

Pond Ash as a Sustainable Backfill for Reinforced Earth (RE) Wall

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MASTER OF TECHNOLOGY

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BY

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CANDIDATE'S DECLARATION

I, Pratham Poonia (24/GTE/18), student of M.Tech. in Geotechnical Engineering, hereby declare that the work presented in this dissertation, entitled “Pond Ash as Sustainable Backfill for Reinforced Soil Walls: Laboratory, Field, and Economic Evaluation,” and submitted to the Department of Civil Engineering, Delhi Technological University, Delhi, in partial fulfilment of the requirements for the award of the degree of Master of Technology, is an authentic record of my own work carried out during the academic session 2024–2026 under the supervision of Prof. Amit Kumar Srivastava. The material presented in this dissertation has not been submitted, in part or in full, for the award of any other degree or diploma of this or any other institution.

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CERTIFICATE BY THE SUPERVISOR

This is to certify that the work presented in this dissertation, entitled “Pond Ash as Sustainable Backfill for Reinforced Soil Walls: Laboratory, Field, and Economic Evaluation,” has been carried out by Pratham Poonia (24/GTE/18) under my supervision, in partial fulfilment of the requirements for the award of the degree of Master of Technology in Geotechnical Engineering from the Department of Civil Engineering, Delhi Technological University, Delhi. To the best of my knowledge, this dissertation embodies the candidate’s own original work and has not been submitted, in part or in full, for the award of any other degree or diploma of this or any other university or institution.

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ABSTRACT

The rapid expansion of highway infrastructure in India has intensified the demand for granular backfill in reinforced soil wall construction, placing sustained pressure on natural borrow sources and renewing interest in industrial by-products such as pond ash as an alternative fill material. This dissertation investigates whether pond ash can serve as a technically sound, code-compliant and economically viable backfill for reinforced soil walls at a live highway project site on the NH-46 Guna-Biaora section (chainage 118+400), where the native fill is a plastic, SC-classified sandy clayey soil.

The investigation proceeds through a comparative geotechnical characterisation of the native soil and pond ash, an assessment of the mechanical and reinforcement-interaction behaviour of pond ash under site-specific loading, an examination of hydraulic and environmental response under seasonal groundwater fluctuation, the identification of field performance monitoring requirements, and an economic and sustainability appraisal of pond ash against conventional borrow material within an Engineering, Procurement and Construction (EPC) project framework.

The native soil exhibits a dry density of 1.821–1.829 g/cc, cohesion of 0.03–0.04 kg/cm² and an internal friction angle of 25.3°–25.9°, with a shallow groundwater table at approximately 3.50 m governing drainage and pore-pressure behaviour. By comparison, the pond ash is non-plastic, contains 6.75% fines, and returns a markedly higher friction angle of 31.50° with negligible cohesion, a maximum dry density of 1.344 g/cc at an optimum moisture content of 25.30%, and full compliance with the gradation and strength criteria of IRC:SP:102-2014. Limit-equilibrium stability checks for the reinforced soil wall section return factors of safety of 1.82 against sliding, 2.45 against overturning and 3.10 against bearing failure, with a global factor of safety of 1.68, all exceeding their respective minimum requirements.

These results indicate that pond ash offers genuine geotechnical and sustainability advantages — reduced dependence on natural borrow material, beneficial reuse of an industrial residue, and favourable frictional behaviour — but also reveal material properties that differ substantially from the native soil baseline, particularly in density and cohesion. The economic case for pond ash is accordingly found to be conditional rather than assured: within an EPC-mode project framework, any cost or schedule advantage depends on verified field compaction, drainage performance and reinforcement interaction, since unvalidated deviations from design assumptions could erode the anticipated savings. The dissertation concludes that pond ash is a technically promising and potentially sustainable backfill alternative for reinforced soil wall construction, whose safe and economical adoption should be confirmed through calibrated field-scale trials and continued instrumented monitoring prior to full-scale implementation.

This thesis addresses the technical, structural, economic, field and sustainability feasibility of using source-specific pond ash as an alternative sustainable backfill material for Reinforced Earth walls, through comparison with conventional soil and compliance with IRC:SP:102-2014.

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CHAPTER 1

INTRODUCTION

1. Overview

The rapid expansion of transportation corridors, urban flyovers, bridge approaches, industrial platforms, and grade-separated highway facilities has increased the demand for retaining systems that are economical, durable, constructible within limited space, and adaptable to variable ground conditions. Reinforced Earth (RE) walls, also referred to in several design references as mechanically stabilized earth walls, have become a widely accepted solution for such applications. An RE wall is a composite soil-reinforcement system in which compacted backfill, reinforcement layers, facing elements, and foundation support act together to resist lateral earth pressure and maintain stability. In comparison with conventional reinforced cement concrete retaining walls, RE walls are generally more flexible, faster to construct, and better suited for locations where differential settlement or staged construction is expected. For these reasons, RE wall technology has found extensive use in highway embankments, bridge abutments, retaining walls, approach ramps, and other transportation infrastructure.

The performance of an RE wall depends strongly on the quality and behaviour of the backfill material. The backfill is not merely a passive mass placed behind the facing; it is the principal medium through which stresses are transferred to the reinforcement. A suitable RE wall backfill should possess adequate shear strength, favourable compaction characteristics, acceptable gradation, sufficient drainage capacity, low compressibility, and compatibility with reinforcement and facing systems. Poorly selected backfill can lead to excessive lateral pressure, inadequate mobilization of frictional resistance, construction difficulties, water retention, post-construction

deformation, and reduced serviceability. Hence, the selection and evaluation of backfill material is one of the most critical stages in RE wall design and construction.

Conventionally, well-graded granular soils, sand, gravelly soils, and locally available moorum are preferred as reinforced fill materials because they offer good drainage, high frictional resistance, and ease of compaction. However, the growing use of RE walls in highways and urban infrastructure has significantly increased the demand for such natural aggregates. In many project locations, high-quality granular backfill is either unavailable nearby or can be obtained only after long-distance transportation. This increases construction cost, fuel consumption, and project duration. The excessive extraction of river sand and natural aggregates also causes environmental concerns, including disturbance of river systems, degradation of local landscapes, depletion of natural resources, and regulatory restrictions on borrow-area and quarry operations. Thus, the continued dependence on conventional backfill materials is increasingly inconsistent with the present need for sustainable and resource-efficient infrastructure.

These limitations have encouraged researchers and engineers to examine industrial by-products as alternative construction materials. Among these, coal ash generated from thermal power plants has received considerable attention because of its large-scale availability and its potential use in geotechnical works. Coal ash is generally produced in the form of fly ash and bottom ash. In wet disposal systems, fly ash and bottom ash are mixed with water and transported as slurry to ash ponds, where the solids settle after water is drained or recycled. The resulting deposit is commonly known as pond ash or ponded ash. Since coal-based thermal power generation produces large quantities of ash, its storage in ash ponds requires substantial land and creates long-term disposal, handling, and environmental management problems. Productive utilisation of pond ash in civil

engineering applications can reduce pressure on ash pond storage, conserve natural aggregates, and support sustainable construction practices.

Pond ash is of particular interest for RE wall backfill because it may exhibit several characteristics favourable for earthwork applications. Depending on the source, location within the ash pond, and proportion of fly ash and bottom ash, pond ash may contain sand-sized particles with non-plastic fines, relatively low specific gravity, moderate permeability, and frictional behaviour that can be useful in compacted fills. At the same time, pond ash is a highly source-dependent material. Its gradation, fines content, unit weight, compaction response, drainage behaviour, and shear strength may vary significantly from one thermal power plant to another and even within different zones of the same ash pond. Therefore, it cannot be accepted as RE wall backfill merely because it is available in large quantity. It must be systematically tested and compared with conventional soil before its suitability can be established.

The present study investigates the suitability of pond ash as a sustainable backfill material for Reinforced Earth (RE) wall construction. The engineering properties of pond ash are studied and compared with conventional soil to assess its gradation, compaction behaviour, unit weight and shear strength. Its suitability is further evaluated against the relevant requirements of IRC:SP:102-2014 and through RE wall stability calculations. The study also examines the economic and sustainability benefits of replacing conventional backfill with pond ash, along with field verification of its compaction performance. Overall, the research aims to determine whether pond ash can provide a safe, technically suitable and cost-effective alternative for RE wall applications.

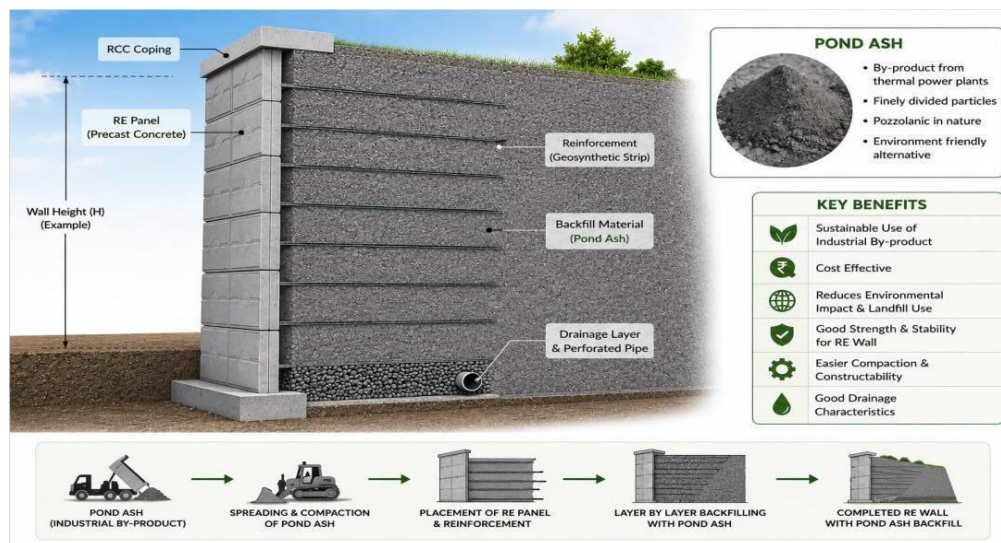


Figure 1.1: Conceptual representation of pond ash as sustainable backfill for a Reinforced Earth wall
 (Source: <https://share.google/yQBs9btHaseUJhM75>)

Coal ash materials can perform effectively in reinforced soil and backfill applications when their engineering properties are properly understood. Compacted bottom ash has pullout resistance close to natural sand, whereas uncompacted placement can reduce pullout resistance substantially, making compaction control a critical construction requirement (Pant et al., 2019). Pond ash, bottom ash and fly ash can also function as structural fills in mechanically stabilised earth walls when fines content, drainage, compaction and shear strength remain within acceptable limits (Pant, 2020; Reddy, 2022). These findings establish that coal ash materials are not automatically suitable or unsuitable; their performance depends on gradation, density, fines content, compaction, shear strength, drainage and interaction with reinforcement.

