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Research Article

Effect of Wetting and Drying Cycle on the Behavior of Teff Straw Ash-Stabilized Expansive Soil

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This study explores the impact of wetting and drying cycles on teff straw ash-stabilized expansive soil, with a focus on enhancing its mechanical properties for road subgrade applications. Expansive soil, characterized by continuous swell and shrink behavior, undergoes cyclic testing to establish equilibrium and critical density. The mitigating effects of teff straw ash on soil damage and its influence on expansive soil's mechanical attributes are investigated. Laboratory results classify natural expansive soil as A-7-5 and CH according to AASHTO and USCS standards, respectively. Using a one-dimensional odometer apparatus, six wetting–drying cycles are conducted on teff straw ash-stabilized expansive soil to observe its behavior at equilibrium. Scanning electron microscopy reveals a disordered bond between soil particles and teff straw ash, intensifying with increased wetting–drying cycles. X-ray diffraction analysis is performed on samples subjected to different curing times, indicating heightened cation exchange and pozzolanic reactions as curing duration increases, thereby reducing soil expansiveness. A 96-hr socked California Bearing Ratio (CBR) test assesses subgrade strength. The CBR values for natural soil fall below the Ethiopian Road Authority (ERA) standards for low-volume roads. In contrast, expansive soil stabilized with teff straw ash at 10%, 15%, and 20% exhibits substantial increases in CBR values (3.7, 6.7, and 8.9, respectively), meeting the ERA standards. This suggests that teff straw ash stabilization renders expansive soil suitable for low-volume road subgrades, aligning with ERA standards. This comprehensive study provides valuable insights into the potential use of teff straw ash as an effective stabilizer for expansive soils, offering sustainable solutions for road construction in regions characterized by expansive soil challenges.

1. Introduction

Vast areas of vertisols, a type of expansive soil, are found in many tropical nations. Their dramatic swelling and shrinking during wet and dry seasons put countless houses, highways, and bridges at risk of collapse, potentially causing injuries, fatalities, and billions of dollars in economic losses. In developing countries such as Ethiopia, critical infrastructure like high-rise buildings, roads, and bridges remains underdeveloped. The absence of expansive soil management compounds these challenges, as this type of soil exhibits significant swelling and shrinking tendencies, particularly during seasonal variations. The deformation of expansive soil exceeds conventional elastic or plastic theories, presenting a pressing concern for construction projects [1]. Fluctuations in expansive soil can lead to either swelling, increasing volume, or shrinking, causing sudden reductions in volume [2]. The process of water penetration into the soil, known as infiltration, is a key component of the surface water cycle. Deformation in expansive soil follows a consistent pattern, resulting in the formation of cracks that, over time, contribute to substantial damage or failure in any structure built upon it. Numerous global studies, including those conducted in Ethiopia, have delved into the complexities of expansive soil and its behaviors. This study conducted comprehensive laboratory tests using representative soil samples obtained from the field. By subjecting the samples to repetitive wetting and drying conditions, the research aimed to identify any altered behaviors in cyclic actions. The objective was to determine the stability of problematic expansive soil under different conditions and evaluate its physical and mechanical properties across various seasons [2, 3]. The findings revealed that the shear strength

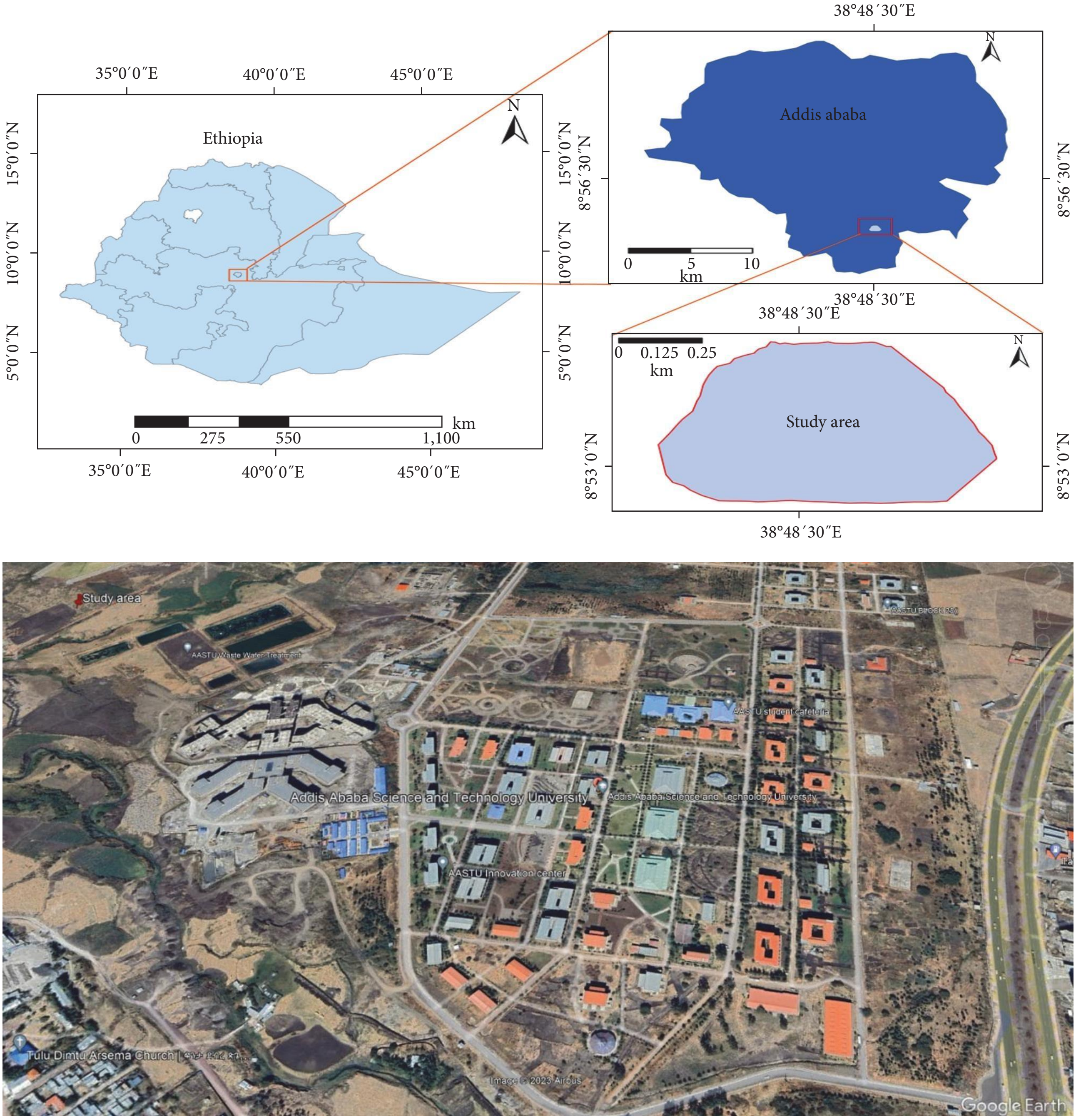


Figure 1: The location of the study area [22].

