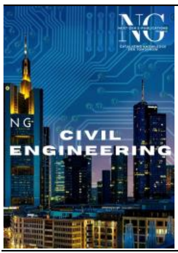

NG Civil Engineering
Volume 1, Issue 1 (January-March), 2025, (24-31)
ISSN (Online): 3107-569X

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Research Article

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A Study on the Strength and Consolidation Characteristics of High-Concentrated Ash Slurry

Abinash Mohanta*

[1]Capital Engineering College, Bhubaneswar, 752055, India

*Corresponding author email ID: abinash07552@gmail.com

HIGHLIGHTS

- Pond ash maintains a consistent dry density of ~1.4 g/cc with no significant change over time.
- HCSD and LCSD systems exhibit nearly identical permeability (~1.3 × 10^{-4} cm/sec).
- HCSD pond ash shows higher MDD and lower OMC, making it suitable for embankment construction
- Findings support the use of HCSD pond ash in infrastructure projects.

ARTICLE INFO

Article History:
Received: 05 January 2025
Revised: 21 February 2025
Accepted: 16 March 2025
Published: 31 March 2025

Keywords:
Ash Slurry
Geotechnical Properties
Strength
Sustainability

ABSTRACT

High Concentration Slurry Disposal (HCSD) is a modern technique for disposing of fly ash generated in thermal power plants. This study investigates the geotechnical behavior of HCSD pond ash, focusing on its density, permeability, and compaction characteristics. Laboratory tests on samples collected from an ash pond at Vedanta Aluminium Limited, Jharsuguda, revealed that the dry density of pond ash remains stable at approximately 1.4 g/cc over time. The permeability of settled HCSD ash was found to be 1.3 × 10^{-4} cm/sec, which is comparable to that of conventional Lean Concentration Slurry Disposal (LCSD) systems, indicating no significant improvement in impermeability. Proctor compaction tests demonstrated that increased compaction effort results in higher maximum dry density (MDD) and lower optimum moisture content (OMC), making HCSD pond ash a suitable material for embankment construction. These findings highlight the potential for sustainable utilization of HCSD ash in infrastructure projects, offering an environmentally viable alternative for ash management.

1. INTRODUCTION

The growing reliance on electricity generation with coal has resulted in a tremendous increase in the volume of coal combustion residues produced, including fly ash. For many disposal and management methods of fly ash, environmental and geotechnical issues can arise due to the volume produced and the potential for groundwater contamination, air pollution, and land disposal concerns. Fly ash is typically disposed of in a slurry form in ash ponds, but slurries have a significant amount of water and a low concentration of fly ash, which can create stability

https://doi.org/10.66132/ngce20250104

issues, shallower settling, and environmental concerns. Because of these issues, disposal with high-concentrated ash slurry (HCAS) has come into the spotlight as a potentially viable alternative to address these concerns. HCAS is a paste-like mixture with a low water content that may promote improved geotechnical properties, including shear strength, permeability, and consolidation behavior. The geotechnical behavior of HCAS is important to understand to develop safe and sustainable disposal systems and for potential reuse applications in geotechnical and construction engineering. The rheological and mechanical properties of HCAS are affected by many factors, including particle size distribution, water content, chemical composition, and external loading conditions.

The behavior of high-concentrated ash slurry in terms of its strength, settlement characteristics, and interaction with the surrounding environment remains a subject of extensive research. The present study aims to investigate the geotechnical properties of HCAS, focusing on aspects such as compressibility, permeability, shear strength, and consolidation characteristics. The findings from this research will provide valuable insights into the feasibility of utilizing HCAS for sustainable ash disposal and possible applications in land reclamation, embankment construction, and ground improvement techniques.

Over the past decade, there has been a substantial surge in electricity generation in our nation. A significant proportion of this electricity is generated by coal-fired thermal power plants, which rely on the burning of coal. As a result, a substantial amount of ash is produced in these plants. Currently, India generates more than a hundred million tonnes of ash annually. Proper management of this ash is crucial, requiring efficient utilization, transportation, and environmentally secure storage. However, only a small percentage is used in manufacturing industries such as brick production, cement manufacturing, and road construction. The majority of the ash is disposed of in slurry form in ash ponds.

