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# Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 10, No. 11, November, 2024

# Enhancement of Expansive Soil Properties by Water Treatment Sludge Ash in Landfill Liners

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Received 02 August 2024; Revised 09 October 2024; Accepted 17 October 2024; Published 01 November 2024

**Abstract**

This study aims to enhance the suitability of expansive clayey soils for use as landfill liners by incorporating water treatment sludge ash (WTSA). Expansive soils, prone to swelling and desiccation cracking, compromise landfill liner integrity, increasing the risk of groundwater contamination. Local soils often do not meet the requirements for hydraulic conductivity and stability, prompting the use of additives like bentonite. However, bentonite-treated soils still face challenges in tropical regions due to moisture loss and cracking. This research investigates the effects of adding WTSA to bentonite-treated soils to mitigate swelling and shrinkage issues. Several geotechnical tests were conducted, including hydraulic conductivity, free swell percentage, swelling pressure, volumetric shrinkage, and desiccation cracking. Results show that WTSA significantly reduces hydraulic conductivity, free swell percentage, and swelling pressure, meeting the standard requirements for liners (hydraulic conductivity of at least $1\times10^{-9}$ m/s and volumetric shrinkage of at least 4%). Moreover, WTSA addition reduces desiccation cracking to acceptable levels, demonstrating its potential as an effective reinforcement material. This study introduces an innovative approach to using WTSA, a waste product, as a sustainable alternative to conventional liner materials, reducing environmental impact and enhancing landfill liner performance.

*Keywords:* Enhancement; Expansive Soil; Free Swelling; Water Treatment Sludge Ash; Landfill Liner.

## 1. Introduction

The adaptability of expansive soils presents significant challenges to both surface and subsurface infrastructure development. Their inability to withstand fluctuations in environmental conditions, such as external pressure or moisture infiltration, leads to considerable volumetric changes (swelling and shrinking), which compromise the integrity of supporting infrastructure and can result in eventual failure. In addition to concerns regarding structural stability, a significant issue that limits the applicability of these soft soils in engineering is their use as landfill linings, which are designed to mitigate leachate from waste containment facilities located above or below ground [1]. Expansive soils are problematic due to their tendency to swell upon water absorption and subsequently shrink. Swelling primarily occurs due to water infiltrating between clay particles, causing them to separate.

Consequently, the volumetric changes caused by swelling and shrinkage typically challenge infrastructure that is not explicitly designed to handle such movement [2]. It should also be noted that these particular soils consist of clay minerals, which have the inherent ability to expand and contract in response to moisture fluctuations. Recently, there has been heightened focus and concern regarding expansive soils. Numerous techniques have been explored to detect and control the volumetric fluctuations of expansive soils. One such technique involves the use of admixtures to regulate these alterations, thereby facilitating soil stability. Various additives have been successfully employed to address the issue of

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http://dx.doi.org/10.28991/CEJ-2024-010-11-04

problematic soils and achieve soil stabilization through the use of fly ash, cement, silica fume, and lime [3-7]. Adding admixtures to expansive soil for stabilization enhances soil strength by limiting the potential for volumetric changes; however, further innovative approaches are still needed to reduce soil swelling and improve soil strength characteristics [8].

Numerous studies have investigated natural, manufactured, and byproduct materials and their potential use as stabilizers for altering clayey soils [9-12]. The bentonite clay used for landfill liners must possess essential hydraulic qualities to prevent seepage within the landfill, given its swelling, shrinking, and heating characteristics [13]. Research suggests that soft soils may be efficiently treated to enhance their engineering properties, thereby reducing their problematic nature and increasing their suitability for demanding geotechnical applications [14]. The ionic characteristics of hydrating fluids significantly impact self-healing ability and reduce hydraulic conductivity, thus enhancing the longevity of liners [15]. Chemical stabilization has been used as an effective method to improve the engineering properties of expansive soils for soil stabilization applications. The alteration of bentonite with WTSA has shown that the wet-dry cycle significantly influences self-healing and hydraulic properties [16]. In a similar study by Qiu & Yu (2008) [17] indicated that WTSA-enhanced natural bentonite has superior water retention potential during both wetting and drying processes. The effectiveness of this treatment is significantly dose-dependent, necessitating further optimization.

This research primarily aims to predict the plasticity, swelling percentage, and pressure of expansive soil. The composition of expansive soil will be achieved by mixing natural clay with bentonite in a 20% ratio. This will create expansive soil, which will then be treated with sludge ash, a byproduct of water treatment, as this waste is generated in large quantities daily.

## 2. Used Material

### 2.1. Clayey Soil

The natural soil was mixed with 20% bentonite to create the soil samples. The natural soil was taken from the Al-the-Amer site, located in Baghdad at a latitude of 33°44′ North and a longitude of 44°50′ East, as shown in Figure 1. Bentonite was purchased from a commercial supplier. The chemical and physical properties of the natural soil are summarized in Table 1. After preparation in the laboratory at 60°C for forty-eight hours, the natural soil was ground and sieved to pass through a No. 40 (0.425 mm) sieve. The following types of soil samples were prepared:

- Type A soil: Natural soil obtained from the Al-the-Amer site.
- Type B soil: A mixture of natural soil with 20% bentonite (by dry weight).
- Type C soil: A laboratory-created mixture of natural soil, 20% bentonite, and 15% water treatment sludge ash (by dry weight). Figure 2 illustrates the grain size distribution for Type A soil.


**Figure 1. A map illustrates the research site Al-Amer Location**

**Table 1. Presents the physical-chemical parameters of the soil used in the study**

| Index-property | Natural soil | Bentonite e |
|---|---|---|
| Natural moisture-content % | 3 | - |
| Specific-gravity (Gs) | 2.7 | 2.27 |
| Plasticity-index (PI)% | 24 | 281 |
| Gravel % | 0 | - |
| Sand % | 1.3 | - |
| Silt % | 33.7 | - |
| Clay % | 65 | - |
| Gypsum- % | 4.99 | - |
| SO3 % | 2.32 | - |
| Symbols of the soil (USCS) | CL | - |
| Liquid-limit (L.L) % | 47 | 312 |

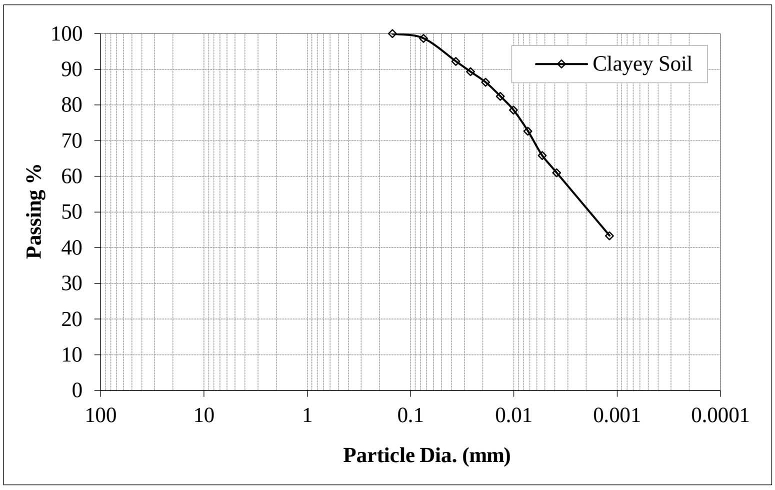
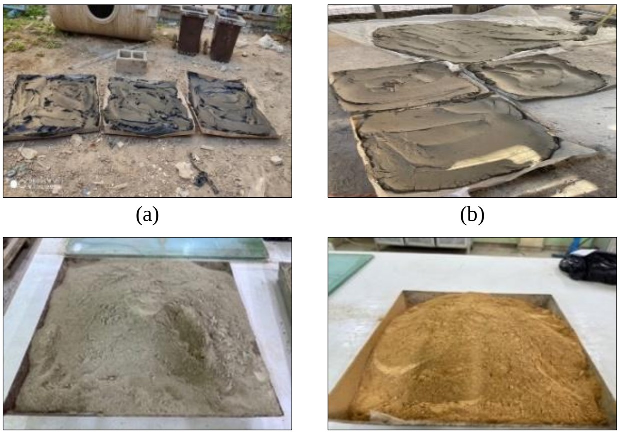



**Figure 2. Particle size distribution of normal soil**

## 2.2. The Preparation of Sludge Ash for Water Treatment

As shown in Figure 3**,** the wet sludge was first placed in steel pans and exposed to the sun to dry it out and prepare it for grinding. To prepare the dry sludge for incorporation into expansive soil mixes, the Civil Laboratories at the University of Technology used equipment from Pascall Engineering/GATWICK Road to perform a mechanical crushing process. The dry sludge was first baked at 105–110°C. Using a CARBOLITE-CWF 1200 furnace, the dry powdered sludge was then subjected to thermal treatment for four hours at a temperature of 800°C [18, 19]. Figure 3 compares the appearance of the water treatment sludge before and after burning. Ash from the water treatment sludge showed a weight reduction of 20 to 21% of the dry sludge.



(a) (b) (c) (d)

**Figure 3. Several stages of the WTS thermal treatment process: (a), (b), (c) before heating. and (d) after heating**

### 2.3. Leachate

Throughout the experimental activity, the leachate used in the research was collected from the lysimeters of each individual once per week. Given that the waste is presumed to consist of a wide variety of components, the produced leachate is expected to represent the primary components of municipal solid waste in Baghdad. Before being utilized in the tests, the samples were stored in a refrigerator at a temperature of four degrees Celsius. According to the results shown in Table 2**,** the Department of Environment and Water at the Ministry of Science and Technology analyzed the leachate to determine its physicochemical properties. The analysis was conducted according to standard procedures outlined by the American Public Health Association (APHA). A few sample photographs are shown in Figure 4.

**Table 2. Leachate was analyzed for its physical and chemical properties**

| Configurations | Quantity | Configurations | Quantity |
|---|---|---|---|
| **Heavy metals (mg/L)** | | **Variables of a physical** | |
| Manganese | 9.11 | Hardness (mg/L) | 1800 |
| Zinc | 6.10 | Total Dissolved Solids (TDS) (mg/L) | 9570 |
| Lead | 3.44 | pH | 5.5-7.0 |
| Iron | 57 | Density(g/ml) | 1.07 |
| Cadmium) (%) | 0.13 | Electrical Conductivity (EC) (mS/cm) | 15.61 |
| Copper | 0.9 | **Environmental Quality (mg/L)** | |
| Nickel | 0.36 | Biochemical Oxygen Demand BOD5 | 5052 |
| Chromium (%) | 7.45 | Chemical Oxygen Demand COD | 18540 |
| **Anions (mg/L)** | | BOD5/CODCr | 0.39 |
| Nitrate NO3-N | 13.46 | Total Suspended Solids (TSS) | 6300 |
| Ammonium $NH_4$ + | 1.83 | Ammonia | 462 |
| Sulphate SO4-2 | 497 | | |
| Phosphate PO4-P | 11.2 | | |
| Chloride Cl | 3370 | | |

(a) (b) (c)

**Figure 4. (a) The lysimeters, (b) the sample leachate is taken from the lysimeters, and (c) Lysimeter leachate pipes**

## 3. Characteristics of Water Treatment Sludge Ash

### 3.1. Chemical Composition

Table 3 compares the chemical analysis test results with the chemical composition of water treatment sludge ash (WTSA). The following comparison demonstrates which material is preferred for improving swelling:

- It is observed that WTSA contains a high amount of pozzolanic material, including a significant quantity of silica ($SiO_2$ ), which leads to a notable reduction in pore size. Additionally, the transition zone thickness is increased, and with the presence of densely packed C-S-H gel, this will result in a more densified structural composition [20, 21].

