



Evaluation of Sustainable Stabilization of Expansive Soil Using Bagasse Ash and Polypropylene Fibers

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ABSTRACT

The current study aims to improve free swell, swell pressure, cohesion (C), and internal friction angle (θ) of expansive soil using Bagasse Ash (BA) and Polypropylene Fibre (PPF) with varying percentages. The properties of untreated and treated soils were determined by the one-dimensional consolidation test and the unconsolidated undrained (UU) triaxial compression test. X-ray diffraction (XRD), Scanning Electron Microscopy (SEM), and Energy-dispersive spectroscopy (EDS) analysis were utilized. The results showed that the addition of BA in untreated soil decreased the free swell, swell pressure, and cohesion (C) by 64.86%, 61.54%, and 20.90%, respectively, and increased the internal friction angle by 47.19%. The test results further revealed that the inclusion of 20% BA and 1% PPF in untreated soil decreased the free swell, swell pressure, and C by 78.38%, 76.92%, and 45.45%, respectively, while increasing the internal friction angle by 57.09%. The test results of untreated soil indicated illite, kaolinite, montmorillonite, and non-clay minerals, predominantly quartz. Moreover, the XRD result of the treated soil showed the reduction of montmorillonite content. Further variation in the behavior of treated soil was confirmed using SEM and EDS analyses. These results would provide a deep understanding of the optimum contents of BA and PPF for treating the expansive soils to address the potential hazards in the construction.

Keywords: Expansive soil, Bagasse ash, Polypropylene fiber, Internal friction angle, Stabilization, XRD, SEM, EDS.

INTRODUCTION

The sub-grade soil is important for the pavement's sustainability during the service life (Vaiana et al., 2021). The sub-grade materials should have sufficient strength to withstand the induced stresses due to traffic loadings and climatic conditions. The behavior of

unbound layers in pavements has great importance in determining the service life of pavements (Kafle et al., 2024). The weak sub-grade soil contributes to the major part of the failure of pavements due to the retention of moisture, low strength, settlement, and lower durability (Selvi, 2015).

The shrinkage and swelling behaviors in the sub-

grade soil are considered the main reasons for the failure of the sub-grade layer (Amakye & Abbey, 2021). Expansive soils tend to change volume when in contact with moisture (Selvakumar et al., 2024; Alnmr et al., 2024). The swelling and shrinking behaviors represent the main hindrance to the use of expansive soils in different engineering infrastructures (Selvakumar et al., 2024; Soltani et al., 20119). The formation of longitudinal cracks and uplifting of pavement structure are common failures of pavement structures resulting from the shrinkage and swelling behaviors of expansive soils. The properties of sub-grade materials comprising expansive soils can be enhanced with the addition of various additives. The additives help stabilize the expansive soil and improve its mechanical and shear properties (Reddy et al., 2015; Cheng and Huang, 2019; [Ahmad et al., 2024](#)). There is a high degree of reduction of swelling in expansive soils when these are stabilized with chemical additives (Reddy et al., 2015). The replacement of black cotton soil (BCS) with 3% lime and 15% volcanic ash shows a significant effect in enhancing the soil for use in construction (Cheng & Huang, 2019).

Taha et al. (2020) investigated the effect of PPF on the mechanical properties of the soil and exhibited the enhancement of the properties of the soil. Jayawardane et al. (2020) examined the effect of Polypropylene Fibre (PPF) on the marine clay and showed an improvement in the expansive and compressibility behaviors of the soil. Hatmoko and Handoko (2020) investigated the effect of BA and polyester fiber on organic soil and inferred an increase in the internal friction angle of soil. Akbari et al. (2021) applied PPF in the soil and showed improvements in the strength and durability of the soil. Arya et al. (2022) conducted an experimental study using varying percentages of BA and concluded that the CBR was improved due to the addition of BA in black cotton soil.

Awadalseed et al. (2022) examined the potential of BA for the replacement of cement as a stabilizing agent and showed that BA increased the CBR comparable to cement. Adnan et al. (2023) reviewed the potential of BA and concluded that BA not only improved the performance of the soil, but also decreased the material cost. Gadouri and Meziani (2023) assessed the behavior of PPF-modified soil already contaminated by sulfate and concluded the effectiveness of PPF in the soil. Meziani and Gadouri (2023) evaluated the free swell

behavior of expansive soil and showed a reduction in the free swell value. Hamid et al. (2024) explored the influence of PPF on CBR of expansive soil and showed an increase in CBR due to the addition of PPF in the soil. The addition of fly ash showed improvements in plastic behavior, compressive shear strength, and penetration resistance of expansive soils (Ahmad et al., 2024).

Mujtaba et al. (2018) used Ground Granulated Blast Furnace Slag (GGBFS) to modify the properties of expansive soil, and found that 50% GGBFS reduced the liquid limit and plasticity index and improved CBR. Swell pressure was reduced from 153 kPa to 0 kPa and from 128 kPa to 0 kPa with the addition of 50% and 30% GGBFS. Hussein and Ali (2019) reported that 2% of PPF produced less swelling and shrinkage, and Ali et al. (2020) showed that PPF enhanced UCS, E_{50} , and CBR and decreased the free swell and swell pressure of the soil. Similarly, another study revealed that PPF decreased plastic index, liquid limit, and swell pressure and increased plastic limit of expansive soil (Tiwari & Satyam, 2019). Malekzadeh and Bilsel (2014) also found that the use of PPF significantly reduced the swell and swell pressure. Studies have shown that Bagasse Ash improved Standard compaction, UCS, CBR, swell potential, one-dimensional consolidation, and elevated the unconfined compressive strength (Dang et al., 2021; Sadeeq et al., 2015). Barasa et al. (2015) showed that lime and bagasse ash at the optimum ratio of 4:1 gave the best results for plasticity index (PI), CBR, compaction and consolidation tests. Table 1 summarizes the different stabilizing materials used in treating expansive soils to enhance their mechanical properties. Bagasse ash decreased free swell and improved unconfined compressive strength and CBR (Hasan et al., 2016).

A study established the use of cement and other additives in the stabilization of sub-grade soils with economic benefits (Marik et al., 2022). It is reported that the use of rice husk ash has a substantial impact on improving the shrinkage of treated soil (Onyelowe et al., 2021). The treated soils have up to four times the compressive strength of untreated soils, and rice husk ash has a great role in this context (Seco et al., 2011). The use of lime has a significant impact on changing the compressive strength properties of expansive soils (Du et al., 1999). The use of fly ash for treatment has economic benefits to stabilize the soil, as it reduces the swell potential and increases the hydraulic conductivity

(Nalbantoglu & Gucbilmez, 2001; Nalbantoglu, 2004). A study indicated that waste marble dust and fine cinder gravel are effective in improving the strength of stabilized expansive soils, and 16% is the optimum content for replacement (Belihu et al., 2025). The wetting cycle and drying conditions tend to impact the behavior of lime-stabilized expansive soils (Rao et al., 2001). It is reported that soil properties using X-ray diffraction testing provide better ways to monitor the

possibilities of failures in treated soil layers. Various additives and materials are being used to modify the characteristics of soils for use in pavement sub-grades. This study aims to improve expansive soils using two different waste materials; i.e., Bagasse Ash and PPF. The effect of various percentages of additives was noted on the plasticity, swell potential, swell pressure, cohesion, and angle of internal friction.

