ASEAN Engineering Journal

Full Paper

MECHANICAL AND MICROSTRUCTURAL IMPACTS OF LIME SLUDGE ON POND ASH AS A FILLER MATERIAL

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Article history
Received
20 February 2025
Received in revised form
04 October 2025
Accepted
16 March 2026
Published online
31 August 2026

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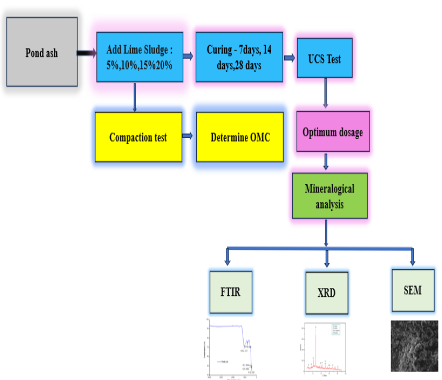
Graphical abstract



Abstract

Pond ash, a residue generated from thermal power plant operations, presents significant environmental challenges and land management issues in its disposal. Lime sludge is also a by-product of water softening and paper mill industries, with few applications in the agriculture and construction industries. This study investigates the influence of the dosage of lime sludge on the mechanical, chemical and microstructural properties of pond ash for its applications as filler material. This research considered lime sludge dosage in 5%, 10%, 15%, and 20% as the variable. The optimum moisture content was evaluated for all dosages using compaction tests. The unconfined compressive strength of the samples after 7 days,14 days and 28 days was assessed to determine the optimum dosage. Unconfined compressive strength tests demonstrated significant strength improvements, with values rising from 67 kPa for untreated pond ash to 149 kPa at 7 days, 296 kPa at 14 days, and 386 kPa at 28 days, identifying 15% lime sludge as the most effective dosage. To study the microstructural characteristics of the lime sludge stabilised pond ash, FTIR, XRD and SEM analysis were conducted. Results show that lime sludge significantly improves pond ash's strength, making it a suitable filler material for geotechnical applications like embankments, pavement subgrades, and backfill materials. This research highlights the effectiveness of lime sludge as an economical and sustainable stabilizing agent for the practical use of pond ash.

Keywords: Lime Sludge, Pond Ash, Microstructure, Unconfined Compressive Strength, and Compaction.

1.0 INTRODUCTION

Thermal power plants generate a significant quantity of fly ash and bottom ash as during electricity generation. The ashes are the residue derived from the combustion of anthracite or bituminous coal. Pozzolanic properties of fly ash enables its usage in cement production, brick manufacturing and road construction. Bottom ash is mixed with water and disposed to open lands, leading to the formation of pond ash. While pond ash has potential environmental benefits, its improper disposal leads to severe environmental challenges such as soil contamination, groundwater pollution, and occupation of valuable land. The land occupied by the discharged pond ash from thermal power plant loses fertility further prohibiting the reclamation of the polluted land. The proper utilization of pond ash can help mitigate these issues. The primary composition of pond ash consists of silicon dioxides, aluminium oxides, magnesium oxide and iron oxides [1].

The silica in pond ash plays a crucial role in enabling pozzolanic reactions by reacting with calcium hydroxide in the presence of water [2]. While it possesses pozzolanic properties, it does not exhibit cementing behaviour as it has low calcium oxide (CaO) content [3]. This problem is overcome by the addition of suitable admixture such as lime, cement and other industrial byproducts like lime kiln dust, cement kiln dust GGBS, lime sludge, marble dust. [4][5][6] [7] [8]. Many researches [7] [9] [10] [11] indicates that pond ash stabilisation can effectively enhance various soil engineering properties, including plasticity index, UCC, CBR and swell index.

Pond ash can be utilised as a filler material in various geotechnical applications such as embankment fills, pavement bases etc. [7] [1] [9]. Its lightweight nature, affordability, and advantageous technical characteristics make it an excellent choice for construction applications [7] [12]. Moreover, pond ash can be combined with soil as a stabilising agent to improve the bearing capacity. Using pond ash as a sustainable material for constructions applications presents a valuable opportunity to minimize its environmental pollution of soil and water while supporting infrastructure development [13] [14].

Lime sludge is residue from water treatment plant and the paper industry. In India, 4.5 million tons of lime sludge is generated by various sectors [15] [16]. Large quantities of lime sludge are generated each year and is disposed in lagoons incurring additional costs for the treatment plants [18]. Lime Sludge is silty and has lower strength so it cannot by itself used as a construction material. It can be used as municipal landfill applications but due to its less permeability nature it cannot be used in pavement applications. If lime sludge is mixed with any admixture, it can be a construction material for civil engineering applications [19].