The disposal of fly ash has become a significant environmental concern in recent years. Both fly ash and bottom ash are typically mixed and transported hydraulically to ash ponds using centrifugal pumps. The conventional method, known as Lean Concentration Slurry Disposal (LCSD), presents several challenges, including excessive water consumption, stability issues, and environmental hazards. To address these problems, many industries have recently adopted the High Concentration Slurry Disposal (HCSD) system as an alternative.

HCSD is a modern technique for disposing of fly ash from thermal power plants, offering several advantages over the conventional LCSD method. Understanding the behavior and efficiency of the HCSD system in comparison to LCSD can provide valuable insights for improving ash disposal strategies in thermal power plants. This study focuses on laboratory and field investigations of the geotechnical properties of HCSD, which will help in assessing its benefits and environmental impact

High Concentration Slurry Disposal (HCSD) is an advanced method for managing fly ash generated in thermal power plants due to coal combustion. Compared to the conventional Lean Concentration Slurry Disposal (LCSD) system, HCSD offers several advantages, including reduced water consumption, improved stability, and minimized environmental impact.

This study is significant as it provides a comprehensive understanding of the geotechnical behavior of HCSD, which is crucial for optimizing ash disposal strategies. By analyzing and comparing the geotechnical properties of HCSD and LCSD, this research will aid thermal power industries in making informed decisions regarding efficient and sustainable ash management. The findings will contribute to enhancing the safety, environmental sustainability, and economic feasibility of fly ash disposal systems.

2. REVIEW OF LITERATURE

The extensive application of ash slurry transportation methods across various sectors has led to significant research on the subject. Understanding the geotechnical behavior of high-concentrated ash slurry is essential for optimizing its transportation efficiency. This study reviews previous research that has contributed to this field.

In a study conducted by Zhang et al. (2023), the impact of varying levels of fly ash and slurry concentration on the consolidation strength of grouting materials was explored. Utilizing a damage constitutive model, the researchers were able to characterize the nonlinear deformation of internal pores during the initial compaction phase. Their findings indicated that as the proportion of fly ash increases, the setting time escalates exponentially, while the strength diminishes linearly. The interplay between fly ash content, slurry concentration, and resultant strength was best represented by a quadratic polynomial function. Ultimately, the study determined that the most effective mixture for on-site mining filling consisted of Type I fly ash at a 50% concentration combined with a 60% slurry concentration.

Wang et al. (2024) examined the physical, mechanical, and microstructural properties of fly ash-based geopolymer concrete. The study highlighted the role of fly ash in improving the strength and microstructural compactness of the material. The findings indicated that the strength of the geopolymer concrete increased with a decrease in fly ash particle size and an increase in curing age.

Sun et al. (2024) explored the impact of fly ash on the mechanical performance of grouting slurry used for fractured rock mass reinforcement. The research showed that incorporating fly ash can improve the strength and compactness of the matrix, and optimize the slurry's fluidity and workability for better grouting performance.

Han et al. (2024) evaluated the effect of freeze-thaw cycles on the strength of soils stabilized with cement and fly ash. The study found that the strength of stabilized soils was significantly affected by freeze-thaw cycles, with variations depending on the type and concentration of stabilizers used.

Qin et al. (2024) investigated the hydration and strength evolution of concretes incorporating high volumes of fly ash. The research highlighted the importance of curing conditions and the role of fly ash in improving the long-term strength and durability of concretes.

Min et al. (2024) examined the impact of colloidal nanoSiO2 on the hydration process of fly ash. The study found that the addition of nanoSiO2 can enhance the early-age strength and improve the microstructural properties of FA-based materials.

Sun et al. (2024) explored the rheological and strength performances of geopolymer materials made from limestone dust and bottom ash. The research highlighted the potential of these materials for grouting and deep mixing applications, with findings indicating significant improvements in strength and workability.

Han et al. (2024) investigated the injectability of a mixed slurry composed of coal gangue and fly ash. The study assessed the influence of factors like volume concentration and particle size on the slurry's density, viscosity, and water extraction rate, providing insights into the optimal mix for grouting application.

Wang et al. (2024) conducted proportioning tests to develop high-strength, low-viscosity grouting materials by incorporating fly ash. The research aimed to meet the reinforcement requirements of micro-fractured rock masses, with findings indicating the optimal mixture ratio for improved strength and fluidity.

Qin et al. (2024) focused on optimizing the mixture ratio of grouting slurry for overburden separation layers. The study considered the impact of fly ash on the slurry's performance and identified the optimal ratio for improved strength and fluidity in mining applications

3. METHODOLOGY

3.1. Data collection

From Vedanta Aluminium Limited, Jharsuguda plant, disturbed and undisturbed samples were collected; field tests were also conducted.

