

Article

Sustainable Stabilization of Clay Soil Using Lime and *Oryza sativa*-Waste-Derived Dried Solid Digestate

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Abstract

Clay-rich soils are stabilized using fly ash, cement, lime, or solid waste with chemical activators to improve strength and reduce moisture-induced settlement. This study explores the stabilization of clay using lime and dried solid digestate (DSD) derived from food waste to improve its strength. A clay sample was treated with varying proportions of DSD (1–5%) along with 4.5% lime, by dry weight of soil. Samples were compacted at optimum moisture content and cured for periods of 0, 7, 14, and 28 days. The improvement in geotechnical behavior was assessed through Atterberg limits, unconfined compressive strength (UCS), and microscopic analyses, including X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR). Compared with untreated clay (62.03 kPa), the results show that adding 2% DSD and lime significantly increased compressive strength (446.5 kPa) and decreased plasticity by 69%. X-ray fluorescence (XRF) analysis revealed that the lime contained 81% of high calcium oxide (CaO), which supports pozzolanic and carbonation processes, whereas DSD served as a supplementary additive. Hence, the integration of DSD in soil stabilization offers a dual benefit: enhancing geotechnical performance and promoting environmental sustainability by diverting food waste from landfills and supporting circular resource use.

Keywords: clayey soil; lime; dried solid digestate; compressive strength; microscopic analysis



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1. Introduction

Soil stabilization techniques are applied to enhance the strength, durability, and workability of expansive soils, with the added benefit of lowering construction costs. Traditionally, stabilizing materials such as cement, lime, and fly ash have served as primary stabilizers to improve soil properties, particularly in road construction and earthworks projects. However, with rising demand for sustainable construction practices and waste management solutions, waste materials with binding characteristics are widely used as a secondary additive in soil stabilization in recent years.

Over two billion tons of Municipal Solid Waste (MSW) is produced per year worldwide due to urbanization and rising consumption standards, which endangers the ecosystem [1,2]. The developing country produces between 109.5 and 525.6 kg of MSW per person annually, while industrialized nations usually generate between 521.95 and 759.2 kg [3]. Waste from industries, construction, agriculture, wastewater treatment, and

other sectors contains valuable resources but remains untapped. Since these wastes are hazardous to the environment, immediate action is required to eliminate them. The transition to natural energy sources and strengthening waste management strategies for recycling and product recovery play a key role in mitigating this worldwide problem.

Anaerobic digestion (AD) is a highly effective method currently used for managing organic waste [4,5]; it is more efficient to convert organic waste into resources that can be used [6,7] for improving the economy with a reduction in greenhouse gas (GHG) emissions, water pollution, and the quantity of waste that ends up in landfills [8]. AD is a naturally occurring process, such as in the stomachs of cows, but it can be regulated and optimized in biogas plants to increase methane production. Biogas primarily consists of 45–75% methane (CH_4) and 25–55% carbon dioxide (CO_2), with trace amounts of hydrogen sulfide (H_2S) and hydrogen (H_2) [9]. AD produces digestate as a residual product, yielding approximately 0.20–0.47 tons per ton of food waste processed in a reactor [10]. The processed digestate has potential properties that can be used in the engineering field, reducing GHG in the environment. Research on digestate applications has progressed significantly, with early studies laying the groundwork for the usage of digestate in agriculture [8,11,12]. In recent years, the scope of research has expanded to broader applications in biofuel production and materials science [13,14]. The literature highlights emerging areas, such as biocomposite development [15] and crude protein recovery [16], reflecting growing innovation in the field. The progression of studies in these areas indicates an increasing interdisciplinary interest in digestate use, highlighting its function in a circular economy and sustainable waste management strategies.

Recent research has focused on applying the solid fraction digestate rather than whole digestate to minimize the environmental impact and facilitate broader applications, such as an alternative to mineral—and fossil-based amendments and fertilizers [10,17,18]. Solid digestate is recognized as a beneficial soil amendment; however, it must be sterilized or pasteurized to reduce its high microbial load and mitigate the potential increase in greenhouse gas emissions, particularly CO_2 [11,19]. With its economic value, constant availability, and recyclability, solid digestate holds significant potential to be valorized as a raw material in diverse applications. Few studies have explored potential strategies for managing the solid fraction of digestate within waste-to-energy technologies, particularly for solid biofuels [14]. This fraction undergoes further processing through thermochemical methods to generate syngas and pyrochars [12] or is subjected to additional anaerobic digestion (AD) to produce biomethane [20], bioethanol, and biodiesel [21].

Biochars derived from digestate have been recognized for their role in CO_2 capture [22], a precursor for advanced bio-adsorbents [23], and a raw material for supercapacitors [24,25]. Other emerging approaches include bioethanol and biodiesel purification [26], digestate pre-treatment to improve AD efficiency [27], and integration with value-added processes [28]. After proper treatment and chemical activation, the mineral composition of digestate, such as SiO_2 and Al_2O_3 , exhibits pozzolanic properties. It has potential as a pozzolanic material, enabling partial substitution of cement in civil construction [29].

Conventional additives, such as lime/cement with and without industrial byproducts, have been widely studied for clay stabilization; research on food-waste-derived dried digestate remains limited. In particular, the impact of digestate from *Oryza sativa* (rice) waste and cow dung, alone or in combination with lime, on the mechanical properties and long-term performance of expansive soils remains scarcely explored. This study addresses these gaps by investigating the potential of dried digestate to improve soil strength and stability, highlighting a sustainable alternative to traditional stabilizers.

Based on the application of digestate discussed and considering the research gap, this study focuses on utilizing solid digestate as a secondary additive along with the initial

consumption of lime (ICL) for expansive soil stabilization. Initially, the digestate was collected through anaerobic digestion of cooked rice waste (CRW) in a lab-scale method. A solid–liquid separation method is adopted to separate the digestate into liquid and solid portions. The solid digestate is then dried and added as a secondary additive to clayey soil along with the ICL to enhance soil strength. To conduct the experimental part, the samples were prepared with DSD contents ranging from 1% to 5%, along with 4.5% lime. Then the tests were performed on both untreated and treated clay after different mellowing periods to evaluate the influence of dried digestate on enhancing the index and mechanical properties of the clayey soil. Additionally, mineralogical, structural, and chemical analyses were performed using XRD (Empyrean, Panalytical, The Netherlands), SEM (EVO18, CARL ZEISS, Jena, Germany), and FTIR (IRAffinity-1, Shimadu, Japan) techniques. The combined findings confirmed the potential of DSD-lime treatment to improve soil performance for geotechnical applications and also contribute to sustainable land management by reducing waste and minimizing environmental impact.

2. Materials and Methods

The experimental work in this study was conducted in two stages. In the first stage, cooked rice waste (CRW) was shredded and anaerobically digested with cow dung as an inoculum in a laboratory-scale batch digestion to assess biogas production. The resulting substrate (digestate) was subsequently used for further characterization analysis. The second stage focused on examining the application of digestate obtained from the digester. The overall workflow of the study is illustrated in Figure 1.