Primary composition of lime sludge consists of calcium, silica, and aluminium, along with smaller quantity of iron, magnesium, and sulphur. Trace elements such as zinc, chromium, selenium, lead, and cadmium are present in minimal quantities [20]. In water treatment plants, lime sludge forms during the softening process when lime (calcium hydroxide) is added to eliminate impurities like calcium and magnesium ions. This reaction produces insoluble precipitates, such as calcium carbonate ($CaCO_3$), which are subsequently removed via sedimentation or filtration. The resulting lime sludge contains calcium compounds along with residual organic matter and other substances like magnesium hydroxide.

Lime sludge has a potential to be a stabilising agent, as it is composed of calcium and silica which can initiate pozzolanic reactions. The stabilisation process occurs when the calcium oxide present in the lime sludge reacts with water to form calcium hydroxide [10]. This hydration reaction catalysts the cation exchange of calcium ions replacing the sodium and hydrogen ions in the soil. Further the ettringite gel formation occurs due to the pozzolanic reactions [20]. The stabilisation is facilitated by alkaline pH environment provided lime sludge. The stabilisation pond ash improves its strength and becomes more resilient to stresses. This technique offers a sustainable option for the utilisation industrial byproducts lime sludge and pond ash.

Coban (2018) [17] found that lime sludge stabilisation of loess soil improves the plasticity index and strength of the soil. Many researchers observed reveal that lime sludge reduced the swelling property of expansive clay and increased maximum dry density [21]. Literatures report that addition of 12 % lime sludge content was the most effective optimum dosage for soil stabilization [15]. Chemical assessment suggests that the lime sludge has chemical properties comparable to that of lime which is a stabilising agent under use since ancient time.

Recent studies have explored the potential of pond ash (PA) and sludge pond ash (SPA) as sustainable additives for soil stabilization. Pesraklou (2023) [22] demonstrated that adding SPA to clay improves its unconfined compressive strength (UCS), increases optimum moisture content (OMC), and reduces maximum dry unit weight (MDUW), with 10% SPA yielding optimal results. Sudhakar (2019) [23] found that lime-treated PA significantly enhances UCS, California Bearing Ratio (CBR), and Resilient Modulus (MR), making it suitable for pavement subbase layers. Similar findings were reported by Mogili et al. (2020, 2021) [24,25], who also validated resilient behavior using stress-dependent models. Vidyadhara and co-author (2023) reviewed the use of pond ash in cement and geopolymer composites, noting its potential as a fine aggregate or binder after proper treatment. Naga (2022) [26] highlighted improved strength and thermal characteristics of green concrete incorporating pond ash and GGBS, supported by regression-based predictions. Pande (2023) [27] developed a lightweight, eco-friendly geomaterial using PA, cement, and expanded polystyrene (EPS), while Pant (2019) [28] confirmed the suitability of PA in reinforced soil structures through comparable pullout resistance to sand. Lastly, Randhawa (2021) [29] showed that cement and fiber additions improve the strength and flexural performance of pond ash-based fill materials, with optimal fiber content at 0.75%. Together, these studies underline the viability of pond ash and sludge pond ash in enhancing the geotechnical and environmental performance of soils and construction materials.

This study examines the stabilisation of pond ash using various proportions (5%, 10%, 15%, and 20%) of lime sludge to determine the most effective dosage that improves the properties of pond ash. The long-term reactivity and pozzolanic activity of lime sludge under different curing periods provides in depth knowledge of its behaviour compared to conventional approaches that focuses on immediate effects. This investigation combines the output of UCS and compaction tests with advanced techniques like FTIR, XRD and SEM to evaluate the influence of lime sludge dosage in the strength, mineralogical and morphological properties of pond ash. The study focuses on the impact of lime sludge on the strength variations across different curing intervals and offers a detailed analysis of strength development with varying curing period. FTIR and XRD are used to analyse the detailed chemical alterations in the compounds and detect the newly formed compounds like, calcium-silicate-hydrate gels. SEM analysis highlights the transformation of rounded particles of pond ash after the stabilisation process.

Despite extensive studies on soil stabilization using individual binders like lime or cement, limited research exists on the long-term comparative evaluation of these stabilizers when used with industrial by-products such as pond ash. Most existing studies focus on short-term strength improvements, often neglecting microstructural changes and the chemical mechanisms that govern strength development over extended curing periods. Additionally, there is a lack of integrated approaches combining mechanical testing (e.g., UCS) with advanced analytical techniques such as FTIR and SEM, which are crucial for understanding the pozzolanic activity and durability of stabilized mixtures. This study aims to bridge these gaps by providing a comprehensive analysis of pond ash stabilization using lime and cement over 7, 30, and 120 days of curing, supported by chemical and microstructural investigations and strength optimization through RSM.

