standard Proctor compaction test was performed to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the material mixtures. Subsequently, further testing was conducted with OMC replaced by the liquid alkali activator (LAA) solution to facilitate geopolymerization. The mixtures were then tested for unconfined compressive strength (UCS), and resilient modulus (M_R) characteristics on specimens compacted at MDD with the moisture content corresponding to OMC replaced by LAA. For the preparation of UCS and M_R samples, static compaction was used to achieve MDD and OMC. To allow adequate geopolymerization and achieve the desired mechanical properties, all specimens were cured for 7 days in a humidity chamber maintained at standard temperature and relative humidity conditions, simulating field environmental conditions [7]. This curing process was critical to the activation of the fly ash-based geopolymer binder and the stabilization of the OB soil. The UCS test was employed to determine the strength characteristics of the mixture, while the M_R test was conducted using repeated load triaxial (RLT) apparatus to evaluate the resilience of the stabilized mixtures under cyclic loading conditions representative of traffic stresses. Based on the test results, a recommended material mixture was proposed for the effective pavement subgrade of mine OB soil. A detailed experimental flow chart outlining the study methodology is presented in Fig. 4.

5.1. Compaction Characteristics of Mixtures

The Standard Proctor test was conducted in accordance with ASTM D698-12 [16].

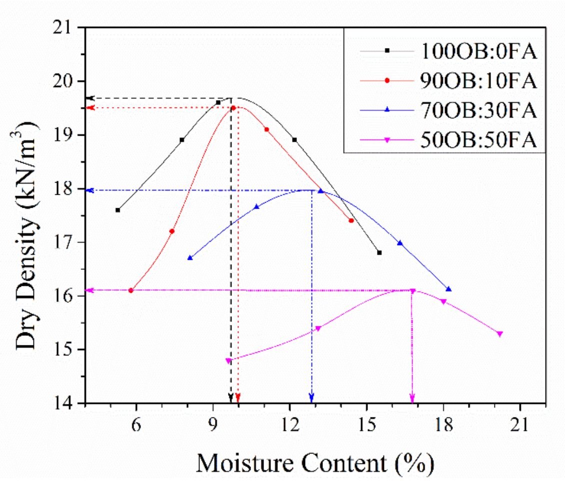


Fig. 5 Results of Proctor compaction testing for the selected material mixtures

The compaction curves for each of the aforementioned mixtures were presented in Fig. 5, where the MDD and OMC were also indicated with the dotted lines. Table 2 gives the values of MDD and OMC for the mixtures.

Table 2 MDD and OMC for the various mixtures

Mixture	MDD (kN/m^3)	OMC (%)
100OB:0FA	19.7	9.8
90OB:10FA	19.5	10.0
70OB:30FA	18.0	12.9
50OB:50FA	16.1	16.8

5.2. Unconfined Compressive Strength (UCS)

UCS is a measure of strength development in a stabilized mixture. The selected material mixtures and liquid alkali activator were thoroughly mixed, and the mixtures were compacted using the static compression method to prepare cylindrical specimens measuring a height of 10 cm and diameter of 5 cm. The samples were compacted at MDD and OMC, with the OMC replaced by the LAA. The compacted samples were then demolded using a sample ejector and trimmed with flat plates to achieve a proper finish. Fig. 6 illustrates the preparation of UCS sample.

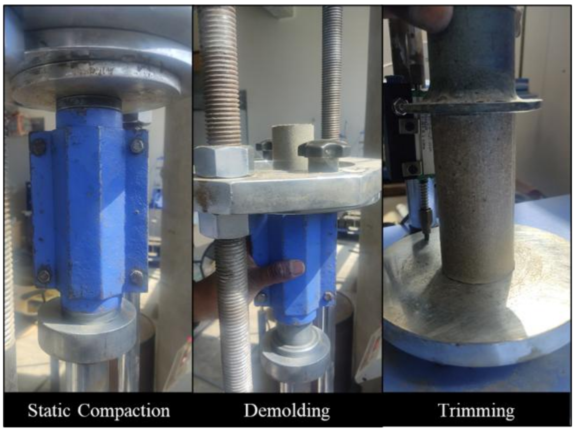


Fig. 6 Preparation of UCS samples for mine OB-fly ash mixtures

The prepared samples were covered with a plastic film and subjected to seven days of curing under standard temperature of 25 ± 2°C and relative humidity of 95% in the humidity chamber to ensure proper geopolymerization [7]. The UCS test was carried out following ASTM D2166-06 [17] guidelines. Three replicate tests were performed for every mixture in the UCS test. The UCS values presented in Fig. 7 represent the mean value of the three test results, accompanied by error bars indicating variability.