The importance of gradation, fines content, drainage, and field validation is also evident from earlier work on fly ash and other ash-based fills. Vashi et al. (2010) reviewed the use of fly ash as backfill in reinforced earth structures and noted that the scarcity of sand and growth of infrastructure construction make alternative fill materials technically and economically relevant,

provided that shear strength, compressibility, pullout resistance, permeability, and code requirements are satisfied. Kumar and Kalliamani (2016), using numerical simulation, reported that replacing conventional soil with fly ash as retained fill reduced lateral earth pressure and wall displacement under static and dynamic conditions. Although fly ash is not the same as pond ash, these studies support the broader understanding that lightweight ash-based materials can reduce stresses in retaining systems, but they must be evaluated with due attention to their physical and mechanical behaviour.

Studies specifically involving pond ash further support its potential as a sustainable fill material. Sharma (2013) investigated pond ash, sand, and their mixtures for reinforced earth wall applications and reported that pond ash was coarse like sand but had lower shear resistance, while pond ash-sand mixtures showed improved pullout response compared with either material used alone. The study also highlighted the need for field validation. Reddy (2022) evaluated pond ash, bottom ash, and copper slag as fill materials in reinforced earth retaining walls under non-seismic and seismic conditions. In that work, pond ash from NTPC Simhadri was reported as a coarse-grained silty sand with non-plastic fines, low specific gravity compared with conventional moorum, measurable frictional strength, and semi-pervious behaviour. The thesis concluded that pond ash and bottom ash could reduce bearing pressures and reinforcement tension compared with conventional moorum, and that ash-based fills may provide cost advantages, particularly for greater wall heights. These findings indicate that pond ash can be a technically promising material, but the conclusions remain source-specific and require verification for any new pond ash sample before field use.

Pond ash can also be improved or adapted for other backfill applications, but such developments do not eliminate the need for basic suitability assessment. Lime stabilisation can improve strength

and microstructural bonding with suitable dosage and curing, while ponded ash-based backfill mixtures can satisfy workability and strength requirements in selected applications (Le et al., 2018; Vilasini et al., 2025). These findings show the broader potential of pond ash in sustainable construction. However, the present research is not a stabilisation study or a controlled low-strength material study. Its focus, as defined by the methodology flowchart, is to evaluate pond ash as a backfill for RE wall applications through material collection, geotechnical characterisation, compaction testing, direct shear strength evaluation, IRC:SP:102-2014 compliance checking, comparison with conventional soil, cost analysis, sustainability assessment and final suitability recommendations.

The present study is therefore necessary to develop a source-specific and methodology-based assessment of pond ash as a sustainable backfill material for RE walls. By collecting pond ash from a thermal power plant and comparing it with conventional soil used in RE wall construction, the study can establish whether pond ash satisfies the essential requirements of gradation, unit weight, compaction behaviour, shear strength, drainage-related suitability, and IRC:SP:102-2014 compliance. The comparison with conventional soil is important because the engineering decision is not whether pond ash is useful in an abstract sense, but whether it can reasonably replace or supplement natural backfill in actual RE wall construction. The cost analysis further addresses the economic feasibility of material procurement, transportation, and handling, while the sustainability assessment evaluates the benefit of using an industrial waste material to conserve natural resources and reduce disposal problems.

Thus, the present investigation is positioned at the intersection of geotechnical performance, code-based suitability, construction economy, and sustainable material utilisation. It does not assume that pond ash is automatically acceptable, nor does it reject pond ash because of its waste origin.

Instead, it follows a systematic testing and evaluation programme in which pond ash and conventional soil are collected, characterised, compacted, sheared, checked against IRC requirements, compared technically and economically, and assessed for sustainability benefits. This sequence directly supports the formulation of clear research objectives, which are presented in the following section.

2. Objectives of the Study

The objectives of the present study are derived from the approved methodology flowchart and the research gap established in the preceding discussion. The study aims to evaluate pond ash as a sustainable backfill material for RE wall applications through the following objectives:

- To determine and compare the engineering properties of pond ash and conventional soil through laboratory testing, including material characterization, compaction, and shear strength evaluation.
- To assess the suitability of pond ash as RE wall backfill in accordance with the requirements of IRC:SP:102-2014 and evaluate its construction feasibility.
- To compare pond ash and conventional soil in terms of cost-effectiveness, sustainability, and overall suitability, and to provide recommendations for field application in RE wall construction.
- To investigate the potential of pond ash as an alternative and sustainable backfill material for Reinforced Earth (RE) wall applications.

CHAPTER 2

LITERATURE SURVEY

[Vilasini P.P, et al., (2025)]

Evaluated the long-term chemical stabilization of Class F pond ash using 2% to 8% lime over a 120-day curing period. An optimal lime dosage of 6% was determined to maintain the matrix pH above 12.4, which is required to sustain pozzolanic activity. Unconfined Compressive Strength (UCS) tests showed a significant strength increase, rising from 67 kPa (untreated) to 2,719 kPa at 120 days. Advanced characterization via FTIR, XRD, and SEM-EDS verified that raw quartz and mullite minerals were consumed to form crystalline calcium silicate hydrate (C-S- H) and calcium aluminate hydrate (C-A-H) gels. The study concludes that 6% lime stabilization successfully remedies the low cohesion and initial strength deficiencies of raw pond ash, providing a dense, stable alternative for structural highway fills, subgrades, and embankments.

[Reddy R., (2022)]

In his doctoral dissertation examines the technical and environmental performance of alternative industrial byproducts—pond ash, bottom ash, and copper slag—as structural fills in reinforced earth retaining walls. Large-scale direct shear and pullout tests evaluated the interface shear parameters of geocomposite and woven geotextile reinforcements under optimum moisture and saturated conditions. Structural configurations from 4 m to 10 m were designed to satisfy non-seismic (BS 8006) and dynamic seismic (AASHTO) safety factors across Zones II to V. The results indicate that the low dry unit weight of coal ash minimizes active lateral thrusts, geogrid tension demands, and foundation bearing pressures. Economic analysis confirms that substituting conventional moorum with pond or bottom ash reduces total wall construction costs by 13% to

23%, offering a safe, low-cost structural solution.

[Aali Pant (2020)]

In his doctoral thesis assesses the individual engineering viability of bottom ash, pond ash, and fly ash fractions as alternative structural fills in mechanically stabilized earth (MSE) walls. Physical, chemical, and electrochemical indices were validated against IRC:SP:102, FHWA, and BS 8006 guidelines. Large-scale horizontal pullout testing (ASTM D6706) demonstrated that densely compacted bottom ash and low-fines pond ash (60% fines) or uncompacted placement led to a 30% to 70% reduction in pullout resistance. 3D finite element simulations in PLAXIS matched experimental results within a $\pm 10\%$ to 20% margin. The research concludes that bottom ash functions as an ideal sand substitute, whereas pond ash requires horizontal sand drainage blankets, and fly ash mandates strict field quality controls against moisture saturation.

[G.V. Ramana, et al., (2019)]

In his study investigates the shear strength and geogrid interface friction parameters of coal bottom ash from two thermal power plants for application in reinforced soil structures. Large-scale horizontal pullout tests (ASTM D6706-01) were conducted on polyester geogrids, using natural river sand as a reference baseline. The non-plastic bottom ash was classified as silty sand (SM) with high internal peak friction angles up to 40° due to mechanical grain interlocking. Compacted bottom ash achieved pullout resistance identical to sand, whereas uncompacted samples suffered a 30% to 60% capacity loss. Stability analysis of a 9-meter MSE wall indicates that the low dry unit weight of bottom ash reduces active lateral earth pressures, lowering the required reinforcement layers. Environmental leachability testing via TCLP confirmed heavy metal concentrations remain safely within drinking water limits.

[Tri Ho Minh Le, et al., (2018)]

In his experimental study evaluates the fresh and hardened performance of flowable backfill mixtures developed using varied ponded ash-to-sand ratios, cement binders, and air foam contents. All formulated slurries exhibited self-leveling flowability spreads between 200 mm and 250 mm, eliminating the need for mechanical layer compaction. Compaction free strengths scaled up with cement and ash content but were reduced by increased air foam or cyclic freeze-thaw exposure. A full-scale road testbed trench backfilled with a 100% ponded ash mixture was monitored using a light falling weight deflectometer (LWD), verifying an early-age elastic modulus of 105 MPa. The study concludes that flowable ponded ash serves as a viable, sustainable alternative to granular soil fill, maintaining long-term strengths below 1.4 MPa to facilitate automated placement and easy future re-excavation.

[Mohammad Fariyaz Ahmed, et al., (2017)]

Evaluates the engineering properties of pond ash and bottom ash obtained from the Vijayawada Thermal Power Station to determine their utility as structural fill alternatives. Index characterization via sieve analysis classified the bottom ash as poorly graded sand and the pond ash as fine granular sand. The specific gravity values were low (1.7 for pond ash and 2.2 for bottom ash), highlighting their lightweight benefit over conventional structural soils. Standard moisture-density compaction curves displayed flat profiles, indicating that both ash types can be compacted efficiently across a wide placement moisture range. The low dry unit weight reduces lateral active earth pressures behind retaining structures and minimizes subgrade settlement. The paper concludes that utilizing these industrial byproducts saves significant capital costs related to land acquisition and aggregate transport logistics.

[Umesh Kumar N, et al., (2016)]

In his research investigates the static and dynamic seismic behavior of geosynthetic- reinforced earth retaining walls constructed with lightweight fly ash backfill. Two-dimensional plane strain finite element simulations were conducted under fully drained parameters using PLAXIS software. The numerical modeling demonstrated that replacing conventional granular soil with fly ash achieves a 75% reduction in static lateral active earth pressure and a 55% reduction under dynamic seismic conditions. Horizontal wall facing displacements were reduced by 35% under static loading and by up to 75% during seismic earthquake shaking. This enhanced stability is directly driven by the low wet unit weight of the fly ash (13.82 kN/m^3), which reduces the driving active failure wedge forces. The study concludes that fly ash serves as an excellent lightweight fill material that prevents earthquake-induced sliding and overturning failures.