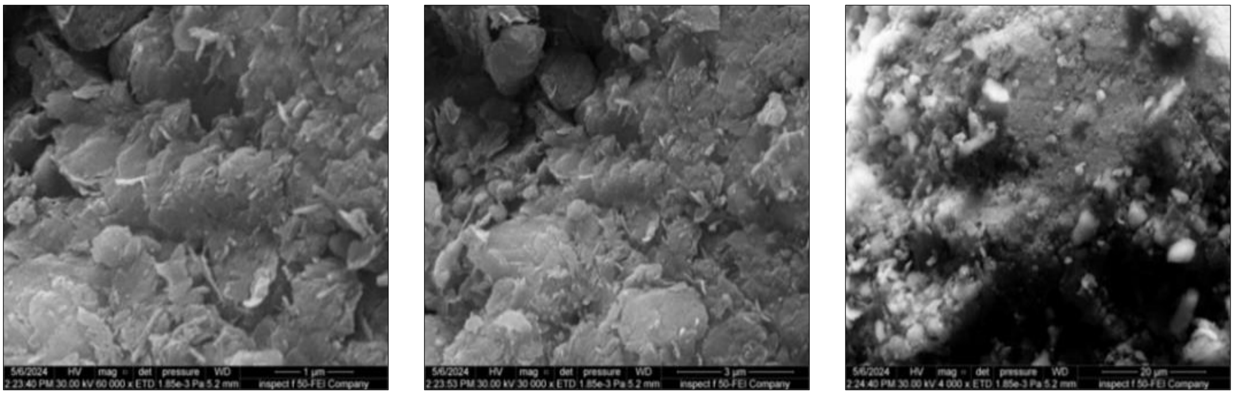
**Table 3. WTSA chemical formula**

| Item | Value % |
|---|---|
| Silica $SiO_2$ | 45.763 |
| Aluminum oxide $Al_2O_3$ | 18.164 |
| Iron oxide $Fe_2O_3$ | 7.120 |
| Oxide Calcium CaO | 15.892 |
| Sulfur trioxide $SO_3$ | 1.341 |
| Magnesium oxide MgO | 7.375 |
| Sodium oxide $Na_2O$ | 0.924 |
| Phosphorus pentoxide $P_2O_5$ | 0.377 |
| Chloride Cl | 0.067 |
| Potassium oxide $K_2O$ | 1.918 |
| Titanium dioxide$TiO_2$ | 0.747 |
| Chromium oxide $Cr_2O_3$ | 0.028 |
| Manganese oxide MnO | 0.130 |
| Nickel oxide NiO | 0.020 |
| Copper oxide CuO | 0.012 |
| Zinc oxide ZnO | 0.026 |
| Rubidium oxide $Rb_2O$ | 0.007 |
| Strontium oxide SrO | 0.038 |
| Lead monoxide PbO | - |
| SiO2 + Al2O3 + $Fe_2O_3$ | 71.047 |

The water temperature in the samples is reduced, and the mixture requires less water due to its surface area and particle size [22, 23]. WTSA has a low calcium carbonate (CaO) content. Because WTSA contains lower levels of sulfate and alkali, it has fewer detrimental effects on soil, such as reducing cavities and cracks (ASTM C, 2010). Adverse effects on soil can occur when sulfate and alkali combine. The quantity of silicon, ferric, and aluminum oxide in the pozzolanic materials, as determined by ASTM C618, was comparable to WTSA. These pozzolanic materials possess some cementitious properties and are therefore classified as class-C pozzolanic materials. The calcined natural pozzolan used in WTSA has a class N value of 71.1, qualifying it as "calcined natural pozzolan complying with class-C requirements. "Although WTSA is not a natural pozzolan, based on its chemical composition, it can be classified as a natural pozzolan [24-26].

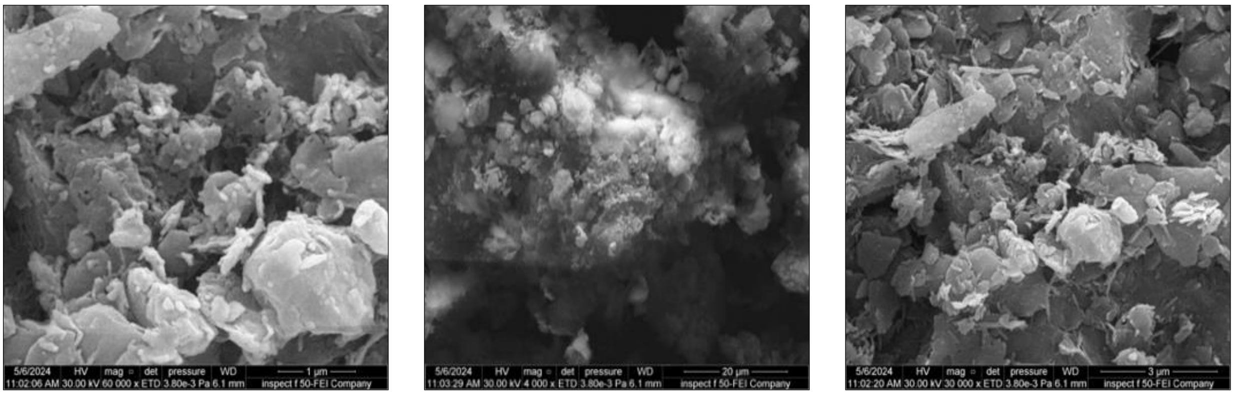
### 3.2. The Scanning Electron Microscope (Often Referred to as SEM)

The SEM examination of WTSA provides valuable insights into its surface morphology, microstructure, and chemical composition, which are essential for understanding its properties and optimizing its performance across various industrial and environmental sectors. Field emission scanning electron microscopy (FE-SEM) was applied to investigate the changes in the microstructural characteristics and fabric of the soil particles under different conditions. As shown in Figure 5, the SEM results indicated that the clay particles exhibited a flaky distribution and a sheet-like structure. Additionally, the clay soil contained numerous micropores. The effect of incorporating 15% water treatment sludge ash into the natural soil is shown in Figure 6. When water treatment sludge ash (WTSA) is introduced into expansive soil, it fills these pores and strengthens the connections between the various natural soil particles. Several studies, including those by Montalvan et al. (2016), Marchiori et al. (2022), and Godoy et al. (2019) [27-29], observed similar mineralogical findings with the presence of goethite. Other studies, such as Bandieira et al. (2021) [30] and Silva (2021) [31], also identified gibbsite. Despite the variety of methods used to evaluate pozzolanic activity, WTS is predominantly amorphous, though a crystalline portion, similar to soil, may be present. Quartz, muscovite, and kaolinite were identified in both materials. The morphology of WTSA is displayed in Figure 7. As mixing water is closely related to the specific surface area of the particles, WTSA particles tend to be finer and less agglomerated compared to other particles. The finer materials, when interacting with the interfacial area between soil particles, reduce the porosity of the soil, decreasing voids and surface area, which in turn enhances the strength and durability of the soil [32-34].



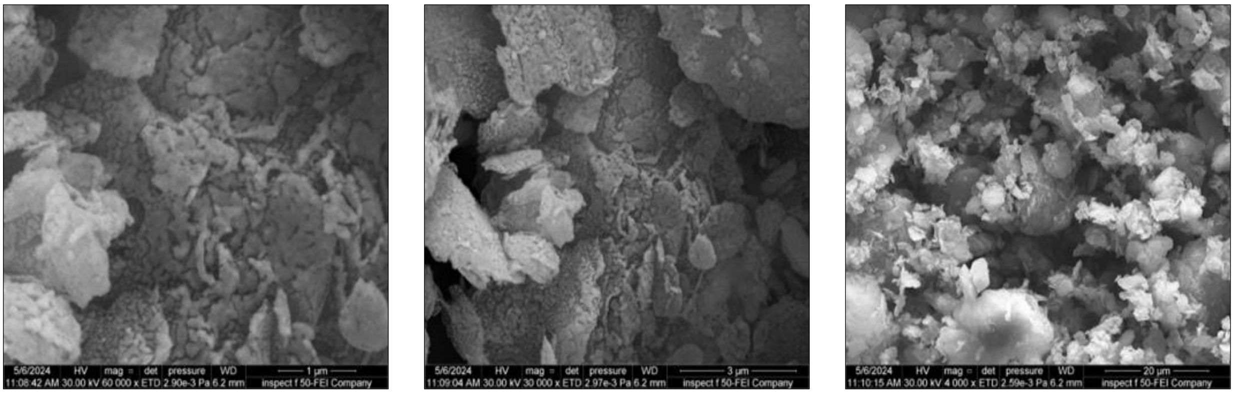
(a) (b) (c)

**Figure 5. FE-SEM images of soil A. (a) Zoom on a grain at 1 µm,; (b) zoom on a grain at 3 µm, (c) zoom on a grain at 20 µm**



(a) (b) (c)

**Figure 6. FE-SEM images of soil A with 15%WTSA. (a) zoom on a grain at 1 µm, (b) zoom on a grain at 3 µm, (c) zoom on a grain at 20 µm**



(a) (b) (c)

**Figure 7. FE-SEM images of Magnesium oxide. (a) zoom on a grain at 3 µm, (b) zoom on a grain at 3 µm, (c) zoom on a grain at 20 µm**

## 3.3. Energy Dispersive Spectroscopy (EDS)

According to the core concept of spectroscopy, the fundamental idea is that every element has a distinct atomic structure that allows it to exhibit an extraordinary assortment of peaks on its electromagnetic emission spectrum, mainly responsible for its characterization capabilities. From Figures 8 to 10, Al, Si, and Ca may be seen in distinct peaks on the EDS micrographs of soil treated with WTSA. In the presence of WTSA, these peaks provide evidence that hydration and pozzolanic activities are taking place, which results in stable molecules. After analyzing the data obtained from the EDS, it was found that the peaks of oxygen and silica were the greatest, followed by the peaks of calcium, which were the lowest. Following the occurrence of hydration and pozzolanic reaction, which increased strength, the peaks of calcium indicate that these processes had taken place. The consumption of amorphous silica achieved a further strengthening of the production of novel compounds. In Tables 4 to 6, the EDS analysis results for 15% WTSA samples are provided. As this evidence demonstrates, the slow process of pozzolanic reaction is necessary to create more cementitious compounds. The gain in strength may be attributed to these characteristics. It has been shown via EDS micrographs that the intensity peaks of Ca, Si, Al, and O grow substantially greater as the amount of WTSA increases. The generation of pozzolanic reaction products may be responsible for a rise in the ratio of Ca:Si with WTSA content [35].