Table 1. Different stabilizing materials used for the improvement of expansive soil

| Stabilizing Material | Testing Methods | Results | Authors |
|---|--|---|------------------------------|
| Polypropylene Fibre (PPF) | Unconfined compression, direct shear, swelling, and shrinkage tests | Improvement in shear strength | Cai et al. (2006) |
| Bagasse Ash | Shrinkage limit, L.L, P.L, P.I, Free Swelling Pressure, and Swell Index. | BA effectively improved the existing expansive sub-grade soil. | Gandhi (2012) |
| Bagasse Ash and Lime | Atterberg limits test, plasticity index test, compaction test, and CBR. | Improvement in OMC and CBR. Reduction in MDD and soil plasticity. | Wubshet and Tadesse (2014) |
| Polypropylene Fibre (PPF) | Direct shear test, UCS. | The use of PPF for reinforcing clayey soils is recommended. | Teja (2016) |
| PPF and Fly Ash | Standard Proctor Test, UCS, Tri-axial shear test. | The best percentages of PPF and fly ash were found to be 1.5% and 15%, respectively. | Deshpande and Puranik (2017) |
| Bagasse Ash and Marble Industrial Waste | XRD, SEM, XRF, Atterberg limits, UCS, swell pressure, and free swell test. | 3%-5% BA and/or 8%-10% MIW is suggested to gain strength and achieve a reduction in plasticity. | Jalal et al. (2017) |
| Bagasse Ash | Compaction, unconfined compressive strength. | Bagasse ash improved the compaction and unconfined compressive strength. | Srinivasa et al. (2017) |
| Bagasse Ash | Unconfined compressive strength. | Bagasse ash upgraded the unconfined compressive strength. | Jamsawang et al. (2017) |
| Bagasse Ash | Compaction, CBR, and Standard Proctor Test. | Significant improvement of MDD and CBR with the addition of 4% bagasse ash. | Rao et al. (2018) |
| Polypropylene Fibre (PPF) and Cement | Grain size analysis, Standard Proctor Test, UCS, CBR test. | 1.5% of PPF produced maximum dry density and minimum swelling. | Langade et al. (2019) |

MATERIALS AND METHODS

Figure (1) shows a schematic flowchart of the

research work. It includes the literature review, material selection, preparation of BA, characterization of material properties, swell and swell pressure test, triaxial

tests, X-Ray Diffraction Analysis (XRD), Scanning Electron Microscopy (SEM) Analysis, and Energy Dispersive X-ray Spectroscopy (EDS) Analysis.

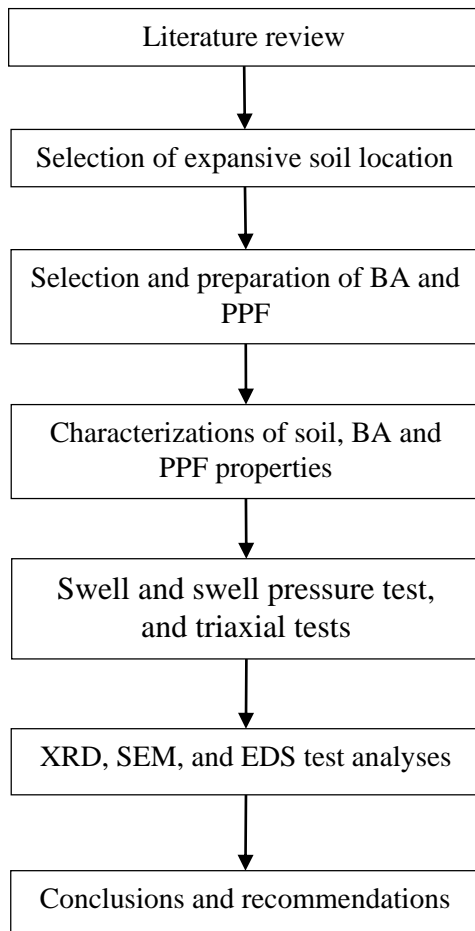


Figure (1): A schematic flowchart of the research work

Soil

The soil was obtained from Choti- a town 20 km away from Dera Ghazi Khan, Punjab, Pakistan, because this area is more prone to expansive soil. The location map is shown in Figure (2). The soil was collected from the site at a depth of 5ft from the natural surface level after excavating a pit. The standard procedure was adopted in the collection of the required soil sample. The soil was tested in the laboratory according to the international standards, and the results are summarized in Table 2.

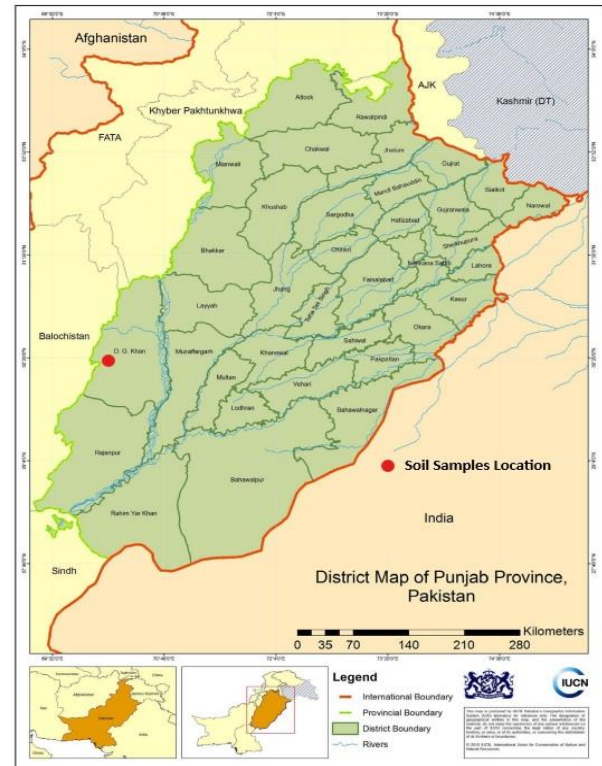


Figure (2): Soil sample location (source: International Union for Conservation of Nature (IUCN))

Bagasse Ash (BA)

The sample of bagasse waste was collected from a fruit shop located near Raiwind Road, Lahore, Punjab, Pakistan. The bagasse waste was dried in the sunlight to remove the moisture content. The dried bagasse was then ground in the grinder. This ground bagasse was put in the furnace at a temperature of 900°C for 2 hours for the preparation of BA. The physico-chemical properties of BA are shown in Table 3. Testing was performed with varying percentages from 10% to 30%; however, the optimum percentage was found to be 20%. Therefore, testing was conducted for physico-chemical analysis by mixing 20% of BA with the soil.