The UCS results indicate that as the fly ash content increases, the UCS strength also increases. The addition of 50% fly ash (FA) to the overburden (OB) soil with LAA results in a 66% increase in UCS strength compared to the UCS of OB soil with LAA alone. FA particles are finer and contain more reactive silica (Si) and alumina (Al) than OB soil, enhancing the geopolymerization process [7, 18]. When the alkali activator is added, it breaks the Si-O-Si and Si-O-Al bonds in the FA, releasing Si^{4+} and Al^{3+} ions into the solution. These ions then form aluminosilicate oligomers, which further condense into a cementitious material. This material forms a very strong N-A-S-H (sodium-alumino-silicate-hydrate) gel, leading to a significant increase in the mechanical strength of the stabilized soil. The improved strength is due to the formation of this strong gel network, which binds the soil particles together more effectively than in the unstabilized soil [6].

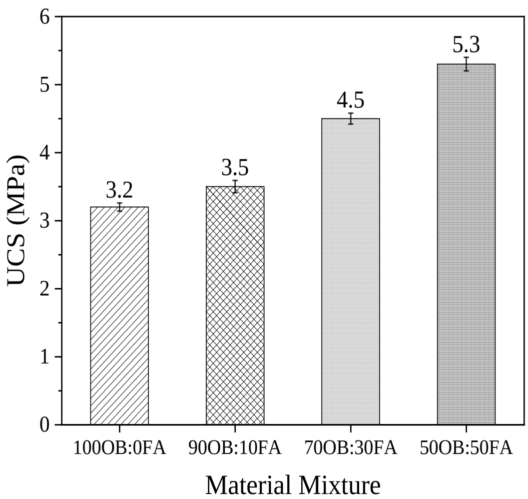


Fig. 7 UCS values for the selected material mixtures

5.3. Resilient Modulus (M_R)

Resilient modulus is analogous to elastic modulus and represents the ability of materials to recover their shape under repeated loading, such as stresses caused by tire wheels on road surfaces [19]. This property is crucial for designing road subgrade structures

For this study, cylindrical specimens with dimensions of 10 cm in diameter and 20 cm in height were prepared for all material mixtures. These specimens were compacted at their respective MDD and OMC, with the OMC replaced by the LAA solution to achieve stabilization. The samples were then cured for 7 days in a humidity chamber maintained at standard temperature of 25 ± 2°C and relative humidity of 95%, as detailed in the previous section. Following the curing process, the stabilized mixtures were subjected to resilient modulus testing to evaluate their mechanical performance under cyclic loading conditions. The test was conducted using the Repeated Load Triaxial (RLT) apparatus, as shown in Fig. 8, which provides a detailed representation of the setup used for this evaluation.

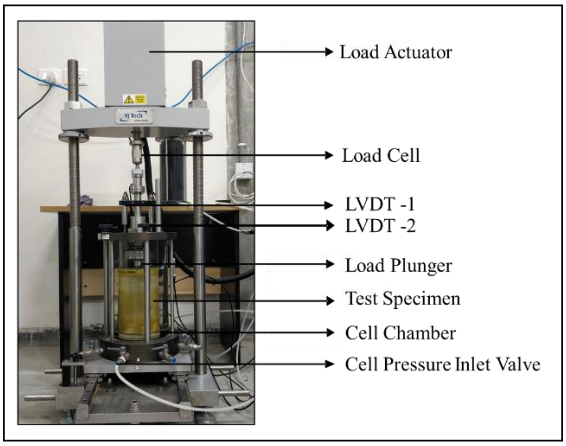


Fig. 8 Repeated load triaxial test setup

Fig. 9 (a) illustrates a schematic representation of the sample setup in RLT test, providing a detailed depiction of the applied loads on the specimen. The standard loading procedure followed as per AASHTO T307-99 [20]. A haversine-shaped load is applied repeatedly for 0.1 seconds, followed by a 0.9-second rest period, enabling the assessment of the response of the material to dynamic stress conditions, as shown in Fig. 9 (b). Before resilient modulus testing, specimens underwent preconditioning with a confining pressure of 41.4 kPa and deviator stress of 27.6 kPa applied 1000 times. During the RLT test, specimens were subjected to various confining pressures and deviator stress conditions, with 100 cycles for each loading sequence. Fig. 9 (c) shows the confining pressure and axial stress combinations used in each loading sequence recommended by AASHTO T-307-99 [20]. To ensure accurate measurement of axial strain, two external LVDTs were installed on the chamber to continuously monitor deformations throughout the test. Resilient modulus values were determined by monitoring stress and strain during the last five loading cycles.