3.2 List of experiments conducted:

3.2.1 In-situ density test

The in-situ density test was conducted using several essential pieces of equipment. Core cutters with internal diameters of 10 cm and 10.4 cm and effective heights of 12.7 cm and 13.8 cm, respectively, were used for sample collection. A soil excavating tool was utilized to assist in extracting undisturbed samples. An oven was used to dry the samples for water content determination, while balances were employed to measure the mass of the core cutter with and without the sample. Additionally, metal containers were used for storing and drying the extracted soil samples.

Undisturbed fly ash samples were collected from the ash pond at Vedanta Aluminium Limited, Jharsuguda, using core cutters. Before use, the inner surfaces of the core cutters were greased to facilitate easy removal of the samples. The mass and volume of the empty core cutters were first measured and recorded. The core cutter containing the fly ash sample was then weighed, and its total mass was noted.

To determine the water content, a portion of the collected sample was extracted from the core cutter and placed in an oven for drying. After drying, the sample was reweighed, and the water content was calculated.

The bulk density of the fly ash was then determined using the formula:

Bulk Density(γ)=Mass of Soil in Cutter/Volume of Cutter

3.2.2 Variances of bulk density, water content and dry density with time at field

To conduct the study, three distinct locations within the ash pond at Vedanta Aluminium Ltd., Jharsuguda, were selected and designated as sites A, B, and C. Initially, the empty mass and volume of the core cutter were determined and recorded. Subsequently, samples were extracted from each site using the core cutter. The mass of the core cutter, inclusive of the undisturbed sample, was then measured for each site. Additionally, a specified number of samples from the core cutter of each site were collected for subsequent oven drying to ascertain the water content. This procedure was repeated at intervals of 2, 6, 20, 24, and 48 hours to evaluate the bulk density, water content, and dry density at each time point for each site.

3.2.3 Standard proctor test

During the laboratory testing process, a mold was secured to a base plate at its lower end and to an extension piece at its upper end. The mass of the mold, when attached only to the base plate, was measured. To begin the experiment, 2.5 kg of ash sample that had been dried in an oven was taken and mixed with 10% water. The prepared mixture was then compacted into the mold in three equal layers, with each layer receiving 25 hammer blows from a height of 30.5 cm. After compacting all layers, the top extension was removed, and any excess ash was trimmed off using a straight edge. The mass of the mold, along with the base plate and the compacted sample, was then recorded. A few samples of ash were also taken from the middle of the mold for subsequent drying to determine the water content. This entire procedure was repeated five additional times, each time increasing the percentage of water added to the ash sample.

3.2.4 Modified proctor test

In the laboratory experiment, a mold was affixed to a base plate at its lower end and to an extension piece at its upper end. The mass of the mold, when connected solely to the base plate, was measured. To start the procedure, 2.5 kg of ash sample that had been dried in an oven was taken and combined with 10% water. The resulting mixture was then compacted into the mold in five equal layers, with each layer receiving 25 hammer blows from a height of 45.7 cm. After compacting all layers, the top extension was removed, and any excess ash was trimmed off using a straight edge. The mass of the mold, along with the base plate and the compacted sample, was then recorded. A few samples of ash were also taken from the middle of the mold for subsequent drying to determine the water content. This entire procedure was repeated five additional times, each time increasing the percentage of water added to the ash sample. In this modified version, only the compact energy was increased. The following formulae were used for the calculation purpose.

3.2.5 Specific gravity test

Specific gravity is defined as the ratio of the unit weight of a given sample to the unit weight of water at a specific temperature. To determine this, four density bottles were first dried in an oven and then cooled in a desiccator. Subsequently, 50 g of ash sample that had been dried in the oven was weighed and placed into each bottle. Air-free distilled water was then added to each bottle, which was subsequently placed in a vacuum desiccator for 1 hour. After being removed from the desiccator, the mass of each bottle containing the dry ash and water was measured and recorded. Next, each bottle was filled solely with air-free distilled water, cleaned thoroughly on the outside to ensure no water droplets remained, and weighed again. This identical procedure was carried out for the remaining three density bottles.