Polypropylene Fiber (PPF)

In this study, PPF was purchased from “FOSPAK” located in Quaid-e-Azam Industrial Estate, Lahore, Punjab, Pakistan. The size of PPF varied from 6 mm to 12 mm in length, as shown in Figure (3). Tests were conducted with the addition of various dosages of PPF, ranging from 0.5% to 1.5%; however, the optimum was found to be 1% of PPF for further testing. Final testing was performed for physico-chemical analysis by mixing

1% PPF and 20% BA in the soil. The physico-

mechanical characteristics of PPF are shown in Table 4.



Figure (3): Polypropylene fibres

Particle Size Analysis of Soil and Hydrometer Analysis

This test was performed on the untreated soil as per the guidelines given in ASTM D 1140-1. The particle size distribution was determined by performing sieve analysis using a sieve set of 1", ¾", No. 4, No. 10, No. 40, No. 100, and No. 200 sizes. After performing sieve analysis, a hydrometer test was conducted for fine-grained soil to determine soil particle size finer than sieve No.200. For this test, an amount of 50 g of dry and pulverized soil was used as per the standard procedure given in ASTM D 7928-16.

Atterberg Limits

ASTM D-4318 was used to perform Atterberg's limit tests on the untreated soil sample that passed through the No. 40 sieve. The LL test was performed using the Casagrande apparatus, and the PL test was performed by rolling soil samples on a smooth glass plate using the palm. The soil was classified based on the outcomes of sieve analysis, hydrometer analysis, and consistency limits using both USCS and AASHTO classification systems, and the results are summarized in Table 2.

Maximum Dry Density (MDD) and Optimum Moisture Content (OMC)

The MDD and OMC of untreated soil were obtained by performing a modified proctor test using ASTM D-1557-12. The sample of soil was compacted in five layers using 25 blows on each layer with a 4.5-kg hammer at a height of fall of 18 inches in a standard mold having a volume of around 944cm³.

Swell and Swell Pressure Test

The swell potential test was executed according to ASTM D-2435 to investigate the compressibility, swell potential, and swell pressure characteristics of untreated and treated soils. The diameter of the ring used was 50 mm, and the height was 20 mm, while the volume was 39.27 cm³. The ring sample was extruded from a compacted modified compaction sample. The sample was positioned in the odometer and filled with water to check the behavior under severe conditions. The soil sample was permitted to swell under a seating pressure of 1 psi for 24 hours. After 24 hours of swelling, a load was applied to get the zero swelling value. The swell pressure value was determined by dividing the load applied to get a zero reading by the area of the sample.

Triaxial Compression Test

A triaxial compression test was performed in unconsolidated undrained conditions according to ASTM D-2850 to find the strength and stress-strain relationships of untreated and treated soils. Specimens were remolded in the laboratory at OMC, and MDD was found from the modified proctor test. Specimens, after preparation, were placed in a rubber membrane and set in a triaxial chamber. This triaxial chamber is then placed in position in the axial loading device. The cell pressure was enlarged to the required value for the first trial; i.e., 50 kPa, 100 kPa for the second trial, and 150 kPa for the third trial. After this, the shear load was exerted on the sample at a strain rate of 1%/min. The change in length (ΔL) and deviator stress (σ_d) were noted at 10 seconds. The test was sustained up to the

deviator stress and showed an ultimate value at 20% of axial strain. The soil specimen was weighed, and the sample was placed into the oven. The test was repeated for the second and the third specimens at the cell pressure of 20 psi for the second sample and 30 psi for the third sample.

X-Ray Diffraction Analysis (XRD)

X-ray diffractometry (XRD) is a technique to analyze crystalline structures. It is a non-destructive, non-contact, multi-purpose tool that works on the principles of Bragg's Law. The central profiles of resultant patterns against Bragg angle (2θ) and diffracted intensity in counts or counts/sec are collected specifically for each material. The main assembly of the diffractometer contains a copper $K\alpha$ ($\theta = 15.4 \text{ \AA}$), an X-ray high tension generator, a proportional counter (detector for collection of sample information), and a processing unit.

Scanning Electron Microscopy (SEM) Analysis

Scanning electron microscopes (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS) are now widely used in the study of surface and elemental analysis. SEM provides high-resolution pictures that define the micro-morphology of samples. An energy dispersive spectrometer records the quantum energies from 1 and 40 keV or more concurrently by a multi-channel analyzer. SEM/EDS can be used in many

applications for environmental sciences. For this research work, SEM analysis for untreated and treated soils was performed.

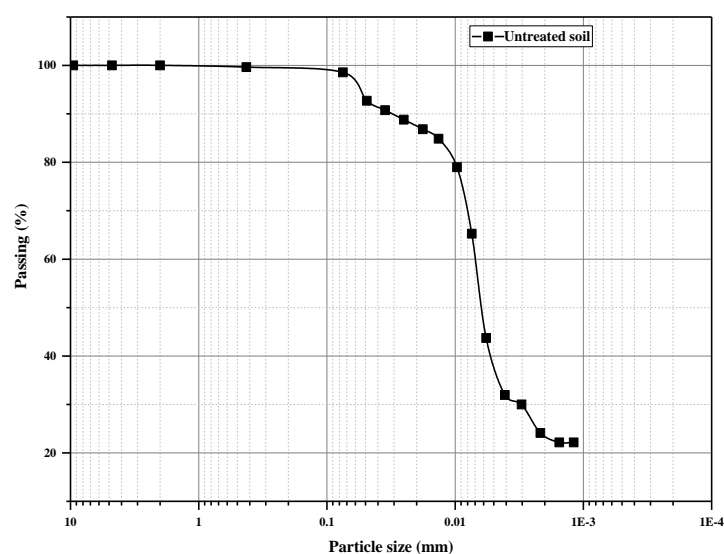
Energy Dispersive X-ray Spectroscopy (EDS) Analysis

The EDS is an advanced method that aids in examining the elements of a specified sample. The key principle of EDS to function is the ability of high-energy X-rays to expel 'core' electrons from an atom.

RESULTS AND DISCUSSION

Basic, Physico-chemical, and Physio-mechanical Properties of Material

Particle size distribution for soil that retained No.200 sieve was determined using the standard procedure as per ASTM D 1140-11, and for material that passed through the No. 200 sieve as per ASTM D 7928-16. According to the results, the untreated soil is a mixture of 1% sand, 11% silt, and 88% clay. Moreover, the particle size distribution of untreated soil is shown in Figure (4). Atterberg's limit test results of untreated soil are given in Table 2. The results show the LL, PL, and PI values as 55%, 24%, and 31%, respectively. The other properties, like natural moisture content, specific gravity, classification, and compaction parameters of untreated soil, are also shown in Table 2.