[K. Lini Dev and R. G. Robinson (2015)]

Reviewed the geotechnical application of controlled low-strength materials (CLSM or flowable fills) using non-plastic pond ash collected from the Ennore Thermal Power Station. Sieve analysis categorized the material as silty sand (SP-SM) containing 6% fines and a specific gravity of 2.25. Slurry designs mixed with 2% to 3% cement generated self-leveling flowability spreads of 200 mm to 300 mm, allowing compaction-free pumping in restricted zones. The hardened mixtures achieved a low 28-day UCS ($<0.7 \text{ MPa}$) and favorable CBR values between 14% and 33%, matching standard compacted granular bases. Permeability testing indicated that an increased fines content effectively reduces the internal seepage coefficients. The study concludes that flowable pond ash CLSM serves as a reliable, low-settlement alternative behind retaining walls and inside utility trenches where standard compaction equipment cannot be deployed.

[Ms. Vashi Jigisha M., et al., (2010a)]

Reviewed analyzes the engineering performance and soil-geosynthetic interface friction behavior of fly ash for bulk utilization in reinforced earth retaining structures. Driven by the expanding expressway and flyover projects across India, the authors highlight the urgent need for sustainable alternatives to increasingly scarce natural river sand. Synthesis of global triaxial and direct shear data indicates that fly ash compacted at optimum moisture content exhibits high peak shear parameters and excellent mechanical rigidity. Geosynthetic-reinforced walls with fly ash backfill offer distinct advantages, including a flexible structural footprint, reduced deadweight, and rapid construction over soft soils. Frictional stress transfer along geogrid apertures is shown to be governed by the specific reinforcement layout and soil wedge failure angles. The study concludes that fly ash utilization addresses both ecological and material scarcity limits, recommending instrumented field monitoring to establish national design standards.

[Dr. C.H. Solanki, et al.,(2010b)]

In his technical review investigates the friction boundaries and performance parameters of fly ash backfills interacting with geosynthetic layers in mechanically stabilized earth systems. The paper outlines how the unit weight and interface interaction coefficient of a backfill directly govern the structural life and internal stability of the wall. Densely compacted fly ash matrices satisfy standard strength and rigidity criteria, acting as a lightweight fill that minimizes active driving stresses against the wall facing. Review of large-scale direct shear and pullout tests confirms that non-plastic fly ash can replace sand in bulk infrastructure, yielding significant project economy.

However, the interface interaction coefficient remains highly sensitive to moisture changes, particle size distributions, and grid junction interlocking. The authors conclude that fly ash bulk utilization provides excellent environmental and financial returns, but emphasize that long-term field tracking is required to map settlement and seepage trends.

[N. Moraci and D. Giofrè (2006)]

This paper presents a comprehensive analytical method to evaluate the pullout resistance of extruded geogrids embedded in compacted granular soils, establishing a framework that is frequently adapted for alternative lightweight fills like pond ash and bottom ash. The research emphasizes the complex interaction between soil moisture content, degree of compaction, and geosynthetic interface friction. The study details that the ultimate pullout resistance of geogrids is strictly governed by the skin friction mobilized along the longitudinal ribs and the passive earth thrust acting against the transverse members. The authors conclude that accurately establishing pullout interaction coefficients through large-scale testing is critical for the internal stability design of Mechanically Stabilized Earth (MSE) walls, particularly when backfill materials are subjected to varying vertical confining pressures.

2.1 State of the Art

Reinforced Earth (RE) wall technology has become one of the most widely adopted retaining systems in modern transportation and infrastructure projects because of its flexibility, cost-effectiveness, and ease of construction. Traditionally, well-graded granular materials such as sand, gravel, and moorum have been used as backfill due to their high shear strength, good drainage characteristics, and reliable field performance. However, the increasing demand for these natural materials has resulted in their depletion, higher transportation costs, and growing

environmental concerns. As a result, researchers have shifted their attention towards the use of sustainable alternative materials that can reduce the dependence on natural resources without compromising engineering performance.

Among the various alternative materials, pond ash has received considerable attention because it is produced in large quantities by thermal power plants and poses a significant disposal challenge. Instead of treating pond ash as an industrial waste, many researchers have investigated its potential use in geotechnical applications. Previous studies have shown that pond ash generally possesses non-plastic behaviour, relatively low unit weight, and satisfactory shear strength, making it a potential backfill material for Reinforced Earth walls. However, its engineering properties are highly influenced by factors such as particle size distribution, fines content, moisture condition, and the source from which it is collected. Therefore, its suitability cannot be assumed without proper laboratory evaluation.

Recent research has mainly focused on evaluating the engineering behaviour of pond ash through laboratory investigations, including grain size analysis, specific gravity, compaction characteristics, and direct shear tests. At the same time, researchers have emphasized that the acceptance of pond ash as a backfill material should not depend only on its environmental benefits but also on its compliance with codal requirements related to strength, compaction, drainage, and gradation. In addition, economic feasibility and sustainability have become equally important considerations while selecting backfill materials for modern infrastructure projects.

Although several studies have reported encouraging results, a comprehensive evaluation of pond ash as RE wall backfill is still limited. Most previous investigations have concentrated on individual aspects such as material characterization, reinforcement interaction, numerical modelling, or stabilization techniques. Very few studies have combined laboratory characterization, compaction behaviour, shear strength evaluation, compliance with IRC:SP:102-

2014, comparison with conventional soil, cost analysis, and sustainability assessment within a single experimental framework. Moreover, since the properties of pond ash vary from one thermal power plant to another, its performance must be evaluated for the specific source before it can be recommended for field applications.

2.2 Conventional Backfill Materials

2.2.1 Definition and types of conventional backfill

In the context of RE walls, conventional backfill refers to natural or routinely used borrow materials that have historically been accepted for reinforced fill because of their favourable gradation, strength, drainage and compaction behaviour. Sand, gravelly soil, moorum, crushed rock pieces, cobbles and granular soils are typical conventional materials. Coarse-grained materials such as gravel, sand, pond ash, crushed rock pieces and cobbles are commonly used as backfill materials in retaining walls and other filling applications. Sand and moorum are common field materials in reinforced earth retaining walls because granular fills provide good drainage and mobilise better frictional resistance with reinforcement.

The main reason for the preference for conventional granular materials is that they behave predictably when compacted. Clean sand and gravelly materials generally have low plasticity, relatively high permeability and high internal friction. Moorum, commonly used in Indian road and retaining-wall works, is a naturally occurring gravelly or silty gravelly material whose suitability depends on gradation and fines content. In comparative RE wall evaluation, moorum serves as the conventional reference fill against which bottom ash, pond ash and copper slag can be assessed. This is important for the present thesis because the engineering question is not whether pond ash is theoretically useful, but whether it can perform reasonably when compared with a conventional soil normally used in RE wall construction.

2.2.2 Desired engineering properties

A suitable conventional backfill for an RE wall should be free from deleterious organic matter, reasonably well graded, non-plastic or low plastic, compactable to the required density, sufficiently permeable and capable of mobilising adequate shear resistance. It should also be compatible with the reinforcement and should not promote chemical degradation of metallic or polymeric components. MSE wall fill materials are generally assessed against gradation, shear strength and electrochemical criteria in national and international guidelines. **IRC:SP:102-2014** is particularly relevant for Indian practice because it provides guidance for reinforced soil walls and requirements related to fill suitability.

The desired mechanical behaviour is governed mainly by the angle of internal friction and density achieved during compaction. Granular materials are favoured because they can develop high frictional resistance and moderate dilation when dense. Positive dilation can occur in dense bottom ash and sand at relative density of about 80 percent under normal stresses between 20 and 80 kPa, with dilation decreasing as normal stress increases. This behaviour illustrates a broader principle: dense granular or sand-like materials can mobilise high shear resistance, but the effect of dilation is stress-dependent.

Compaction characteristics are equally important. Conventional backfills are generally compacted in layers to a specified relative compaction. Backfills are normally compacted in layers at not less than 95 percent of the **Standard Proctor** unit weight at the desired water content. This requirement is directly connected with the present thesis methodology, which includes **Standard Proctor** compaction testing to determine optimum moisture content and maximum dry density. The **OMC-MDD** relationship helps determine the moisture condition and density at which the backfill should be placed in the field.

2.2.3 Advantages, limitations and environmental concerns

The advantages of conventional backfill materials are well understood: high shear strength, predictable compaction, good drainage, availability of design experience and acceptance in codes. These qualities reduce uncertainty during design and construction. For contractors, granular natural fills are familiar materials, and quality control methods such as sieve analysis, moisture content testing, unit weight determination and compaction testing are standard.

The limitations are now becoming more serious. Natural sand and aggregates are finite resources, and their extraction can disturb river channels, borrow areas and local landscapes. Transportation from distant sources increases cost, fuel use and carbon emissions. Future availability of sand as backfill cannot be assumed, and alternative local or waste materials must be considered as RE retaining wall construction continues to expand.

From an economic perspective, conventional backfills may appear simple at the design stage but become expensive when suitable borrow sources are far from the project site. Cost includes material procurement, royalty or excavation, loading, transportation, placement and compaction. The economy of using ash or conventional soil depends strongly on transportation distance. Even a technically superior material may become uneconomical if it must be hauled over long distances.

2.2.4 Suitability of conventional materials for RE walls

Conventional materials remain the benchmark against which sustainable alternatives must be evaluated. Sand and moorum provide reference behaviour for gradation, compaction and shear strength. Moorum is useful as a comparison material for pond ash, bottom ash and copper slag in reinforced earth retaining wall design. Yamuna sand provides a reference for bottom ash pullout

behaviour, while sand also provides a useful comparison for pond ash and pond ash-sand mixtures. These comparisons show that the suitability of a sustainable backfill must be demonstrated relative to a material already accepted in practice.