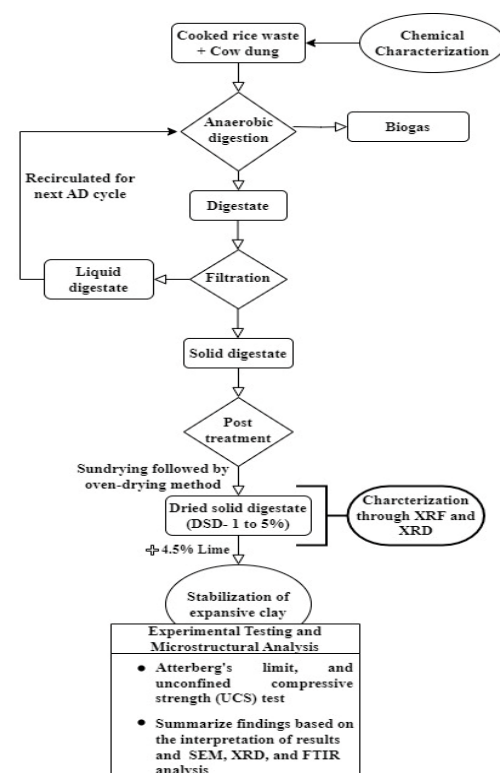


Figure 1. Flowchart of the experimental methodology used in this study.

2.1. Substrate and Inoculum

Only CRW was included in the current study to ensure consistency in the digestate application. After collecting the sample, the waste was chopped into small pieces to enhance biodegradation. Fresh cow dung (Bovine feces) was obtained from a local dairy farm and served as a microbial seed to initiate anaerobic digestion. Sodium hydroxide (NaOH) pellet

was procured from M/s Shyial Chemicals, Chennai, Tamil Nadu, India. It was added to maintain the optimal pH, and distilled water was used to adjust the total solids (TS) and volatile solids (VS) content. Total Solids (TS) and Volatile Solids (VS) were analyzed according to the APHA (American Public Health Association) standard methods [30]. The moisture content of the feed (cooked rice waste and cow dung) was determined by drying the samples in a hot air oven at 105 °C until a constant weight was obtained. For calculating TS, another portion of the sample was dried in an oven at 105 °C to a constant weight, and the remaining dry mass was recorded. A portion of the dried sample obtained from the TS test was then heated in a muffle furnace at 550 °C for 2 h to oxidize organic matter. The reduction in weight between the dried sample (105 °C) and the ash sample (550 °C) was recorded as the VS content of the feed. The carbon and nitrogen contents of the feedstock were determined using an Elemental Analyzer (PerkinElmer AD-6, PerkinElmer, High Wycombe, UK) to evaluate the substrate's suitability for biogas production.

2.2. Experimental Setup and Procedure

The anaerobic digestion (AD) process was carried out in plastic digesters operated under batch conditions, with working volumes of 1 L and 5 L. In one setup, the volume of biogas generated was determined using the water displacement technique. In another configuration, a collector was connected to the digester's outlet for gas sampling, which was later analyzed using Gas Chromatography (YL6500 GC, YL instruments, Gyeonggi-do, Korea) coupled with a Thermal Conductivity Detector (TCD). The instrument was controlled using Advanced Pneumatic Control (APC) by Clarity software (version 4.0.3.876). Helium gas was utilized as carrier gas, and sample injection was performed using a 0.2 mL manual gas-tight syringe. The initial temperature of the column was 40 °C, and it increased by 5 °C per minute to reach 250 °C. The schematic representation of the bench-scale AD setup used in this study is provided in Figure 2.

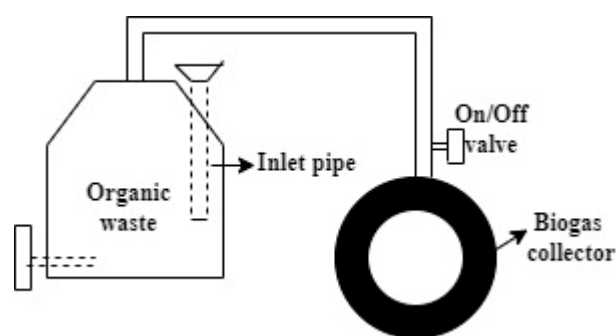


Figure 2. Schematic representation of the bench-scale apparatus used in this study.

The inoculum was prepared by mixing cow dung and distilled water in equal parts (1:1) and allowed to rest overnight. The CRW was collected, shredded, and mixed with inoculum in a 1:1 proportion. The initial pH of this mixture was adjusted to neutrality using NaOH, resulting in a stabilized pH of 7.01 on the day of the experiment. The reactor was loaded with the prepared substrate and sealed to maintain anaerobic conditions and operated at room temperature. The reactor was operated for a hydraulic retention time (HRT) of 30 days, during which it was manually agitated twice daily. It was observed that for 23 days, the generation of biogas production was significant, and the reaction became stable. However, the gas was collected for 30 days and quantified using the water displacement method. The resulting digestate was then pretreated to separate into solid and liquid components. The liquid fraction rich in micronutrients and microbial content can be reused as an inoculum for subsequent AD cycles. The solid fraction was dried to

halt microbial activity, and the dried solid digestate is a potential supplementary material in soil stabilization.

2.3. Soil Stabilization

This research focuses on enhancing the strength and durability of clay soil through stabilization using hydrated lime and dried solid digestate (DSD). Natural clay was sourced from the Thayur lakebed in Kalavakkam, Chennai. The collected soil was air-dried and sieved to eliminate coarse particles. Its geotechnical and mechanical properties were evaluated in accordance with the Bureau of Indian Standards (BIS) code [31–34]. In this study, hydrated lime (M/s Shyial Chemicals, Chennai, Tamil Nadu, India) served as the primary additive, and the initial consumption of lime (ICL) was determined as 4.5%. The chemical composition of the stabilizing materials was analyzed using XRF (EPSILON-1, Malvern Panalytical, Worcestershire, UK). XRF analysis revealed that lime contains 81% calcium oxide (CaO) [35], which is essential for the carbonation reaction.

DSD was incorporated as a secondary additive in varying proportions (1%, 2%, 3%, 4%, and 5%) combined with ICL (4.5%) by dry weight of soil. Cylindrical specimens measuring 38×76 mm were prepared to evaluate the unconfined compressive strength (UCS) of clay amended with DSD and lime. The maximum dry density (MDD) and optimum moisture content (OMC) of the treated clay–DSD with lime blend were determined using a mini-compaction test [36]. Based on the MDD and OMC of untreated clay, the required soil mass was calculated. DSD and lime were manually blended with dry clay, followed by the addition of water to achieve the target moisture level. For each mix ratio of DSD and lime, three specimens were cast and cured for 0, 7, 14, and 28 days. Samples were stored in airtight bags at room temperature (28 ± 2 °C) to prevent moisture loss during curing time. After curing, axial compression tests were conducted at a strain rate of 1.25 mm/min using a 40 kN loading frame. The mix proportion yielding the highest UCS was identified as the optimum additive dosage.

To assess the effectiveness of the stabilization process, various tests were performed, including Atterberg limits, unconfined compressive strength (UCS), and microscopic analyses such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR). The experiments were conducted in triplicate, and the resulting data were analyzed to evaluate the improvements in the engineering properties of the stabilized clay.

3. Results and Discussions

Several approaches to waste management exist, including anaerobic digestion. Studies have shown that the synergistic interactions between the digestion of food waste (cooked rice waste) with cow dung promote methane formation. The maximum potential for methane generation can be assessed, and with appropriate post-digestion processing, the digestate can be utilized to improve soil stability.

3.1. Characterization of Feed and Digestate

The samples were characterized by examining the physical and chemical properties, as shown in Table 1. Assessing feedstock characteristics is essential to the anaerobic digestion (AD) process since it influences the amount and composition of biogas generated and its energy content [37]. The moisture content of cooked rice waste and cow dung was determined by drying at 105 °C for 24 h. The total solids (TS) and volatile solids (VS) of both cooked rice waste (CRW) and cow dung (CD) were measured in triplicate, and the average values are presented in Table 1.

Table 1. Initial assessment of cooked rice waste and cow dung properties.