of expansive black cotton soil decreases under continuous drying and wetting phenomena [4]. Swelling pressure in cement kiln dust-stabilized soil varies based on the initial dry density [5]. Additionally, higher water content in soil correlates with a lower coefficient of air permeability [6]. The ratio of cracks and the number of wetting and drying cycles share a direct relationship [7]. Pores in the soil are categorized into four types based on their size: small pores, mesopores, macropores, and cracks [8]. Repetitive wetting and drying cycles alter the arrangement of soil samples, affecting their properties [9]. During drying–wetting cycles, swelling pressure and potential gradually decrease until reaching equilibrium [9]. Fatigue stress causes the original soil particles to lose structure, with each particle attempting to separate from the specimen [10]. Once stabilized, the soil exhibits insignificant property changes in moisture variation compared to natural soil [11, 12]. Advanced soil property XRD tests confirmed that mineralogy contributing to soil expansiveness significantly diminishes with the addition of stabilizers. Wetting and drying actions are also notably increased [12, 13]. XRF results highlight the potential of teff straw to enhance the engineering performance of expansive soil [14]. The process of changing soil qualities has existed since prehistoric human habitation. Ancient civilizations such as the Chinese, Romans, and Incas employed a variety of strategies to reinforce deficient soil qualities [15]. Ion exchanges to stabilizers play a critical role in stability by reducing swelling property [16]. The pozzolanic reaction produces cementitious forms called calcium aluminate hydrate (C—A—H) and calcium silicate hydrate (C—S—H). The Ca^{+2} ion in teff straw ash combines with soluble silica and alumina to create C—A—H and C—S—H [17, 18]. During the cation exchange process, monoatomic elements such as K + and Na+ ions in clay particles are replaced by divalent elements in the additives. The process occurs when alkaline oxides like CaO and MaO react with water and separate into Ca^{+2} and Mg^{+2} ions, which subsequently replace the monovalent ion in the clay particle via ion exchange [17, 19, 20]. The flocculation–agglomeration is depicted by the rearranging of clay particles from a parallel flat structure to a more random shape [17, 21]. Frequently, the size of clay particles grew and reduced the plasticity, thereby improving the quality and strength of the entire soil matrix [20].

2. Materials and Methods

2.1. Study Area and Sampling Technique. The study focuses on the Addis Ababa region, with specific attention to Akaki Kality, a subcity situated within Ethiopia's capital city. Positioned at an elevation of 2,355 m above sea level, the study area presents unique characteristics. Notably, a portion of the soil originates from the elevated terrains of the city, including areas such as Entoto, suggesting that it is likely transported soil. The investigation is concentrated in the vicinity of the Addis Ababa Science and Technology University compound within the Akaki Kality Subcity. To ensure targeted and purposeful data collection, a nonprobability or purposive sampling method is employed in this study. This deliberate approach allows researchers to selectively choose sampling locations based on specific criteria relevant to the study's objectives. For a visual representation of the study area, please refer to Figure 1 which illustrates the precise locations where soil samples are collected.

2.2. Characterization of Expansive Black Cotton Soil. The study focuses on expansive black cotton soil in the vicinity of the Addis Ababa Science and Technology University. The selection of the test pit followed a nonprobabilistic approach aligned with the research objectives. Drawing on engineering judgment and visual inspection, samples were specifically collected at a depth ranging from 1.5 to 2 m. Given the potential for expansive soil in the study area, a disturbed sample was extracted to assess the soil's expansiveness. Subsequent investigations were conducted, with Table 1 presenting the general properties of expansive black cotton soil and Table 2 detailing the index properties of the expansive soil. The final Table 3 provides insight into the proportion of expansive black cotton soil and teff straw ash during soil modification. This comprehensive approach aims to characterize and understand the unique qualities of the soil, laying the groundwork for potential modifications or interventions in construction projects in the region.

2.3. Teff Straw Ash. To obtain teff straw ash (TSA), the initial step involves collecting straw fiber directly from local farmers. Subsequently, an open-air combustion technique is employed to produce the teff straw ash. The raw teff straw, its fiber, and the resulting burnt ash are visually represented in Figure 2, providing an overview of the transformation process. For a detailed analysis of the oxide composition, an XRF test is conducted at the Ethiopian Geological Survey main laboratory, elucidating the compounds present in teff straw ash. In accordance with the results gleaned from the XRF analysis, the pozzolanic properties of TSA are determined. In line with ASTM C618-03 standards, teff straw ash is classified as a class C material, possessing both pozzolanic and limited cementitious properties. Subsequently, the ash undergoes sieving through a 425-mesh sieve, producing a finely graded sample suitable for stabilizing soil. Table 4 outlines the general oxide composition of teff straw ash, providing insight into its elemental makeup. Furthermore, the mix design of teff straw ash concerning natural expansive soil is systematically presented in Table 3. These findings contribute to a nuanced understanding of teff straw ash's characteristics and its potential role in soil stabilization endeavors. Durability test process is shown in Figure 3.

Table 1: Properties of natural black cotton expansive soil.

Type of test	Test method	Result
Depth of sampling (m)	1.5–2	—
Natural moisture content (%)	ASTM D2216	12
Linear shrinkage (%)	ASTM D4943	23.4
Grain size analysis		
Clay	ASTM D422	73.6
Silt		22.42
Sand		3.05
Gravel		0.93
Atterberg limits		
Liquid limit	ASTM D4318	87
Plastic limit		38.1
Plasticity index		49
Classification of soil		
AASHTO	—	A-7-5
USCS		CH
Specific gravity		
Gs (g $(cm)^2$)	ASTM D854	2.71
Swell characteristics		
Free swell percent	IS 2720	110
Standard compaction		
MDD (g $(cm)^3$)	ASTM D698	1.27
OMC (%)		33
Soaked CBR value (%)	T193	1.7
Color	—	Black

2.4. Methodology Workflow. The intricacies of the research methodology are succinctly illustrated in Figure 4, showcasing the step-by-step process undertaken in the current study. Each soil sample is meticulously prepared, conforming to the specific shape and size criteria essential for the corresponding laboratory tests. The preparation adheres rigorously to the standards set by ASTM, ASHTO, IS, and BS, ensuring precision and consistency across all testing procedures. This

Table 2: Summary of index properties of black cotton soil at different teff straw ashes.

TSA (%)	Liquid limit	Plastic limit	Plasticity index	Linear shrinkage
0	87	38.1	49	23.44
5	85	48	37.4	20.28
10	90	59.5	30.5	17.06
15	91	64.5	26.3	13.95
20	92	66.6	25.6	10.82

Table 3: Mix design of soil with teff straw ash.

Sample combination	Mixing proportions	BCS	TSA
BCS	Black cotton soil	100	0
BCS + TSA	Black cotton soil + TSA	95	5
BCS + TSA	Black cotton soil + TSA	90	10
BCS + TSA	Black cotton soil + TSA	85	15
BCS + TSA	Black cotton soil + TSA	80	20

(a) (b)

Figure 2: Teff straw additive used for the research: (a) raw teff straw and (b) teff straw ash after burning.

Table 4: Chemical properties of teff straw ash.

Oxide	Value (%)
Silica (SiO_2)	47.20
Alumina (Al_2O_3)	4.10
Iron oxide (F_2O_3)	0.82
Calcium oxide (CaO)	8.46
Magnesium oxide (MgO)	2.46
Sodium oxide (Na_2O)	<0.01
Potassium oxide (k_2O)	18.04
Manganese oxide (MnO)	0.08
Phosphorpentoxide (P_2O_5)	3.11
Titanium oxide (TiO_2)	0.01
Loss on ignition (LOI)	12.46

adherence to established standards guarantees the reliability and relevance of the results obtained from the diverse laboratory analyses conducted during the research.

2.5. Microscopic Analysis (SEM). The microscopic examination, performed through scanning electron microscopy (SEM), utilized the JCM-6000 PLUS benchtop SEM JEOl machine. This advanced equipment was employed at the microbiology laboratory within the applied biology stream of Adama Science and Technology University (ASTU), situated in the eastern part of Ethiopia's Oromia regional state. The SEM analysis captured detailed images during the soil's progression through various wetting and drying (WD) cycles. At distinct magnification rates—100x, 300x, 50x, 600x, and 20x, 1,500x—each cycle was meticulously observed. This approach allowed for a comprehensive exploration of the soil's microstructural changes at different scales, enhancing our understanding of its behavior under varying environmental conditions.

2.6. XRD Analysis of Soil Across Various Curing Times. The mineralogical composition of expansive black cotton soil was meticulously examined through X-ray diffraction (XRD) analysis, providing insights into both major and minor building blocks. The study involved the preparation of soil samples subjected to different curing times: 1-day curing, 4-day curing, 14-day curing, and 28-day curing. The objective was to discern any mineralogical variations in the oxide composition over the course of these curing durations. During the XRF test, quartz (SiO_2) emerged as the predominant

Figure 3: Durability test process: (a) sample curing, (b) prepared sample covered by plastic bag, (c) unconfined compression test after several curing time, and (d) failure mode of the sample.