For the present thesis, conventional soil is therefore not merely a control sample. It is the engineering baseline. Grain size distribution, specific gravity, Atterberg limits where applicable, natural moisture content, unit weight, **Standard Proctor** compaction parameters and direct shear strength parameters of conventional soil provide the reference against which pond ash can be judged. If pond ash shows acceptable gradation, low plasticity, manageable **OMC-MDD** behaviour, adequate shear strength and reasonable drainage-related suitability, it may be considered a viable alternative. If deficiencies are identified, they must be stated clearly rather than hidden by general sustainability claims.

2.3 Modern Sustainable Backfill Materials

2.3.1 Pond ash

Pond ash is the principal sustainable material relevant to the present thesis. It is formed when fly ash and bottom ash from thermal power plants are mixed with water and conveyed as slurry to ash ponds, where the solids settle after water is drained or recycled. Because it is deposited hydraulically, pond ash is not a uniform manufactured product. Its properties depend on the combustion process, coal source, disposal method, degree of segregation in the pond and the proportion of fine fly ash to coarser bottom ash. Pond ash may contain less fines near the inflow point and more fines near the outflow point, making source and sampling location important.

The engineering potential of pond ash lies in its low specific gravity, non-plastic nature, sand-sized fraction and possible frictional behaviour. Pond ash collected from Vijayawada Thermal

Power Station is non-plastic, has specific gravity around 1.7 and can be considered an economical fill material where other engineering requirements are satisfied. Pond ash from NTPC Simhadri has been characterised as a coarse-grained silty sand with 15 percent non-plastic fines and 85 percent sand-sized particles. Its maximum dry density is about 1.21 g/cc, optimum moisture content is about 11.1 percent and angle of internal friction is about 33 degrees at **OMC-MDD** condition. These values suggest that, where pond ash is relatively coarse and non-plastic, its mechanical behaviour can be comparable to conventional granular fills.

Pond ash also offers sustainability benefits. It uses an industrial by-product that otherwise occupies large ash pond areas and creates disposal concerns. Its use as backfill can reduce the demand for natural sand and moorum. Ponded ash can be used in backfill mixtures with good flowability and field performance where the application requires a flowable material. Pond ash-based controlled low strength flowable fills can also be produced with limited cement content for applications where conventional compaction is difficult. Although flowable fills differ from compacted RE wall backfill, they reinforce the broader conclusion that pond ash can be converted from a disposal liability into a construction resource.

The limitations of pond ash are equally important. Pond ash with fines content below about 50 percent can show shear and pullout behaviour comparable to natural soil, but drainage must be ensured through additional horizontal drainage layers. When the fines content exceeds about 60 percent, pond ash may behave closer to fly ash and may not be suitable without design safeguards. This is a key point for the present thesis because the methodology includes grain size distribution, compaction, direct shear and IRC compliance checks. A sustainable material should not be accepted solely because it is waste-derived; it must satisfy engineering criteria.

2.3.2 Fly ash

Fly ash is the finer fraction of coal ash collected from flue gases, commonly through electrostatic precipitators. It is generally finer than bottom ash and may contain a high percentage of silt-sized particles. Its low unit weight can reduce lateral earth pressure, but its high fines content and lower permeability may limit its direct use as reinforced fill unless it satisfies relevant specifications or is used with adequate drainage and design safeguards.

A reinforced earth retaining wall with fly ash as retained fill can develop lower lateral earth pressure and wall displacement than a comparable soil-filled wall under static and dynamic conditions. This behaviour indicates that lightweight ash materials can reduce earth pressure demand. Fly ash may be technically and economically useful when it satisfies shear, compressibility, pullout resistance and permeability criteria. However, proper field trials, quality control and drainage provisions remain essential before using fly ash in reinforced earth structures.

2.3.3 Bottom ash

Bottom ash is the coarser ash collected from the bottom of the furnace. It usually has a more granular texture than fly ash and may resemble sand in some engineering aspects. Bottom ash from thermal power plants can have angles of shearing resistance and geogrid pullout resistance comparable to natural sand where the grain size distribution is similar. Because bottom ash is lighter than sand, the design of a 9 m MSE wall can require fewer reinforcement layers with bottom ash than with sand, mainly due to lower lateral active earth pressure.

Bottom ash is also affected by compaction. Uncompacted bottom ash can reduce pullout resistance substantially compared with compacted material. Bottom ash generally satisfies shear strength and electrochemical criteria in major guidelines, although some samples may not satisfy every gradation requirement depending on the code considered. It is non-plastic and coarser than pond ash, with specific gravity higher than pond ash. It can be lighter than moorum by about 50 percent while maintaining frictional characteristics suitable for reinforced earth retaining wall applications.

The main advantage of bottom ash is its granular behaviour and lower unit weight. Its limitation is that it may not be available in the same form at all power plants, especially where ash is mixed and hydraulically deposited as pond ash. For this thesis, bottom ash is important because it explains why the coarser fraction of pond ash contributes favourably to shear strength and drainage.

2.3.4 Recycled aggregates and construction and demolition waste

Recycled aggregates and construction and demolition (C&D) wastes are modern sustainable backfill materials produced from demolished concrete, masonry, pavement layers and building debris. Their use reduces the burden on landfills and conserves natural aggregates. Recycled concrete aggregate, crushed bricks and recycled asphalt pavement can be assessed with geogrid reinforcement through large-scale direct shear testing. Among these C&D materials, recycled concrete aggregate can mobilise higher shear resistance than recycled asphalt pavement, while poor interlocking between geogrid and some recycled fills can reduce the benefit of reinforcement.

The C&D waste findings are important because they show that sustainability alone does not guarantee good interaction with reinforcement. Particle angularity, gradation, crushing potential, contaminants and interface interlocking control performance. Recycled concrete aggregate may be promising where it is clean, angular and well graded, but crushed bricks and recycled asphalt pavement may behave differently due to weaker particles or bituminous coating. Thus, C&D wastes require the same type of characterization and shear assessment as pond ash.

The relevance of recycled aggregates to the present thesis is comparative rather than central. They demonstrate the broader movement towards circular construction materials, but they are not the focus of the methodology. The methodology is specifically aligned with pond ash and conventional soil, and therefore C&D materials are discussed only as part of the sustainable backfill landscape.

2.3.5 Copper slag and other metallurgical by-products

Copper slag is a by-product of copper smelting and behaves as a heavy, angular, granular fill. In comparative RE wall evaluation with pond ash, bottom ash and moorum, copper slag shows high

specific gravity, almost no fines and very high frictional strength compared with moorum and coal ash materials. Because of its high angle of internal friction, it provides strong resistance to sliding and overturning. However, its high unit weight results in larger foundation bearing pressure than lighter fills such as pond ash and bottom ash.

This contrast is valuable for understanding sustainable backfill selection. A material with very high shear strength is not automatically the best backfill if its unit weight increases lateral and foundation stresses. Pond ash and bottom ash may have lower friction angle than copper slag, but their lower unit weight can reduce bearing pressure and reinforcement tension. Bottom ash and pond ash can induce lower bearing pressures compared with moorum, and pond ash can reduce maximum reinforcement tension compared with moorum. Thus, sustainable backfill evaluation must balance shear strength, unit weight, drainage, cost and foundation response.

Blast furnace slag and foundry sand are possible geomaterials in the wider sustainable backfill context. However, the direct experimental evidence available for metallurgical by-products is stronger for copper slag than for steel slag or mine waste. Therefore, these other metallurgical materials should be treated cautiously unless separate project-specific data are available.

2.3.6 Other sustainable materials

Scrap tyre chips, municipal solid waste mixtures, phosphogypsum road applications, quarry dust and foundry sand are part of the broader movement toward sustainable geotechnical construction. Sand-scrap tyre chip mixtures can reduce displacement and dynamic pressure in retaining wall models, and sand-tyre mixtures can improve pullout response compared with tyre shreds alone. Municipal solid waste mixed with sand may also be possible as a fill under controlled conditions. These materials are relevant because they show the diversity of waste-derived alternatives being considered for reinforced soil systems.

However, these materials are not equally mature for RE wall backfill. Some raise concerns related to durability, compressibility, decomposition, leachability, variability and long-term deformation. Phosphogypsum and municipal solid waste require environmental assessment beyond ordinary geotechnical testing. Quarry dust and foundry sand may be useful in controlled low strength materials or as granular components, but they do not have enough direct relevance to be treated as central alternatives for the present thesis. Therefore, they are included as part of the sustainable-material evolution but are not developed as major themes.

2.4 Gap in Literature

- Very few studies have integrated engineering performance, cost-effectiveness, and sustainability assessment to provide practical recommendations for the field application of pond ash as a backfill material in Reinforced Earth walls.
- The engineering properties of pond ash vary significantly with coal source, combustion process, and disposal conditions. However, few studies conduct source-specific

characterization and compare pond ash directly with conventional backfill soil using identical testing procedures and acceptance criteria.

- Most existing studies are confined to laboratory investigations with limited demonstration of the practical applicability of pond ash in Reinforced Earth (RE) wall construction. The present study addresses this gap by validating laboratory findings through site-based implementation and practical evaluation of untreated pond ash as RE wall backfill.

CHAPTER 3

METHODOLOGY

3.1 Selection of Materials

3.1.1 Methodological framework

The method used in this study follows a step-by-step framework for evaluating pond ash as a sustainable backfill for Reinforced Earth (RE) wall applications. The process starts with gathering materials and preparing samples. It continues with physical characterization, compaction testing, and shear-strength evaluation. The laboratory results then lead to compliance with IRC:SP:102-2014, comparative assessment, cost analysis, sustainability assessment, and recommendations for field use. This sequence reflects a thoughtful engineering approach. The suitability of a backfill material cannot be determined from any single property considered alone. A material may be environmentally friendly but structurally unsuitable if it has poor gradation, excessive plasticity, an unfavorable compaction response, or low shear strength. Conversely, a material with acceptable strength may still be impractical if it has high handling, transportation, or placement costs. This framework treats suitability as a combined outcome of physical, mechanical, regulatory, economic, and environmental factors evaluated together, rather than the result of any one test. The proposed methodology is designed to establish a clear relationship between the measured properties of pond ash and its actual performance as RE wall backfill. Each stage of the investigation provides inputs for the subsequent stage, thereby reducing uncertainty in the final suitability assessment. The laboratory characterization is used to establish the basic material behaviour, while the mechanical testing provides the parameters required for engineering evaluation and design calculations. These results are then interpreted with respect to the relevant code requirements and compared with conventional soil as the reference backfill material. The final assessment therefore combines laboratory evidence, analytical performance, economic considerations, sustainability aspects, and practical field requirements rather than relying on a single material property.