The study explores various lime sludge dosages, to provide an approach to determine the optimal lime sludge content for effective pond ash stabilisation. By confronting the environmental challenges related to pond ash disposal, the research promotes sustainable geotechnical practices through the use of lime sludge, a largely underutilized industrial waste material. By incorporating mechanical and chemical analyses over different curing periods, the study provides essential insights for the utilization of pond ash as a filler material and contributing for the development of eco-friendly construction materials. Additionally, the findings highlight the potential of lime sludge as a viable additive for enhancing the long-term performance of stabilized materials. This work provides a broader understanding of sustainable waste management in construction and underscores the importance of innovative byproduct reuse in achieving environmental and engineering goals.

2.0 METHODOLOGY

2.1 Materials

2.1.1 Pond Ash

The ash was sourced from Ramagundam thermal power plant located in Andhra Pradesh, India, displayed in Figure 1(a). The ash was dried and sieved through a 4.75 mm sieve and stored. The basic physical property tests were carried out in laboratory to know the particle size distribution, specific gravity, moisture content.

(a) (b)

Figure 1 (a) Pond Ash and (b) Lime Sludge

Table 1 Physical Properties of pond ash and lime Sludge

S. No.	Property	Pond Ash	Lime Sludge
1	Specific Gravity	1.93	2.26
2	Maximum dry density (kN/m^3)	10.81	-
3	Optimum moisture content (%)	24.6	-
4	Colour	Grey	White
5	Uniformity Coefficient (C_u)	3.92	3.20
6	Coefficient of curvature (C_c)	1.25	1.02
7	Moisture Content (%)	26.2	28.36

Table 2 Chemical Composition of pond ash and lime Sludge

S. No.	Constituents	Composition (%)	
		Pond Ash	Lime Sludge
1	SiO_2	48.70	3.42
2	Al_2O_3	26.69	1.81
3	MgO	3.73	2.14
4	Fe_2O_3	7.85	0.58
5	CaO	4.56	53.61
6	Loss of Ignition	7.8	37.75
7	Others	0.59	0.43

2.1.2 Lime Sludge

The lime sludge samples were obtained from a Water treatment facility in Chennai is displayed in Figure 1(b). The physical properties of the pond ash lime sludge were mentioned in Table 1. The chemical composition of the lime sludge primarily consists of calcium, silica, and aluminium, with minor elements including iron, magnesium, and sulphur is shown in Table 2. The lime sludge was carefully oven dried for 24 hours to reduce moisture content before sample preparation.

2.2. Sample Preparation

For the stabilization of pond ash using lime sludge, samples were prepared by mixing pond ash with lime sludge at dosages of 5%, 10%, 15%, and 20% by the dry weight of pond ash. The required amount of water, determined based on the Optimum Moisture Content (OMC) obtained from the Standard Proctor Test, was gradually added to the dry mix to ensure adequate moisture for compaction. The materials were thoroughly mixed by hand until a uniform and consistent blend was achieved. The pond ash–lime sludge mixtures were compacted into cylindrical moulds of 80 mm height and 40 mm diameter for Unconfined Compressive Strength (UCS) testing. The compacted specimens were immediately sealed in plastic wrap to maintain moisture content and then placed in a vacuum curing chamber. The samples were cured for 7, 14, and 28 days under controlled temperature and humidity conditions.

For microstructural analysis (SEM and FTIR), small segments were cut from the UCS-tested samples corresponding to the optimum lime sludge dosage identified from strength results. The details of mix proportions were mentioned in the Table 3.

Table 3 Mix proportions for sample preparation

S. No.	Mix number	Pond ash (%)	Lime sludge (%)
1	M-1	100	0
2	M-2	95	5
3	M-3	90	10
4	M-4	85	15
5	M-5	80	20

2.3 Test Procedure

2.3.1 Compaction Test

Standard Proctor compaction tests were conducted for each lime sludge dosage to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), as per IS: 2720 (Part 7) guidelines. The samples were compacted using 2.5kg hammer dropped from a height of 300mm in a standard Proctor mould in three layers, with each layer receiving 25 blows from the hammer. The results of the compaction tests were analysed to calculate the OMC and MDD for each dosage of lime sludge in pond ash.