The free swell and swell pressure are shown in Tables 5 and 6, respectively. The free swell of untreated soil was reduced from 7.4% to 1.6% due to the addition of BA and PPF. Similarly, the swell pressure of untreated soil reduced from 162 kPa to 37 kPa due to the addition of BA and PPF. Meziani and Gadouri (2023)

carried out an investigation using PPF and reported the reduction of the swell potential of the soil. The swell pressure was decreased due to the addition of 20% BA and 1.0% PPF, as 61.54 % and 76.92%, respectively. Similarly, the free swell was reduced from 7.4% to 1.6% due to the addition of BA and PPF in the soil.

Table 2. Basic properties of untreated soil

| Parameters | Values |
|---|-------------------------|
| Soil type as per USCS | CH (Fat Clay) |
| Soil type as per AASHTO | A-7-6 (20) |
| Liquid Limit (LL) | 55 % |
| Plasticity Limit | 24% |
| Plasticity Index (PI) | 31 |
| Specific Gravity (G_s) | 2.664 |
| Maximum Dry Unit Weight (γ_{dmax}) | 18.55 kN/m ³ |
| Optimum Moisture Content (OMC) | 13.6 % |

Table 3. Physico-chemical properties of BA

| Physical /Chemical Names | Composition (%) |
|--------------------------------|-----------------|
| Color | Black |
| Density (g/cm ³) | 2.25 |
| Particle size (μ m) | 100 |
| SiO ₂ | 65.48 |
| Al ₂ O ₃ | 5.78 |
| Fe ₂ O ₃ | 4.23 |
| CaO | 1.87 |
| MgO | 1.32 |
| K ₂ O | 6.31 |
| Na ₂ O | 1.03 |
| P ₂ O ₅ | 1.34 |
| SO ₃ | 0.17 |
| Cl ₂ | < 0.1 |
| MnO | 0.06 |
| TiO ₂ | 0.26 |
| L.o.I | 10.5 |

Table 4. Physio-mechanical properties of PPF

| Properties | Values |
|---------------------------------|--------------------|
| Color | Transparent fibres |
| Length (mm) | (6 - 12) \pm 1 |
| Density (gm / cm ³) | 0.92 |
| Shape | Straight |
| Diameter (mm) | 0.031 |
| Tensile Strength (Mpa) | 559 -700 |

| | |
|-----------------------|--------------------------|
| Elongation (%) | 21-25 |
| Elastic Modulus (MPa) | 3.000 – 3.500 |
| Chemical Base | 100% polypropylene fibre |
| Melt Point (°C) | 159 |
| Ignition Point (°C) | 366 |

Table 5. Free swell of untreated and treated soil

| Soil (%) | BA (%) | PPF (%) | Value of Free Swell (%) |
|----------|--------|---------|-------------------------|
| 100 | 0 | 0 | 7.4 |
| 90 | 10 | 0 | 4.35 |
| 80 | 20 | 0 | 2.6 |
| 70 | 30 | 0 | 2.6 |
| 79.5 | 20 | 0.5 | 2.1 |
| 79 | 20 | 1.0 | 1.6 |
| 78.5 | 20 | 1.5 | 1.6 |

Table 6. Swell pressure of untreated and treated soil

| Soil (%) | BA (%) | PPF (%) | Value of Swell Pressure (kPa) |
|----------|--------|---------|-------------------------------|
| 100 | 0 | 0 | 162.145 |
| 90 | 10 | 0 | 124.727 |
| 80 | 20 | 0 | 62.364 |
| 70 | 30 | 0 | 62.364 |
| 79.5 | 20 | 0.5 | 49.891 |
| 79 | 20 | 1.0 | 37.418 |
| 78.5 | 20 | 1.5 | 37.418 |

Results of Unconsolidated Undrained (UU) Test

The strength properties, like cohesion (C) and angle of internal friction of untreated soil and treated soil with BA and a combination of BA and PPF were determined under unconsolidated undrained (UU) conditions according to ASTM D-2587. Nine remolded samples were tested in a triaxial compression machine; each sample was tested at three cell pressures of 50 kPa, 100 kPa, and 150 kPa. For untreated soil, major principal stresses at (50 kPa, 100 kPa, and 150 kPa) were 360 kPa, 435 kPa, and 515 kPa, respectively, as shown in Figures (5, 6, and 7). Further, by adding various percentages of Bagasse Ash (10% to 30 % by weight) and PPF (0.5% to 1.5% by weight) in untreated soil to calculate maximum percentages of Bagasse Ash and PPF; afterward, no variations in γ_3 occurred. 20 % of BA and 1.0% of PPF showed a maximum increase in γ_3 . At the addition of 20% of Bagasse Ash, γ_3 increased from 360 kPa, 435 kPa, and 515 kPa to 374 kPa, 509 kPa, and 643

kPa, respectively. At the addition of 1.0% of PPF, γ_3 increased from 374 kPa, 509 kPa, and 643 kPa to 383 kPa, 551 kPa, and 715 kPa, respectively.