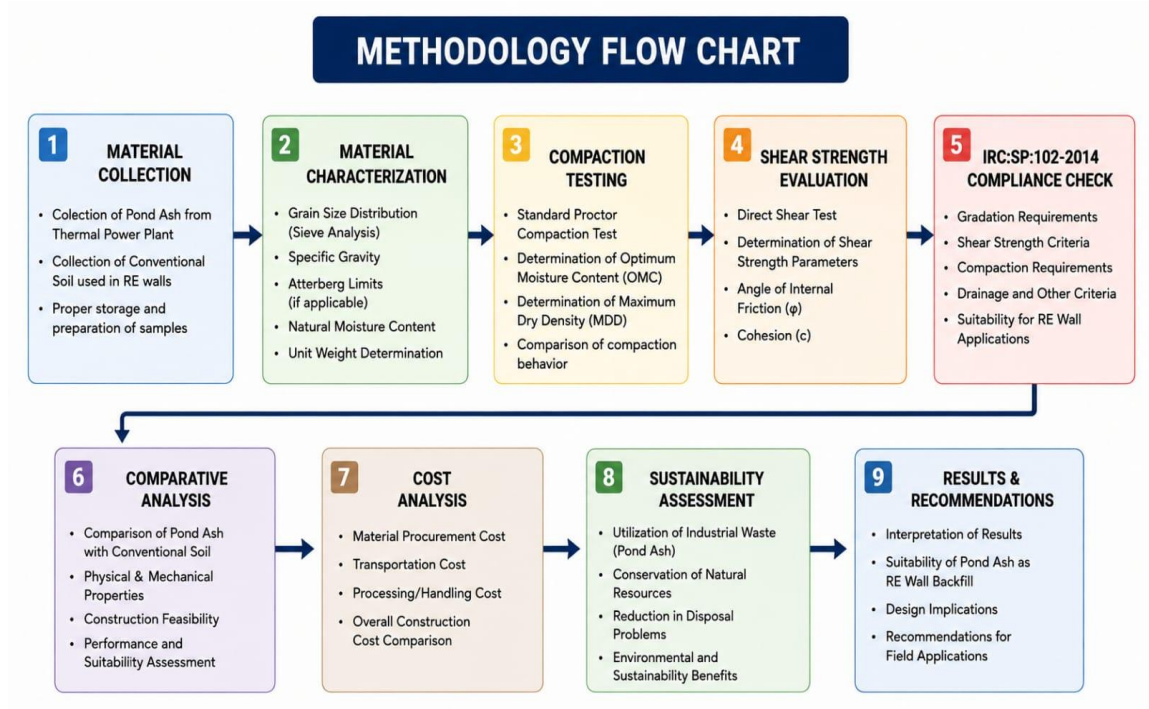


Figure 3.1: Methodology flow chart adopted for evaluating pond ash as RE wall backfill

The current experimental program is limited to the tests and evaluation stages needed to support this research flow. The physical characterization includes grain size distribution through sieve analysis, specific gravity, Atterberg limits when applicable, natural moisture content, and unit weight determination. The mechanical evaluation involves Standard Proctor compaction testing and direct shear testing. These tests provide the optimum moisture content (OMC), maximum dry density (MDD), cohesion (c), and angle of internal friction (ϕ). These factors are crucial for the upcoming code-compliance check, comparative analysis, and cost and sustainability assessment. Tests like triaxial compression, California Bearing Ratio, unconfined compression, pull-out testing, chemical leachability testing, and permeability testing are not part of the current experimental scope. They were not included in the approved research flow, and their exclusion is mentioned here to clarify the study's boundaries for readers.

3.1.2 Scientific justification for selecting pond ash

Pond ash has been chosen as the main alternative material because it is a large-volume by-product from thermal power plants that can be reused in geotechnical applications. It forms when fly ash, collected from

flue gases using electrostatic precipitators or bag filters, and bottom ash, collected from the base of the furnace, are mixed with water and sent to an ash pond for disposal. During this process of hydraulic transport and settling, particles are sorted by size and density. Coarser, denser particles from bottom ash tend to settle closer to the discharge point, while finer particles from fly ash stay in suspension longer and are carried further into the pond. The resulting deposit is not a manufactured material with a fixed composition; instead, it is a naturally graded, variable ash mass. Its properties depend on the type of coal used, the boiler and ash-handling setup, the sluicing process, and the specific spot sampled within the pond.

This dependence on the source is key to the current method. Since pond ash does not behave uniformly, we cannot accept it as RE wall backfill just because it is widely available. We must determine its suitability for the specific sample used in this thesis through direct testing, rather than by comparing it to other sources. Previous studies of coal-ash fills consistently highlight gradation, fines content, compaction condition, and drainage behavior as the main properties that determine acceptability in reinforced soil and structural fill applications (Pant et al., 2019; Pant, 2020; Reddy, 2022). These are the exact properties that the current testing program aims to assess.

For RE wall construction itself, backfill has to deliver stability, stability, drainage and constructability on the face, concurrently. The backfill material is desirable from all four viewpoints due to its possible existence of significant sand fraction size, non-plastic to low-plastic-content material and low unit-weight from that of natural materials (due to porous and semi-vesicular shape of ash particles) in view of high earth pressure relief on face and load on foundation relief of wall. The presence of large proportion of fly-ash fraction size causes a relatively less permeable material and may become unstable when saturated in moisture. Thus gradation and checking of plasticity should not ignore for design purpose. So, decision to evaluate the pond ash may be decided on hypothesis of its behaviour in lieu of utilizing industrial by-product.

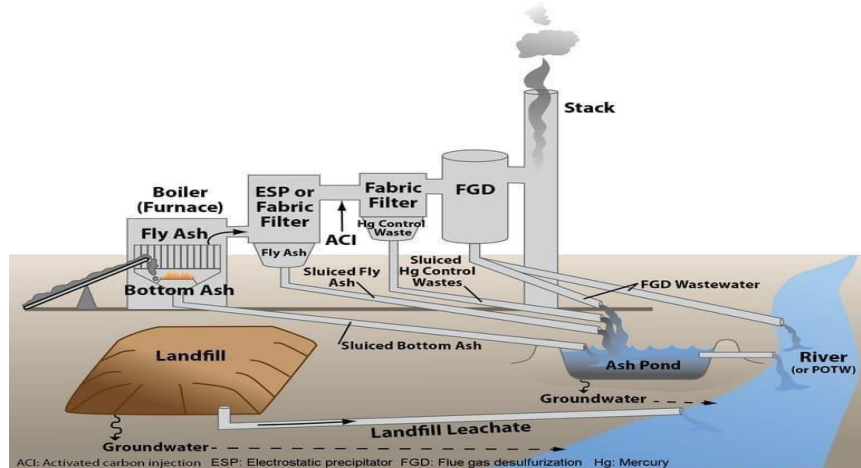


Figure 3.2: Schematic representation of ash generation and disposal in a thermal power plant
(Source : <https://share.google/dDgs2Ng07vYLTg4uu>)

Pond ash is also chosen due to resource/disposal aspects as will be discussed below which complements, and does not replace, the engineering considerations described previously. The typical geomaterials in common use, that is the natural sand and gravelly soil, and moorum must come from naturally occurring deposits. Extraction of these materials continually takes from burrow pits, from the banks of river systems, and local topography. Pond ash on the other hand, is already there (an industrial by product already sitting in ash pit storage, hence occupying that capacity). Utilisation of the ash in a RE wall simply takes it out of the storage area, and reduces by its volume requirement the requirement to quarry a certain volume of similar sized aggregate (and transport it). Although it will be argued in the next chapter that because the ash should be reused, testing should be thorough. Again however this argument has been excluded and, as will remain the case in this thesis, pond ash remains a geomaterial awaiting assessment on the basis of its actual performance Characteristics, its source alone determining nothing.

3.1.3 Engineering requirements of RE wall backfill

Backfill in an RE wall plays a structural , not simply void-filling role. In conjunction with the layers of reinforcement and the facing system, it becomes a compoundsoilmass, stableinternally on the basis that the backfill can engage adequate frictional force on the reinforcement , stableexternally on the basis of shear resistance in the reinforced block , andserviceablein the long term on the basis that water can drain out to

prevent the build-up of hydrostatic pressure behind the facing . Hence a preferred backfill material should be reasonably well graded, free from injurious material, non-plastic or of low plasticity, compaction-worthy, sufficiently permeable, and able to achieve adequate shear strength in a compacted state. When the reinforcement is one of the geo-synthetics, particle size and angularity are also critical to determining interface frictional properties and inter-lock so that pull-out resistance is maximized and influence reinforcement performance during and after installation of the backfill material .

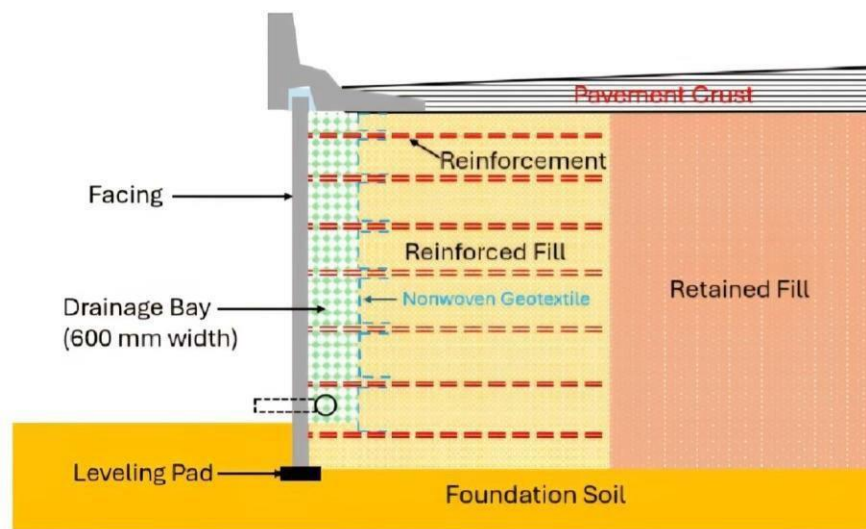


Figure 3.3: Typical cross-section of a Reinforced Earth wall system
 (Source : <https://share.google/TyzEfh40YyGmNPkk>)

This methodology examines these requirements using a step-wise series of tests, where each test constrains the alternatives remaining in the next step. Grain size distribution determines whether material can be thought of as granular or fines-rich which, in turn influences the interpretative outcomes of every following test. Specific Gravity and Unit Weight ‘bulk up’ this distribution, representing the degree of it by means of density and the likely contribution of both lateral- and vertical- pressure arising from it. Atterberg Limits determines the presence of plastic fines which may inhibit drainage or effect compaction. Natural Moisture Content determines the material in as-delivered form, preceding lab preparation. Standard Proctor Compaction produce the OMC and MDD, the criteria on which field compaction efforts are judged, and

beyond which shear tests are prepared; direct-shear defines that shear- strength against which we check structural stability. Standard OMC and MDD are finally cross referenced, to IRC:SP:102-2014 limits.