Chemical Characterization	Feed	
	Cooked Rice Waste	Cow Dung
Moisture content (%)	77.95 ± 0.3	80.58 ± 0.2
pH	5.47	6.75
TS (%)	22.01 ± 0.4	19.41 ± 0.1
VS (%)	19.39 ± 0.1	15.24 ± 0.2
VS/TS	87.93	78.52
Carbon (%)	45.56	38.47
Nitrogen (%)	1.328	2.14
C/N ratio	34.31	17.98

The cooked rice waste had a high moisture content of 77.95% and a slightly acidic pH (5.47), with an average total solid (TS) content of 22.05%. The cow dung (CD) exhibited a moisture content of 80.58%, a near-neutral pH (6.75), and a moderate C/N ratio of 17.98:1. CD had an average TS of 19.41% and a VS of 15.24% [38]. The moisture content ranged from 68% to 80%, indicating that the feed had sufficient moisture for anaerobic digestion [39]. The average total solids (TS) content of cooked rice waste is 22.01%, within the typical range of 7.62% to 23.70% for food waste reported in the literature [40–42], and 20–22% of TS is considered to attain optimal volumetric productivity in anaerobic digestion (AD) systems [43]. A volatile solid (VS) to TS ratio greater than 80% indicates an abundance of biodegradable organic material, which promotes microbial activity and increases biogas production [44].

Microbial growth depends on the nutrients carbon (C) and nitrogen (N), with carbon acting as an energy source and nitrogen being necessary for the synthesis of proteins and nucleic acids [45]. A low C/N ratio results in excessive ammonia and volatile fatty acids (VFAs), preventing anaerobic digestion (AD) [46]. In contrast, a high C/N ratio can slow biodegradation [47]. Rice waste has a high carbon content (45.6%), while cow dung has a more balanced composition and helps to change the overall C/N ratio to the optimal range of 20–30% [48,49]. This improved balance supports efficient microbial activity and increases biogas generation.

3.2. Biogas Production from a Small-Scale Digester and pH Effect

At a temperature of 28 ± 2 °C, the experiment investigated the digestion of CRW and CD using a substrate-to-inoculum ratio of 1:1. Ojewumi et al. [50] state that single substrates often fail to provide sufficient buffering capacity and nutrients that hinder anaerobic digestion. In this process, cow dung serves as a source of microbes for ensuring the stability of the digestive process. At the same time, CRW contributes readily degradable organic matter as a high-energy substrate, enhancing biogas generation [51].

Two separate setups were prepared for the degradation process to facilitate biogas production. Of the two digesters, one was designated for measuring the volume of gas produced using the water displacement method, and the other was utilized for collecting gas samples for composition analysis. The digesters were manually shaken twice daily to promote homogeneity. Gas measurements were recorded at 24 h intervals. Biogas production was monitored over 30 days. The most effective methane synthesis during anaerobic digestion occurs when the system's pH remains between 6.5 and 7.5. During the experiment, the pH was maintained consistently above 6.5 to create favorable conditions for microbial activity [52,53]. The changes in pH and biogas production throughout digestion are depicted in Figure 3.

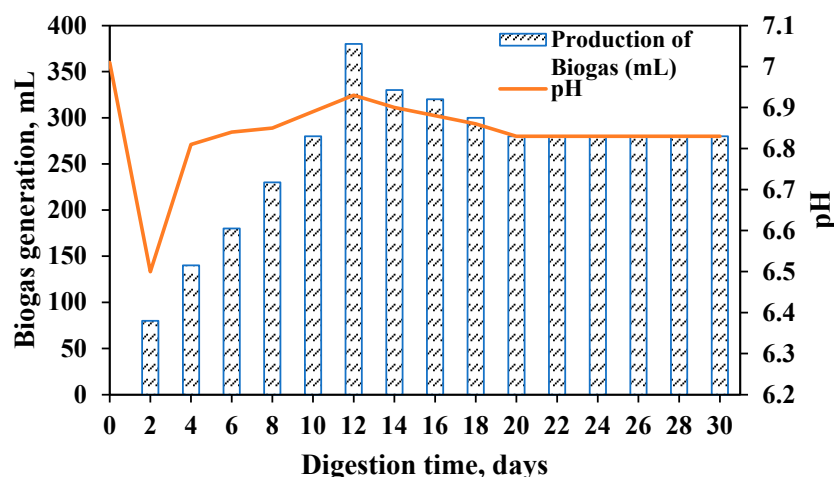


Figure 3. Variation in biogas production and pH for AD of CRW during the 30-day digestion period.

The lag phase of microbial growth resulted in lower biogas generation during the first two days of monitoring. However, because methanogens multiply exponentially, biogas output significantly increases during the 4th to 14th day. On day 14, the maximum amount of biogas produced (380 mL) was recorded. After the 20th day of digestion, consistent gas production is attained until the 30th day, and the maximum gas production occurs in the neutral pH range of 6.88 to 6.93. This happened due to insufficient or depleted substrate, which serves as a nutrient for methanogenesis during biogas generation [54]. A similar trend was observed, with the results indicating that digester gas production (210 mL) was stabilized after the 15th day and peaked by day 30 [55]. After the biogas was produced, it was collected in a tube, linked to another digester setup, and its composition was examined using gas chromatography (GC). The result revealed that the biogas contained 53.65% methane (CH_4), 45.52% carbon dioxide (CO_2), and 0.83% hydrogen sulfide (H_2S). These findings indicate that the biogas is combustible, as its methane content exceeds 50% of the total composition [56]. However, the biogas produced in this study is not feasible for commercial applications due to its methane concentration of 54%. A methane content exceeding 70% is necessary for biogas to be suitable as a biofuel in combined heat and power (CHP) systems [57,58]. Nevertheless, the methane level in the obtained biogas makes it suitable for cooking and heating applications [59]. Rahman et al. found that co-digesting kitchen and poultry waste at 37 °C enhanced methane content and increased biogas production by 16% compared with digestion at room temperature [60].

3.3. Characterization and Application of Solid Residue Digestate

Digestate is another byproduct of the AD process, whose form and composition vary based on the input feedstock. The direct application of digestate as a value-added resource in agricultural or industrial sectors was limited due to its high microbial levels. Hence, with proper treatment, digestate can be effectively converted into a valuable resource that ensures the safety and sustainability in recycling applications [61].

In this study, the solid fraction was separated from the digestate through a dewatering process, such as filtration and subsequent drying using the natural evaporation method. After that, the sample was kept in an oven at 105 °C until a stable mass was achieved. This is helpful to avoid inconvenience for further storage, transport, and utilization of digestate [62]. This treatment not only reduced the water content of the solid digestate but also improved its overall quality. Prolonged thermal exposure promotes the inactivation of pathogenic microorganisms present in untreated digestate. The combined effect of heat and moisture removal restricts microbial survival and subsequent regrowth, thereby enhancing the hygienic safety of the material [63]. Michele et al. reported that the organic fraction

of municipal solid waste (OFMSW) subjected to AD followed by one week of biodrying/biostabilization yielded a high-quality output material that was free from pathogenic indicators such as *Salmonella* and *Escherichia coli* [64]. Hence, the resulting material is thus safer for handling and more suitable for reuse in geotechnical applications.

3.3.1. Chemical Composition and Mineralogical Study of Dried Solid Digestate

The dried solid digestate (DSD) is ground to obtain a uniform size and used as a secondary additive in soil stabilization after characterization through XRF and XRD. The chemical composition of DSD was analyzed through XRF, as listed in Table 2.

Table 2. Chemical composition of DSD and clay.