2.3.2 Unconfined Compressive Strength (UCS) Test

The UCS tests were performed on cured samples at the intervals of 7,14 and 28 days to evaluate the strength of stabilized pond ash as per code IS 2720 Part 10: 1991. The UCC machine of capacity 50 kN was used. An Axial load was applied using a compression testing machine until samples ruptured was determined by dividing the peak load by the cross-sectional area of the specimen. The loading was applied at a constant strain rate of 1mm/min. The failure was tracked according to loading in the proving ring and deformation in the dial gauge. The stress strain curved were plotted to analyse the peak axial stress.

2.3.3 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis was performed to investigate the chemical changes and formation of cementitious products in stabilized pond ash. FTIR spectroscopy was done on the stabilised pond ash samples cut from the UCS tested samples. A 2 mg sample of pond ash was finely powdered and mixed with potassium bromide powder to create pellets. These pellets were placed in the Nicolet Summit FTIR spectrometer (Thermo Fisher Scientific). The infrared rays are passed into the samples. The output is shown in the form of peaks of specific bandwidths. These bandwidths wavenumber is used to identify the functional groups of elements developed due to the stabilisation process. The spectra were recorded for the range of 4000-400 cm⁻.

2.3.4 X-ray Diffraction (XRD)

X-ray Diffraction (XRD) analysis investigates the mineralogical transformations in stabilised pond ash. The samples used for the test was cut from UCS sample. Finely powdered samples were analysed using a Unique D8 diffractometer to identify minerals formed after the stabilisation. The analysis covered a 2θ range of 10° to 70°, allowing for the detection of diverse crystalline phases. XRD samples were obtained from cylindrical specimens used in UCS tests, and the results were compared against standard reference patterns from JCPDS data files to identify newly formed compounds.

2.3.5 Scanning Electron Microscopy (SEM)

The microstructural images of lime sludge-stabilized pond ash samples were analysed using Scanning Electron Microscopy (SEM). A Carl Zeiss EVO 18 microscope, with a resolution of 3 nm and a magnification range from 1x to 1,000,000x, was used for the analysis, offering detailed imaging under both high vacuum and variable pressure conditions. Microstructural examinations were conducted on samples extracted from the UCS test specimens.

3.0 RESULTS AND DISCUSSION

3.1 Compaction Test

The compaction results for the lime sludge stabilized pond ash samples are presented in terms of OMC and Dry Density is shown in Figure 2. As the dosage of lime sludge increased, the OMC values showed moderate variations, with the lowest value observed at 5% lime sludge (23.35%) and the highest at 10% lime sludge (24.82%). The variation OMC demonstrates that the inclusion of lime sludge has lesser impact on it.

For Maximum Dry Density (MDD), measured in kN/m³, increased with higher lime sludge content. The MDD ranged from 10.81 kN/m³ for the untreated pond ash to 11.32 kN/m³ for the 20% lime sludge dosage. This variation demonstrates that lime sludge has a beneficial impact on the compaction of pond ash and attributes its stabilization. The rise in MDD values with increasing lime sludge content indicates improved compaction and densification.

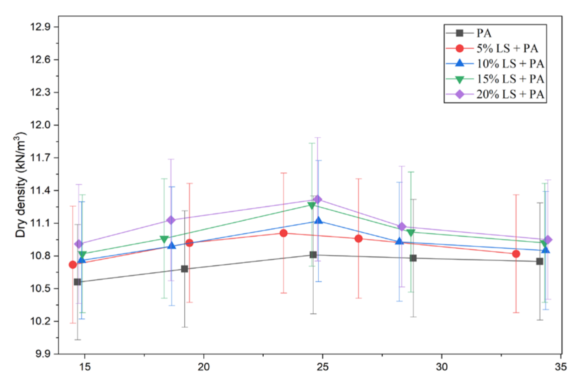


Figure 2 Variation of DD and OMC with different percentages of Lime sludge in Pond ash