3.1.4 Material collection, storage and preparation

Collection of Material -The first methodological step consists in the collection of pond ash from Chhabra Thermal Power Station and the RE soil at the selected near by construction site, respectively. Field sampling and source description (i.e., ash type and location, soil origin and types, the mass samples and collected on, transport conditions) shall be performed, and shall be registered in the fieldwork diary to enable it be reported, as oppose to specified at the methodology stage, because the properties for the material should reflect the actual tested material instead of a description generic type of RE material. Each material obtained from sampling is characterized by a sample code and stored separately to prevent contaminación between different samples.

Soil sample Preparation The procedures for preparation of soil samples for index and mechanical tests to be used in this program follow established methods for handling disturbed samples according to IS 2720 (Part 1). Pond ash is prepared with special consideration to prevent stratification of finer particles during storage and transport, and in case of ordinary soil visual inspection for over size particles roots and organic and foreign inclusions. Both types of samples are air dried for required test procedures dried, mixed and prepared for test in a uniform method mainly through a quartering operation. By preparing the two samples with the same approach, any future differences in results obtained by test are due to differences between the materials and not due to the process of sample preparation or manipulation.

3.2 Material Characterisation (Pond Ash)

3.2.1 Origin and generation process

Source of Coal-based Thermal Power Plants Pond ash is formed in coal-based thermal power plants as the joint residue of the two separated combustion products: (i) fly ash; the portion carried with the flue gas and arrested by bagfilters (BFs) or electrostatic precipitators (ESPs); and (ii) bottom ash; the larger, commonly clinker-like portion which is separated at the bottom of the furnace and intermittently conveyed to a combined ash disposal facility in suspension with water. When such bottom ash and fly ash are jointly moved by a mixture of air and water to an ash disposal reservoir, they are collectively referred to as the pond ash, which settles down hydraulically in the basin. The differences in both in situ size, shape and density (apart from sorting due to hydraulic transport and the differential settling velocities of particles) between the two original Fractions and, to the extent these differences vary; according to the source coal, boiler operation, ash handling system and the nature of the deposition and the age of the deposit may mean that any two ponds of pond ash, let alone two ponds from different plants, and indeed within a particular pond according to location, cannot be regarded as having identical properties. This inherent reason of variation leads to why in this methodology specimen testing of ash, and not source analogy is considered (Pant, 2020; Ahmed et al., 2017; Reddy, 2022).

3.2.2 Physical characteristics and particle morphology

The physical behaviour of a particular sample of pond ash depends on its constituents derived from the unique mix of fly and bottom ash, the form of which controls its grading of particle size, its individual shape and surface texture, its specific gravity, and its moisture condition. The fly-ash part will generate small, typically spherical and porous/void spaces within that sphere ("cenospheres" is the term used in the combustion ash literature, referring to small, often hollow spheres; very large cenospheres that contain smaller spheres are called "plerospheres"). That form of partial hollowness is a reason that some pond ash has a lower average specific gravity for a given bulk volume than the bulk volume of natural earth soil would have. Bottom-ash produced, in contrast, forms particles of larger size and irregular, angular shape which some have visually compared more closely with lightly sintered clinkers than with the rounded particles of weathered natural soil or sand grains. In general terms, those pond ash samples having more of

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the coarser, bottom- ash like particulate behaviour are preferred for use in reinforced back fill by reason of better drainage properties and tendency to higher particle interlocking and thus better ultimate strength, while the pond ash consisting primarily of fly- ash like particles should be more critically assessed because high contents of fine particulates often cause problems by limiting permeabilities, influencing difficulty of compaction control and changing the behaviour to be monitored in later shear strength testing. Particle morphology will therefore be discussed only qualitatively with a view to helping in interpretation of some test results in section 3.3; the direct use of an image-forming or other 'visual' morphological examination method (eg scanning electron microscopy) lies outside the present programme.

3.2.4 Chemical and mineralogical characteristics

The chemical nature of pond ash essentially reflects both the nature of the original mineral coal constituent and the changes wrought upon this material during the process of combustion. Coal ash material in this context is invariably dominated by an amorphous, glassy aluminosilicate matrix formed when the molten mineral matter coalesces on rapid cooling throughout and after the combustion episode, with much smaller quantities of crystalline phases - especially quartz, mullite and iron compounds (iron oxides/sulfides etc.), with or without other mineral constituents of the ash depending upon the specific parent coal and combustion conditions - that failed to fully vitrify, and, finally, with a residual proportion of unburned carbon representing the degree to which combustion went towards completion. It seems this is broadly and indisputably the compositional regime to expect from materials of this class, however it will not be possible to quantify proportions of constituent species without dedicated chemical and/or mineralogical sampling - x-ray fluorescence for bulk composition, x-ray diffraction for crystallographic form, or loss-on-ignition - which lie outside of the parameters of the present project and should be documented separately if they arise.

3.2.5 Engineering behaviour and environmental significance

Pond ash is considered for throughout this thesis as a 'simple compacted backfill', using its acceptability being judged solely against whether it achieves gradation, compaction, drainage & shear strength criteria. In the eventuality that 'fit for purpose' is demonstrated for a pond ash material this, however then proceeds

with the checks that the measured properties of the selected materials achieve current codes; otherwise this would be a more guarded 'conditional fit' - either restricted, requires additional drainage or rejected. This fairly prudent approach is maintained throughout the procedure whereby the criteria of acceptability is based solely on measured behaviours of the material and never purely on its sustainable derivation.

Pond ash also has a sustainability implication related to its rate of generation and the long term load placed upon land from ash pond disposal. Effective use of pond ash in construction can minimise the quantity of ash requiring permanent burial and reduce the amount of naturally occurring material which would have had to be mined for use as replacement backfill. In transport engineering applications - with their ubiquitous reliance on RE walls for embankments, approaches and flyovers - even a small percentage of ash replacement for the conventional backfill material would translate into a very tangible saving in resources. However this contribution, once again as insisted in throughout the chapter - requires support through demonstration of site performance, drainage characteristics and code compliance - not a replacement for them.

3.3 Laboratory Testing

3.3.1 General testing programme and quality control

The laboratory testing programme outlined below ensures that the necessary properties of pond ash and the alternative 'conventional' soil for RE backfill are investigated logically: Index and density-related tests first-to identify the material and its generic characteristics; compaction test-to determine the optimum moisture-content-maximum-dry-density (OMC–MDD) relationships for both field placement and preparing shear-test samples; direct shear test-lastly, to determine the parameters required for structural design, input to code compliance, for a comparative analysis, a costing analysis, and for an assessment of relative sustainability.



Figure 3.4: Hydrometer analysis

All tests are conducted on a representative sample, prepared according to IS2720(1). If the quantity of the sample required for test is needed, it will be homogenized and reduced to the amount required by mixing well until no evidence of segregation is detectable prior to the commencement of test. Where it is not done earlier the apparatus are calibrated and cleaned as appropriate prior to the use of the same to suit the particle size range of the material being tested.

If the samples are moisture susceptible for natural moisture content are not exposed in open air but are immediately put into an air tight containers.

A data sheet for each test includes sampling reference no, test date, specimen condition, Apparatus and Method Number Used, Remarks, Raw data and calculation details, results & graph as well. In case any value deviates largely it can be repeat by repeating lab procedure or additional testing by prior procedure. For example: In direct shear, the failure envelope may not have a clear linear line; further tests may be carried out depending on availability of specimen and based on lab practice.

The laboratory work described within the thesis framework intentionally restricted to follow the tests performed, for better soil-reinforcement modelling interaction in ge mechanics framework. Tests as modified Proctor compaction, triaxial testing, permeability testing California Bearing Ratio (CBR) testing and also unconfined compressive testing, etc are beyond the thesis range of research though these tests may yield beneficial information's about soil behavior, thus not been included here in. Specially it has to be clarify that no criterion can be applied which is not mentioned and approved, and any procedure has to stick with the established protocol so far no deviation can be accounted, that too even from accepted value if procedure had deviate in one part of tests.

3.3.2 Grain size distribution by sieve analysis

Particle size distribution testing shows the distribution between various particle sizes present in pond ash and conventional soil. It is one of the first soil characteristics for RE wall backfill that shows suitability as the gradation controls drainage, behavior under compaction and shear, and the interaction between the fill and the reinforcement. A coarse (sand-sized) particles is a favorable characteristic over fines, assuming other properties are also suitable. The test also shows if the sample of pond ash is behaving more like sand or a fined-rich ash deposit, that is how subsequent tests will be interpreted.

The relevant standard is IS 2720 (Part 4) particle size analysis, although ASTM D6913/D6913M may be utilized in circumstances where ASTM specification is utilized. A dry representative sample of material is

separated into sizes using a series of sieves (from largest mesh openings down to smaller mesh openings); where fines need to be reliably separated from coarser material, wet sieving below the 75 micron sieve is employed. Each sieve is weighed for retained mass and percentage retained, cumulative percentage retained and percentage passing are derived; these points are plotted as a gradation curve which can be assessed for classification and the IRC:SP:102-2014 gradation check.