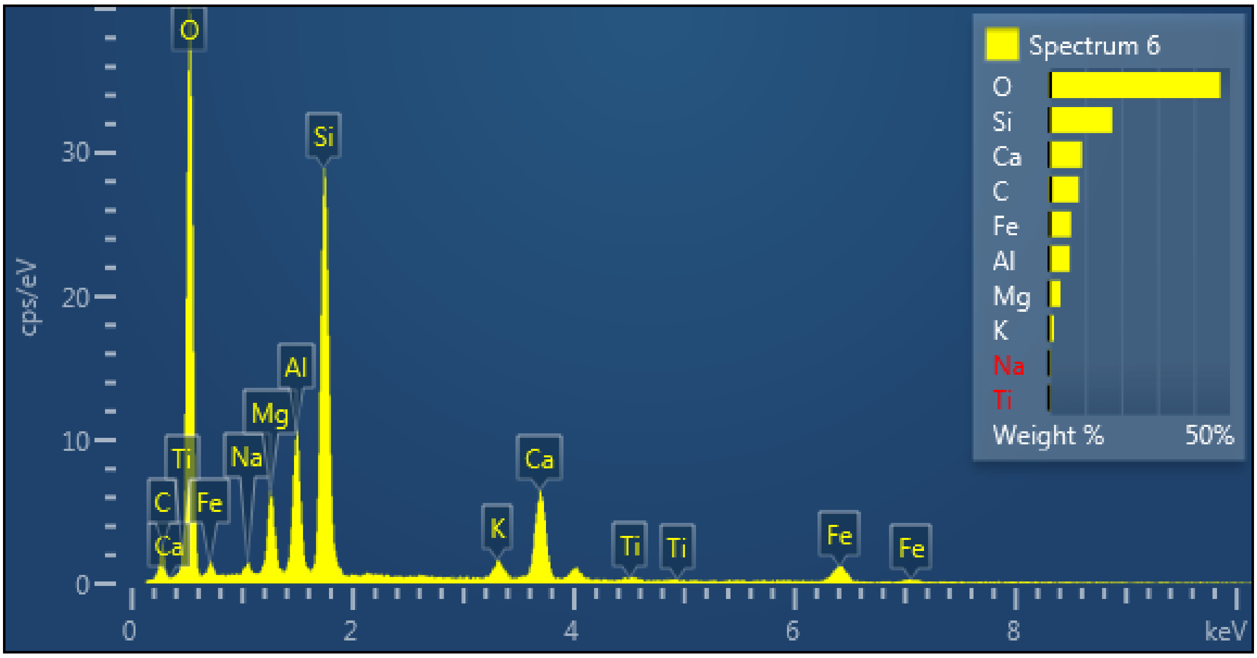



**Figure 8. EDS of the soil A**

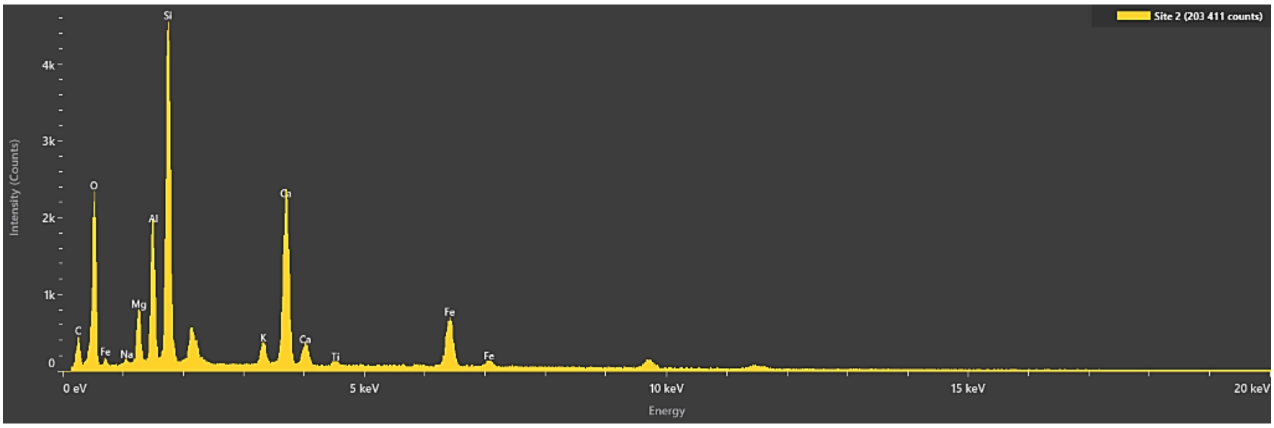



**Figure 9. EDS analysis for WTSA**

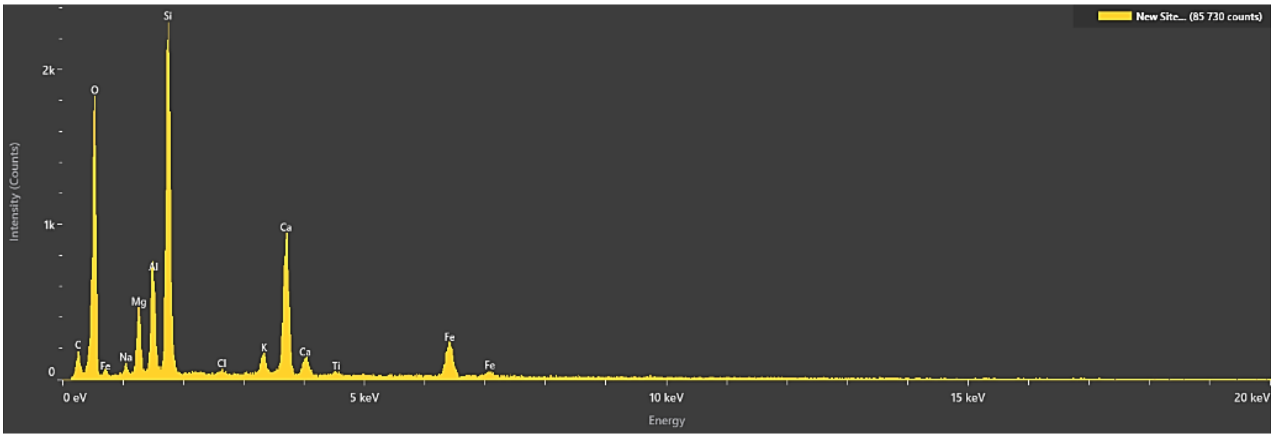



**Figure 10. EDS analysis for soil+15%WTSA**

**Table 4. The mineralogy of soil A, as determined by the EDS analysis findings**

| Element | Weight (mg/kg) | Standard Label (mg/kg) |
|---|---|---|
| | Soil (A) | Soil (A) |
| Si | 18.01 | 5.72 (Kaolinite) |
| | | 4.07 (Illite) |
| | | 3.09 (Quartz) |
| | | 0.82 (Montmorillonite) |
| | | 3.11 (Wollastonite) |
| | | 1.20 (Albite) |
| O | 47.39 | ALL |
| AL | 5.73 | 1.97 (Kaolinite) |
| | | 1.1 (Illite) |
| | | 1.61 (Montmorillonite) |
| | | 1.05 (Albite) |
| C | 8.27 | 8.27 (Calcite) |
| Ca | 9.16 | 4.42 (Calcite) |
| | | 4.74 (Wollastonite) |
| Na | 0.53 | 0.53 (Albite) |
| K | 1.48 | 1.48 (Halite) |
| Fe | 6.13 | 6.13 (Goethite) |
| Mg | 3.27 | 3.27 (Dolomite) |
| S | 0 | 0 Pyrite |
| Cl | 0 | 0 (Halite) |

**Table 5. The mineralogy of WTSA, as determined by the EDS analysis findings**

| Weight % Error | Weight % | Atomic % Error | Atomic % | Element |
|---|---|---|---|---|
| 0.4 | 11.6 | 0.6 | 19.2 | C |
| 0.8 | 41.4 | 0.9 | 51.5 | O |
| 0.1 | 0.5 | 0.1 | 0.4 | Na |
| 0.1 | 3.5 | 0.1 | 2.9 | Mg |
| 0.1 | 7.0 | 0.1 | 5.2 | Al |
| 0.1 | 17.5 | 0.1 | 12.4 | Si |
| 0.0 | 1.3 | 0.0 | 0.7 | K |
| 0.1 | 10.8 | 0.1 | 5.4 | Ca |
| 0.1 | 0.5 | 0.0 | 0.2 | Ti |
| 0.1 | 6.1 | 0.1 | 2.2 | Fe |

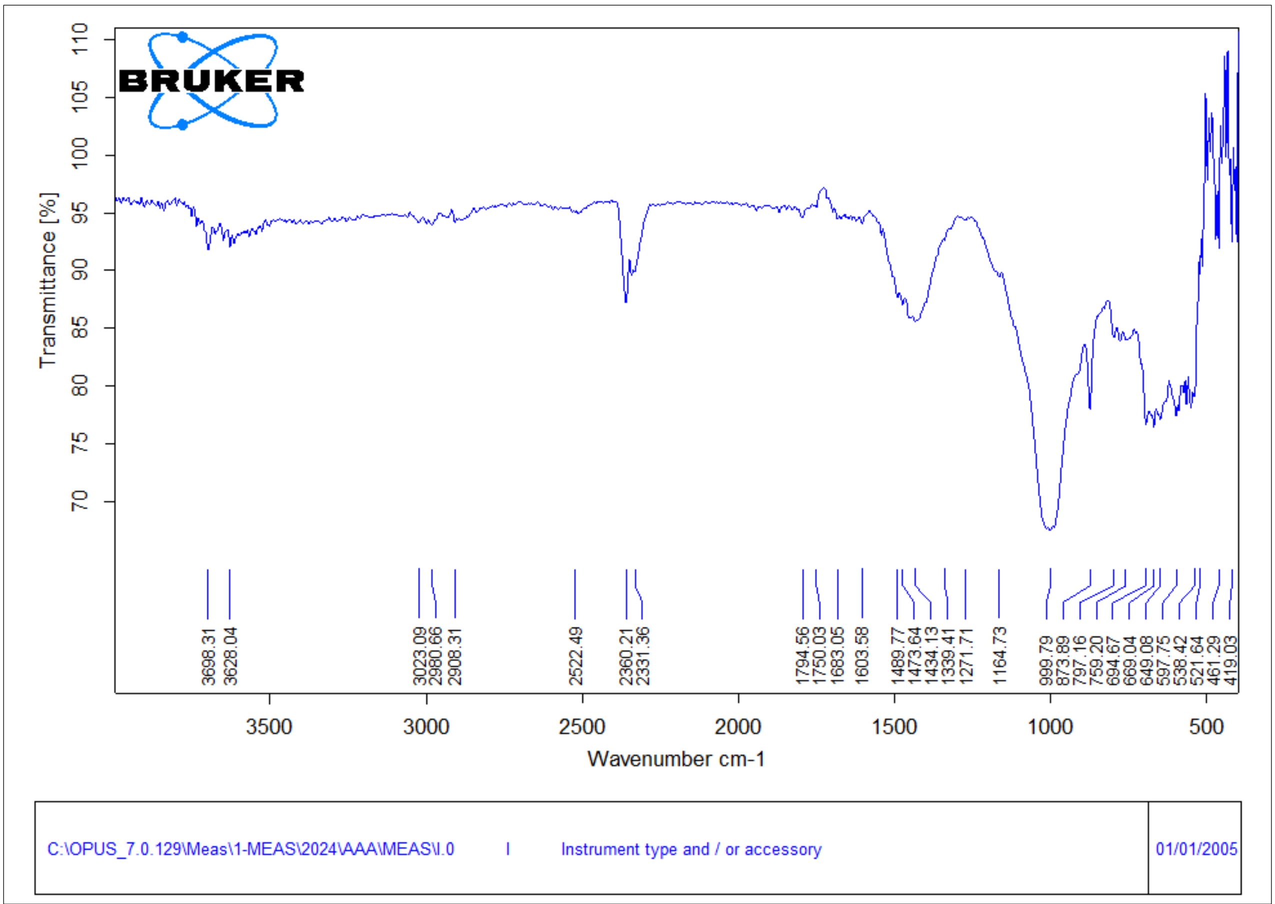
**Table 6. The mineralogy of soil+15%WTSA, as determined by the EDS analysis findings**

| Weight % Error | Weight % | Atomic % Error | Atomic % | Element |
|---|---|---|---|---|
| 0.5 | 17.1 | 0.8 | 26.4 | C |
| 0.8 | 42.2 | 1.0 | 48.8 | O |
| 0.1 | 0.6 | 0.1 | 0.5 | Na |
| 0.1 | 2.6 | 0.1 | 2.0 | Mg |
| 0.1 | 4.8 | 0.1 | 3.3 | Al |
| 0.1 | 22.7 | 0.1 | 14.9 | Si |
| 0.1 | 0.9 | 0.0 | 0.4 | K |
| 0.1 | 5.2 | 0.0 | 2.4 | Ca |
| 0.1 | 0.3 | 0.0 | 0.1 | Ti |
| 0.1 | 3.6 | 0.0 | 1.2 | Fe |