Fig. 10 illustrates the variation in resilient modulus across tested mixtures under different deviator stress and confining pressure conditions as shown in Fig. 9 (c). The solid horizontal lines in the figure represent the average M_R values derived from 15 loading sequences, providing a clear comparison among the mixtures. The RLT test results indicated that higher fly ash (FA) content in mixtures corresponded to increased resilient modulus values (refer to Table 3), attributed to enhanced geopolymerization of FA particles as discussed in the earlier section. These findings align with prior research, reinforcing the reliability of the results [7]. A notable 182% increase in average resilient modulus values was observed for mixtures with 50% FA replacement in overburden (OB) soil. Geopolymerization of FA proved more effective than that of OB soil alone, yielding higher resilient modulus values.

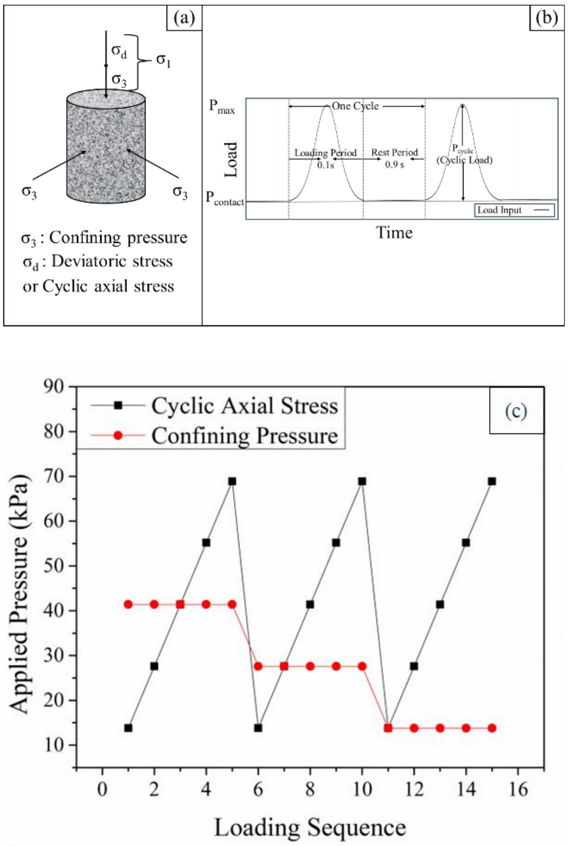


Fig. 9 Visual depiction of RLT testing including (a) schematic representation of sample and applied loads; (b) haversine-shaped loading of axial stress; (c) combination of applied confining and axial stresses for each sequence

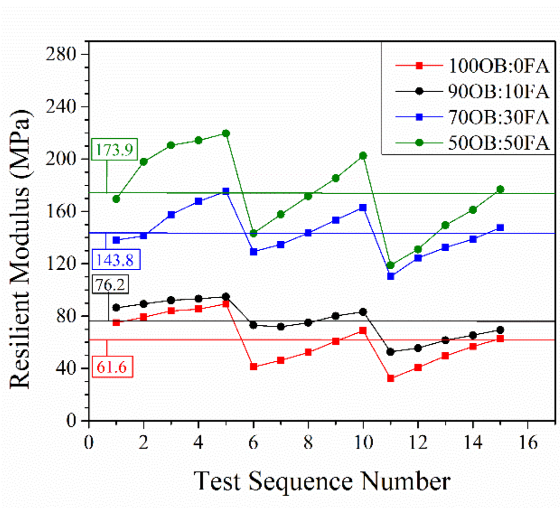
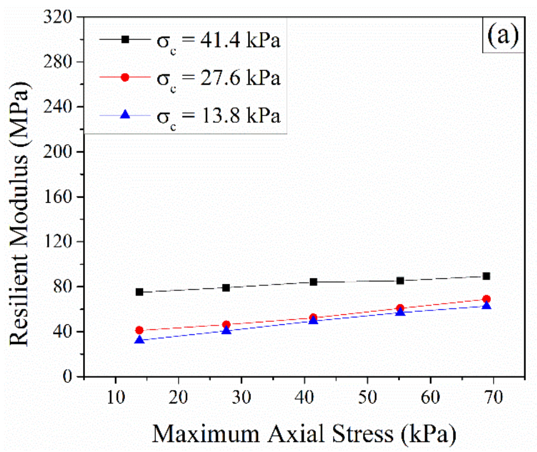


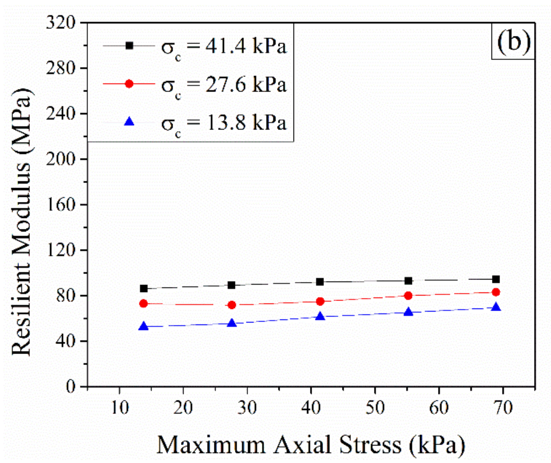
Fig. 10 Variation of resilient modulus values with each loading sequence for the tested material mixtures