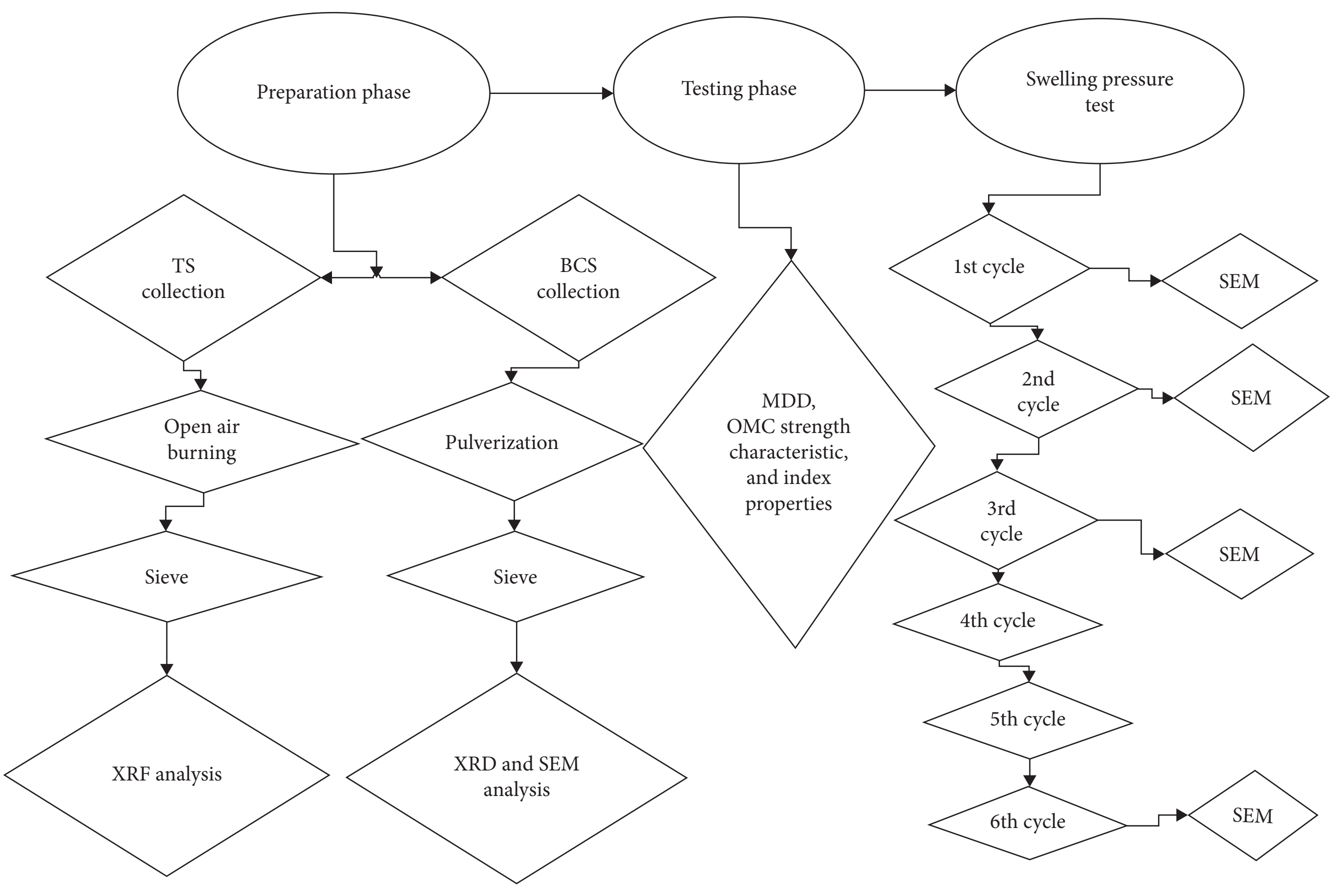


Figure 4: The general work methodology flow chart of the current study.

element in the expansive black cotton soil. However, as the soil underwent diverse curing times, a discernible reduction in the quantity of quartz was observed. This dynamic exploration through XRD analysis at various curing intervals contributes valuable information about the evolving mineralogical composition of the soil, shedding light on its structural transformations over time.

2.7. Advantages of the Study. Optimizing poor subgrade soil should be approached in a manner that minimizes its impact on the ecosystem [16]. The use of large quantities of carbon and hydrogen sulfide is strictly prohibited. Generally, the release of unnecessary chemicals into the environment has a detrimental impact. For instance, stabilizers containing heavy metals may contaminate subsurface water through leaching [16]. Understanding the pH of the soil and conducting chemical analyses of stabilizers, such as XRF, are crucial for utilizing ecofriendly materials effectively. Recently, biomass waste has emerged as a significant contributor to environmental degradation and has experienced rapid growth [23] necessitating its efficient utilization for various purposes. In the study by Bezabih et al. [24], teff straw ash was found to have lower production costs, carbon dioxide emissions/carbon footprint, and energy consumption compared to traditional materials. Additionally, it has socioeconomic benefits for society by generating additional income for farmers, creating new job opportunities, and fostering a sustainable and clean environment. In contrast to traditional chemical stabilizers, which require vast amounts of energy and resources and are used in expensive construction processes, agricultural waste additives are biodegradable and more cost-effective [15]. The consistent use of agricultural byproducts in soil stabilization promotes environmental cleanliness by ensuring sustainable waste management practices.

3. Results and Discussion

3.1. General. This study delves into the influence of six wetting and drying cycles on swelling pressure, seeking equilibrium in each instance. Notably, the swelling pressure of natural black cotton expansive soil surpasses that of black cotton soil stabilized by Teff straw ash. A noteworthy trend emerges during the 3rd and 4th wetting and drying cycles, where the swelling pressure exhibits a notable increase compared to the 1st or subsequent cycles. This observed escalation can be attributed to variations in the initial moisture content. The initial sample, prepared at its optimum moisture content and maximum dry density during the 1st wetting and drying cycle, experiences a drying process that diminishes its initial moisture content, thereby manifesting heightened swelling characteristics. This dynamic exploration sheds light on the intricate interplay between wetting and drying cycles, moisture content variations, and the resulting swelling pressure. The utilization of Teff straw ash in soil stabilization emerges as a significant factor in mitigating swelling pressure, offering valuable insights for soil engineering and construction practices.

3.2. Impact of Teff Straw Ash on CBR Value. The study assesses the influence of teff straw ash (TSA) on California Bearing Ratio (CBR) values using both soaked and unsoaked CBR testing methods. Focusing on soaked CBR, a comprehensive evaluation was conducted over a 96-hr soaking period to gauge subgrade soil strength across varying percentages of TSA. Results reveal a direct correlation between TSA inclusion and enhanced CBR values. Specifically, a 5% TSA inclusion boosts soil strength by 49.71%, while a 10% inclusion elevates the CBR value by 114.03%. Further increments demonstrate even more substantial improvements: a 15% TSA inclusion yields a 287.45% increase, and the maximum 20% TSA inclusion leads to an impressive 414.09% enhancement in subgrade strength. Figure 5 visually depicts the progressive variation in CBR values corresponding to different TSA percentages. This comprehensive analysis underscores the significant role of teff straw ash in reinforcing subgrade soil, providing valuable insights for optimizing soil stabilization practices in construction and engineering applications. XRF analysis is conducted to assess the chemical composition of the teff straw ash additive. According to ASTM standards, the majority of the material comprises Al_2O_3, Si_2O_3, and Fe_2O_3, which are classified as pozzolans containing amorphous siliceous and aluminous compounds [18, 25]. This information is presented in Table 5. Since teff straw ash meets the minimal criteria outlined in ASTM standards for class C pozzolan material, the specific reaction occurring between expansive soil and TSA is pozzolanic. This reaction provides long-term durability, as demonstrated by the patterns illustrated in Figure 6.