Elements in Oxide Form	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	SO ₃	P ₂ O ₅	TiO ₂	MnO	Cr ₂ O ₃
DSD, Wt. %	40.99	10.96	14.77	13.01	8.24	4.44	3.38	1.11	0.20	0.15
Clay, Wt. %	66.00	20.00	1.70	8.80	1.80	0.12	-	1.32	0.11	-

According to the analysis, SiO₂, Al₂O₃, CaO, and Fe₂O₃ are the major components found in the DSD. The next most significant quantities are K₂O, SO₃, and P₂O₅, and trace amounts of other elements such as TiO₂, MnO, and Cr₂O₃ are present in the DSD. Materials that contain SiO₂ or a combination of SiO₂ and Al₂O₃ are referred to as pozzolans, and they are not capable of binding on their own. On the other hand, it chemically reacts with lime at room temperature when finely distributed and exposed to water, producing compounds that exhibit binding properties. These properties ensure that the pozzolans are used to manufacture building materials such as brick, ceramics, and SCM [65].

The organic fraction of the DSD was assessed through the Loss on Ignition (LOI) method. The dried sample was combusted in a muffle furnace at 560 °C for 2 h. The measured LOI value was 45.6%, indicating a moderate proportion of residual organic matter, which reflects a moderate level of stabilization and a significant mineral fraction.

Based on various studies, the mineral composition system of sludge and sludge ash is plotted as a ternary diagram (Figure 4). From the plot, the primary oxide component values (SiO₂—32.8%; CaO—14.3%; Al₂O₃—14.2%) of sewage sludge ash (SSA) represent an average of 215 samples from 135 articles (1972–2017) across Europe, Asia, North America, and Africa. This implies that SSA could be used as a cementitious substance in soil stabilization, mortar, and concrete.

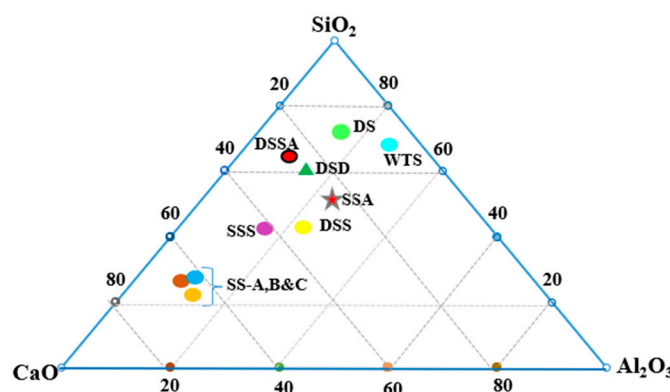


Figure 4. Ternary diagram of CaO-SiO₂-Al₂O₃ composition system of sludge, sludge ash, and DSD, where SS—sewage sludge (from Plant A, Plant B, and Plant C), SSS—solid sewage sludge, DSS—dehydrated sewage sludge, SSA—sewage sludge ash, DSSA—dewatered sewage sludge ash, DS—dried sludge, WTS—water treatment sludge [66–70].

Similar mineral compositions in clay and PC (Portland cement), including CaO , SiO_2 , Al_2O_3 , and Fe_2O_3 , are found in the sludge [71,72]. The concentration of this oxide composition in the sludge and sludge ash varies based on the source and chemical treatment adopted. Pretreatment processes, such as dewatering and thermal treatment, further improved their properties. Similarly, the oxides of elements such as Si, Al, Ca, and Fe in the DSD are essential factors that influence pozzolanic activity when added as a stabilizer in soil stabilization.

3.3.2. XRD Analysis of DSD

The diffraction pattern of DSD is shown in Figure 5. It displayed the presence of a crystalline phase, accompanied by an amorphous peak with a small hump. The predominant minerals found in DSD are Quartz (Q), Calcite (Ca), and Kaolinite (K). According to literature, the diffraction angles at $2\theta = 26.5, 32.9, 40.2, 45.9, 50.1, 60,$ and 68.4° were referenced as quartz (SiO_2), the observed peak at $2\theta = 29.5, 39.5,$ and 42.3° were identified as Calcite (CaCO_3), whereas the other peak formed at 27.9° referred as muscovite ($\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$) [73–76].

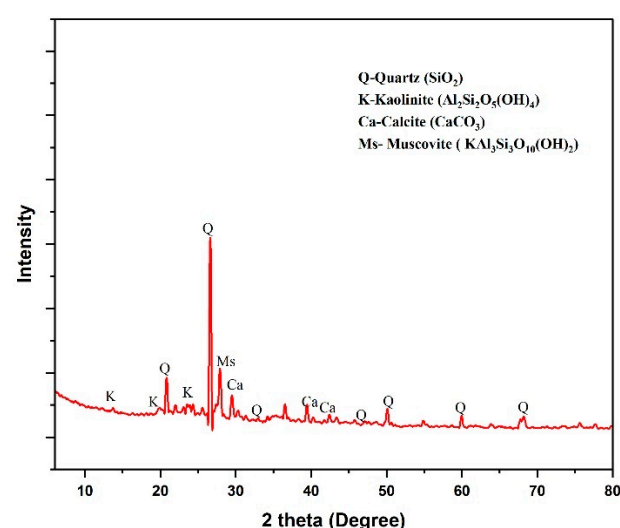


Figure 5. Identification of mineral phase in dried solid digestate by XRD analysis.

DSD's chemical composition significantly influences its mineral phases and reactivity in soil stabilization. Reactive minerals, including calcium-rich phase (calcite) and kaolinite (aluminosilicates), are observed to enhance pozzolanic reactions [77], which in turn increases the strength and durability of soil. As a result, DSD is to be used as a secondary additive for geotechnical applications [78].

3.4. Characterization of Clayey Soil (Chemical, Engineering, and Mineralogical Aspects)

Following the study on the characterization of DSD, it is essential to analyze the properties of clayey soil to understand the behavior and interaction with additives (DSD and ICL). The chemical composition of clay is analyzed through XRF and reported in Table 2. The result reveals that the main constituents, SiO_2 and Al_2O_3 , highly influence the reactivity of clay when it is mixed with a suitable activator such as lime and pozzolanic material like DSD. The presence of such components is confirmed through the XRD profile of the clay [79].

From a geotechnical perspective, the clay's properties provide insight into the necessity of stabilization. These characteristics have been previously analyzed in an earlier study [35], following the procedure specified in the relevant BIS codes. The analyzed soil sample consists of 39% clay, 52% silt, and 9% sand. Atterberg's limits indicate a liquid limit (LL) of

76% and a plasticity index (PI) of 52%, classifying the soil as high plastic clay (CH). It has a maximum dry density (MDD) of 12.5 kN/m³, an optimum moisture content (OMC) of 32%, and an unconfined compressive strength (UCS) of 62 kPa, measured per BIS 2720: part 10 guidelines [34]. The PI value of 52% highlights its capacity to retain water. This leads to difficulty in construction applications and exacerbates its tendency for swell and contract behavior. Therefore, the stabilization method is required to improve its load-bearing capacity and minimize changes in volume [80].

The mineral composition of the clay and lime was examined using X-ray diffraction, with the resulting XRD profiles presented in Figure 6a,b. The analysis revealed that the clay consists of quartz (Q), kaolinite (K), and illite (I) as the main mineral phases. These phases were identified by comparing the observed peaks in the XRD patterns with those reported in previous studies. Peaks observed at 2θ values of 20.6°, 26.9°, 50°, and 68.1° correspond to quartz, while peaks at 27.7° and 42.4° indicate the presence of illite, and a combination of kaolinite–illite–quartz, respectively [81,82]. The observed minerals affect the soil's chemical and physical properties, including its swell-shrinkage behavior and cation-exchange capacity. According to Supandi et al. (2019), the findings revealed that illite's presence increases natural moisture content, void ratio, and wet density while reducing cohesion, friction angle, and strength of clay materials [83]. The XRD pattern of lime (Figure 6b) shows a higher intensity peak corresponding to calcium hydroxide and a lower intensity peak corresponding to calcium carbonate, indicating that calcium hydroxide is the dominant mineral phase in the lime sample.