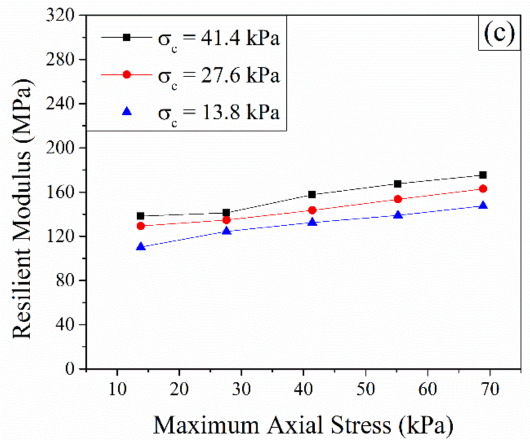
Table 3 Average Resilient Modulus (M_R) values and percentage increase with FA addition.

Mixture	Average M_R (MPa)	M_R increase compared to 100OB:0FA (%)
100OB:0FA	61.6	0
90OB:10FA	76.2	24
70OB:30FA	143.8	133
50OB:50FA	173.9	182

For all the mixtures considered in the study, it was observed that increasing confining pressure enhanced the M_R of the all the specimens (refer to Fig. 11). This trend indicates that higher levels of confinement led to denser and stronger specimens, resulting in increased stiffness and higher resilient moduli. Additionally, at a given confining pressure, increasing the deviatoric stress led to a corresponding rise in M_R values, as shown in Fig. 11. This behavior can be attributed to the phenomenon of stress hardening, where densely packed specimens subjected to elevated mean effective stress and cyclic loading exhibit a reduction in axial strain. These effects contribute to the observed rise in M_R values, reflecting improved stiffness and mechanical performance under cyclic loading conditions [21].







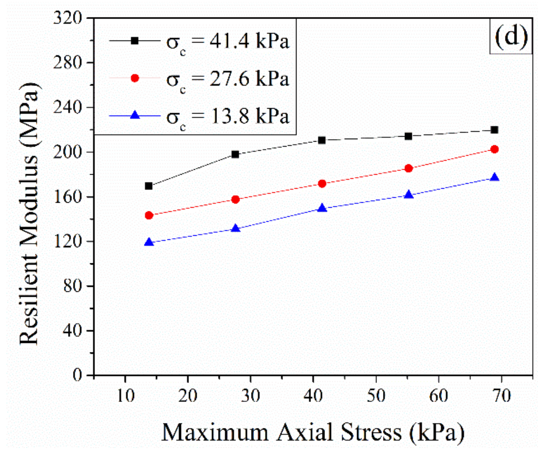


Fig. 11 Resilient modulus vs. maximum axial stress for (a) 100OB:0FA; (b) 90OB:10FA; (c) 70OB:30FA; and (d) 50OB:50FA

6. CONCLUSIONS

This study explored the use of fly ash-based geopolymer as a stabilizing additive for mine overburden (OB) soil in pavement subgrade applications. Following conclusions drawn from the experimental investigation:

1) The addition of fly ash increased the UCS of OB soil, with a notable 66% increase observed in mixtures containing 50% fly ash. This enhancement is attributed to the effective geopolymerization process, which strengthens the soil mixture.
2) The Repeated Load Triaxial (RLT) tests revealed that higher fly ash content in the mixtures led to significant increase in resilient modulus values. Specifically, mixtures with 50% fly ash replacement showed an impressive 182% increase in average resilient modulus compared to OB soil alone. The improved resilient modulus is a result of better particle interlocking and packing provided by the geopolymerized fly ash.
3) Although the 50OB:50FA mixture exhibited slightly superior performance, the improvement over the 70OB:30FA mixture was marginal.

Given the abundant availability of mine OB at coal mine sites and the need to transport FA from external sources, the 70OB:30FA mixture is identified as the optimal choice, balancing material utilization, mechanical performance, and practical feasibility.

Hence, it was concluded that the addition of fly ash-based geopolymer significantly improves the mechanical properties of mine OB soil, making it a viable and sustainable option for pavement subgrade applications. This approach enhances subgrade performance and promotes eco-friendly practices by using industrial waste. Future research can explore its use for base and subbase applications, including the effects of curing time and temperature, variations in LAA percentages, and NaOH concentrations.

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