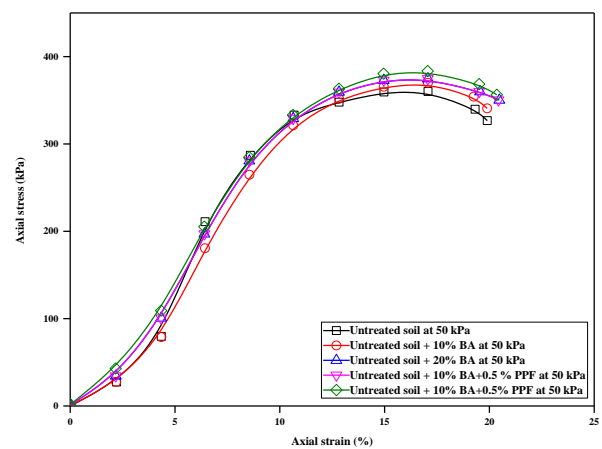


Figure (5): Stress-strain behavior of different soils at 50 kPa

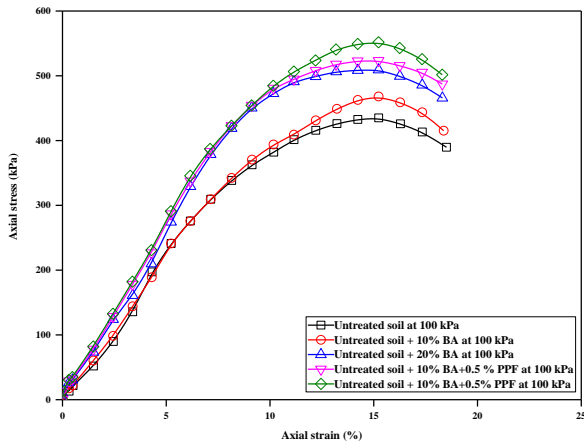


Figure (6): Stress-strain behavior of different soils at 100 kPa

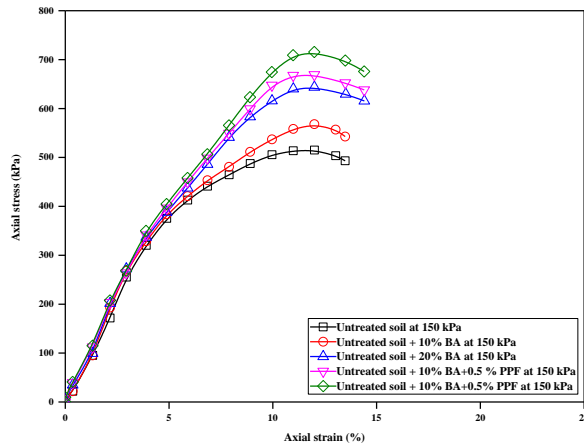


Figure (7): Stress-strain behavior of different soils at 150 kPa

A decrease in ‘C’ values was found with increasing the contents of additives. A maximum decrease from 110 kPa to 87 kPa in C values due to 20% BA mixed with untreated soil, and a decrease from 87 kPa to 60 kPa at the addition of 1.0% PPF mixed in 20% BA with parent soil were observed, as exhibited in Table 7. For untreated soil, the internal friction angle is 13.73°. The maximum increase in internal friction angle values of treated soil is 26° at 20% BA and 32° at 1% of PPF mixed in 20% BA, as shown in Table 7. Table 7 shows that the increase in BA and PPF contents causes an increase in the internal angle of friction and a decrease in the cohesion properties of the treated soil sample with the decrease of natural soil contents. Other studies have also shown the benefits of treating expansive soils using industrial bagasse and low-alkali cement to mitigate hazards resulting from expansive soil (Yong & Ouhadi, 2007; Liu et al., 2024). Testing results show that 20% replacement with BA is best to treat expansive soils, which is consistent with another study’s results (Awadalseed et al., 2022). In addition to a 20% replacement with BA, this study’s results showed that 1% use of PPF along with 20% BA has an optimum impact on cohesion and increases the internal angle of friction.

Table 7. Cohesion (C) and friction angle values of treated soil with BA and PPF

| Natural Soil (%) | Bagasse Ash (%) | Polypropylene fiber (%) | Cohesion (C) kPa | Increase in Friction Angle |
|------------------|-----------------|-------------------------|------------------|----------------------------|
| 100 | 0 | 0 | 110 | 13.73 |
| 90 | 10 | 0 | 95 | 17.1 |
| 80 | 20 | 0 | 87 | 26 |
| 70 | 30 | 0 | 87 | 26 |
| 79.5 | 20 | 0.5 | 68 | 29.2 |
| 79 | 20 | 1.0 | 60 | 32 |
| 78.5 | 20 | 1.5 | 60 | 32 |

Results of XRD Test

The XRD patterns of untreated soil and soil treated with 20% BA & 1% PPF are given in Tables 8 and 9, respectively. By combining the peak positions and intensities, it is observed that the peak pattern in Figure (8) after the addition of 20% BA and 1% PPF exhibited

a change in the crystalline structure of the untreated soil. The XRD investigation exhibits that Montmorillonite (M), Quartz (Q), Calcite (CA), Illite (I), Kaolinite (K), and Chlorite-serpentine (CH) are the main elements observed in the pattern. The results of the peak center and intensity of various elements for untreated soil in

Table 8 show that Calcite (CA) and Illite (I) have high intensities, and for treated soils with 20% BA and 1% PPF in Table 9, Montmorillonite (M) and K-CA-I have high intensities compared to other elements. CA and CA-I elements have the highest peak center, whereas M

and K-CA-I have the lowest peak center. The XRD pattern in Figure (8) shows that the intensity of Montmorillonite (M) decreased in the treated soil, which justified the result of lower swell pressure in the treated soil.

Table 8. XRD peak positions of untreated soil

| Element | Peak Center | Intensity |
|-----------------|-------------|-----------|
| I | 27.08827 | 155.90505 |
| CA | 29.50292 | 294.56181 |
| Montmorillonite | 33.42827 | 98.51991 |
| K-CA-I | 36.53635 | 93.3328 |
| CA-K-I | 39.07483 | 120.75769 |
| CA | 47.94092 | 100.55667 |
| Montmorillonite | 53.47603 | 83.24938 |

Note: Montmorillonite (M), Quartz (Q), Calcite (CA), Illite (I), Kaolinite (K), Chlorite-serpentine (CH).

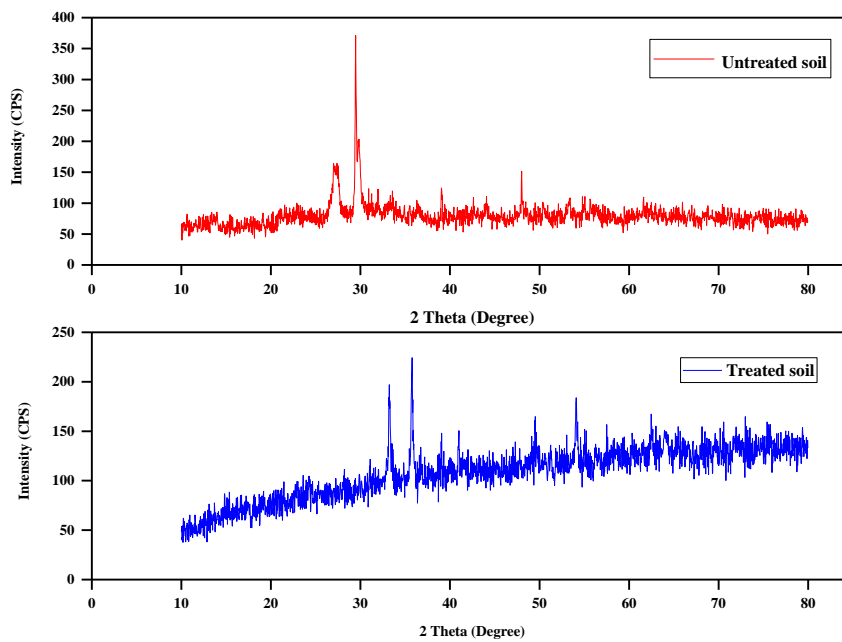


Figure (8): XRD patterns of untreated soil and treated soil

Table 9. XRD peak positions of treated soil with 20% BA and 1% PPF

| Elements | Peak Center | Intensity |
|----------|-------------|-----------|
| M | 33.29908 | 77.25372 |
| K-CA-I | 35.66974 | 86.13308 |
| I-KQ | 54.07158 | 60.4807 |
| K-CA | 49.62792 | 39.87762 |
| CA-I | 62.58682 | 41.63267 |
| CA | 64.1708 | 42.31542 |
| K-CA-I | 41.01701 | 36.04631 |

Note: Montmorillonite (M), Quartz (Q), Calcite (CA), Illite (I), Kaolinite (K), Chlorite-serpentine (CH).