3.2 Unconfined Compressive Strength Test

The peak axial stress values for stabilized pond ash samples with varying lime sludge dosages (5%, 10%, 15%, and 20%) were evaluated over curing periods of 7, 14, and 28 days to assess the increase of strength is shown in Figure 3. As the lime sludge content increased, there was a noticeable improvement in peak axial stress across all curing periods. At 5% lime sludge, the peak axial stress increased from 85 kPa at 7 days to 156 kPa at 14 days (an improvement of 83%), and 223 kPa at 28 days (an improvement of 162%). For 10% lime sludge, the stress values rose from 105 kPa at 7 days to 165 kPa at 14 days (an improvement of 57%), and 268 kPa at 28 days (an improvement of 155%). At 15% lime sludge, the peak axial stress improved significantly, from 149 kPa at 7 days to 296 kPa at 14 days (an improvement of 98%), and 386 kPa at 28 days (an improvement of 159%). The highest peak axial stress was observed at 20% lime sludge, with values increasing from 132 kPa at 7 days to 328 kPa at 14 days (an improvement of 148%), and reaching 456 kPa at 28 days (an improvement of 245%). These results demonstrate that lime sludge significantly enhances the UCS of pond ash, with higher lime sludge dosages leading to greater strength development over time. Additionally, longer curing periods contributed to further strength gains, indicating the continued pozzolanic reactions and cementitious compound formation within the stabilized pond ash [30].

3.3 Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR analysis peaks of pond ash and pond ash containing 15% lime sludge is shown in Figure 4. The wavenumbers of samples demonstrate chemical and structural transformations resulting from stabilization. In untreated pond ash, characteristic peaks are at 412.500 cm^{-1}, 421.408 cm^{-1}, 429.588 cm^{-1}, 775.066 cm^{-1}, and 1042.221 cm^{-1}.The peaks correspond to silicate and aluminosilicate compounds. These peaks are associated with bending and stretching vibrations typical of silicate minerals are shown in Table 4 [9] [31]. Upon treatment with lime sludge, shifts in wavenumbers and significant intensity changes highlight chemical interactions and the formation of new phases.

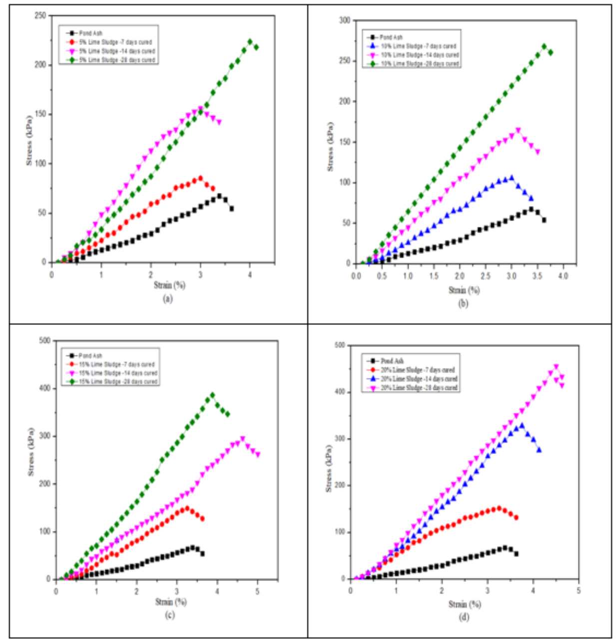


Figure 3 Unconfined compressive strength of lime sludge-stabilized pond ash at 7 d, 14 d and 28 d of curing period: (a) 5% Lime sludge, (b) 10% Lime sludge, (c) 15% Lime sludge, (d) 20% Lime sludge ash

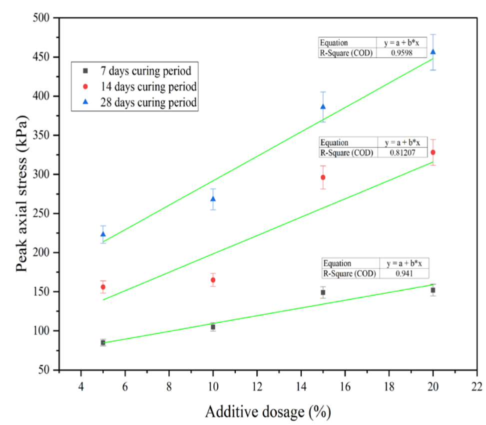


Figure 4 R^2 and equation plot for Peak axial stress of lime sludge-stabilized pond ash at 7, 14, and 28 days of curing.

In Figure 4 For all curing periods, the relationship between additive dosage and peak axial stress follows a linear trend, as shown by the fitted regression lines. The R^2 values of 0.941 for 7 days, 0.812 for 14 days, and 0.959 for 28 days, suggest a strong correlation, especially for the 7 and 28-day periods. The 28-day samples exhibit the highest peak axial stress across all dosages, highlighting the continued formation of cementitious compounds such as calcium silicate hydrate (C–S–H) over time, which enhances the bonding and load-bearing capacity of the stabilized material.

Error bars indicate minor variability in the test results, affirming the reliability and repeatability of the experimental outcomes. Overall, the figure confirms that both additive dosage and curing period are key parameters influencing the strength development of lime sludge-stabilized pond ash.