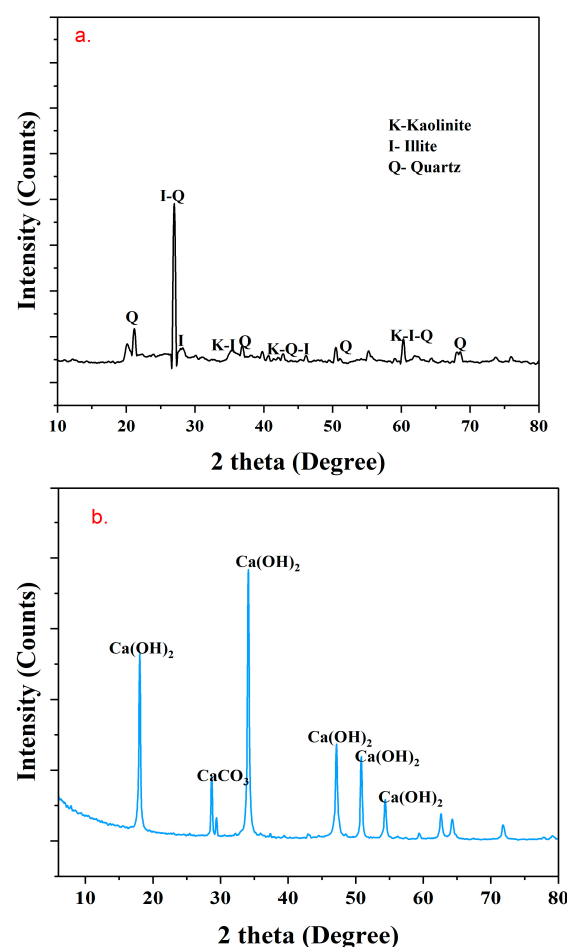


Figure 6. Mineralogical composition of (a) clay and (b) lime using XRD analysis.

The mineralogical and geotechnical properties of clay suggest the need for stabilization to make it suitable for engineering applications. As previously examined on the properties of DSD, the additives in clay enhance its mechanical characteristics by facilitating pozzolanic reactions. Additional experimental research focusing on strength improvement and microstructural changes could offer valuable insights into the role of DSD in stabilizing clay.

3.5. Impact of Additives on Plasticity Index, Compaction, and Strength of Clay

The stabilization mechanism of clayey soil was changed by combining 1% to 5% DSD with 4.5% lime. The impact of alteration on plasticity, compaction characteristics, unconfined compressive strength (UCS), and microscopic analysis was investigated in this study.

3.5.1. Atterberg's Limits

The plasticity characteristics of soil are typically defined by Atterberg's limits, including the liquid limit (LL), plastic limit (PL), and plasticity index (PI), which is the numerical difference between LL and PL. Figure 7 illustrates the variations of LL, PL, and PI in response to DSD-lime treatment on clayey soil after a 28-day curing time. The graph shows that the addition of DSD along with lime significantly reduces the LL and PI compared with untreated clay (denoted as C in Figure 7). The clay exhibited an LL of 75.8%, PL of 23.5%, and PI of 52.3%. At 1% DSD with 4.5% lime mix, the LL reduced to 53.5% and PI decreased to 23.9%. The results show that increasing DSD content with ICL from 1% to 5%, the LL and PI decrease, with the minimum of 47.6% and 16.4% observed at 2% DSD, indicating optimal plasticity reduction. Similarly, the PL gradually increased from 23.5% to 31% at 2% DSD with 4.5% lime mix, reflecting enhanced soil workability.

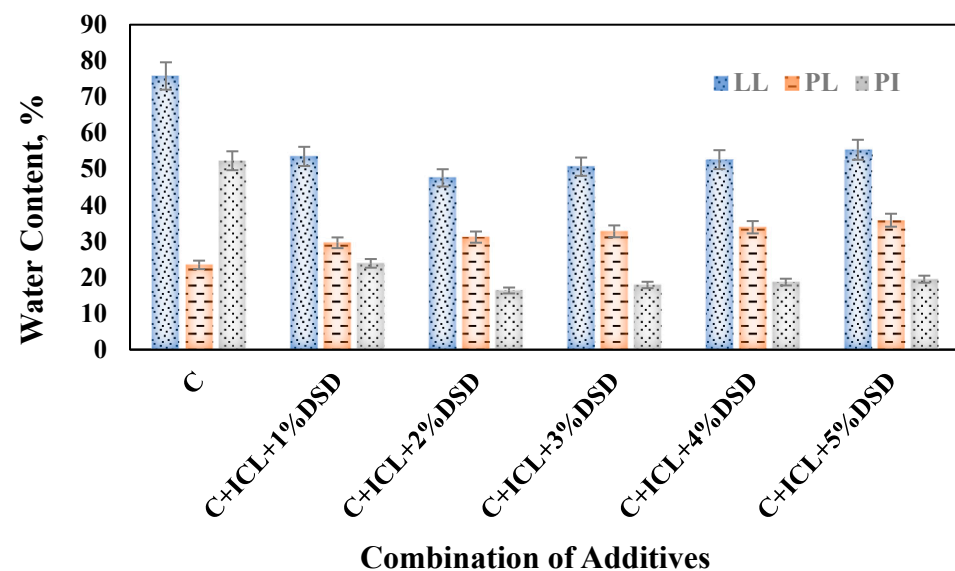


Figure 7. Effect of additives on Atterberg's limit of clayey soil.

It acts as a filler rather than significantly contributing to water holding, reducing LL and the organic content in the DSD, making LL and PI increase at a higher percentage. This is similar to the observation made when filter sludge from the sugarcane industry is used to improve the UCS strength of expansive clay [84].

ICL causes clay particles to flocculate, resulting in the formation of coarser aggregates, which decreases water retention and lowers LL. Cementitious products are created when pozzolanic reactions are triggered by the lime's reaction with the clay and DSD. These substances stabilize the clay and reduce its plastic behavior, contributing to the PI decrease.

ment [85]. The combined effects of flocculation, structural change, and decreased water adsorption improved the clay's overall stability and workability. This is due to the addition of minor DSD and ICL, which lowers LL and PI [86].

Incorporating an increased proportion of dried solid digestate into clay results in higher LL, PL, and PI. This is attributed to the fine particle size and organic matter in the DSD, which improve the soil's water retention capacity and enhance its plastic characteristics. The presence of hydrophilic components broadens the moisture range in which the soil remains workable, thereby raising its consistency limits. Consequently, higher DSD content elevates soil plasticity, potentially influencing workability and shrink–swell behavior, and necessitating careful optimization of the DSD dosage for engineering applications [87].