### 3.4. Fourier Transform Infrared Spectroscopy (FTIR)

Using an FTIR spectrometer, the existence of organic and inorganic chemicals in soil and WTSA was investigated, and the obtained FTIR spectrums are shown in Figure 11. The identification of the various minerals that are found in the soil and WTSA may be accomplished by the analysis of the adsorbent spectrums. To ascertain which peaks in the spectrums represent which functional groups of chemicals are present in the soil and WTSA samples, the peak analyzed the spectrums. Sludge and clay soil were the two types of materials that were used for the analysis. According to the FTIR spectrum analysis findings, several groups of wave numbers at certain band peaks have been identified in soil and WTSA, respectively. These groups number nearly 11 and seven, respectively. Considering everything, it was discovered that around seventy percent of the functional groups for WTS are comparable to the functional group for the soil itself. The wave numbers of both soil and WTSA were 3700-3584, suggesting that both systems are in the same range. The functional group that O-H stretches out. The soil and the WTS have the same wave number in the absorbent band, which occurs between 1670 and 1600, 1050 and 1150. These wave numbers are attributed to the C=O stretch, C-O bending, and C=C bending phenomenon. Also noticed in the soil and WTSA spectrum were the same adsorbent bands at wave numbers from 800-770 and 760-740. These bands suggested that the C-H bending was occurring in both spectral regions. However, four (4) functional groups are not present in the WTSA sample compared to the soil sample.

The functional categories in question are the C=C-H asymmetric stretch, the H-C-H asymmetric and symmetric stretch, the N=C=O stretching, and the S-CΞN stretching. According to the findings of the FTIR investigation, most of the absorbent bands discovered in the soil and the WTSA are associated with organic molecules. This may be proposed due to aliphatic, aldehyde, and ketone compounds. The presence of inorganic chemicals like amide and sulfate may be indicated by the bands exclusively seen in soil (wave numbers 2000–2500 and 2700–3200). There is a possibility that the permeability of the material might be affected by aldehyde and ketone, both of which are notorious for their poor solubility in water. One of the most important characteristics of a good landfill liner is that it should be made of a material that is less soluble in water. This will prevent fluid from seeping into the material, which will, in turn, lower the permeability value. In addition, ketone-based compounds are appropriate for engineering applications because they can withstand high temperatures, have a very low moisture absorption rate, and resist stress cracking. These characteristics are particularly advantageous for developing a protective layer for waste sites. According to the findings of this investigation, which are based on a comparison between the organic functional groups of soil and WTS, chemical analysis has shown that WTS has the same traits as soil. Therefore, water treatment sludge has the potential to be presented as an alternate material for the lining of landfills.

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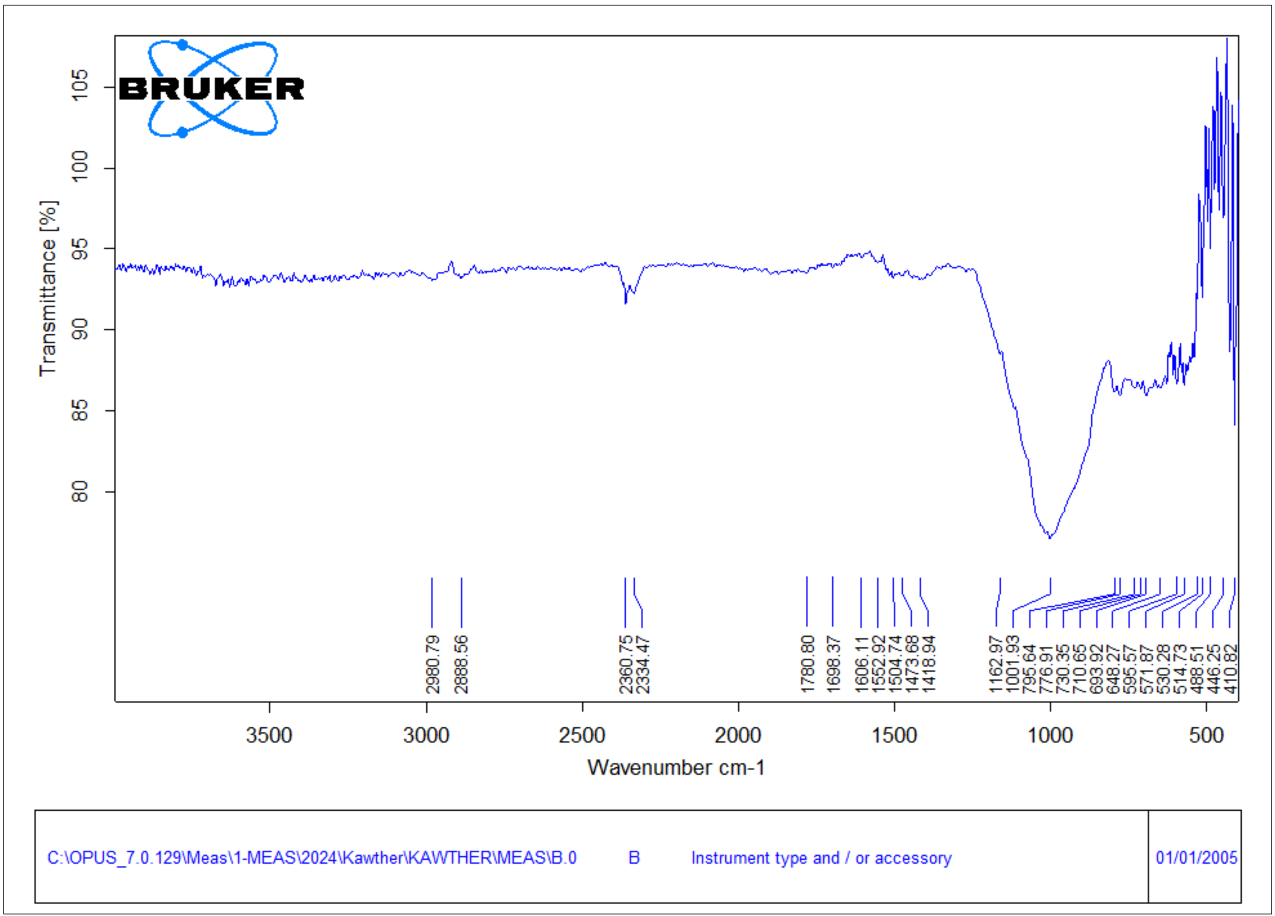
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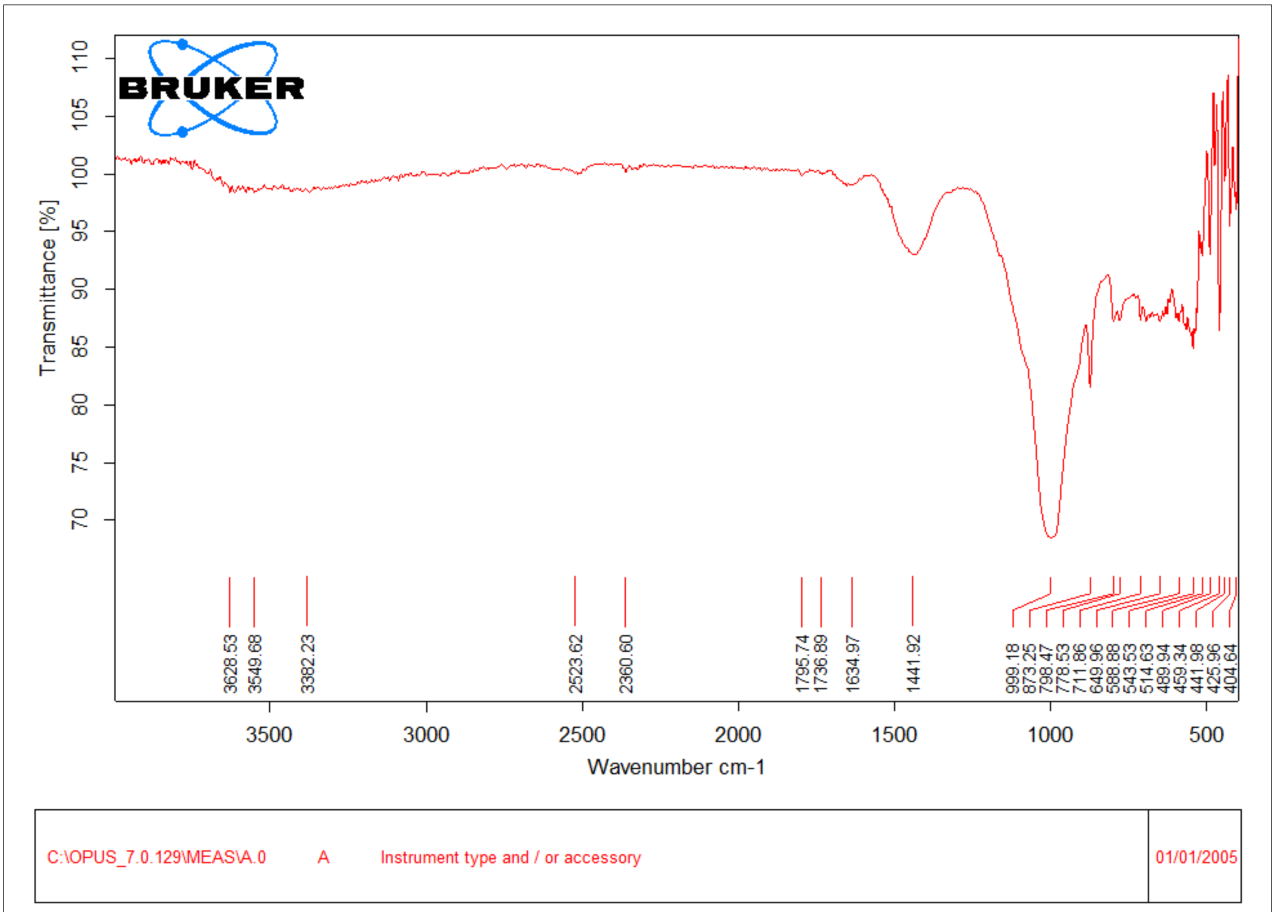
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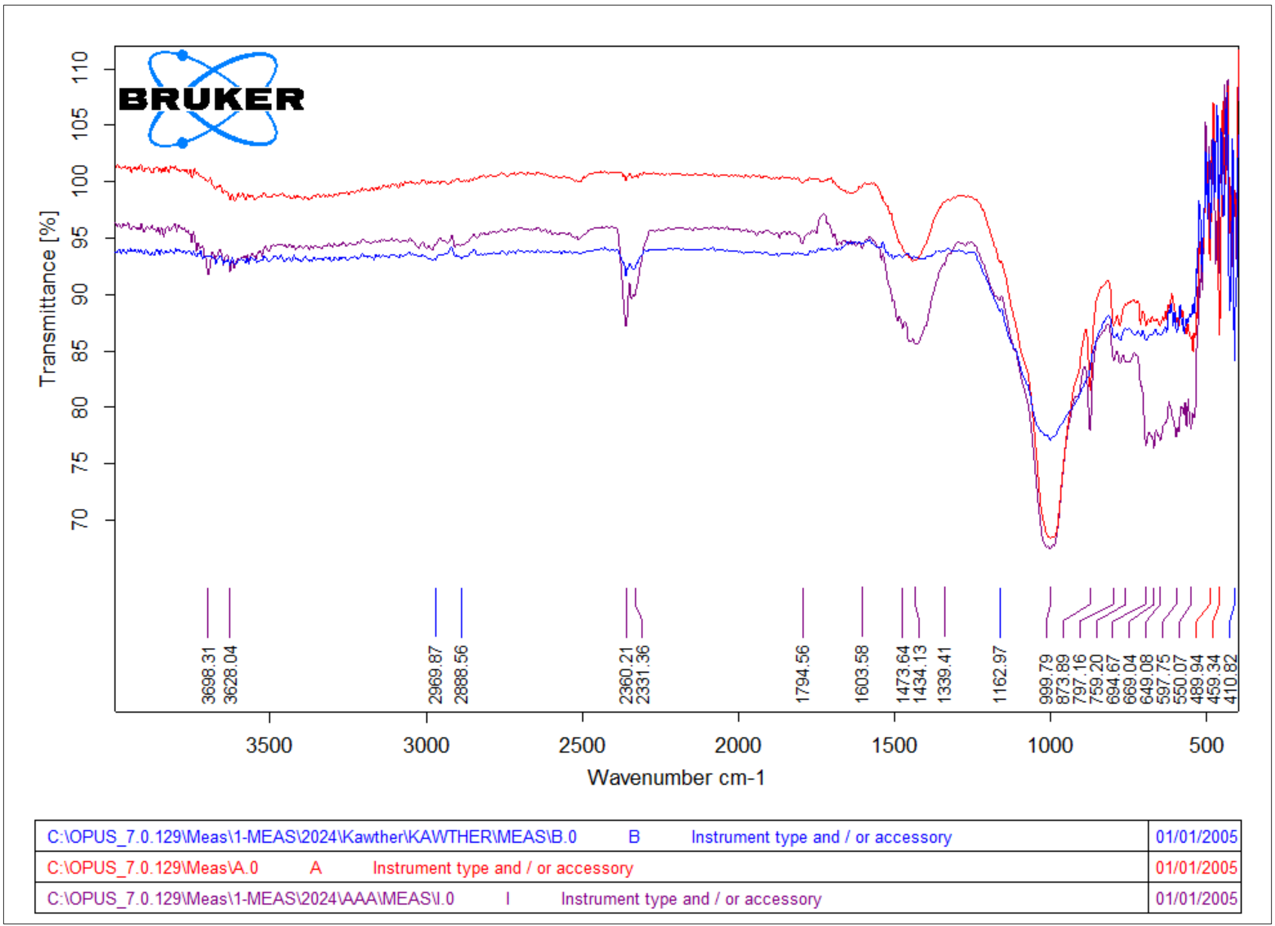