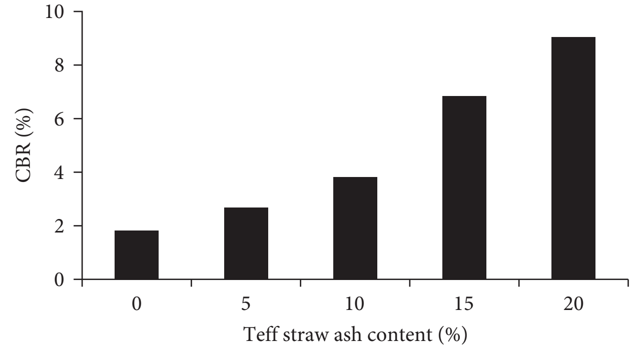


Figure 5: Various CBR values at different teff straw ash contents.

Table 5: Chemical requirement for pozzolana [1].

Chemicals	Pozzolans class		
	N	F	C
$(SiO_2) + (Al_2O_3) + (F_2O_3)$ (min. in percent)	70	70	50
SO_3 (max. in percent)	4	5	5
Moisture content (max. in percent)	3	3	3
Loss of ignition (max. in percent)	10	12	6

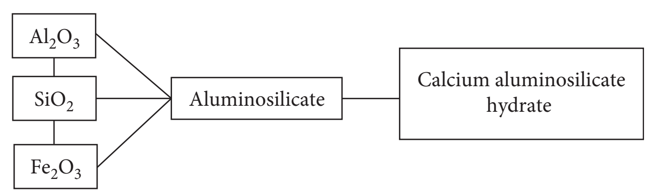


Figure 6: Specific pattern of pozzolanic reaction [18].

The higher electrochemical potential of aluminum, silicon, or iron ions in ashes can displace hydrogen ions in the soil, leading to the formation of denser aggregates or flocs through a pozzolanic process [18]. Several studies have demonstrated that the pozzolanic process improves the engineering properties of clay.

3.3. The X-ray Diffraction (XRD) Analysis. The XRD analysis of black cotton soil initially showcases a prevalence of quartz minerals, with other minerals represented by small peaks,

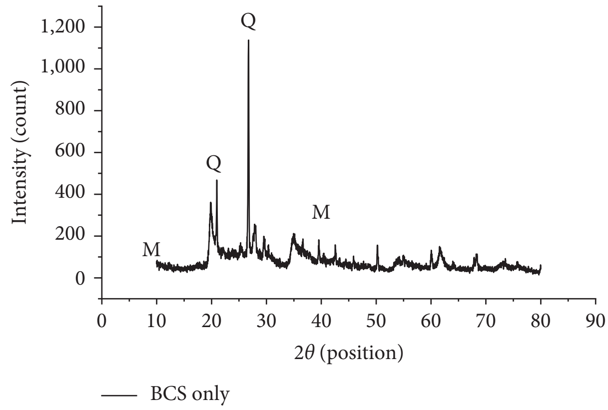


Figure 7: XRD pattern of expansive black cotton soil Q, quartz; M, montmorlite.

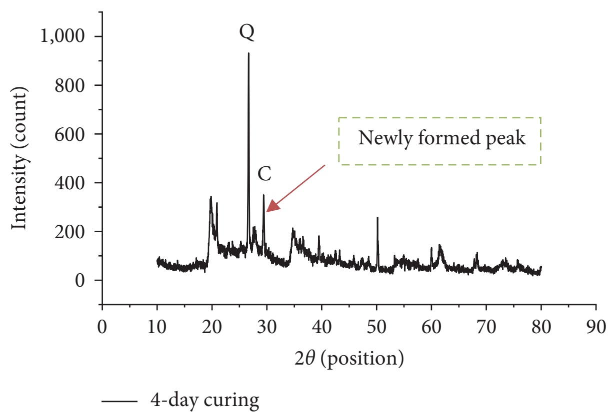


Figure 8: XRD pattern of 4-day cured expansive soil Q, quartz; C, calcite.

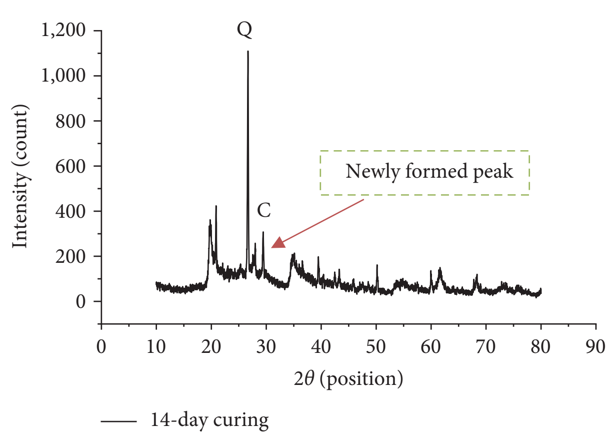


Figure 9: XRD pattern of 14-day cured sample Q, quartz; C, calcite.

albeit not recognized by ICDD. This study undertakes a meticulous comparison of the angular position of diffraction peaks with findings from various journals, as depicted in Figure 7. The detailed XRD pattern of expansive black cotton soil is comprehensively presented in the figure. Figure 8 illustrates the XRD analysis of a 4-day curing sample, while Figure 9 portrays the XRD of a 14-day curing sample. The

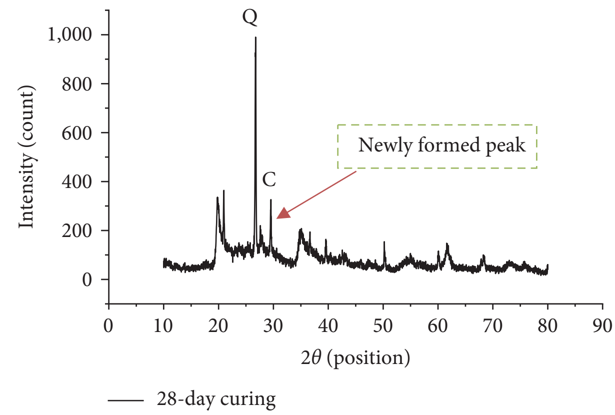


Figure 10: XRD pattern of 28-day cured samples Q, quartz; C, calcite.

intensity of XRD for the 28-day curing sample is showcased in Figure 10 and Figure 11 presents the combined XRD pattern. The alignment of the diffraction angles and angular positions of minerals aids in deciphering the mineralogical composition. XRF results affirm quartz as the major constituent of black cotton soil (BCS). This correlation is substantiated by the XRD findings, indicating a predominant presence of quartz minerals in BCS. The matching process considers the diffraction angle and angular position of minerals. Notably, montmorillonite minerals, as identified in the research of Atahu et al. [26] and Jain et al. [13], are evident at 10^0, with a peak deformation noted at 39.5^0, aligning with the observations detailed in the research of Woldesenbet [12] and Jain et al. [13]. This systematic approach enhances our understanding of the intricate mineralogical shifts influenced by teff straw ash across different curing times.

3.4. Integrated Wet Sieve and Hydrometer Analysis. The characterization of soil, particularly in the realm of expansive black cotton soil, is pivotal for accurate classification. Within soil classification parameters, sieve analysis plays a crucial role, offering insights into particle distribution. In this study, the wet sieve analysis method is chosen to discern the distinctive qualities of black cotton expansive soil, aligning with various standard methods. The amalgamation of wet sieve and hydrometer analysis provides a comprehensive understanding of the expansive black cotton soil's properties. The derived percentages are indicative of the soil's composition: clay comprises 73.6%, silt stands at 22.42%, fine sand constitutes 1.48%, coarse sand makes up 1.57%, and particles retained on the 4.75 mm sieve account for 0.93%. These results underscore the predominance of clay particles in the soil, illuminating its fundamental composition. By employing this integrated approach, the study aims to enhance the precision of soil classification, facilitating a more nuanced comprehension of the intricate properties inherent to expansive black cotton soil.