3.5.2. Compaction Characteristics

The mini-compaction test was conducted to determine the optimum moisture content (OMC) and maximum dry unit weight (MDD) for clay soil mixed with varying percentages (%) of DSD and ICL. The optimum water content initially decreased with increasing DSD content, reaching its lowest value at 2% DWTS. The filler effect of DSD, which lowers the amount of free water available for lubricating soil particles, is responsible for this decrease. At first, adding DSD and lime increased the dry unit weight, reaching a peak at 2% DSD (13.2 kN/m^3). After this, the maximum dry unit weight started to drop. The dry unit weight decreased to 12.35 kN/m^3 , 12.19 kN/m^3 , and 12.05 kN/m^3 with an increase in DSD. This reduction in maximum dry unit weight is likely due to the formation of additional voids and a decrease in the cohesion between soil particles as the DWTS content increases. The excessive presence of DWTS may have disrupted the soil matrix, resulting in lower compactness and reduced densification efficiency.

The test findings (Figure 8) show that the soil's densification properties improved up to 2% DSD substitution. The dry unit weight declined, and the ideal water content increased at 3%, 4%, and 5% combination mix of DSD with ICL. As reported by Noorzad and Motevalian, with increasing sludge content, the maximum dry density improved; however, when the lime-to-sludge ratio reached 90:10, a slight decline in maximum dry density was noted [88]. This suggests that an overabundance of DSD hinders compaction efficiency by increasing the soil's water demand and reducing its particle packing capacity.

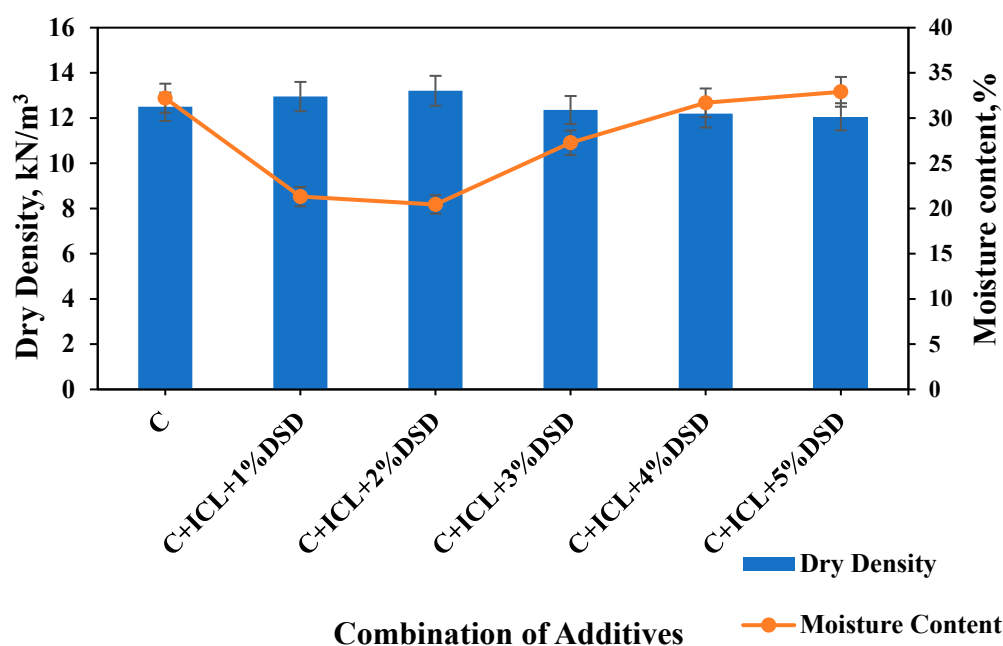


Figure 8. Effect of additives on clay's compaction properties.

3.5.3. Compressive Strength of Clay

Unconfined compressive strength (UCS) tests were conducted with varying amounts of additives (1–5% of DSD + 4.5% lime), as shown in Figure 9, to evaluate the strength of the mixed clayey soil. The results indicate that for different dosages of DSD, the UCS of the sample cured for 28 days is significantly higher than those cured for 0, 7, and 14 days. The strength of clayey soil modified with 1%, 2%, 3%, 4%, and 5% DSD and lime exhibited a significant improvement, increasing from 72.43 kPa to 374.1, 446.5, 298.5, 287.2, and 209.1 kPa at 28 days for the DSD-lime-treated samples. Similar observations were found by Umar et al. [89], Taki et al. [86], and Alrubaye et al. [90]. The highest compressive strength was observed at 2% DSD with ICL (446.5 kPa) across different curing periods, beyond which the strength gradually declined. A comparable trend was noted in the research conducted by James et al. [91] and another study by James and Pandian (2016), where the incorporation of 0.25% sugarcane press mud as a secondary additive in ICL-stabilized soil resulted in a 27.05% increase in strength [92]. As reported by Çetin et al. (2024), the combination of 1% FS (Ferrochromium Slag) and 1% AG (Agar Gum) biopolymers significantly increased the unconfined compressive strength (UCS) of clay soil from 175.5 kPa to 258.9 kPa after 21 days of curing. This improvement is attributed to the synergistic effect of both additives, enhancing particle bonding and soil stability [93]. This finding supports the observed improvement in our study, suggesting that the addition of suitable secondary stabilizers significantly enhances soil strength and stability.

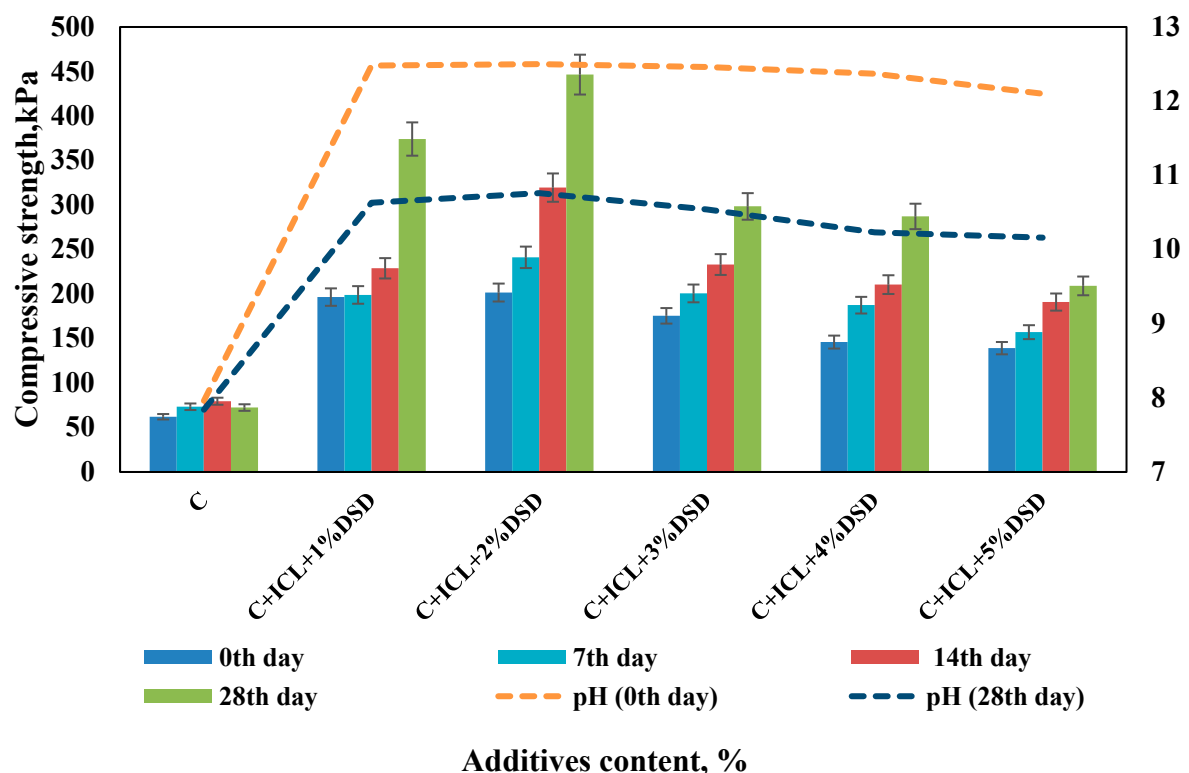


Figure 9. Effect of additives on strength and pH of clay after curing period of 0, 7, 14, and 28 days.