(d)

**Figure 11. FTIR (Fourier Transform Infrared Spectrometer) spectra of (a) Soil (b) WTSA (c) Soil+15% WTSA (d) In one Figure (a), (b), (c)**

## 4. Testing Program

The majority of experiments were conducted at the soil mechanics laboratory inside the Department of Civil Engineering at the University of Technology. The specifics of the testing program are shown in Figure 12.

## 5. Volumetric Shrinkage (VSS)

If the soil water content is reduced from a specific value to the soil shrinkage limit, it causes a volumetric shrinkage. Volumetric shrinkage refers to a reduction in the soil volume, represented as an initial soil volume percentage water content [36]. Compaction was performed on air-dried soil of varying gradations by the techniques described in BS 1377: Part 4: 1990 at a range of moisture contents in comparison to the moisture level that was determined to be optimal. These gradations were chosen to assess whether or not they meet the need of the regulatory requirements, which is 4%. This criterion has been widely established by the vast majority of scientists and authorities on environmental issues for volumetric shrinkage at varied moisture contents [37, 38]. In applications for waste containment, a liner that contains any soil that exhibits a volumetric shrinkage strain of more than 4% after it has been dried out cannot be employed. The procedures for compacting the air-dried soil of varied gradations were detailed in the document that was part of the British Standard 1377:1990. These techniques were used at the optimum moisture content OMC. After that, the samples were extracted from the cylindrical moulds and allowed to dry at 26 degrees Celsius plus or minus two degrees for thirty days on a bench in the laboratory, as shown in Figure 13. The diameters and heights of each sample were measured daily using a Vernier calliper with an accuracy of up to 0.05 millimetres. The volumetric shrinkage strain was calculated using the average heights and diameters [39]. (Figures 14-a and 14-b) illustrate Volumetric Shrinkage Strain (VSS) variations that occur over time at various Molding Water Contents (MWC).

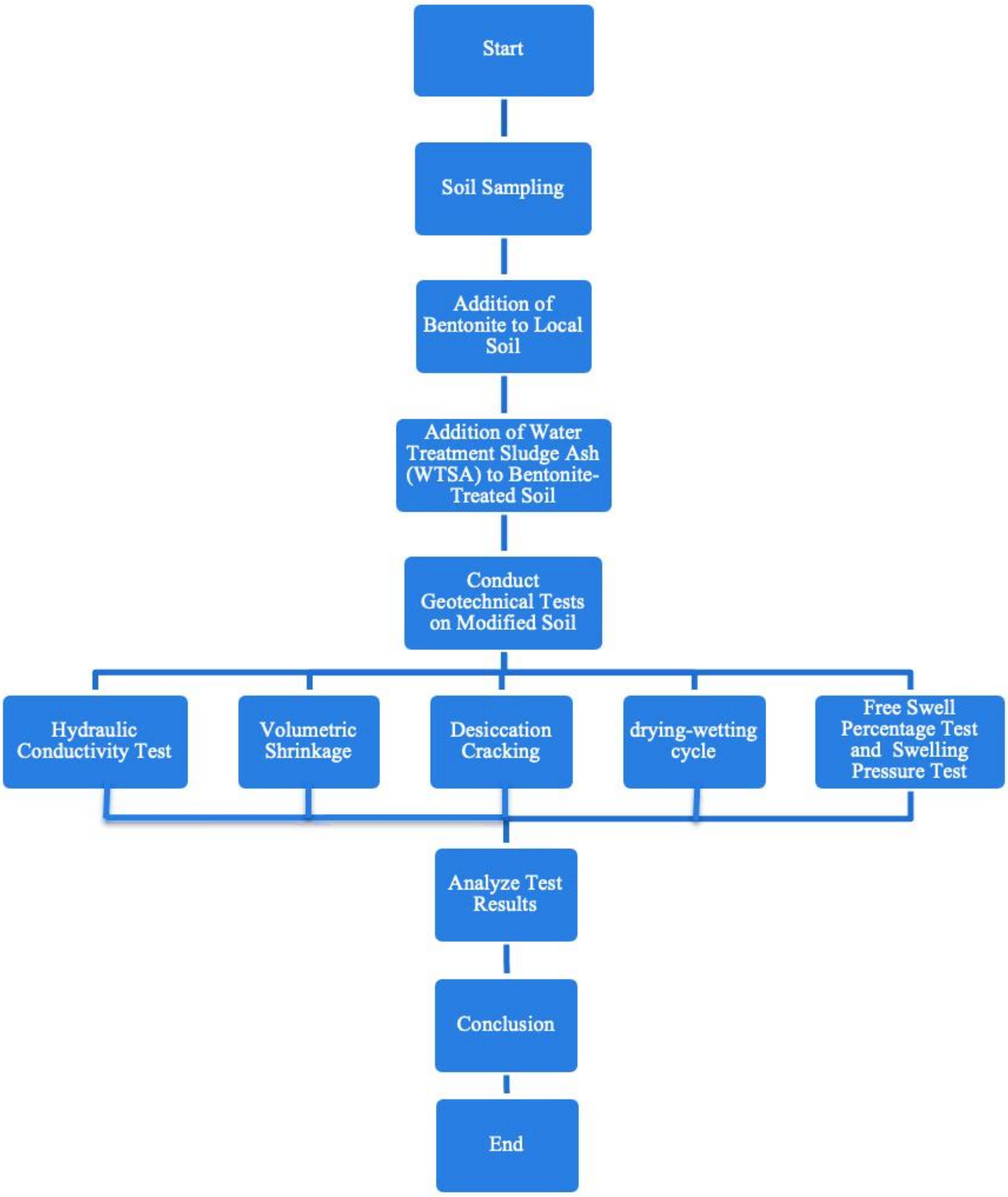



**Figure 12. Flow chart of the testing program**

**Figure 13. Drying of specimen**

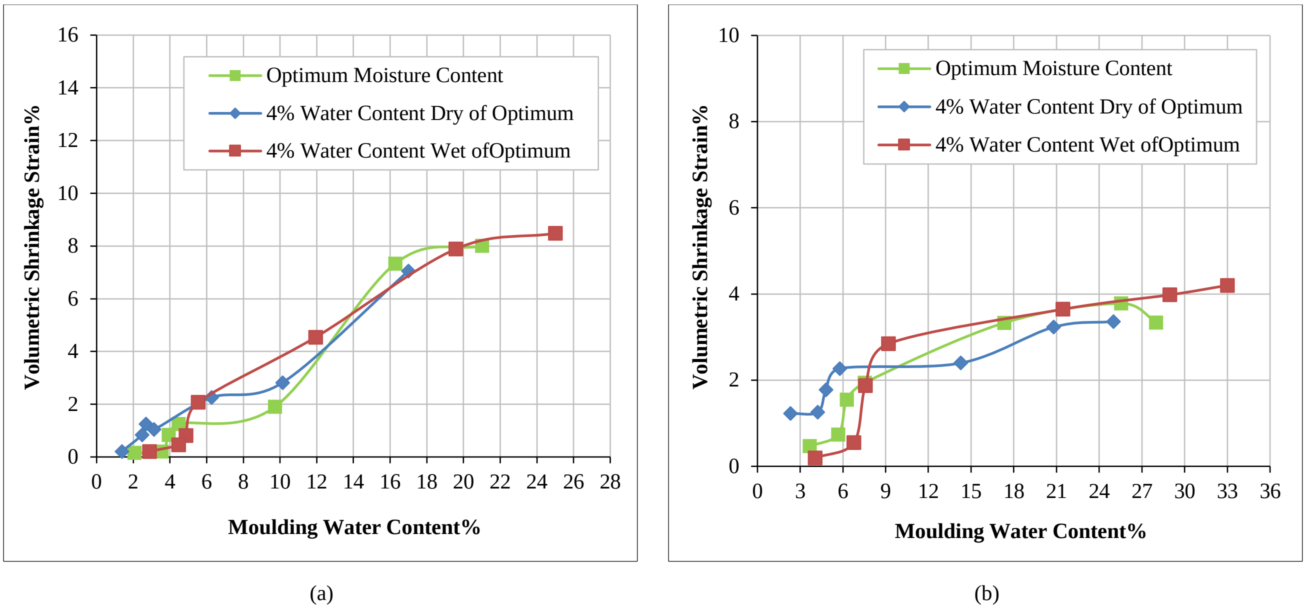



**Figure 14. Volumetric shrinkage versus molding water content for a) unreinforced specimens; b) WTSA-reinforced specimens**

All used materials exhibit a significant rise in VSS within the first five to ten days of drying. This rise is consistent across all used materials. After that, the gradations will progressively become consistent until the substance is completely dry. Because the volumetric shrinkage strain is connected to the moulding water content, this indicates the relationship between the two; the more significant the moulding water content, the higher the volumetric shrinkage strain. According to Osinubi & Ebermu (2008) [40], the quantity of water escaping the pore spaces of compacted soil samples is directly related to the amount of volumetric shrinkage. After more moulding water content, it covers and fills more vacant spaces in the soil sample, resulting in greater shrinkage after the sample is dried. The average diameters and heights were used to calculate the volumetric shrinkage strain, as specified in Equation 1 [39-41]. At a moulding water content of 12.5 percent, the legal maximum allowable volumetric shrinkage strain of 4 percent was attained for the expansive soil compacted at the OMC using the Proctor effort. Following treatment with 15% WTSA, the maximum volumetric shrinkage strain of 4% was recorded at 25.8%. Cracking was seen in a smaller quantity in soil specimens treated with 15% WTSA.