3.5. Dry Density and Moisture Content Variation with Additive Percentages. Analysis of compaction test results reveals significant distinctions in the maximum dry density (MDD) values across different percentages of additives. Expansive black cotton soil demonstrates a higher MDD compared to other TSA-stabilized expansive black cotton soils. In contrast, the optimal

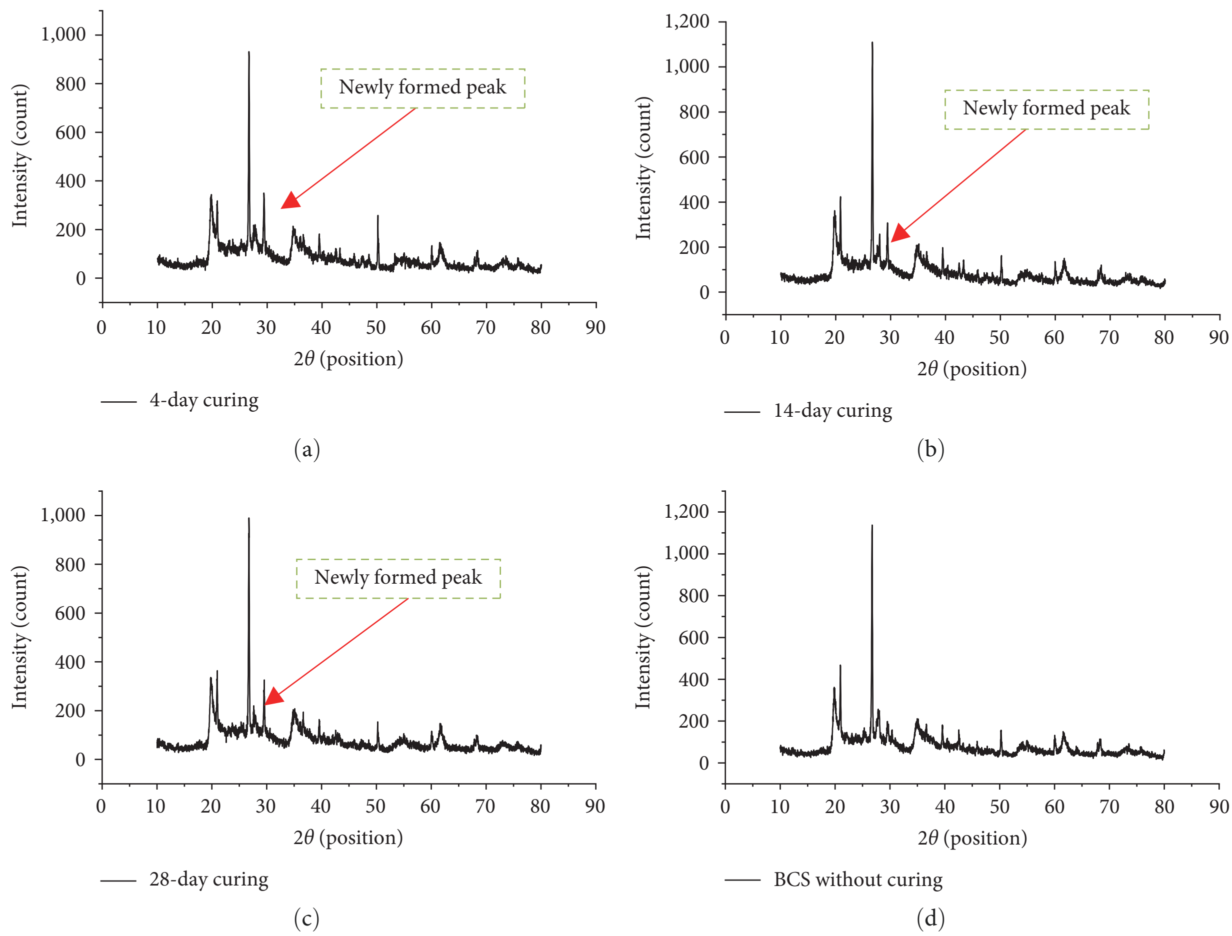


FIGURE 11: Combined figure of XRD patterns at different curing times: (a) 4-day curing, (b) 14-day curing, (c) 28-day curing, and (d) natural black cotton soil.

moisture content (OMC) value for teff straw ash (TSA) stabilized black cotton soil surpasses that of natural black cotton soil. This variation can be attributed to the dissimilarity in specific gravity between black cotton soil and teff straw ash. Notably, experimental results affirm that the specific gravity of black cotton soil is notably higher than that of teff straw ash. These findings are visually summarized in Figure 12, elucidating the intricate relationship between moisture content and density variations with different percentages of additives. The nuanced interplay between soil and stabilizing agents, as uncovered through compaction tests, offers valuable insights for optimizing soil engineering practices and construction protocols.

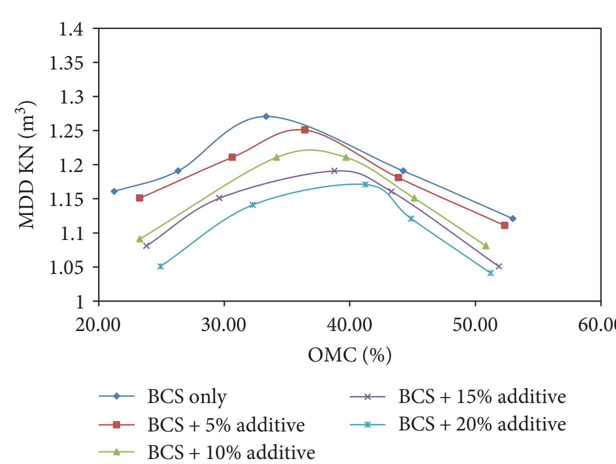


FIGURE 12: Dry density moisture content relationship at various percentage teff straw ashes.

3.6. Impact of Wetting and Drying Cycles on Soil Microstructure. The microstructural arrangement of natural black cotton soil undergoes transformative shifts during consecutive wetting and drying (WD) cycles, as depicted in SEM images. This analysis spans the 1st to the 6th WD cycle, revealing distinctive behaviors and structural modifications. Figures 13, 14, 15, 16, and 17 encapsulate these observations. In Figure 13, the baseline microstructural arrangement of expansive soil appears scattered, with limited interconnections. Cracks and fractures are present but remain relatively insignificant compared to subsequent WD cycles. Notably, the 1st WD cycle (Figure 14) showcases improved interparticle connections with observable micropores, albeit fewer than in later cycles. As the WD cycles progress, the 2nd cycle (Figure 15) introduces loosened interconnections, discontinuity, detachment, and an increase in pore numbers. The 3rd cycle (Figure 16) witnesses a shift from micropores to small- or medium-sized pores, indicating evolving structural changes. Significantly, as the WD cycle

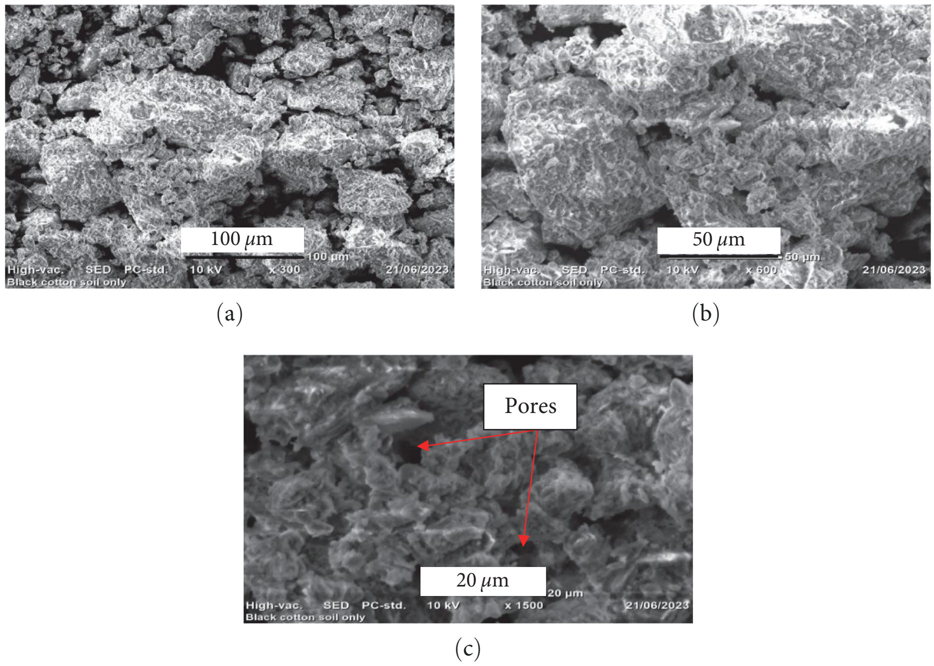


FIGURE 13: SEM image of black cotton soil at different magnifications: (a) ×300, (b) ×600, and (c) ×1,500.