When soil is blended with varying proportions of additives such as DSD with ICL at the optimum water content, chemical reactions occur, producing pozzolanic materials in an alkaline condition. The resultant substances fill the space between clay particles, bond the clay grains, and contribute to strength development [85,94]. The CaO content in DSD and lime (81%) is essential for initiating hydration, which produces Ca(OH)_2 when mixed with water. Increased Ca(OH)_2 enhances the pozzolanic reaction for CSH (calcium

silicate hydrate) and CASH (Calcium Aluminum Silicate Hydrate) formation. This process effectively modifies the soil structure and significantly improves the strength of clay.

The primary physicochemical interactions affecting the engineering properties of clay stabilized with DSD and lime include cation exchange, flocculation of clay particles, pozzolanic reactions, and particle agglomeration. The charge neutralization effect of lime and dried sludge facilitates soil particle agglomeration, improving cohesion and strength development through pozzolanic activity. Lime-driven cation exchange and dissociation reactions enhance soil workability by reducing plasticity and promoting flocculation. When dried digestate contains reactive silica and alumina, it further contributes to soil stabilization through pozzolanic actions, leading to increased strength and durability.

3.6. Microscopic Analysis of Stabilized Clay

Clay stabilization involves chemical and physical modifications that modify the soil's mineralogical composition and microstructure, thereby enhancing its engineering properties. The effectiveness of stabilization depends on the interactions between clay minerals and stabilizing agents, which are examined in this section through SEM, XRD, and FTIR analyses.

3.6.1. SEM and EDS

Figure 10 depicts the microscopic image of a stabilized clay containing 2% DSD + ICL after 28 days of curing. This illustrates the microstructural alterations in the DSD-lime-supplemented clay matrix due to the progression of the pozzolanic reaction between the clay and additives. As illustrated in Figure 10a, which displays distinct particles in natural clay and indicates the absence of an integrated structure in the clay, this supports the UCS value of 72.43 kPa. After the 0- and 28-day curing periods (Figure 10b,c), the natural clayey soil structure has transformed from a particle-based form into a more compact and interlocked structure due to cation exchange reactions and the formation of CSH and CASH. According to Bagriacik and Guner's study, the clayey soil's bearing capacity is increased by multiaxially distributed clusters following the addition of DWTS [95]. Based on Modarres and Nosoudy's findings, the formation of CSH due to a reaction between the additive and soil resulted in higher compressive strength and California Bearing Ratio (CBR) value [96]. Prior research indicates that the structural transformation of clay particles improves their workability and load-bearing capacity.

The EDS analysis revealed a significant variation in the elemental composition of clay before and after stabilization, as presented in Table 3, revealing notable changes resulting from the 28-day curing process. This analysis was performed using a Quantax 200 equipped with an Xflash 6310 (Bruker, Billerica, MA, USA) detector.

Calcium content increased significantly from 1.2 wt% (0.6 at%) to 11.9 wt% (5.84 at%), indicating effective lime incorporation and the formation of calcium silicate hydrate (CSH), calcium alumino silicate hydrate (CASH), and calcite, as confirmed by XRD analysis. Carbon and oxygen contents remained relatively constant, while slight increases in silicon and aluminum suggest the development of additional silicate and alumina reaction products [97]. Hence, these findings confirm that pozzolanic reactions and additive interactions contributed to the chemical transformation of the clay matrix, enhancing its mechanical performance after stabilization.

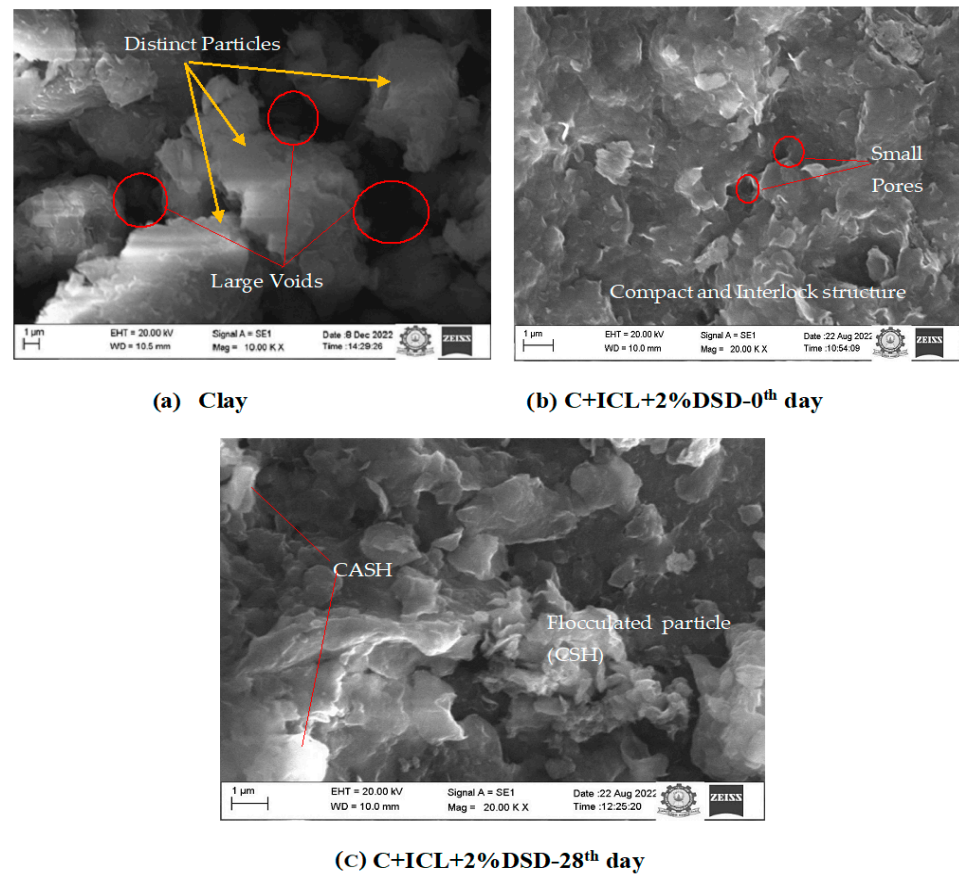


Figure 10. Impact of additives on morphological changes in clayey soil after 28 days of curing.

Table 3. Effect of additives on clay's elemental composition after 28 days of curing.

Element	Clayey Soil		Stabilized Clay (2% DSD + 4.5% Lime)	
	Weight %	Atomic %	Weight %	Atomic %
C	13.0	21.2	11.1	18.2
O	45.3	55.4	45.1	55.4
Si	16.3	11.4	17.4	12.2
Al	5.8	4.2	7.2	5.3
Ca	1.2	0.6	11.9	5.8
Mn	1.8	0.6	-	-
K	0.8	0.4	1.1	0.9
Fe	14.0	4.9	5.4	1.8
Ti	0.4	0.2	-	-

3.6.2. XRD

The diffraction pattern from XRD analysis gives insight into the changes in mineralogical composition in clay stabilization using dried solid digestate and lime, as shown in Figure 11. The natural clay's primary mineral constituents were illite (I), kaolinite (K), and quartz (Q). The addition of dried digestate introduced quartz (Q) and muscovite (MS), and lime provided calcium hydroxide and calcite (Ca). The composition of the DSD-lime-treated clay was muscovite (MS), calcite, quartz (Q), and kaolinite (K). The reduction in peak intensities of Q, K, and I in the stabilized clay can confirm the development of cementitious bonding due to partial dissolution and reaction with additives.