Results of SEM Test

Figure (9) shows the morphology of untreated soil, and Figure (10) shows the morphology of treated soil with 20% BA and 1% PPF, respectively. Magnification scales of the images reveal that the surfaces of both soils differ from each other. The morphology of the parent soil in Figure (9) is categorized by bound-together grains. The untreated soil is comprised of masses

lacking hydrate compounds, which is the reason for compactness and strength. The untreated soil in Figure (9) has a more coherent surface than the treated soil in Figure (10). The scales of both soils show the establishment of agglomerates of bigger material. Further, it is shown that the density improved significantly due to the addition of BA and PPF.

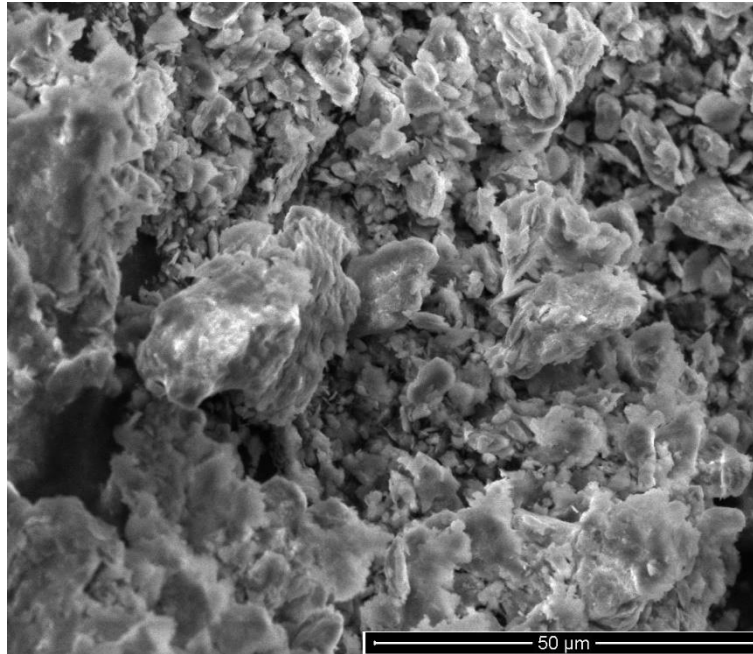


Figure (9): Morphology of untreated soil

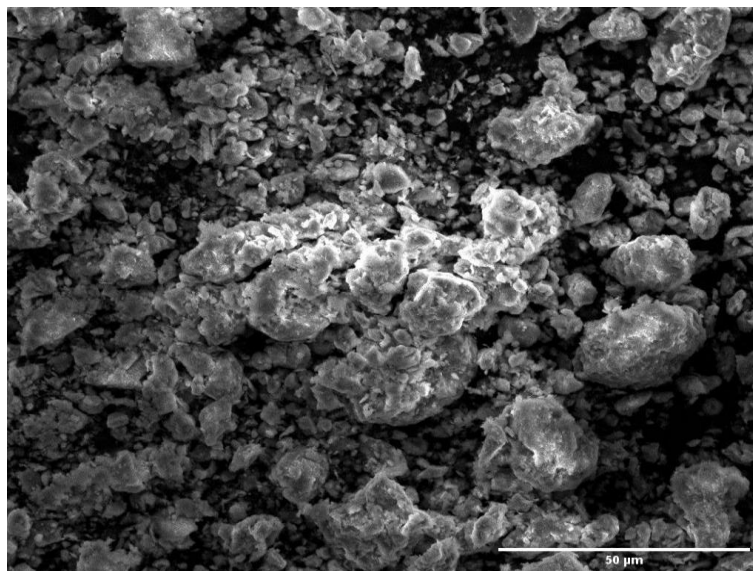
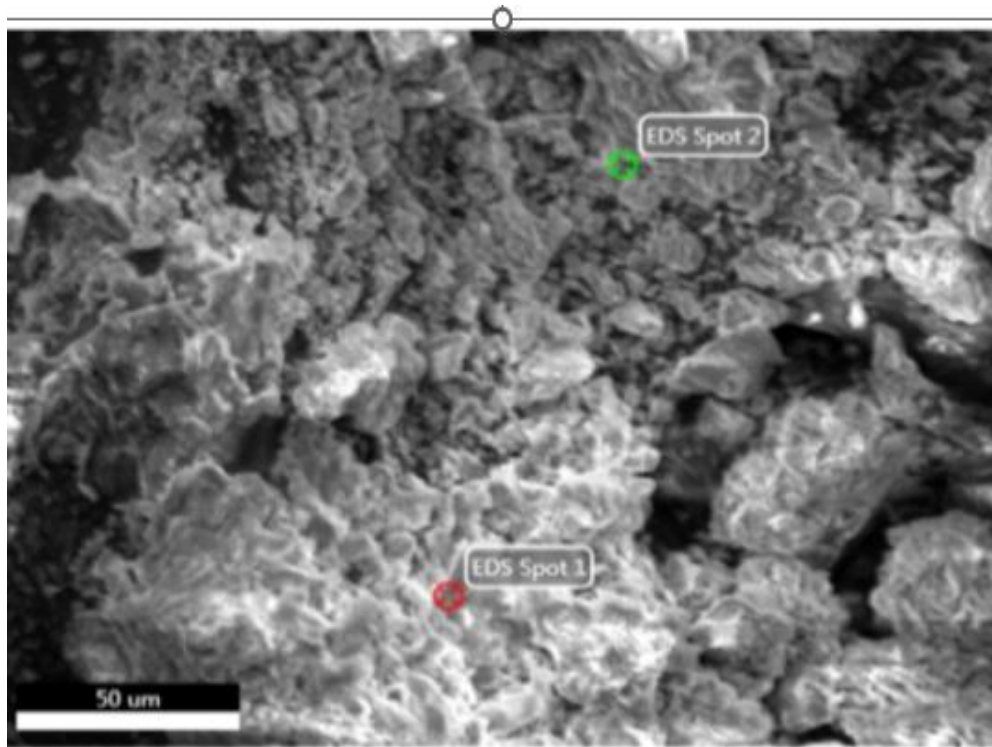