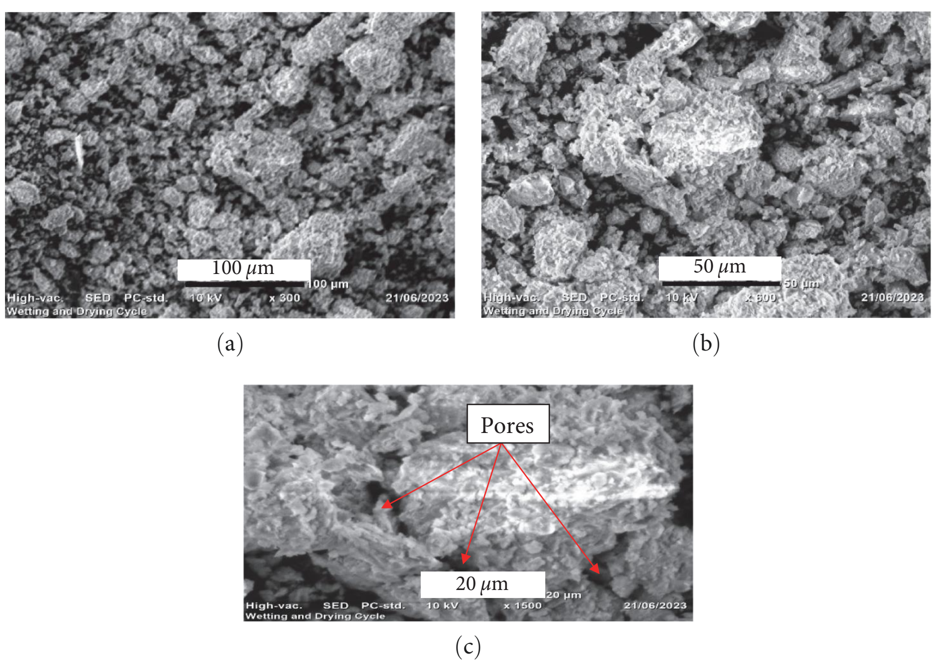
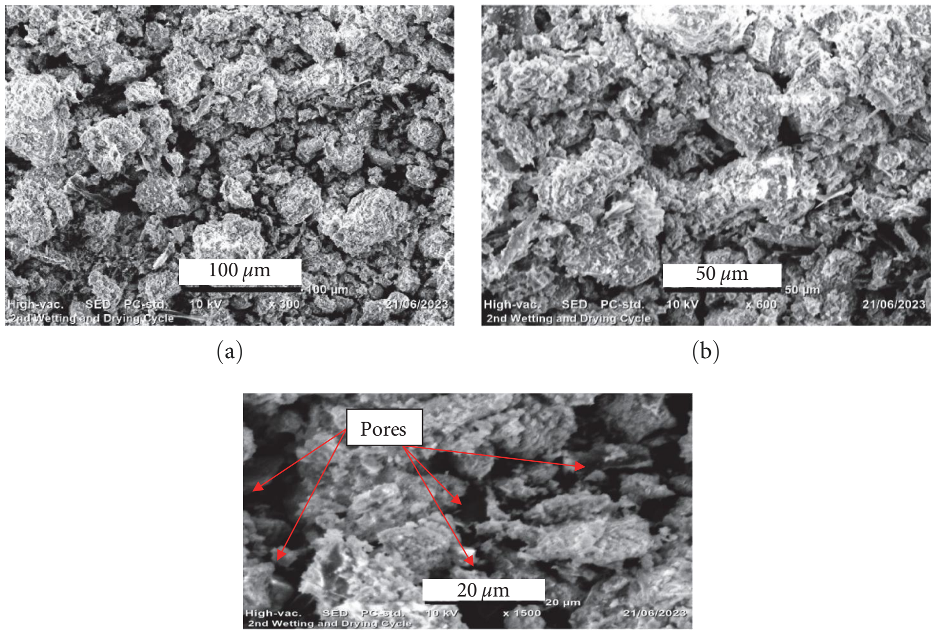


FIGURE 14: Microstructural arrangement of the 1st wetting and drying. (a) ×300. (b) ×600. (c) ×1,500.

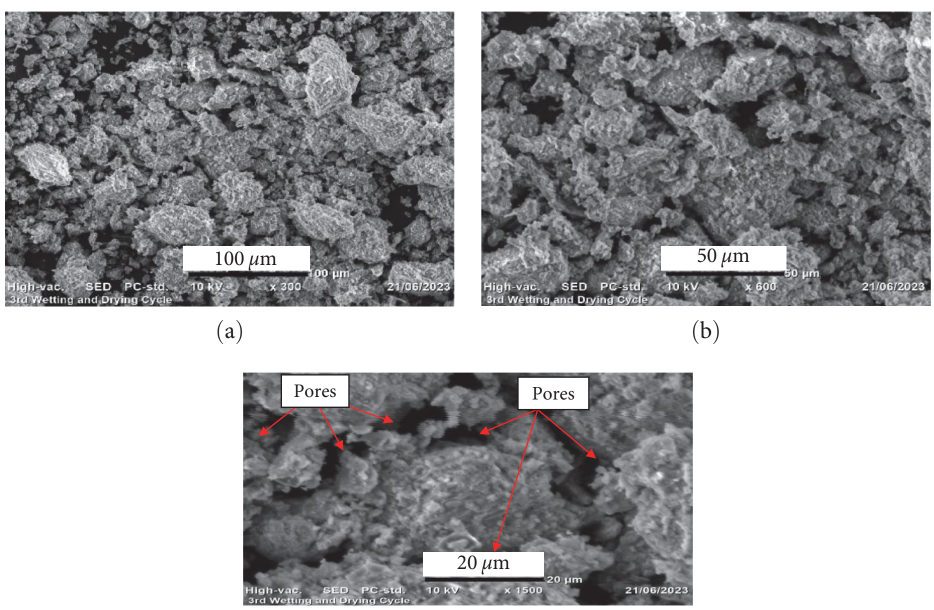
advances, the thickness and quantity of pores rise, illustrating particle detachment. By the 6th WD cycle (Figure 17), the soil structure exhibits a disintegrated arrangement. Cohesion diminishes, micropores enlarge into small and medium pores, and the overall structure becomes scattered and discontinuous. This irreversible fatigue in the microstructure signifies the culmination of damage after six cycles. These visual insights provide a comprehensive understanding of the microstructural alterations induced by repetitive wetting and drying, elucidating the progressive degradation of soil cohesion and integrity.

3.7. Impacts of Wetting and Drying Cycle on the Swelling Pressure. This investigation focuses on the dynamic shifts in swelling pressure over six wetting and drying cycles, conducted to achieve equilibrium. The experimental setup involves samples prepared with a 10% teff straw ash blend,



(c)

Figure 15: Microstructural arrangement of the 2nd wetting and drying. (a) ×300. (b) ×600. (c) ×1,500.