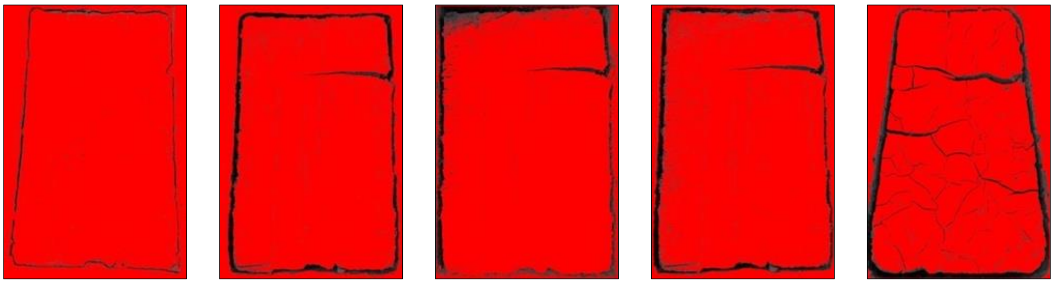
$$VSS = \frac{(\text{Vo}-\text{Vd})}{\text{Vo}} \times 100\% \tag{1}$$

$V_0$ is Wet sample volume, $V_d$ is dry sample volume.

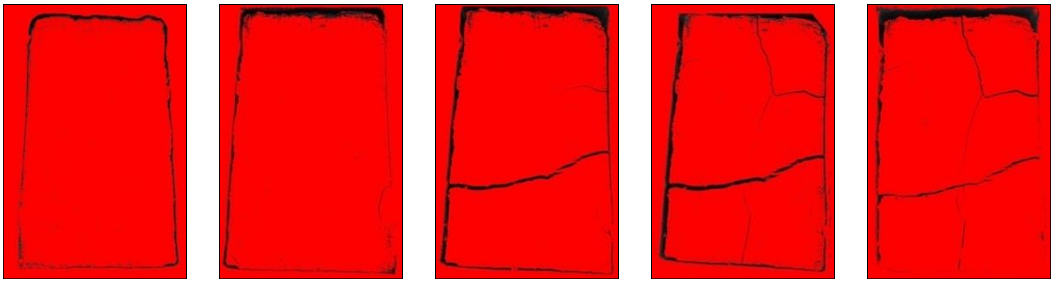
## 6. Cracking due to Desiccation

Soil desiccation fissures may seriously affect the natural environment and the performance of a wide range of earthen constructions. Roads and foundations [42], clay barriers [43], and dams and embankments [44] may all be negatively impacted by these fractures. Cracked soil has a far higher hydraulic conductivity than unbroken soil, making it easier for water and pollution to move through the ground. The implications for landfill liners and coverings are discussed [45]. Desiccation cracking and possible changes to minimize it have been the subject of substantial study to solve these concerns. Because they absorb so much water, expansive soils are especially vulnerable to desiccation cracking. In studies, WTSA has been shown to reduce drying-related cracking significantly. Images of broad and smooth fractures are often transformed into smaller, more irregular ones when WTSA. Based on these results, WTSA has promised as a reinforcing agent for improving the geotechnical qualities of expanding soils. Impermeable liners and coverings in municipal solid waste dumps and WTSA-expanding soil mixtures show great promise. This method not only enhances the performance of liners without considerably raising project costs, but it also helps handle the environmental concerns caused by water treatment sludge heaps. To investigate the influence of WTSA on the desiccation cracking of expansive soil, mixtures of water concentration bentonite liquid limit have been prepared. Later, combinations of soil and WTSA mixes were kept at room temperature for 30 days to dry. The cracked dried samples were photographed and weighted to calculate their water content. This photographing and water content calculation process continued during the 30 days, as shown in Figure 15. ImageJ software was used for picture processing, as seen in Figure 16. The Crack Intensity Factor (CIF) is a technique developed by Miller et al. (1998) [46].

**Figure 15. Photographs of the crack network developed in response to desiccation**



(a)



(b)

**Figure 16. Utilization of image processing techniques by ImageJ software for a) unreinforced specimens b) WTSA-reinforced specimens**

Figure 17 shows the fractured and total area ratio and the relation between water content and CIF for all the tests were quantitatively assessed. Incorporating WTSA significantly impacts the management of desiccation fractures. According to Miller and Rifai (2004) [47], the Crack Reduction Factor (CRF) is a mathematical tool that may quantify the impact of various WTSA components over time, as shown in Figure 18. The calculation of the CRF involves dividing the difference between the CIF of unreinforced specimens and the CIF of WTSA-reinforced models by the CIF of the unreinforced illustration. The impact of WTSA on crack mitigation at different moisture concentrations over time demonstrates a fluctuating tendency toward crack mitigation. On the other hand, the CRF often decreases as the drying process progresses. Water treatment sludge ash plays a significant role in minimizing cracks in expansive soils, primarily due to its pozzolanic properties and ability to enhance soil structure. This ash contains compounds such as silica and alumina, which chemically interact with calcium hydroxide in the soil, forming cementitious substances that increase the soil's strength. As a result, the ash reduces the soil's susceptibility to shrinkage and swelling caused by fluctuations in moisture content. When introduced to expansive soils, sludge ash helps bind soil particles, thereby reducing voids that contribute to the soil's instability. This binding effect leads to a more consistent and stable soil structure with less risk of volumetric changes.

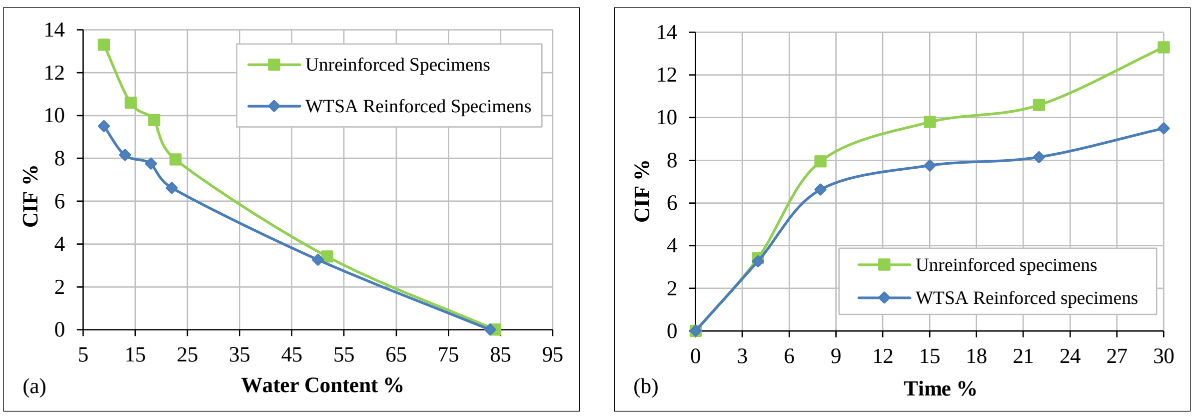



**Figure 17. (a) The crack intensity factor about the water content, (b) the crack intensity factor about the time**

Furthermore, sludge ash assists in moisture retention, mitigating the rapid drying process responsible for the formation of cracks in expansive soils. By stabilising moisture fluctuations, the soil remains more consistent over time. Additionally, expansive soils, which are known for their high plasticity and significant volume changes, experience a reduction in their plasticity index when treated with sludge ash, thereby decreasing the soil's propensity to swell or shrink upon water exposure.

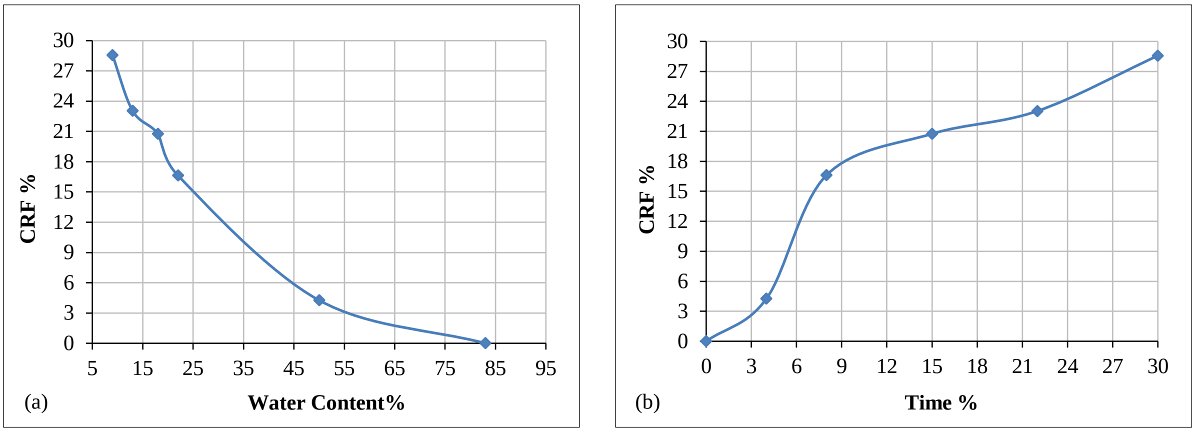



**Figure 18. (a) The crack reduction factor about the water content, (b) the crack reduction factor is about time**

## 7. Effect of Wetting and Drying

After completing the volumetric shrinkage strain measurement, the samples were encased in an impermeable membrane, except the top and bottom of the samples, which were left exposed. Capillaries were allowed to move vertically to allow water to enter the samples. This was done to get the desired effect. After being put in a curing tank, the specimens were submerged in leachate until they reached a depth equivalent to one-third of their height. The leachate temperature was determined to be 28 degrees Celsius, with a standard variation of 2 degrees.

Celsius. The temperature of the leachate was measured. Because leachate had reached the surface of the specimens, it was concluded that the specimens had achieved their maximum saturation level. After that, the specimens were taken out of the laboratory and dried on a table maintained at 28 degrees Celsius with a standard deviation of 2 degrees. After the drying procedure, the samples were again submerged for an additional wetting and drying cycle. Additionally, the samples were dried. This was done to simulate the effect that soaking and drying would have on the specimens that had been compressed.