The equipment includes a set of sieves, top, lid & pan conforming to standard sizes, sieve shaker (mechanical or manual hand shanking), weighing balance, oven, tray, brush and tools for splitting or quartering the sample. After drying the sample (in air or in oven as the case may be), the dried soil was gently broken – the individual particles are not crushed - after being weighed, so as to pass the largest size and then put into the topmost sieve for shanking for prescribed duration or till the retained amount shows insignificant difference by the continued shaking and retained weight in each sieve separately recorded, then add all total weights to check if it compares to sample as in the original and thus any sample loss in between was detected and the result of testing are % of gravel, sand & fines, co-efficient of uniformity co-efficient of curvature (whenever applicable), and overall sieve analyses can be interpreted. These values are input for classification; for check of IRC:SP:102-2014 gradation (compliance with); interpretation for drainage characteristic and for comparing directly the pond ash with normal soils.

3.3.3 Specific gravity

The Specific gravity (s_g) is used to express the relative density of soil solids or the density of ash particles wrt that of water. Since this is a property index in particular it appears into phase-relationship equation as such, into the analysis of compaction results into pond ash. The 'partially hollow and cenospheric' nature of fly ash of the pond ash suggests that its specific gravity is to have a value which would be expected to be lower than that for a conventional soil to match and thus would be expected to reflect less density of the 'ash grains', thus would appear as have a lower value when compared with 'conventional grains'. This has further

implication on the value of the dry unit of pond ash as well as the lateral as vertical stress caused by this pond ash material if it is utilized as the backfill.

The method to use is in accordance with IS 2720 (Part 3) - method for the determination of the specific gravity of soil solids, and if followed at the institution then ASTM D854 may be applied. The basis of the test involves measuring the mass of a known volume of soil solids and comparing this with the mass of an equivalent volume of water (normally measured in a pycnometer bottle or density bottle) at a predetermined reference temperature. All entrapped air must be efficiently excluded, since air that becomes attached to the surfaces of soil particles will significantly affect the result obtained; an allowance is also made for the temperature at which the test is carried out varying from that of the reference temperature.

Equipment is: The density apparatus includes a pycnometer or density bottle, a balance, distilled water, a drying oven, a thermometer, an available vacuum or de-airing device, a wash bottle, and cleaning materials are used. The compacted test samples is placed in the density bottle then after they become evenly scattered by filling up with water then de-aired then they topped the calibration point finally wiped off the surface and weigh up the density bottle filled by solids in the weight method; an empty bottle's mass and water's mass used in the calibration. The result is the specific gravity of solid material which are explained with the soil's dry unit weight and also the lateral active and passive pressure; both relate to soil's ability of soil lateral support.

3.3.4 Atterberg limit

Atterberg-limit testing is carried out only if a soil has an adequate quantity of plastic fines to give a meaningful results. The test yields a liquid and plastic limit. These values can be used to calculate a plasticity index for the fines. Plasticity is important for RE wall backfill because plastic fines are prone to retaining moisture thus impairing drainage, they affect compaction control and may negatively influence the shear strength of the backfill. Many coal and ash mixes fail to demonstrate plastic behaviour under the atterberg test procedures and these would be recorded as being non plastic.

The method adopted is IS 2720(Part 5) for determination of liquid and plastic limit or ASTM D4318 when ASTM procedure is required. The basis of this method is the rational variation of consistency of fine-grained soils with change in moisture content from stiff to soft; i.e., the water content at which the soil will just be on the verge of having zero volume change, (equivalent to turning point with a force), to the lowest content where it still can be molded into a thread of 3 mm in diameter. The instrument consists of Casagrande liquid limit apparatus or cone penetrometer for some standard testing, a grooving tool, a glass plate 120mm by 3mm, a spatula, moisture tins, balance and oven. For liquid limit, fine soil is thoroughly mixed with water and tested over several range of moisture content centered on the transition point. For plastic limit, small amount of soil mixture is taken on glass plate and knead to form a ball, then is pressed in finger and thumb and rolled into a thread of 3mm in diameter. If the thread does not break and retains uniformity, the plastic limit is reached. The parameters - liquid limit, plastic limit and plasticity index - can be utilized to establish that both pond ash and conventional soil is likely to meet the requirement of a low-plasticity fill material to be used for RE wall, and provide support for future analysis of drainage, compaction and shear-characteristics.

3.3.5 Natural moisture content

To measure the water in each material at the time of sampling or testing, the natural moisture content is determined. Water content is significant for both pond ash and conventional soil in its handling, storage, compaction effort, and in the preparation of future test specimens. The water content of pond ash obtained from an ash-pond may range widely, depending upon the deposition history, draining conditions, and whether it was exposed to weather while being dumped. Conventionally, the natural water content of soil upon reaching the laboratory in the field may differ significantly from the water content required for optimum compaction. The appropriate standard for water content determination is IS 2720 (Part 2); ASTM D2216 may be employed in test protocols following ASTM procedure. The procedure is quite basic; one simply measures the mass loss from a moist sample from oven-drying until constant mass is achieved, and then computes water content as a percentage. Even though the procedures are simple, it is a test which depends strongly on sample handling and is thus why samples being tested for natural moisture content are immediately sealed into an airtight container after being obtained.

The following equipment is required: a balance, moisture cans, a desiccator, oven and tongs, from which a representative moist sample is weighed with its container, oven dried per standards, cooled in a desiccator, and then re-weighed. This single value-natural moisture content-is used in all subsequent analysis and calculations, and is particularly helpful in determining whether additional water or drying is necessary to achieve desired moisture content before compaction, and comparing the natural water content of pond ash and conventional soil.

3.3.6 Unit weight determination

Unit weights are used to provide a measure of the material weight relative to their physical volume in the pertinent state – loose, bulk, and compacted; and it directly correlates with lateral earth pressure, foundation pressure, transportation tonnage, and labor requirements. A favorable material can be selected if its low weight offers the right material in RE walls when pressure or strength criteria govern the design, though it should always be interpreted in conjunction with their response to compaction and shearing characteristics.

The actual procedure depends on the laboratory setting and on the conditions to which the sample is being subjected. In circumstances where a compacted specimen is readily available, as the result of a Standard Proctor test, then the unit weight can be determined simply from its mass, once the volume of the mold has been found. Where the test is required for an uncompacted material, then a container whose volume is known is substituted for the mold. The procedure is not designed to be an in-situ test; however, the calculated result separates between bulk, dry, and compacted dry unit weight as each is a uniquely defined quantity for a variety of engineering interpretations to be conducted in subsequent chapters. Laboratory equipment required for the test includes a weighing balance, a mold or container whose volume is known accurately, a straightedge, a scoop, a drying oven, and moisture containers; the specimen is placed in the known-volume container under the desired conditions, struck off level at the top, weighed and the moisture content may then be used to convert the bulk density to the dry density, should this be necessary. Bulk, and where required the dry, unit weight determined from this test will facilitate a directly comparable relationship between pond ash and conventional earth and will provide data which will be analyzed to derive the cost and design interpretations.

3.3.7 Standard Proctor compaction test

Standard proctor compaction test is usually performed for pond ash and a conventional soil at different moisture levels to correlate the dry density and water content of the mix. Thus OMC and MDD, the fundamental basis of field compaction control and preparation of laboratory test specimen, were obtained. The quality of compaction is very critical for RE walls since the insufficient compaction affects mobilization of the shear strength, causes excess post-construction deformation and results in weak interface interaction between the soil mass and reinforcement material (Pant et al. 2019; Pant 2020).

Coal ash backfills are extremely sensitive to the placement water content and have always insisted on inclusion of compaction within their construction methodology for any engineer's structured form of construction (Pant 2020).

The specification is IS 2720 (Part 7) for light compaction which equates to ASTM D698 for Standard Proctor, when that is followed. Test rationale is by placing and then compacting the material into a mould at various water contents with a specified constant, standard force and plotting the dry densities for each and noting MDD and water content associated. A case where an element of the materials under examination display very flat peak, thus making their water content characteristics not so sharply defined as to define an acceptable range are identified explicitly to avoid misleading into a single specific optimum figure, in case of any ashes with varied grain gradings which tend to present such water content – density characteristics.



Figure 3.6: Standard Proctor compaction test setup

The equipment required for the test is a Proctor mould (with base plate and collar) and a rammer, weighing balance, mixing tray, straight edge, moisture containers, oven, measuring cylinder or spray bottle used to add water, and tools to extract compacted sample. Representative soil sample is mixed with the calculated amount of water and compacted in layers by the standard chosen; when the desired volume is reached the collar is removed, the sample is trimmed flush with the top of the mold and the mass recorded, and a portion of the sample is placed in a moisture can to be tested for moisture content. Repeat the process with the mold and several other different percentages of water content covering a sufficient range to establish the complete moisture-density relationship. The observations include the ease of mixing, tendency of segregation, workability and difficulty on compaction, moisture susceptibility and evidence of particle breakage and

shape of the curve plotted. The results obtained, OMC and MDD and the moisture-density relationship are used within this thesis to compare with other soils, prepare direct shear specimens at same or similar moisture content and density, so that field requirement for compaction can be worked out for all soils.

3.3.8 Direct shear test

The shear-strength of the pond ash and the traditional soil can be ascertained from the direct shear test. The result of the shear test is relevant to RE wall backfill in as far as it is the soil shear-resistance which ultimately sustains the integrity of the whole reinforced block of soil. The output of the shear-strength test is what's termed a shear-strength envelope, described by two parameters; cohesion ' c ' and the angle of internal friction ' ϕ '. For Granular or Semi granular soil of the type expected herein it would be expected that is significant and that c will be negligible or at best, an "apparent" cohesion, rather than a real one; a value of c is obtained from the test analysis.



Figure 3.7: Direct shear testing apparatus for shear-strength evaluation

The applicable standard is IS 2720 (Part 13) for the direct shear test, corresponding to ASTM D3080/D3080M where ASTM procedures are followed. The test principle is to place a prepared specimen in a split shear box, apply a selected normal stress, and shear the specimen along a predetermined horizontal plane at a controlled rate of strain while recording shear force and displacement; by testing at least three specimens under different normal stresses, the relationship between normal stress and shear strength is established and the Mohr–Coulomb strength parameters are derived from the resulting envelope.

The testing setup consists of direct shear testing machine, shear box, loading frame, a proving ring or load cell, displacements measuring devices, apparatus for applying the normal load, porous stones or grid plates according to drainage condition required for the test, a balance and trimming tools. Pond ash and conventional soil are carefully prepared in exactly the same way; if the test is meant to duplicate placement of compacted backfill the specimen is prepared according to its specified placement condition. If specified to be comparable to conventionally used RE wall material and the latter is compacted based on some procedure then a similar placement condition based for example on either OMC/MDD from Standard Proctor's test or some clearly specified moisture content and density must be used for both pond ash and conventional soil sample to permit meaningful comparison.