(c)

Figure 16: Microstructural arrangement of the 3rd wetting and drying. (a) ×300. (b) ×600. (c) ×1,500.

aligned with the expansive soil's maximum dry density and optimum moisture content. The drying process is meticulously executed using an oven dryer set at 45°C. Notably, variations in initial moisture content contribute to distinct swelling pressure patterns, with the 2nd and 3rd wetting and drying cycles exhibiting heightened pressure compared to the others. The nuances of these fluctuations are visually depicted in Figure 18, providing a snapshot of swelling pressure dynamics at the commencement of the cycle. This comprehensive approach enhances our understanding of how wetting and drying cycles impact swelling pressure, a critical factor in soil behavior studies and engineering assessments. In this study, the swelling pressure of expansive black cotton soil was initially recorded as 300 kPa. The inclusion of 10% TSA significantly reduced it to 113 kPa during consecutive wetting and drying processes. The swelling pressure

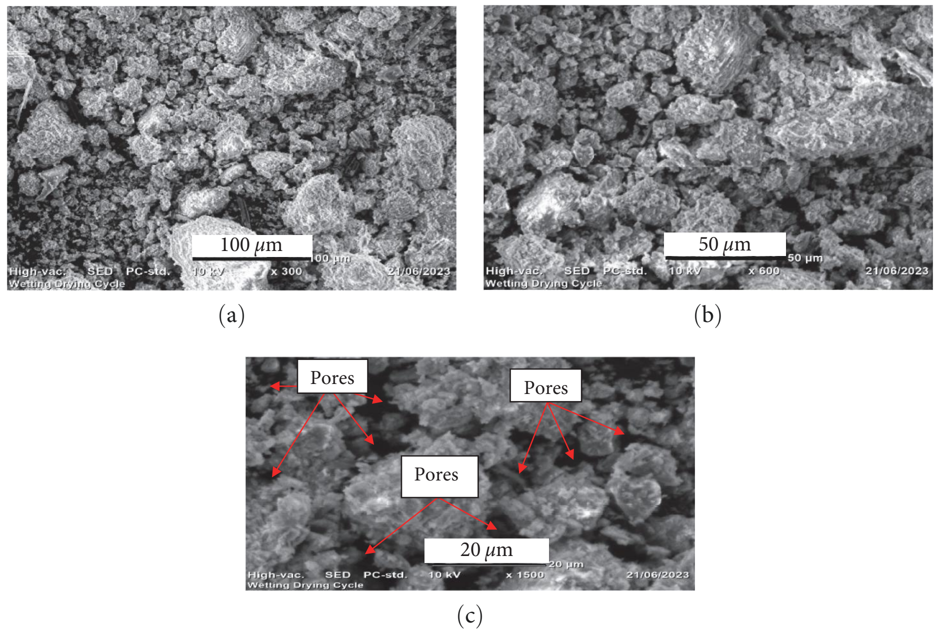


FIGURE 17: Microstructural arrangement of the 6th wetting and drying. (a) ×300. (b) ×600. (c) ×1,500.

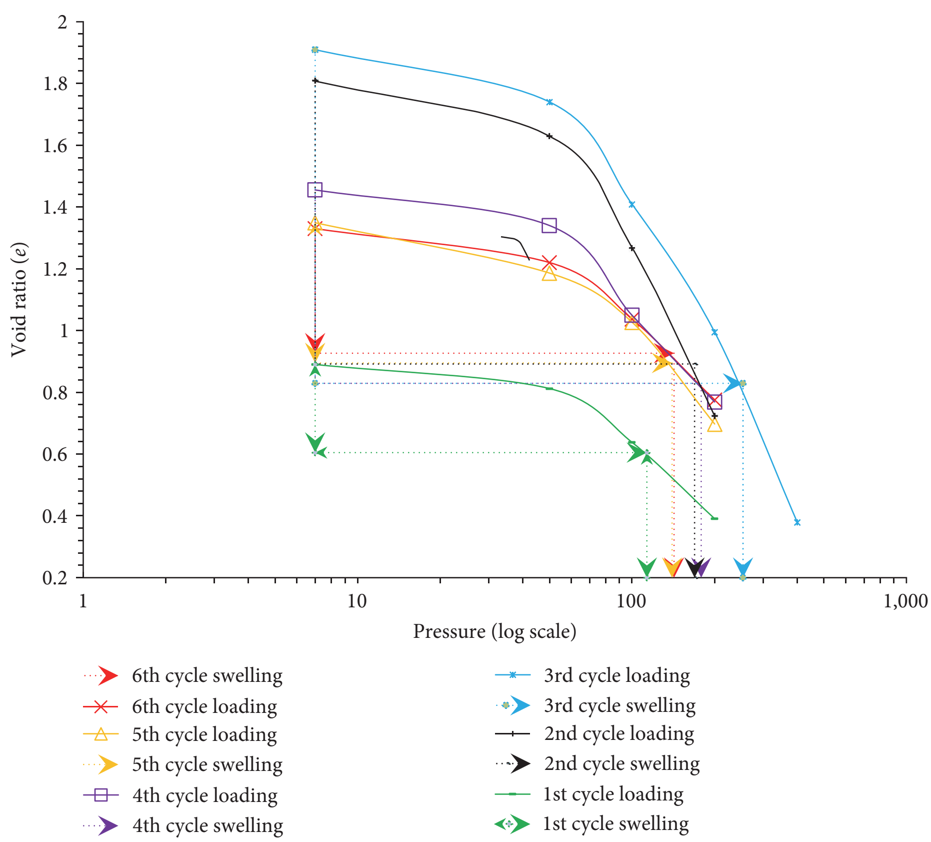


FIGURE 18: Swelling pressure result at different cycles.

varied from the 2nd to the 4th cycle, after which, through several wet–dry cycles, the results showed approximately similar values in the 5th and 6th cycles, hovering around 140 kPa, indicating an equilibrium state where there was no further contraction or expansion during moisture fluctuations. The experiment extensively assessed seasonal variations in soil swelling properties, revealing that from the beginning up to the 4th cycle, swelling pressure fluctuated