3.2.6 Permeability test

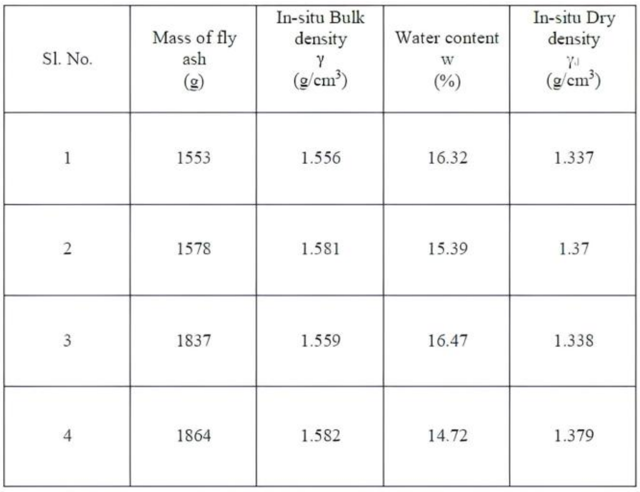
Permeability is a measure of how easily water can pass through a material, such as fly ash, and is essential for tackling various engineering issues. These issues include evaluating seepage through earth dams, quantifying water losses from canals, and determining seepage rates from waste storage facilities. To measure permeability, an undisturbed ash sample was positioned in a permeameter and centered over a porous disc. The drainage base was then attached to the mold. After lightly compacting the sample with a tamper, porous stones were placed on top. The top inlet was connected to a water supply, and the bottom outlet was opened once a steady flow was achieved. The amount of water that flowed through over a specific period was collected in a graduated flask and measured. This procedure was repeated three more times to ensure accuracy.

4. RESULT AND DISCUSSION

4.1 In-situ density test

The in-situ bulk density of ash slurry of the field study was found to be 1.7 g/cm^3, and in-situ dry density was determined to be 1.4 g/cm^3 from four observations given below (Table 1).

Table 1. In-situ density test



Sl. No.	Mass of fly ash (g)	In-situ Bulk density γ (g/cm^3)	Water content w (%)	In-situ Dry density γ_d (g/cm^3)
1	1553	1.556	16.32	1.337
2	1578	1.581	15.39	1.37
3	1837	1.559	16.47	1.338
4	1864	1.582	14.72	1.379

4.2 Variations of Bulk Density, Water Content and Dry Density In a Run of 48 Hours at Different Sites of the Ash Pond

During the field tests conducted at various sites, it was noted that the bulk density remained consistent across each site throughout the duration of the study. Similarly, the water content and dry density exhibited minimal variation for each site. These observations can be further examined in Table 2 and the comparative graphs that follow (Fig.1-11).

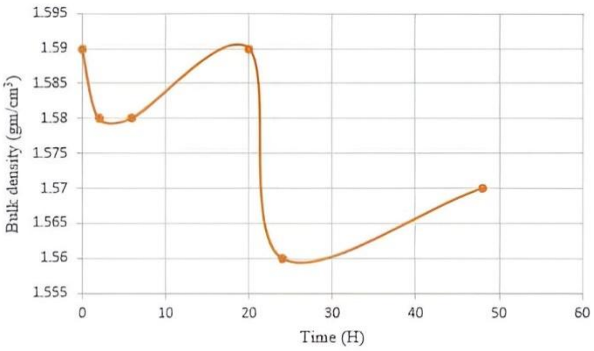


Figure 1. Bulk density vs. time for site 'A'

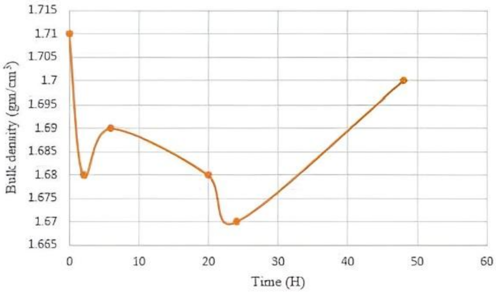


Figure 2. Bulk density vs. time for site 'B'

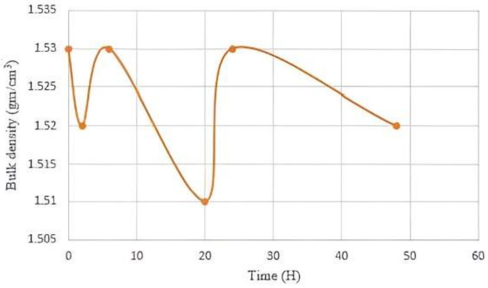


Figure 3. Bulk density vs. time for site 'C'