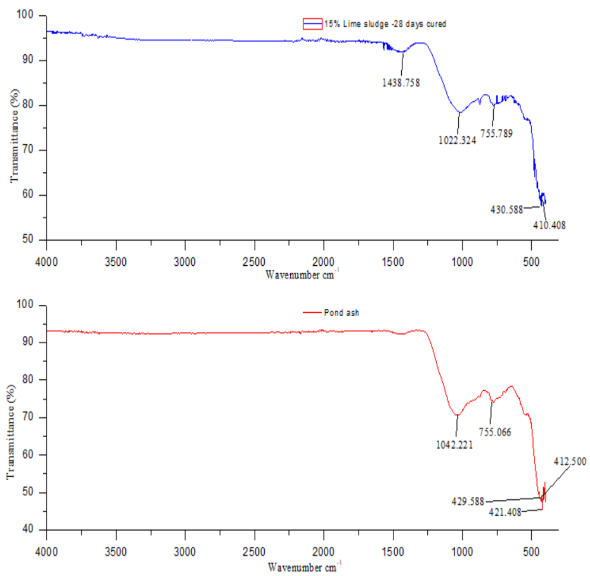


Figure 5 FTIR peaks of Pond ash and 15% Lime Sludge

Table 4 Characteristic absorbance bands of Pond ash and 15% Lime sludge treated Pond ash

Wavenumber range (cm^{-1})	Pond ash	15% Lime Sludge treated Pond ash	Vibrations
400-500	412.5,421.408,429.588	410.408,430.588	O-Si-O Bending
700-800	775.066	755.789	Si-O Symmetric Stretching
1000-1200	1042.221	1022.324	Si-O-Si Asymmetric Stretching
1300-1500	-	1438.758	C-O Stretching

3.3.1 O-Si-O Bending Vibrations (400–500 cm^{-1})

Pond ash showed distinct peaks at 412.5 cm^{-1}, 421.408 cm^{-1}, and 429.588 cm^{-1}, attributed to O-Si-O bending vibrations. After stabilization with lime sludge, these peaks shifted to 410.408 cm^{-1} and 430.588 cm^{-1}, suggesting slight structural changes in the silicate minerals caused by interactions with lime sludge.

3.3.2 Si-O Symmetric Stretching Vibrations (700–800 cm^{-1})

A peak was observed at 775.066 cm^{-1} for untreated pond ash, attributed to the symmetric stretching of Si-O bonds. This peak shifted to 755.789 cm^{-1} in the lime sludge-stabilized sample, suggesting structural modifications in the silicate. The shift is the result from the disruption of silicate linkages and the formation of new bonds due to lime stabilization.

3.3.3 Si-O-Si Asymmetric Stretching Vibrations (1000–1200 cm^{-1})

The asymmetric stretching vibrations of Si-O-Si bonds were identified at 1042.221 cm^{-1} in pond ash. In the lime sludge-stabilized sample, this peak shifted to 1022.324 cm^{-1}, reflecting the reorganization of the silicate structure. The reduction in wavenumber suggests the formation of weaker or more distorted silicate bonds, due to pozzolanic reactions with lime.

3.3.4 C-O Stretching Vibrations (1300–1500 cm^{-1})

The untreated pond ash did not exhibit any notable peaks in this range. However, a new peak at 1438.758 cm^{-1} appeared in the stabilized sample, attributed to C-O stretching vibrations. This peak indicates the formation of carbonate phases due to the reaction between lime and atmospheric CO_2 during stabilization.

The FTIR analysis reveals significant structural changes in pond ash upon stabilization with lime sludge. Shifts in the O-Si-O and Si-O-Si vibrations confirm alterations in the silicate functional groups, while the emergence of a C-O stretching peak indicates the formation of secondary carbonate phases. These changes highlight the chemical interactions between lime sludge and the pond ash , which contribute to enhanced mechanical properties and stabilization efficiency.

3.4 X-ray Diffraction (XRD)

The X-ray Diffraction (XRD) analysis compares the mineralogical composition of untreated pond ash and 15% lime sludge-treated pond ash samples. The XRD pattern shown in Figure 5 clearly demonstrate the crystalline phases present and highlight the changes induced by lime sludge stabilization. In the untreated pond ash (black curve), the dominant mineral phases identified are Quartz (Q), Mullite (M), and minor traces of Magnetite (MA) and Hematite (H). Quartz is observed as the most prominent peak around a 2θ value of 27°, indicating its significant presence in pond ash, similar quartz peak was observed by many studies [9] [11] [32]. Mullite and magnetite phases represent the aluminosilicate and iron oxide components of the pond ash. For the 15% lime sludge-treated pond ash Quartz (Q) remains dominant, additional peaks corresponding to Calcium Hydroxide (K) and Calcium Carbonate © appear, indicating the chemical reactions between lime sludge and pond ash.