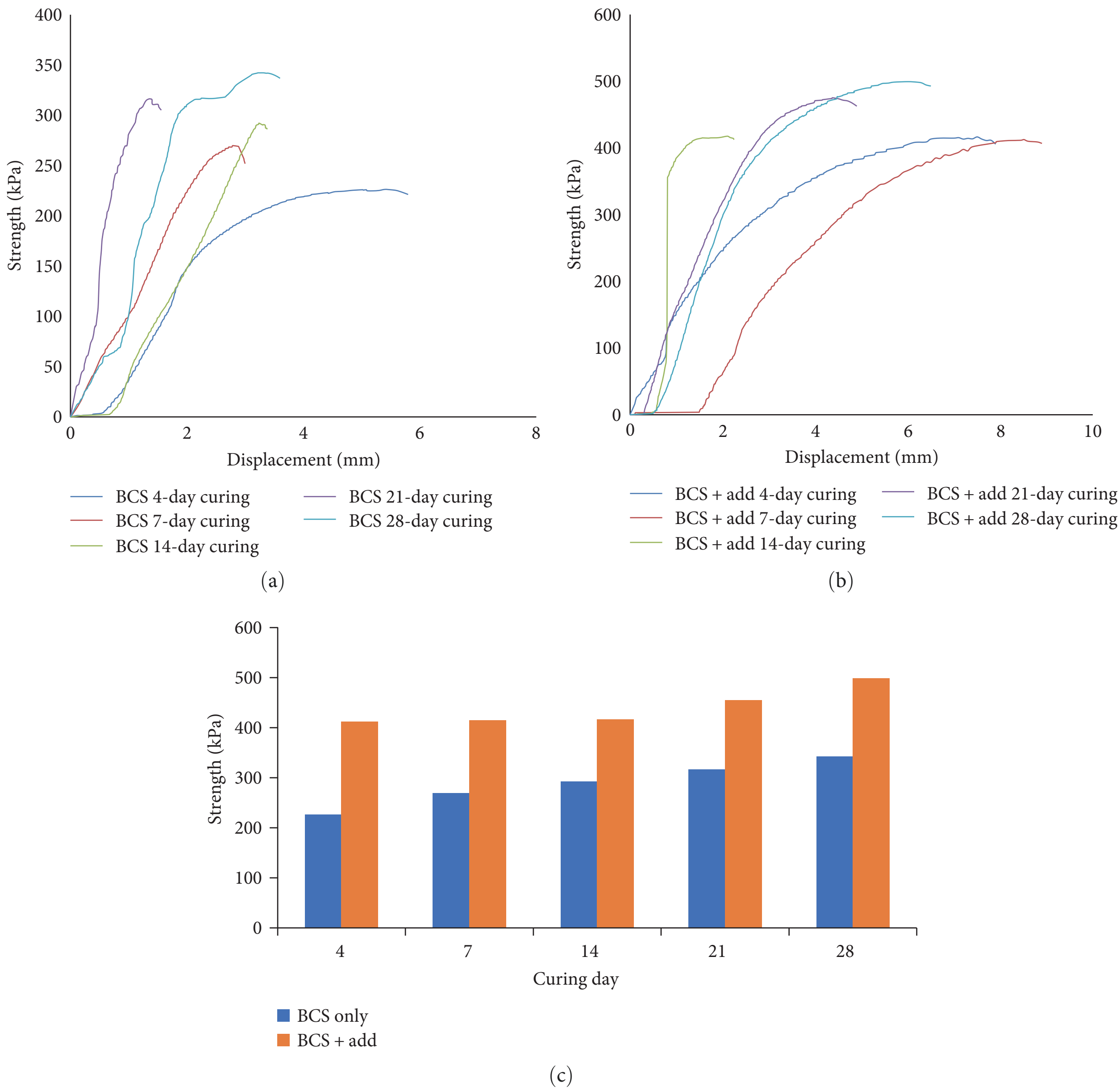


Figure 19: Durability test result: (a) expansive soil, (b) blended expansive soil, and (c) combined result.

due to moisture variations. After the 4th cycle, the soil reached a fatigue state, meaning that further variations in moisture did not significantly affect the swelling properties of the soil.

3.8. Impact of the Additive on Long-Term Durability. This test is conducted following the ASTM D2166 and ASTM D559 test methods, recommended for unconfined compressive strength (UCS) clay soil evaluation. The sample, containing 10% TSA, is compacted in a proctor compaction mold to the appropriate dry density and moisture content. After compaction, the remolded sample is extruded from the mold using a sampler to continue the curing process. Initially, the sample is covered with a plastic bag, soaked in water, and left at room temperature for 4, 7, 14, 21, and 28 days. Subsequently, an UCS test is performed to assess the durability of both natural and blended soil. The results indicate a significant enhancement in durability with increasing curing time for both natural and TSA-stabilized soil. The pozzolanic reaction occurring between TSA and natural soil contributes significantly to the observed property improvements. Figure 19(a) illustrates the durability of expansive soil, Figure 19(b) depicts expansive soil blended with teff straw ash, and Figure 19(c) shows the combined results of expansive soil and blended expansive soil at different curing times. The general durability test result is illustrated in Figure 19.

3.9. Comparison between Previous Study and Current Finding. Extensive research has focused on enhancing the engineering performance of expansive soil by utilizing agricultural byproducts to modify its properties. The findings of the current study are compared with those of previous research conducted

Table 6: Comparisons between previous studies and the current study.

Soil properties	Bagasse ash [27, 29]	Calcined termite clay [27]	Enset ash [28]	Coffee husk ash [15, 30, 31]	Current study
CBR (%)	2.2–9.8	2.2–11.4	1.7–6.7	2.5–12	1.7–8.9
Plasticity index (%)	51.6–12.36	51.6–14.58	40–25	40–25	49–25
Maximum dry density (g) $(cm)^3$	1.56–1.17	1.56–1.27	1.18–1.13	1.58–2.20	1.27–1.17
Optimum moisture content OMC (%)	32.57–45.44	32.57–43.39	32.57–43.39	20–28	33–41

in the same area, revealing similar results. The decrease in maximum dry density (MDD) and the increase in optimum moisture content (OMC) exhibit a consistent pattern, as observed in studies such as [27, 28]. This pattern is attributed to the lower specific gravity of the additive compared to that of the soil. In all studies, the CBR value and plasticity index of the soil are significantly reduced upon the inclusion of the stabilizer. A detailed comparison is presented in Table 6.

4. Conclusion

The microstructural configuration of soil was meticulously examined through scanning electron microscopy, revealing distinctive behaviors. The microstructure of natural black cotton soil (BCS) exhibited a well-interconnected arrangement with minimal cracks and fractures. Conversely, samples subjected to multiple wetting and drying (WD) cycles displayed signs of discontinuity and failure, with fractures becoming more pronounced under severe WD conditions.

The introduction of teff straw ash (TSA) resulted in a decrease in specific gravity due to its lightweight nature compared to BCS. Despite the reduction in specific gravity, the dry density of TSA-stabilized BCS was lower than that of BCS alone. Concurrently, the optimum moisture content increased in TSA-stabilized BCS samples. Notably, the CBR value demonstrated significant improvement with increasing TSA percentages, reaching a remarkable 414.09% enhancement at a 20% TSA inclusion.

Conforming to ASTM C618-03 specifications, TSA was classified as a class C material, possessing both pozzolanic and slight cementitious properties. The addition of TSA led to a reduction in the plasticity index (PI) and an enhancement in unconfined compression strength. As the curing duration increased, the unconfined compression strength also rose, while specific gravity and free swell index decreased with higher TSA percentages.

Unified soil classification and AASHTO classification labeled natural BCS as CH and A-7-5, respectively, indicating its extremely expansive nature and poor quality. The mineralogical studies, conducted over 4–28 days of curing, revealed a reduction in the mineral causes for expansion as curing time increased. Peaks at different positions indicated the formation of calcite compounds and a prolonged pozzolanic reaction.

These findings align with swelling pressure determinations under WD cycles, reinforcing the consistency and reliability of the results. The comprehensive analysis underscores the transformative effects of TSA on soil properties, offering valuable insights for effective soil stabilization and subgrade material improvement.

5. Recommendation

The combustion temperature of teff straw plays a pivotal role in determining the SiO_2 concentration, influencing the pozzolanic characteristics. This prompts a crucial consideration—future studies should meticulously explore various combustion temperatures to comprehend how the percentage of pozzolan may fluctuate. A comprehensive investigation spanning different burning temperatures would illuminate this dynamic relationship, thereby enhancing our understanding of the long-term durability implications.

The SEM sample, extracted from soil subjected to multiple wetting and drying cycles, provided valuable insights. Likewise, the XRD sample, obtained from the UCS test at diverse curing times, offered essential mineralogical information. To bolster the robustness of findings, future studies should consistently employ similar samples for SEM and XRD analyses, ensuring a unified and comprehensive approach.

Expanding on this, varying the combustion temperature of teff straw emerges as a critical avenue for further exploration. Delving into the impact of burning temperature on TSA and expansive soil properties is imperative, given the evident differences in pozzolan content at different temperatures. Notably, at 600°C, the sum of SiO_2, Al_2O_3, and Fe_2O_2 reaches 65.12%, rising to around 77.59% at 750°C, and then stabilizing at 70.64% at 900°C. The zenith of silicate content lies within the temperature range of 600–750°C, signaling a crucial range for optimal pozzolanic properties.

In essence, the call for further investigations, encompassing diverse combustion temperatures and their effects on TSA and expansive soil, resonates as an essential step toward refining our knowledge and ensuring the longevity and sustainability of construction materials.

Data Availability

Data will be made available on request from the corresponding author.

Conflicts of Interest

The author declares there is no conflict of interest.

Authors' Contributions

Dr. Eleyas Assefa and Dr. Siraj Mulugeta conceptualized and designed the experiment. Sisay executed the experiment, crafted the manuscript, and assumed the primary responsibility for the written content. Throughout the experimental process, Dr. Eleyas Assefa and Dr. Siraj Mulugeta provided supervision, guidance, and actively participated in refining and enhancing the manuscript. The collaborative efforts of all authors contributed to the successful execution and comprehensive documentation of the research.

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