Figure (10): Morphology of treated soil with 20% BA and 1% PPF

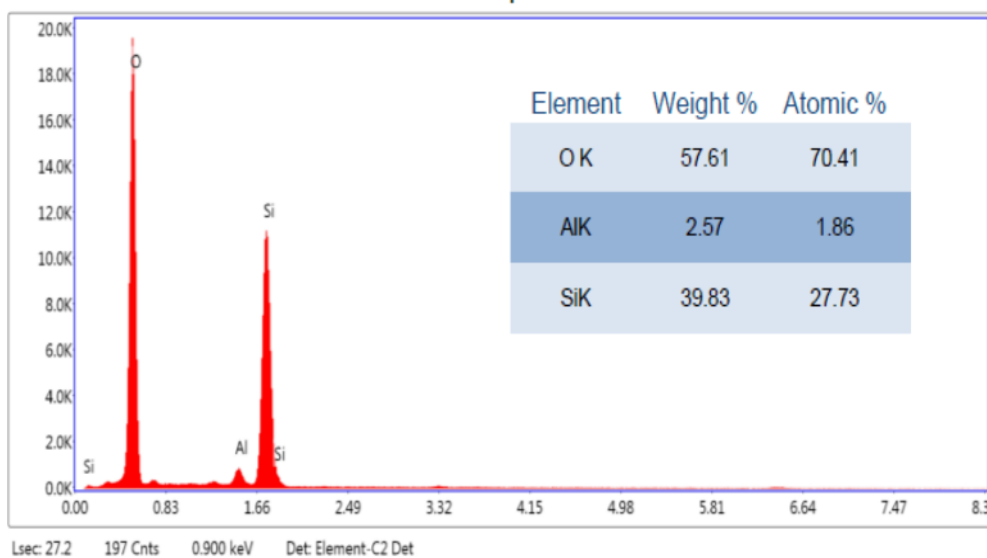
Results of EDS Test

Figure (11) shows the two different spots on the sample of untreated soil where an EDS scan was performed. Figure (11) shows a typical EDS scan of the sample at two changed spots. It is evident from Figure (11) that the composition of the elements is not uniform throughout the sample. Iron was found as a big

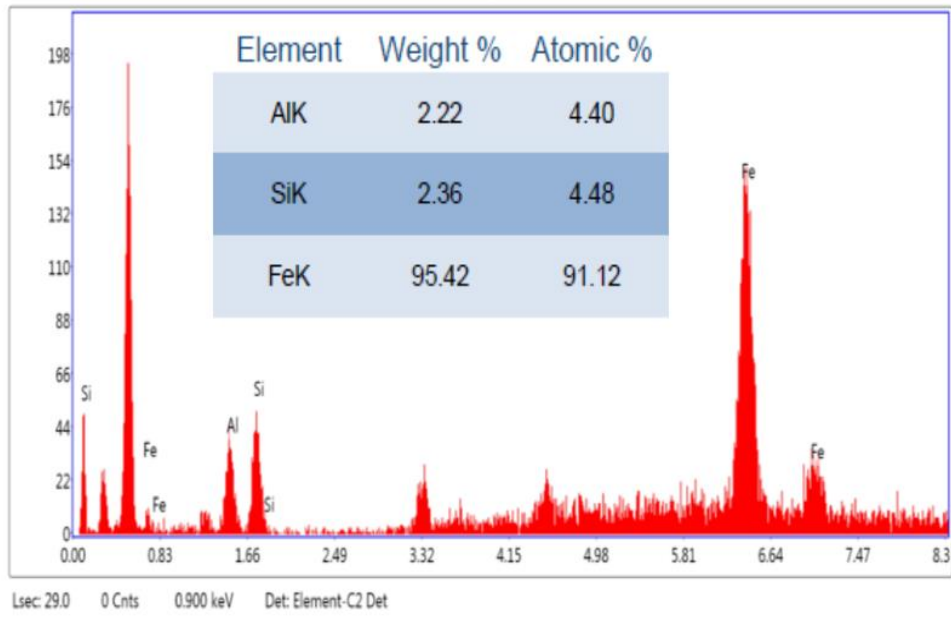
contamination at spot 2, due to which the silicon concentration is not distributed uniformly in the sample. Figure (12) shows the image of soil with the addition of 20% BA & 1% PPF. The composition of the elements after this process is entirely different. Elements found in this case, Mg, Al, O, Si, Fe, and K, are found uniformly on the two different spots.



(a) EDS image of untreated soil (50 µm)