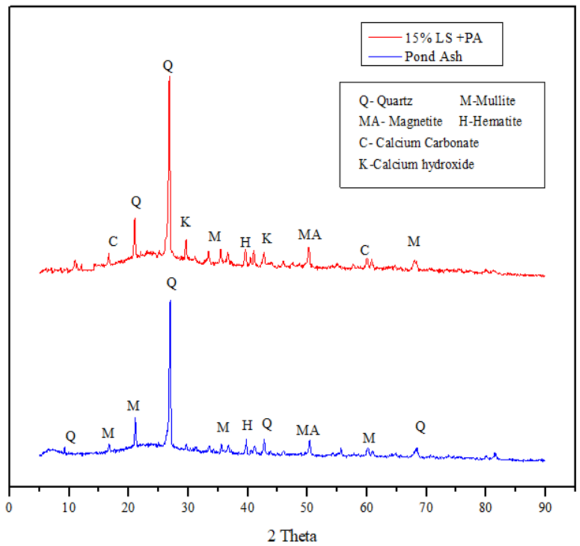


Figure 6 FTIR peaks of Pond ash and 15% Lime Sludge

The of calcium carbonate formation can be attributed to chemical reactions, which result in the development of cementitious compounds. Peaks of Hematite (H), Mullite (M), and Magnetite (MA) are also evident, but their relative intensities appear reduced compared to unstabilized pond ash. The appearance of Calcium Hydroxide (K) and Calcium Carbonate © in the stabilized samples signifies the formation of pozzolanic reaction products such as calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), which contribute to strength enhancement. These compounds are responsible for binding the particles together and improving the overall stability of the material. The comparative XRD patterns demonstrate the mineralogical transformation occurring due to lime sludge treatment, confirming its role in enhancing the stabilization of pond ash. The formation of new cementitious phases indicates the effectiveness of lime sludge in facilitating pozzolanic and carbonation reactions, which are essential for strength development in treated pond ash.

3.5 SEM

The Scanning Electron Microscopy (SEM) analysis reveals the surface morphology and microstructural changes in the pond ash samples before and after stabilization with 15% lime sludge as shown in Figure 8. The SEM images reveal significant variations in the texture, particle arrangement, and bonding characteristics, providing insights into the mechanisms contributing to strength improvement. In Figure 6, the untreated pond ash, the microstructure primarily shows the rounded and spherical particles, similar spherical particles known as cenospheres and plerospheres were observed by Behera (2017) [33] and Bachus (2019) [34] . The particles appear poorly bonded, with visible void spaces. The smooth texture of the ash particles suggests limited reactivity and minimal interaction among the constituents

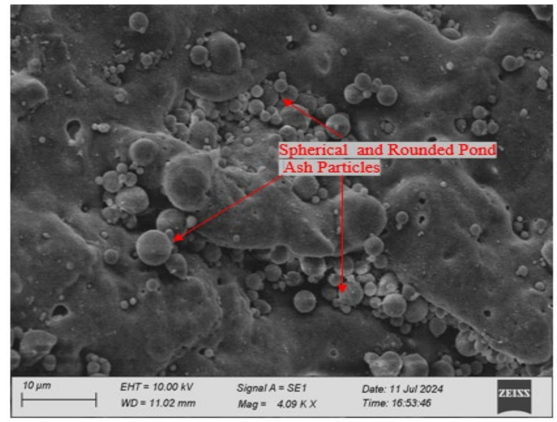


Figure 7 SEM image of Pond ash

After stabilization with 15% lime sludge shown in Figure 7, significant changes in the microstructure are observed. The formation of ettringite on the surface of pond ash particles is clearly visible. The rounded and spherical particles visible in pond ash is replaced by the gel formation over the particles which are in irregular shape. The hydration products, including dense C-S-H and C-A-H gels, are more uniformly distributed and extensively cover the particle surfaces The ettringite gel structures contribute to particle bonding and the overall densification of the sample. Improved bonding among particles is observed in stabilized samples, which is due to the reaction of lime and lime sludge with pond ash, leading to the formation of cementitious compounds. This densification leads to an increased unconfined compressive strength, improving the mechanical strength and stability of the samples.