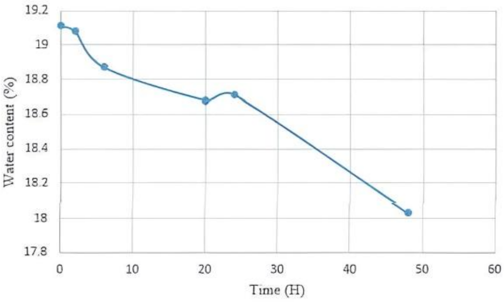


Figure 4. Water Content vs. time for site 'A'

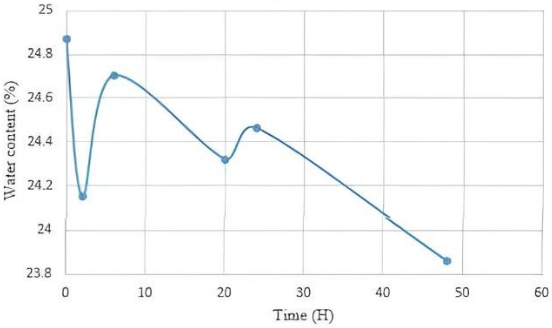


Figure 5. Water Content vs. time for site 'B'

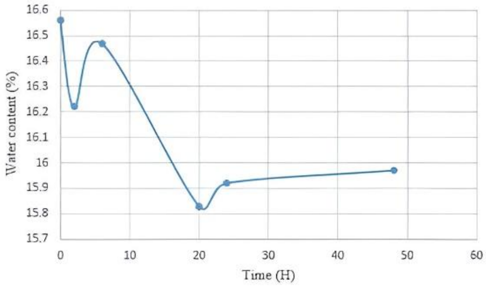


Figure 6. Water Content vs. time for site 'C'

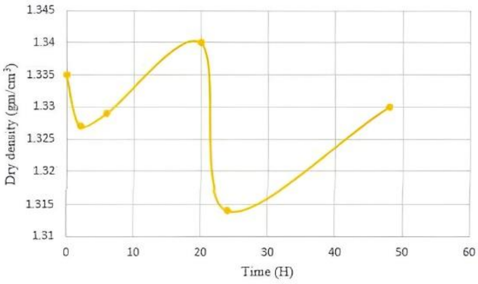


Figure 7. Bulk density vs. time for site 'A'

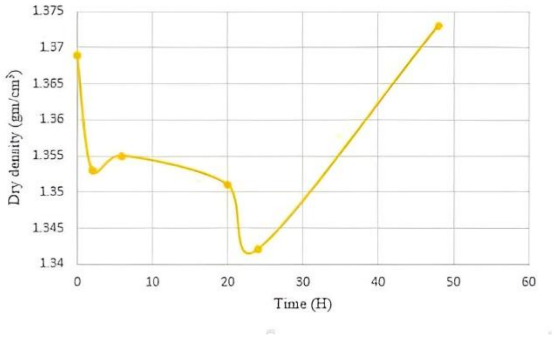


Figure 8. Bulk density vs. time for site 'B'

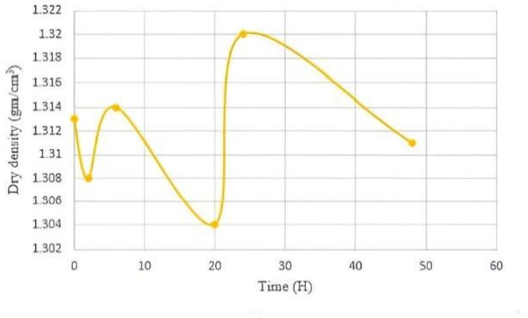


Figure 9. Bulk density vs. time for site 'C'

Table 2. Bulk density, Water content and Dry density of site-A, B, and C at different time intervals

Site, Hour	Bulk density γ(gm/cm3)	Water content w %	Dry density γ_d(gm/cm^3)
A,0 hour	1.59	19.11	1.335
B	1.71	24.87	1.369
C	1.53	16.56	1.313
A,2 hour	1.58	19.08	1.327
B	1.68	24.15	1.353
C	1.52	16.22	1.308
A,6 hour	1.58	18.87	1.329
B	1.69	24.7	1.355
C	1.53	16.47	1.314
A,20 hour	1.59	18.68	1.34
B	1.68	24.32	1.351
C	1.51	15.83	1.304
A,24 hour	1.56	18.71	1.314
B	1.67	24.46	1.342
C	1.53	15.92	1.32
A,48 hour	1.57	18.03	1.33
B	1.7	23.86	1.373
C	1.52	15.97	1.311

4.3 Standard proctor test

The maximum dry density (M.D.D) and the corresponding optimum moisture content (O.M.C) of the ash sample that was collected were found to be 1.367 g/cm³ and 20.13%, respectively. These findings are illustrated in the subsequent observations and graphs.