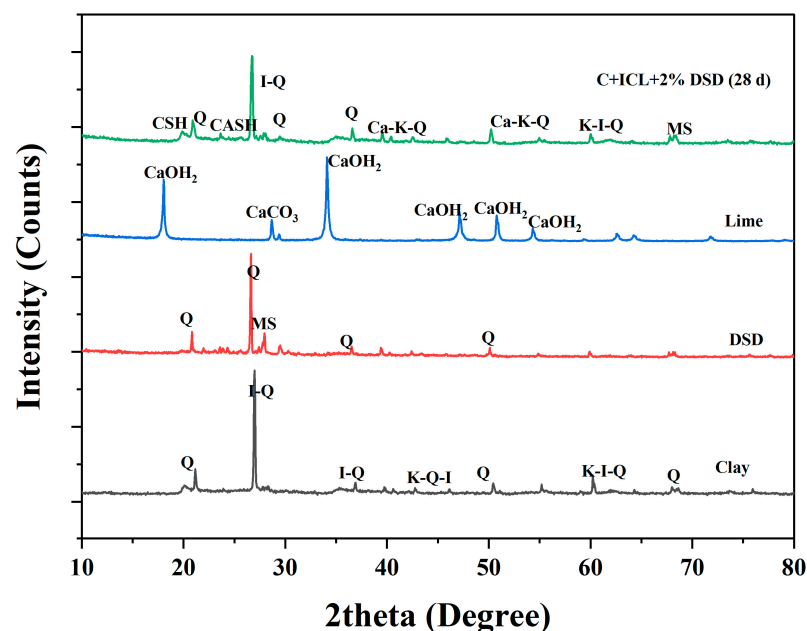


Figure 11. X-ray diffraction pattern of stabilized clay using additives after 28 days of curing.

The XRD analysis of the stabilized clay revealed small humps at $2\theta = 23.6^\circ$, 29.6° , and 50.4° , corresponding to the formation of CASH gel, quartz, and calcite, respectively [35]. The appearance of CASH at 23.6° 2θ after 28 days of curing indicates a pozzolanic reaction between the clay minerals, lime, and additives, which enhances the soil's strength. A reduction in the peak intensity at 27.7° suggests that the corresponding clay minerals participated in the pozzolanic reactions, while slight increases in the intensities at 19.8° and 50.4° indicate the formation or crystallization of new phases, such as CSH gel and calcite [79]. These reactions collectively contribute to the improvement in strength and the reduction in plasticity of the stabilized clay after 28 days of curing.

When hydrated, CaO from lime forms $\text{Ca}(\text{OH})_2$, which reacts with atmospheric CO_2 to produce CaCO_3 , enhancing soil particle bonding and strength. The interaction of calcite and portlandite with wet clay and quartz from sludge promotes ion dissociation (calcium, silicate, aluminate, hydroxide), leading to flocculation and agglomeration [85]. The adsorption of Ca^{2+} by negatively charged clay and sludge particles improves cohesion, resulting in a denser microstructure and enhanced mechanical strength of stabilized clay [98].

3.6.3. FTIR Analysis

The DSD used as a secondary additive contains organic and inorganic components that interact with clay and lime over 28 days of curing, as depicted in Figure 12. These interactions can improve structural integrity or alter the chemical composition of the stabilized clay, as evidenced by peak reductions in the FTIR results. Peaks of 3621.1 and 3639.3 cm^{-1} correspond to O-H stretching, typically associated with hydroxyl groups in clay minerals such as kaolinite. H-bonded O-H stretching and water-related O-H deformation were observed at 3389.2 cm^{-1} and 1632.8 cm^{-1} , respectively [99,100]. Peaks at 990.9 , 776.4 , and 690.2 cm^{-1} indicate Si-O stretching vibrations and deformation or bending of Si-O or Al-O groups [101]. The presence of carbonate from lime, represented by C-O stretching, was identified at 1424.7 cm^{-1} , while the peak at 875 cm^{-1} corresponds to calcite or O-C-O stretching vibrations [35]. These findings suggest that the reactions between lime, DSD, and clay result in the formation of stabilized products, consuming water, hydroxyl groups, and carbonates while modifying the silicate and aluminosilicate structure, ultimately enhancing the properties of the stabilized clay.

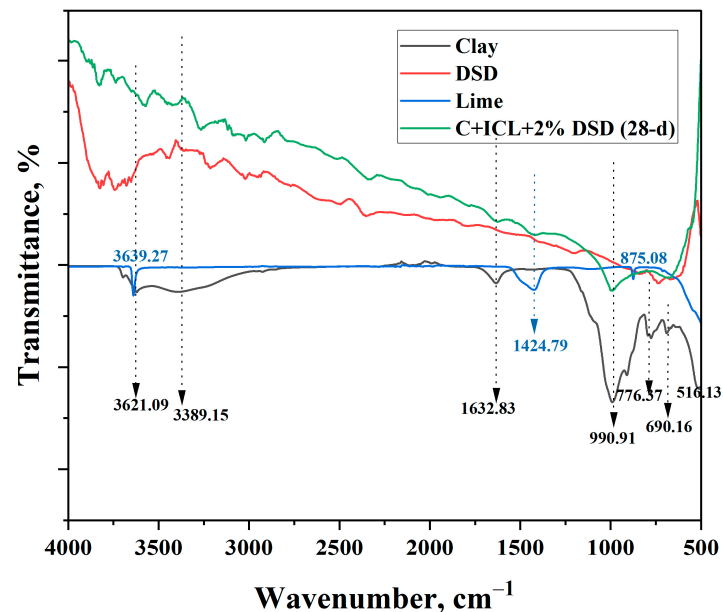


Figure 12. FTIR spectrum of stabilized clay using additives after 28 days of curing.

4. Conclusions

The experimental results confirm that the combined application of hydrated lime and dried solid digestate (DSD) led to notable improvements in the geotechnical behavior of natural clay soil. The following conclusions were derived from experimental and microscopic studies.

- The optimum blend, comprising 4.5% lime and 2% DSD in clay, increased unconfined compressive strength (UCS) from 72.43% to 446.5% and reduced the plasticity index from 52.3% to 11.4% after 28-day curing.
- An innovative feature of this research is the use of DSD produced from cooked rice waste as a sustainable, non-traditional stabilizer, contributing to waste recycling and reducing reliance on conventional chemical stabilizers.
- The stabilization process is driven by lime hydration and carbonation reactions that form calcium carbonate. At the same time, DSD provides reactive minerals that promote ion exchange and pozzolanic reactions, thereby enhancing soil structure and cohesion.
- Microstructural studies using XRD, SEM, and FTIR techniques confirmed the formation of particle agglomeration and flocculation, as well as the development of cementitious materials such as CSH, which supports the observed improvements in soil strength.
- These findings underscore the potential of incorporating waste-based materials in sustainable soil improvement strategies for geotechnical applications.

In this study, the dried solid digestate was generated solely from cooked rice waste as a representative organic substrate to ensure consistent and reproducible results. Although this approach provides useful preliminary insight into the potential of food waste-derived digestate for soil stabilization, it does not capture the compositional variability of actual food waste. Future work should investigate the use of mixed real food waste as feedstock for digestate production to improve the applicability and practical significance of the stabilization method.

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alization, validation, resources, writing—review and editing, and supervision; S.P.P.K., experimental studies. All authors have read and agreed to the published version of the manuscript.

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