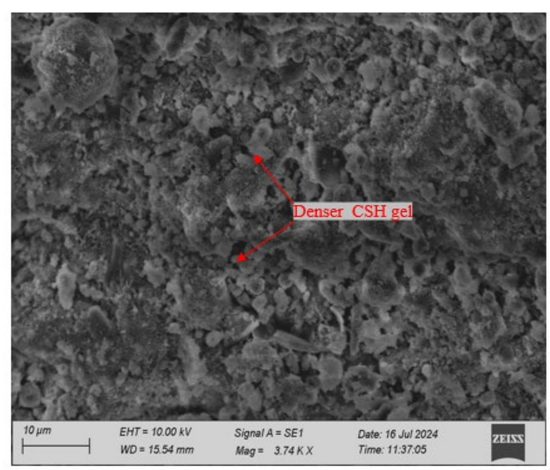


Figure 8 SEM image of Pond ash treated with 15% Lime Sludge

The progressive changes in the SEM images over the curing periods highlight the role of lime sludge in facilitating chemical reactions and the development of cementitious compounds. These changes directly correlate with the observed improvement in strength properties, as the microstructural evolution leads to densification and enhanced bonding within the stabilized pond ash. Similar observations regarding ettringite formation and its role in improving the properties of ash-lime mixtures have been reported by researchers like Suthar (2018) [10] and Mogili (2021) [26]. These studies highlight the significance of C-S-H formation in enhancing the microstructural bonding and densification of stabilized materials.

The enhanced microstructural bonding and densification observed in the SEM images are primarily attributed to pozzolanic reactions occurring between the reactive silica and alumina present in pond ash and the calcium hydroxide released from lime sludge. These reactions lead to the formation of cementitious compounds such as calcium silicate hydrate (C-S-H), calcium aluminate hydrate (C-A-H), and ettringite. The C-S-H gel acts as a binding matrix, filling voids and coating particles, thus contributing to the development of a denser microstructure and improved particle interlock. Ettringite crystals, with their needle-like morphology, further enhance early strength gain by forming rigid frameworks within the matrix. Over time, the continued hydration and pozzolanic activity result in greater connectivity among particles and reduction in porosity, which directly explains the observed improvement in unconfined compressive strength and long-term stability of the stabilized pond ash.

4.0 CONCLUSION

In The study demonstrates that 15% lime sludge is the optimum dosage for stabilizing pond ash, showing significant improvements in strength, density, and microstructural properties:

1. Compaction: For 15% lime sludge, the Optimum Moisture Content (OMC) is 24.54% and the Maximum Dry Density (MDD) is 11.27 kN/m³, indicating improved compaction and densification.
2. Strength: Unconfined Compressive Strength (UCS) increased significantly, reaching 386 kPa at 28 days for 15% sludge, indicating effective pozzolanic reactions and strength development.
3. FTIR analysis reveals that pond ash stabilization has occurred by the appearance of peak at 1438.758 cm^{-1}.Shifts in the O-Si-O and Si-O-Si vibrations confirm alterations in the silicate functional groups, while the emergence of a C-O stretching peak indicates the formation of secondary carbonate phases.
4. XRD analyses confirmed presence of mineral phases Quartz (Q), Mullite (M), and minor traces of Magnetite (MA) and Hematite (H) in untreated pond ash. After the stabilisation peaks corresponding to Calcium Hydroxide (K) and Calcium Carbonate (C) appear, indicating the chemical reactions between lime sludge and pond ash.
5. Microstructure: SEM revealed denser packing, reduced voids, and improved inter-particle bonding, particularly at 15% sludge after 28 days of curing.

In conclusion, 15% lime sludge provides the optimum stabilization of pond ash, delivering improved strength, density, and stability, making it suitable filler material.

4.1 Limitations and Scope for Future Work

Although the present study provides valuable insights into the stabilization of pond ash using lime sludge through mechanical, chemical, and microstructural characterization, certain limitations exist. The experiments were conducted under controlled laboratory conditions, and field-scale validation was not performed. Additionally, long-term durability aspects such as resistance to wet–dry cycles, freeze–thaw effects, and sulfate attack were not considered. The environmental impact and leachability of heavy metals from stabilized samples were also beyond the scope of this study.

Future research should focus on the large-scale application of lime sludge-stabilized pond ash in real field conditions, along with performance monitoring under varying environmental exposures. Further studies are also recommended to assess the long-term environmental safety and sustainability of using industrial by-products in geotechnical applications.

Acknowledgement

We would like to thank Saveetha Institute of Technical and Medical Science University for providing infrastructure

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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