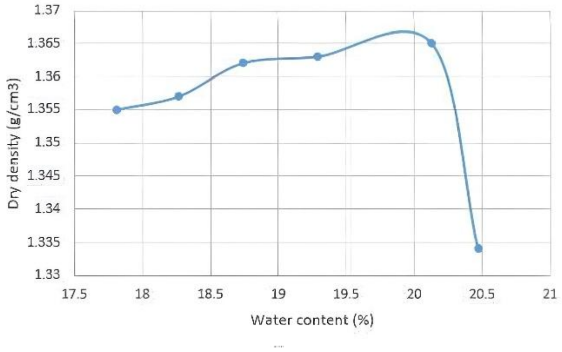


Figure 10. Dry density vs Water content for Standard Proctor test

Table 3. Standard Proctor test

Sl. No.	Wt.ofash (g)	Bulk density γ(g/cm^3)	Watercontent w (%)	Dry density γ_d(g/cm^3)
1	1530	1.597	17.81	1.355
2	1538	1.605	18.27	1.357
3	1551	1.618	18.74	1.362
4	1559	1.627	19.29	1.363
5	1572	1.64	20.13	1.365
6	1541	1.608	20.47	1.334

4.4 Modified proctor test

For this particular test, the highest dry density achieved by the collected ash sample was 1.464 g/cm³, with the ideal moisture content for compaction being 18.19%.

These values are crucial for understanding the compaction characteristics of the ash material and are essential for engineering applications where stability and load-bearing capacity are critical. The detailed observations and graphical representations of these findings are presented in the subsequent sections.

These results highlight the potential of the ash sample for use in construction and civil engineering projects. The maximum dry density indicates the highest possible density that the ash can achieve under the given compaction effort, while the optimum moisture content represents the ideal level of moisture required to achieve this density. These parameters are vital for designing and implementing effective compaction strategies, ensuring that the ash material can support the intended loads without excessive settlement or deformation. The findings suggest that the ash sample exhibits favorable compaction properties, making it a suitable material for applications such as subgrade and subbase layers in road construction, embankments, and other geotechnical structures. Further research could explore the long-term performance and durability of the ash material under various environmental and loading conditions to fully assess its suitability for large-scale engineering projects.

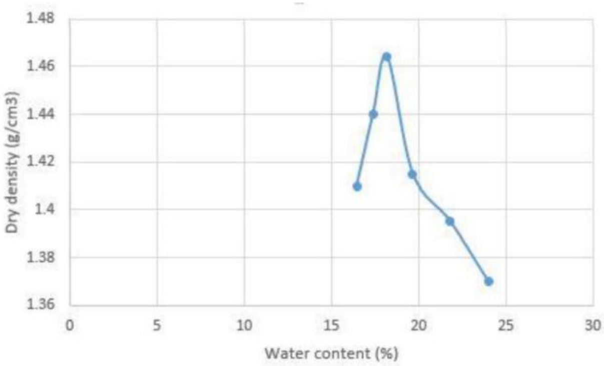


Figure 11. Dry density vs Water content for modified Proctor test

Table 4. Modified Proctor test

Sl. No.	Wt.ofash (g)	Bulk density γ(g/cm³)	Watercontent w (%)	Dry density γ_d(g/cm³)
1	1547	1.64	16.44	1.41
2	1592	1.69	17.38	1.44
3	1628	1.73	18.19	1.464
4	1617	1.694	19.67	1.415
5	1603	1.7	21.82	1.395
6	1613	1.711	23.99	1.37

4.5 Specific gravity test

The specific gravity of the collected ash sample was found to be 2.14. The observations are given below (Table 5).