The capillary flow on samples was seen by physical observation of the specimens. At the same time, they were immersed in leachate and dried for five cycles. For the water to reach the surface, it took fourteen days for samples prepared with a water content that was four percent higher than the optimum content, eleven days for samples that were produced with the optimal amount of water, and nine days for samples that were prepared with a water content that was four percent lower than the optimal amount. The samples treated with fifteen percent water treatment sludge ash exhibited this characteristic. Generally speaking, the rate of capillary rise inside the compacted soil after drying increased with an increase in the quantity of water content and a reduction in the amount of compression effort. This was the case regardless of whether the soil was compacted or not. The cracks and suction surface dimensions were observed and measured during the soaking and drying of the compacted soils. Even though the crack intensity factor (CIF) was used in order to estimate the size of the cracks on the surface, Figures 19-d and 19-e depict the physical behavior of the fractures that were observed. In a general sense, it was shown that high suction caused rapid increases in capillary rise and that treated soils exhibited a greater degree of small cracking than untreated soils.

(a) (b) (c) (d) (e)

**Figure 19. (a) Prepare specimen before the first cycle of wetting (b) first cycle of wetness (c) second cycle of wetness, and (d) after the completion of the second wet-dry cycle (e) the third cycle of wetness**

On the other hand, soils that had a 15% water treatment sludge ash content added to them showed some signs of cracking, although in trace proportions. As can be observed in (Figure 19-e), the untreated soil exhibited an increased number of enormous cracks after the second wetting cycle. This reveals that no permanent changes took place during the first drying cycle. This is because the inter-particle tension formed during the first drying cycle is larger than the stress applied during the compaction process. To add insult to injury, similar forces would be imposed during the subsequent drying cycles. Because montmorillonite, the principal clay mineral, is more active than other clay minerals, these tendencies matched with the studies published by Osinubi & Eberemu (2010) [48] and Albrecht & Benson (2001) [49]. This may be related to montmorillonite being the primary clay mineral. In addition, the influence of swelling and the shift in mass for each cycle were observed. Because of the degradation of the specimens, the overall mass of the wetting and drying process decreases after each cycle. Except for samples that were improved by WTSA, which kept their original flat surfaces, the surface of each sample became concave. In response to an increase in suction. According to these findings, increasing the amount of compaction effort will reduce the swelling that occurs when soil is moist. The samples' vertical deformation was measured throughout the drying and wetting processes, and the findings were reported as the sample's change in height (DH) as a percentage of its starting height at the start of the first drying-wetting cycle.

The findings of variations in vertical deformation for soil samples with varying water contents during drying and wetting cycles showed that samples of untreated expansive soils evaluated at constant temperature underwent compression during the first cycle's drying stage and expansion during the wetting stage. For the samples with optimum water content, 4% water content dry of optimum and 4% water content wet of optimum, the amounts of vertical deformation in the first cycle were 2.8, 3, and 2.1% compression in the drying path and 16.16, 14, and 17.97% expansion in the wetting path, respectively. After five cycles of drying and wetting, the deformation of samples with varying water contents approached an almost constant value. At the equilibrium stage, these values were 20.2, 16.95, and 21% (the equilibrium condition of a sample is defined as the state in which the deformation and void ratio of the sample achieve a reversible condition after wetting and drying cycles). For the samples with the optimal water content, 4% dry of the optimal water content, and 4% wet of the optimal water content, in that order. Results for 15% water treatment sludge-treated expansive soils at the same temperatures as untreated soils are shown in Figure 20. According to this figure, the samples' amounts of compression during the first cycle's drying stage were 2.2, 2.4, and 1.9%. Their amounts of expansion during the cycle's wetting stage were 5.68, 5.3, and 6.33% for the optimum water content, 4% dry of the optimum, and 4% wet of the optimum, respectively. The findings demonstrate that during the fourth cycle, magnitudes of 6.6, 6.1, and 7.6%, respectively, occurred during the drying and wetting cycles.

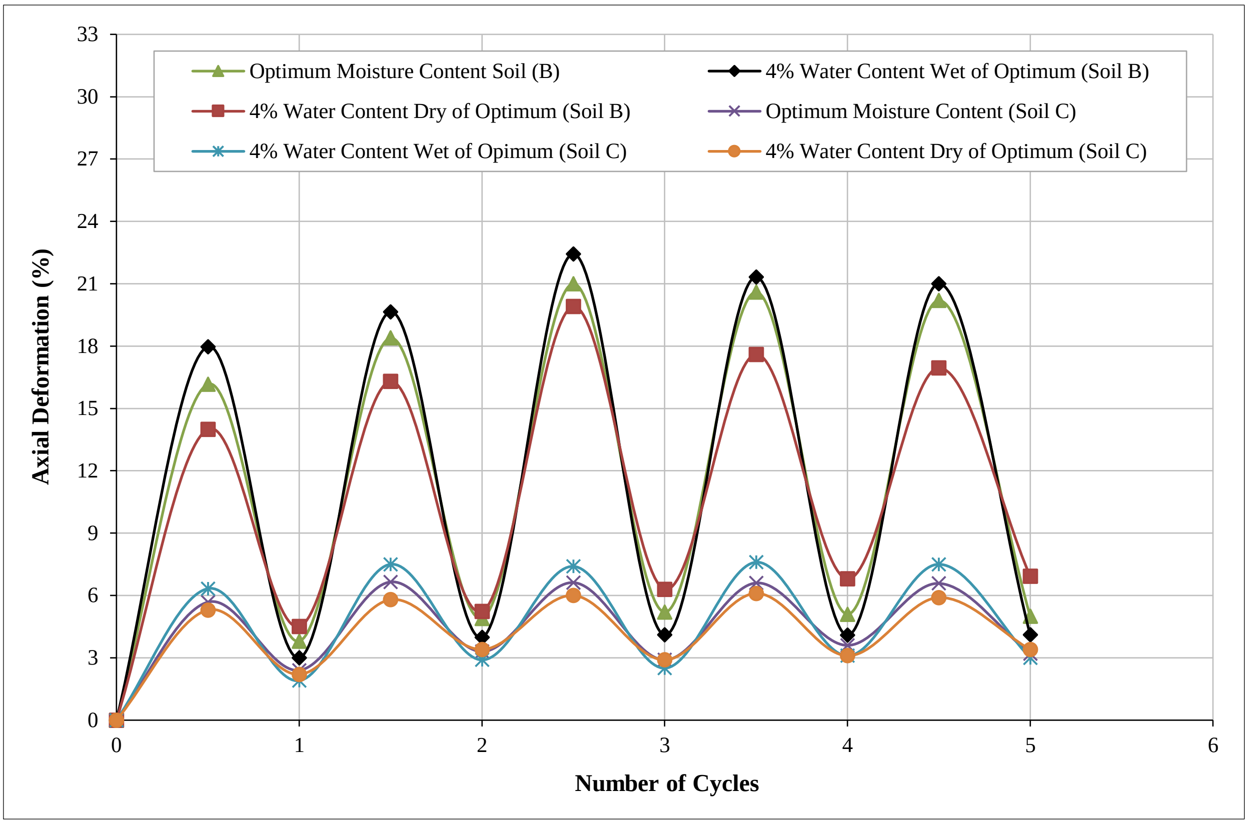



**Figure 20. Vertical deformation in untreated and treated soil throughout the drying and wetting cycles**

## 8. Hydraulic Conductivity

The hydraulic conductivity, a measurement that determines it is recommended that the value of the ease with which a fluid may flow through a material, should be measured at $1 \times 10^{-9}$ m/s, according to recommendations made by the USEPA (1991) [50] and for installed sanitary landfill liners MHLG (2005) [51]. According to Daniel (2012) [52] and Chenna & Chouksey (2024) [53], the most critical component that makes a difference in the effectiveness of hydraulic barriers is measured by their hydraulic conductivity. It is generally agreed that highly permeable soils should not be used for landfills. A high-water penetration rate through this soil may increase the likelihood of groundwater contamination. The soil composition is ideal for clayey and has extremely low permeability [54]. This is because clayey soils are better at protecting groundwater. Samples were prepared for untreated and treated soil liners at times of 7, 14, 21, and 30 days from a small-scale model from the landfill prepared with the maximum dry density and optimum water content and exposed to the pressures generated on the landfill from the waste, the cover, and the estimated external load, as in Figure 21-a. However, after two to three months, the sample is taken from the lysimeters, as in Figure 21-b, which are prepared at the same density and water content under falling head conditions. This was done per the recommendations by Head (1980) [55]. First, a tiny coating of grease was given to the inside surfaces of the molds before they were remolded. This was done to reduce the influence of side-wall leakage during the testing process.

(a) (b) (c) (d) (e)

**Figure 21. (a) small-scale model, (b) Take the sample from the lysimeter at the end of the test, (c) Prepare the test sample, (d) Sample saturation, and (e) Permeability test apparatus**

Additionally, this was done to guarantee that the compacted sample had excellent contact with the mold. After the specimens had been remolded and placed back into the compaction molds, they were submerged in a leachate tank for at least one week. This was done to ensure that the specimens were saturated to their fullest potential. During the saturation process, the specimens were prevented from expanding vertically. Because of this, it is possible to conclude that all specimens still had their initial dry unit weight during the saturation duration. An obvious indication that the material had attained complete saturation was the presence of water outflow flowing through the outputs of the compaction parameters. In addition, before the commencement of the permeation process, the saturated specimens were joined to the falling head permeameter, which was then connected to the leachate, which was contained inside a flexible tube. This was done before the permeation process began. The process continued until flow stability was established and the termination criteria given in ASTM D 5084 were fulfilled (when there was no obvious pattern in hydraulic conductivity over time). Each sample was subjected to a series of repeated tests. It was found that the duplicate test had a coefficient of variance that was lower than 0.5. Figure 22 depicts the change in hydraulic conductivity between clay specimens that have not been treated and those that have been treated with 15% WTSA.

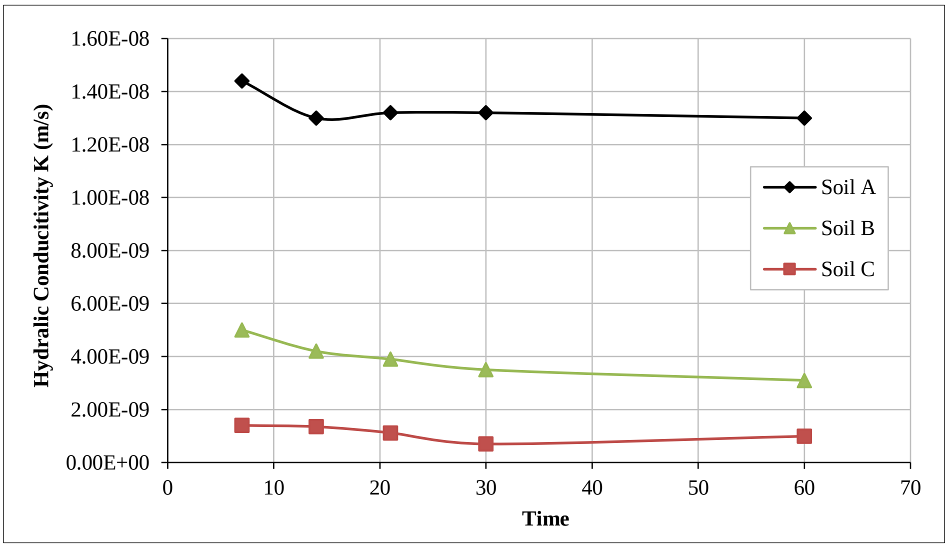



**Figure 22. Variations in the hydraulic conductivity of soils A, B, C with time**

In most cases, the hydraulic conductivity decreased as the amount of WTSA in the mixture increased. This action results from WTSA content increasing the capacity to break down clay aggregates, eliminating the pores between the soil particles. It was observed that an increase in the WTSA content makes the deflocculating of the soil particle easier, which in turn leads to a reduction in the voids and, as a result, a decrease in the hydraulic conductivity [56]. Respectively, for the sample that was permeated with leachate and the sample that was permeated with water. The following equation calculated the hydraulic conductivity k:

$$K = 2.303\frac{al}{At}\log\frac{h1}{h2} \tag{1}$$

where "A" is the specimen's cross-sectional area ($m^2$), "a" is the standpipe's cross-sectional area ($m^2$), "L" is the specimen's length (m), and "k" is the coefficient of permeability ($ms^{-1}$), h1: the beginning height of water in the standpipe (in meters), h2: the end height of water in the standpipe (in meters), and t: the amount of time needed to achieve head drop (in seconds).