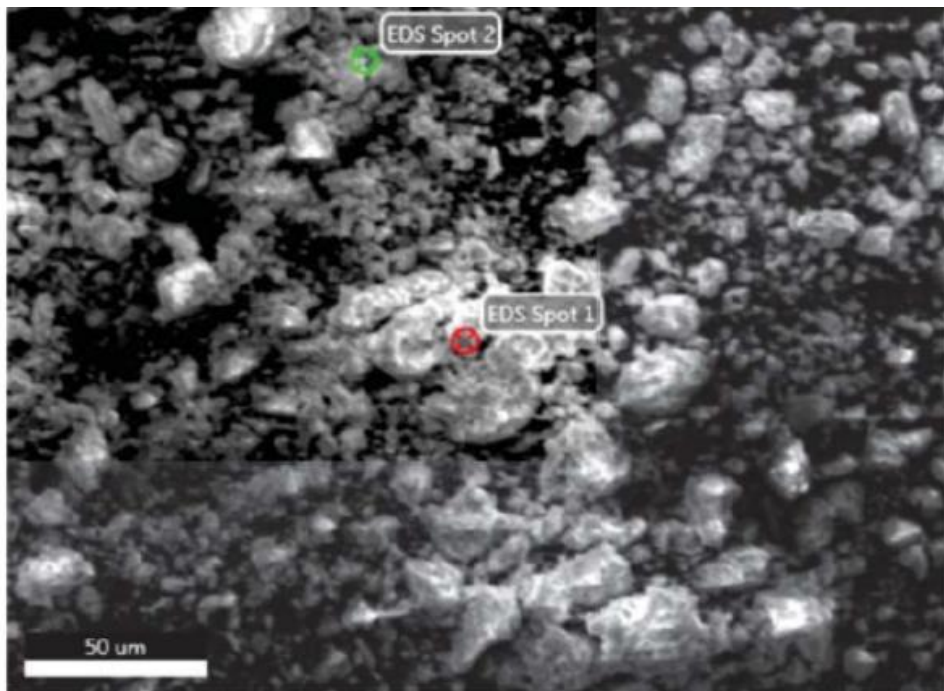


(b) EDS spot 1 results

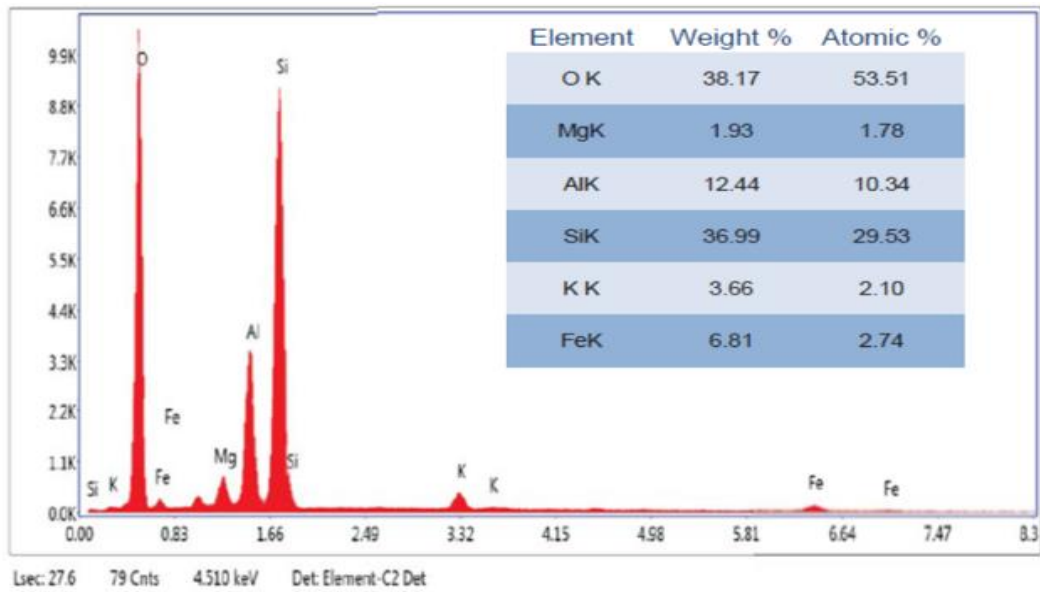


(c) EDS spot 2 results

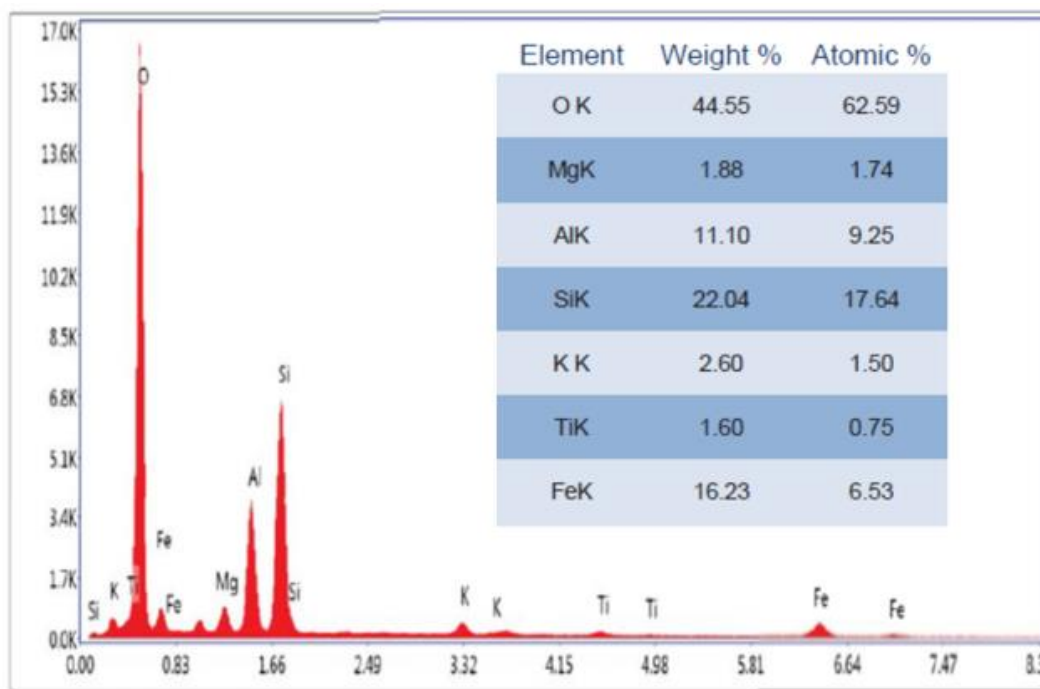
Figure (11): EDS results of untreated soil



(a) EDS of treated soil with 20% BA & 1% PPF (50 µm)



(b) EDS Spot 1 results



(c)EDS Spots 2 results

Figure (12): EDS of treated soil with 20% BA & 1% PPF

Statistical Tests on Experimental Results

The analysis of variance (ANOVA) was performed using Origin 2015 version with a 95% confidence level and 5% significance level to evaluate the combined effect of BA and PPF on the soil. The Tuckey test was

conducted for the comparison of means of the soils. The statistical analysis in Table 10 shows that both BA and PPF have significant effects on the properties of soil, because the p-values related to all the soil properties are less than 0.05.

Table 10. Summary of statistical analysis on experimental results at 5% significance level

| Properties of the soil | Sum of squares | Mean Square | F-Value | P-Value |
|-------------------------|----------------|-------------|-----------|-----------|
| Free swell | 5.005E01 | 5.005E01 | 9.977E02 | 6.022E-05 |
| Swell pressure | 2.333E+04 | 2.333E+04 | 1.796E+07 | 1.854E-04 |
| Cohesion | 3.759E+03 | 3.759E+03 | 2.276E+05 | 1.158E-06 |
| Internal friction angle | 5.017E+02 | 5.017E+02 | 2.640E+04 | 8.602E-07 |

CONCLUSIONS

This study was conducted to identify the effect of BA and PPF on the Atterberg limits, compaction parameters, angle of internal friction, swell potential, and swell pressure of expansive soil. BA was partially replaced in untreated soil by different percentages of 10%, 20%, and 30%, and then, the optimum percentages were again treated with different dosages of PPF, i.e., 0.5%, 1.0 %, and 1.5%. The untreated soil, separately and with the addition of 20% BA and 1.0% PPF; was further examined for crystallinity and structure analysis through XRD, and elemental analysis was accomplished using SEM and EDS techniques. Some useful conclusions have been drawn based on the test results, which are given below.

- The results showed a decrease of 64.86%, 61.54%, and 20.90% in free swell, swell pressure, and cohesion ©, respectively, and an increase of 47.19% in the internal angle of friction at the addition of 20% BA.
- The results exhibited decreases of 78.38%, 76.92%, and 45.45% in the free swell, swell pressure, and C, while an increase of 57.09% was observed in the angle of internal friction due to the addition of 1% PPF along with 20% BA in untreated soil.
- The XRD results of untreated soil confirmed the presence of clay minerals; i.e., Illite, Kaolinite, Montmorillonite, and non-clay minerals, predominantly quartz.
- Moreover, the XRD results of treated soil showed the reduction of Montmorillonite content, resulting in a decrease in C, swell pressure, and free swell.

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- Further variation in the behavior of treated soil was confirmed using SEM and EDS analyses, reflecting a suitable application for highway construction.
- Testing results depict that 20% BA and 1% PPF are the optimum contents of stabilization materials of expansive soil to achieve the desired mechanical properties of the treated soil.
- ANOVA results indicated significant effects of BA and PPF on the properties of expansive soil.

The soil treatment with BA and PPF showed a noteworthy effect on the properties of the expansive soil for practical applications in road sub-grades. The use of BA and PPF at the optimum contents would help in mitigating the potential hazards of expansive soils. Laboratory optimum results have certain limitations in their practical applications, as the climatic and environmental conditions are different in the field. The field applications of using BA and PPF for stabilizing expansive soils should follow the standard test and quality control procedures for full applications of laboratory results. Future studies may focus on evaluating expansive soils from different sites by treating them with different available additives, such as fly ash and lime. Also, future research should focus on assessing the properties of the stabilized expansive soil with BA and PPF at different environmental conditions for a better understanding of the properties. Future studies may also conduct a cost-benefit analysis for a typical civil engineering application, considering the use of stabilized soil with BA and PPF. Despite some limitations, these findings would provide a thorough understanding of treated expansive soils for practical applications in highway construction.

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