Table 5. Specific gravity test

TestNo.	M_1 (g)	M_2 (g)	M_3 (g)	M_4 (g)	Specific gravity G
1	104.58	148.07	373.79	351.64	2.03
2	108.52	155.03	383.06	358.41	2.13
3	97.56	146.32	371.71	345.68	2.15
4	111.69	157.88	385.83	360.27	2.23

4.6 Permeability test (constant head)

The permeability of the ash sample taken from the ash pond was measured at 1.261×10^−4 cm/sec. This value is documented in the subsequent observations (Table 6). This measurement is significant as it provides insight into the flow characteristics of water through the ash material. Permeability is a critical parameter in various engineering applications, particularly those involving water management and containment. A permeability value of 1.261×10^−4cm/sec indicates that the ash sample has moderate permeability, which can influence decisions regarding the design and implementation of structures such as embankments, dams, and waste storage facilities. Understanding the permeability of ash materials helps in predicting seepage rates and in designing appropriate measures to control water flow, thereby enhancing the stability and longevity of such structures.

Table 6. Permeability test

Test No.	Length of specimen L (cm)	Area of permeameter A (cm²)	Hydraulic gradienth (cm)	Time of discharge t (seconds)	Volume of discharge Q (cm³)	Coefficient of Permeability k (cm/sec)
1	15	79	204	600	79.61	$1.235x10^{-4}$
2	15	79	199	600	80.25	$1.276x10^{-4}$
3	15	79	192	600	75.92	$1.251x10^{-4}$
4	15	79	183	600	74.12	$1.282x10^{-4}$

The consistent dry density of pond ash across different locations within the ash pond, as observed in the laboratory tests, suggests a uniform settling behavior of the ash particles. This uniformity is crucial for predicting the long-term stability and performance of ash-based materials in engineering applications. The lack of a significant increase in dry density over time indicates that the ash particles settle relatively quickly, reaching a stable state without further compaction. This characteristic is beneficial for applications where rapid stabilization is required, such as in the construction of embankments or foundations.

The permeability of the high-concentrated settled ash slurry, which was found to be around 1.3×10 ^−4 cm/sec, is comparable to that of lean slurry disposal systems. This finding implies that while high-concentration slurry disposal (HCSD) systems may offer some advantages in terms of handling and transportation, they do not significantly enhance the impermeability of the ash slurry. This is an important consideration for applications where water retention or seepage control is a critical factor. For instance, in the design of waste storage facilities or earth dams, the permeability of the ash slurry can directly impact the risk of water contamination and seepage losses. Therefore, while HCSD systems may be more efficient in terms of material handling, they may not provide substantial benefits in terms of reducing permeability compared to conventional methods.

The results from the Proctor compaction tests highlight the potential of pond ash from HCSD systems for use in embankment construction. The higher maximum dry density (MDD) and lower optimum moisture content (OMC) achieved through greater compactive effort suggest that pond ash from HCSD systems can be effectively compacted to achieve desirable engineering properties. These characteristics are particularly advantageous for constructing stable and durable embankments as they can enhance the load-bearing capacity and reduce the risk of settlement over time. The favorable compaction properties of pond ash from HCSD systems indicate that it can be a viable and cost-effective alternative to conventional materials, especially in regions where ash is readily available. Future research could focus on exploring the long-term performance of pond ash in various engineering applications and developing optimized compaction techniques to further enhance its properties.

5. CONCLUSION

From the laboratory tests conducted on samples collected from specific sites over a defined period, it was observed that the dry density of pond ash at different locations within the ash pond remained consistent at approximately 1.4 g/cc. The findings indicate that there is no significant increase in dry density over time as the ash settles in the pond. The permeability of high-concentrated settled ash slurry collected from the ash pond was found to be around 1.3×10 ^-4 cm/sec, which is comparable to the permeability observed in most lean slurry disposal systems. This suggests that high-concentration slurry disposal (HCSD) does not offer a significant improvement in impermeability compared to conventional lean slurry systems. Proctor compaction tests revealed that applying greater compactive effort to pond ash collected from the HCSD system resulted in a higher maximum dry density (MDD) and a lower optimum moisture content (OMC). This indicates that pond ash from the HCSD system exhibits favorable characteristics for embankment construction, making it a suitable material for such engineering applications.

Conflicts of Interest: The authors declare no conflicts of interest.

Funding: This research received no external funding.

Author Contributions: Conceptualization, AM; methodology, AM; software, AM; validation, AM, Authors have read and agreed to the published version of the manuscript.

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