## 9. Effect of Water Treatment Sludge Ash for Prepared Soil on Free Swell and Swelling Pressure

Figures 23 to 25 show how the prepared soil's free swell and swelling pressure were affected by adding WTSA in varying percentages. They also show the relationship between the two variables. As the WTSA percentage increased to 15%, there was a sharp decrease in the F.S. and S.P., which leveled to a fixed value. As a result, 15% is believed to be the optimal percentage of WTS since it displays the largest decrease in both the F.S. and the S.P. The interaction between the expansive soil and water treatment sludge ash particles and the addition of non-expanding to the expanding soil silt-size particles contributed to the decrease in volume. Consequently, the samples' specific surface area and water affinity diminish, indicating a lower value of swell-shrinkage properties like free-swell and swelling pressure. Additionally, the specific surface area of the samples decreases [57].

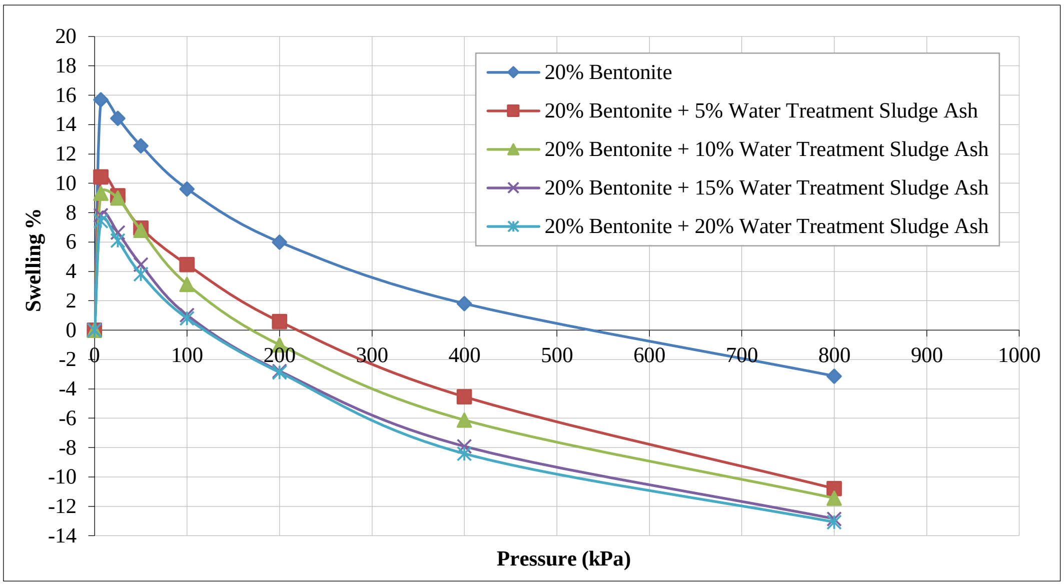



**Figure 23. The 5, 10, 15, and 20% effect on the relationship between prepared soil swelling and pressure WTSA**

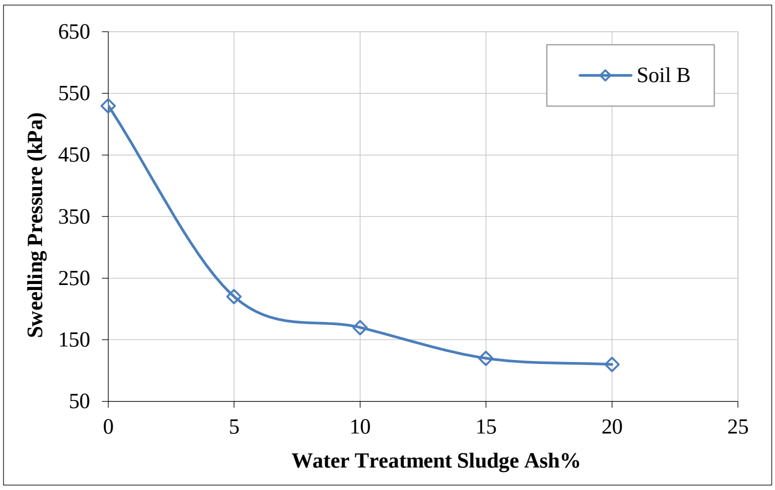



**Figure 24. Relationship between the amount of WTSA and swelling pressure, Soil B**

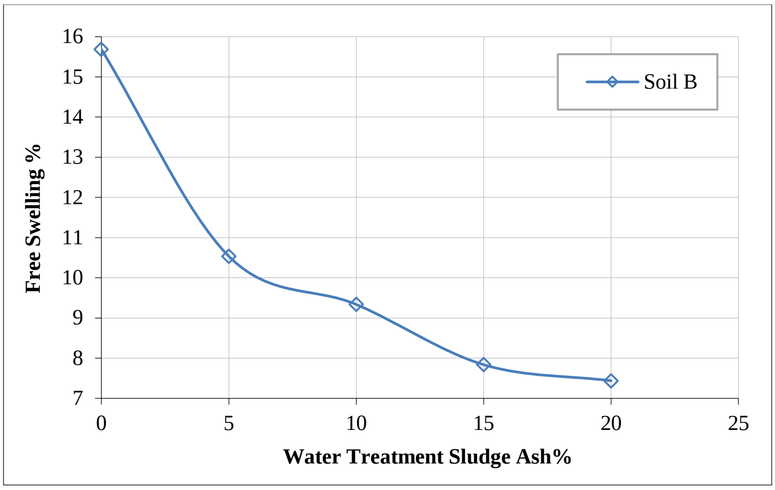



**Figure 25. Relationship between free swelling and the amount of WTSA present**

## 10. Review of Previous Studies on the Characteristics and Performance of Soil Enhanced with Various Materials

The modification of expansive soils through the addition of various materials has a profound impact on their behavior and alters their fundamental properties. Consequently, numerous studies have investigated the effects of different proportions of additives on the characteristics of treated soils. In particular, clay soils exhibit significant changes in their pozzolanic properties, with notable reductions in swelling and shrinkage potential after treatment. Table 7 presents a summary of the key findings from previous studies in this area.

**Table 7. Summary previous studies**

| Aspect | Present Study | Previous Studies | Analysis |
|---|---|---|---|
| Pozzolanic Properties and Chemical Reactions | Water treatment sludge ash (WTSA) contains silica and alumina, which react with calcium hydroxide in soil to form cementitious compounds that enhance soil strength and reduce swelling and shrinkage. | Studies like Al-Rawas et al. (2006) [58] and Dang et al. (2016) [59] showed that pozzolanic materials like fly ash significantly improve soil strength by forming stable compounds, reducing expansion and shrinkage. | The findings are consistent; WTSA has similar properties to other pozzolanic materials such as fly ash, forming cementitious compounds and improving soil stability. |
| Reduction in Swelling and Shrinkage | WTSA binds soil particles and reduces voids, thereby decreasing the swelling and shrinking behavior of expansive soils. It also helps retain moisture, preventing rapid drying that causes cracks. | Phanikumar & Sharma (2007) [60] and Amadi (2014) [61] demonstrated that adding pozzolanic materials like fly ash or lime significantly reduces the swelling potential of expansive soils by improving moisture stability and reducing volumetric changes. | WTSA's ability to reduce swelling and shrinkage is consistent with previous research, indicating its potential as an effective soil stabilizer. WTSA also offers environmental advantages by repurposing waste material. |
| Strength Improvement | WTSA significantly increases soil strength by forming cementitious compounds that bind soil particles together, improving the soil's structural stability. | Osinubi (2006) [62] and Brooks (2009) [63] showed that pozzolanic materials like fly ash improve the unconfined compressive strength (UCS) of expansive soils through similar mechanisms. | WTSA's enhancement of soil strength matches results from previous studies on fly ash, confirming WTSA's viability as a soil stabilizer. |
| Plasticity Reduction | WTSA reduces the plasticity index of expansive soils, making them less prone to volume changes when exposed to moisture. | Studies by Al-Rawas & Goosen (2006) [58] and Brooks (2009) [63] showed that pozzolanic materials reduce the plasticity index, leading to more stable soil behavior under varying moisture conditions. | WTSA effectively lowers the plasticity index, which is crucial for stabilizing expansive soils, aligning with findings on other pozzolanic materials. |
| Environmental and Cost Benefits | The study highlights the environmental benefits of using WTSA, as it repurposes waste from water treatment plants, offering a cost-effective soil stabilization method. | Previous studies by Kalkan (2009) [64] and Amadi (2014) [61] emphasized the cost-effectiveness and environmental benefits of using industrial by-products like fly ash in soil stabilization. | WTSA provides environmental and economic advantages similar to those of fly ash and lime, positioning it as an effective and sustainable material for soil stabilization. |

## 11. Conclusions

Experiments were conducted to determine whether or not it would be possible to reuse WTSA as reinforcing materials in expanding soils, as described in this article. It was decided to emphasize recycling WTSA for use in landfills as a liner and cover material. The most important takeaways from this study may be broken down into the following categories:

- When there is a higher concentration of WTSA, there is less volumetric shrinkage. The most significant decrease may be realized in a specimen with a WTSA value of 15%. It has been shown that using WTSA may effectively reduce the cracked area during the drying process.

- The incorporation of WTSA resulted in a decrease in the hydraulic conductivity of the soil. The drop was more significant regarding bentonite clay (BC) mixes. Nevertheless, the hydraulic conductivity of every BC combination was more than $10^{-9}$ meters per second, which is the minimal value required for landfill liners. The combinations of soil B and soil C had a hydraulic conductivity that was marginally more than $10^{-9}$ meters per second. On the other hand, all of the combinations exhibited a hydraulic conductivity lower than $10^{-9}$ meters per second, making them ideal for use as a material for compacted landfill liners.
- After five cycles of soaking and drying, it was observed that soils containing 15% WTSA exhibited reduced cracking, while soils without WTSA showed an increase in cracking. Increased compactive effort mitigated the effects of swelling during hydration. The findings suggest that incorporating up to 15% WTSA may be effective as a landfill cover material in waste containment systems, promoting the beneficial reuse of this waste product. Furthermore, increased compaction is essential for enhancing material stability.

## 12. Declarations

### 12.1. Author Contributions

Conceptualization, M.Y.F. and K.Y.H.-S.; methodology, M.Y.F. and F.H.R.; validation, K.Y.H.-S..; formal analysis, K.Y.H.-S.; investigation, K.Y.H.-S., M.Y.F., and F.H.R.; resources, K.Y.H.-S.; data curation, K.Y.H.-S.; writing—original draft preparation, K.Y.H.-S.; writing—review and editing, M.Y.F. and F.H.R.; visualization, K.Y.H.-S. and M.Y.F.; supervision, M.Y.F and F.H.R.; project administration, M.Y.F. and F.H.R.; funding acquisition, K.Y.H.-S. All authors have read and agreed to the published version of the manuscript.

### 12.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

### 12.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

### 12.4. Conflicts of Interest

The authors declare no conflict of interest.

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