During testing after having placed the specimen in the shear box and applied the planned normal stress. After allowing some bedding down the specimen is sheared in the horizontal direction until the desired result – either peak shear load, or fully developed residual conditions – is recorded. Shear load, horizontal movement and – if available – vertical movement are recorded throughout the test. Other observations include the manner of peak shear response, evidence of strain-hardening or softening, any dilation or contraction while shearing and particle crushing and sensitivity to moisture if observed. Parameters are calculated: peak shear stress at each normal pressure the relevant strength envelope, resulting cohesion and angle of friction are reported and these directly checked for compliance with relevant design provision inirc:sp:102-2014; they are used in the comparative study of pond ash vs soil and for their subsequent evaluation as alternative material for RE wall construction.

CHAPTER 4

PROBLEM STATEMENT

4.1 Reinforced Earth Wall with Conventional Backfill

4.1.1 Concept and role of the backfill

A Reinforced Earth (RE) wall is a composite gravity structure formed by compacting a granular fill in layers around horizontal reinforcement typically geogrid or metallic strips — anchored to a modular or panel facing. Unlike a conventional retaining wall, which resists lateral earth pressure primarily through its own mass and rigidity, an RE wall derives its stability from the frictional interlock developed between the backfill and the reinforcement: the reinforced soil mass behaves, in effect, as a single coherent gravity block. The backfill is therefore not incidental to the structure; it is a load-bearing structural element in its own right, and its unit weight, shear strength and compaction behaviour directly govern every stability check that follows in this chapter.

Conventional backfill natural granular or granular-like soil such as sand, gravelly soil or moorum has historically been the default choice for RE wall construction because such materials are locally familiar, drain freely, compact predictably and mobilise reliable internal friction. This section develops the complete design basis for an RE wall built with such a conventional backfill, establishing the reference case against which the pond ash alternative is subsequently evaluated in Section 4.2.

4.1.2 Design philosophy and assumptions

The design philosophy adopted here follows conventional limit-equilibrium practice for reinforced soil structures: the reinforced soil mass is treated as a rigid gravity block bounded by the facing, the reinforced length and the wall height, and this block is checked against sliding along its base, overturning about its toe, and the development of adequate reinforcement tension at each reinforcement level. The active earth pressure generated by the retained backfill and by any surcharge is assumed to act on the back of this reinforced block in accordance with Rankine's earth pressure theory, which is applicable where the back of the reinforced zone can be treated as a vertical, frictionless plane a standard and conservative simplification for this class of problem. Foundation bearing failure is not evaluated separately in this chapter, since the applied base pressure is compared directly against the assumed foundation safe bearing capacity as an initial screening check rather than as a full bearing-capacity analysis.

4.1.3 Design parameters and geometry

A wall height (H) of 6.0 m is adopted, representative of a typical highway or bridge-approach RE wall. A live load surcharge (q) of 24 kPa is applied on the retained side to represent highway traffic loading. The foundation soil is assigned a safe bearing capacity (SBC) of 250 kPa and a base friction coefficient (μ) of 0.577, the latter corresponding to a friction angle of approximately 30° at the base interface ($\mu = \tan\phi$). The reinforcement length (L), which also defines the width of the reinforced soil block, is fixed at 5.5 m, and the vertical spacing between successive geogrid layers (S_v) is set at 0.6 m. These geometric parameters are held constant for both the conventional and pond ash cases so that the comparison in Section 4.3 isolates the effect of the backfill material alone.

The retained backfill behind the reinforced block — the natural ground or embankment fill generating the active thrust on the reinforced mass — is assigned a unit weight of 18 kN/m^3 and a

friction angle of 30°. Combining the active pressure from this retained fill with the surcharge load over the wall height gives a total horizontal destabilising force (FH) of 155.84 kN/m and an overturning moment (MO) about the toe of 359.63 kN-m/m. Because FH and MO depend only on the retained backfill and surcharge not on the material used inside the reinforced block — both values remain identical for the conventional and pond ash cases, which is what allows the two designs to be compared directly against a common destabilising demand.

4.1.4 Material properties: conventional backfill (Case A)

The conventional backfill is assigned a unit weight (γ_s) of 19.00 kN/m³, an angle of internal friction (ϕ_s) of 30.0°, and zero cohesion ($c = 0$ kPa). These are representative values for a well-compacted granular fill of the kind conventionally used in RE wall construction, adopted here as standard design assumptions consistent with common practice rather than as site-specific laboratory results; the corresponding testing of the conventional soil sample collected for this thesis is reported separately in Chapters 3 and 5, and the present design comparison uses these representative values so that the two backfill options can be evaluated on a like-for-like design basis.

4.1.5 Active earth pressure and external stability

The active earth pressure coefficient is obtained from Rankine's theory as

$$K_a = \tan^2(45^\circ - \phi/2) \quad (1)$$

where ϕ is the angle of internal friction of the backfill. This coefficient expresses the ratio of horizontal to vertical effective stress under the minimum, or active, stress state that develops as a retaining structure yields slightly away from the retained soil; a lower ϕ produces a higher K_a and therefore greater lateral thrust for a given vertical stress. For the conventional backfill,

$$K_{as} = \tan^2(45^\circ - 30.0^\circ/2) = 0.333 \quad (2)$$

External stability is checked first through the self-weight of the reinforced block, computed as

$$W = \gamma \times H \times L \quad (3)$$

which gives the weight, per metre run of wall, of the reinforced soil prism bounded by the wall height and the reinforcement length. For the conventional backfill,

$$W_s = 19.00 \times 6.0 \times 5.5 = 627.00 \text{ kN/m}$$

The factor of safety against sliding compares the frictional resistance mobilised at the base of this block with the total horizontal destabilising force:

$$\text{FoS sliding} = (W \times \mu) / FH \quad (4)$$

Here, $W \times \mu$ represents the maximum frictional resistance available at the base, governed by the weight of the block and the base friction coefficient, while FH is the horizontal thrust established in Section 4.1.3. For the conventional backfill,

$$FoS \text{ Sliding} = (627.00 \times 0.577) / 155.84 = 2.32$$

This exceeds the conventional minimum requirement of 1.5, indicating a comfortable margin against base sliding.

Overturning stability is assessed by comparing the moment resisting rotation about the toe with the overturning moment generated by the horizontal thrust. Treating the reinforced block as a rectangular prism of uniform weight acting through its centroid, the resisting moment about the toe is

$$MR = W \times (L/2) \quad (5)$$

so that, for the conventional backfill, $MR = 627.00 \times 2.75 = 1724.25 \text{ kN-m/m}$, and the factor of safety against overturning is

$$FoS_{\text{overturning}} = MR / MO = 1724.25 / 359.63 = 4.79$$

comfortably above the conventional minimum requirement of 2.0.

4.1.6 Internal stability: geogrid tension

Internal stability governs the tensile demand placed on each reinforcement layer and is assessed at the most critical level — the bottom-most geogrid, at depth $z = H = 6.0 \text{ m}$, where the vertical overburden stress is greatest. The vertical stress at this depth is

$$\sigma_v = (\gamma \times z) + q \quad (6)$$

which, for the conventional backfill, gives $\sigma_v = (19.0 \times 6.0) + 24 = 138.00 \text{ kPa}$. The corresponding horizontal stress transmitted to the reinforcement is obtained by applying the active earth pressure coefficient to this vertical stress:

$$\sigma_h = K_a \times \sigma_v \quad (7)$$

$$\sigma_h = 0.333 \times 138.00 = 45.95 \text{ kPa}$$

The maximum tension mobilised in the geogrid layer is then obtained by multiplying this horizontal stress by the vertical spacing (S_v) that each layer is required to support:

$$T_{\text{max}} = \sigma_h \times S_v \quad (8)$$

$$T_{\text{max}} = 45.95 \times 0.6 = 27.57 \text{ kN/m}$$

This value of 27.57 kN/m represents the minimum long-term design strength that the geogrid at this level must provide, after accounting for the reduction factors normally applied for installation

damage, creep and durability; it is the governing internal-stability demand for the conventional backfill case.

4.1.7 Reinforcement requirements and engineering behaviour

Because the conventional backfill generates a comparatively high vertical stress and active pressure coefficient, the resulting geogrid tension demand of 27.57 kN/m requires reinforcement of correspondingly higher tensile capacity, particularly at the lower levels of the wall where overburden is greatest. The free-draining, granular nature of conventional backfill supports reliable interface friction with the reinforcement and limits pore-water pressure development, which is favourable for both internal and external stability; its comparatively high unit weight, however, works against the design in every stability check considered above, increasing both the destabilising demand transmitted through vertical stress and the loads that the reinforcement and facing must ultimately carry.

4.1.8 Construction methodology and cost implications

Construction with conventional backfill follows established RE wall practice: the material is placed and compacted in controlled layers behind the facing, with reinforcement laid at each designated level and connected to the facing units as construction proceeds. Because the behaviour of natural granular soils under compaction is well understood and well documented in practice, field quality control is relatively straightforward, though it depends on continuous access to a suitable borrow source of adequate gradation and quality.

The principal cost drivers for conventional backfill are the excavation or quarrying of borrow material, its transportation to site, and the reinforcement demand established in Section 4.1.6, which scales directly with the vertical stress generated by the backfill's unit weight. A detailed

quantification of these costs, and their comparison with the pond ash alternative, is presented in the cost analysis in Chapter 5; the purpose of this section is to establish the design and stability basis from which that later cost comparison follows.

4.2 Reinforced Earth Wall with Pond Ash as Sustainable Backfill

4.2.1 Pond ash as an alternative backfill

Pond ash is evaluated in this section as an alternative to conventional backfill within the same RE wall geometry and design framework established in Section 4.1. As discussed in Chapter 3, pond ash is a hydraulically deposited thermal power plant by-product whose lower specific gravity and generally favourable frictional behaviour make it a credible candidate for reducing both the self-weight and the lateral thrust generated by the reinforced block. Its acceptability, however, rests entirely on whether its measured properties allow the same stability checks applied to conventional backfill to be satisfied — an outcome that is verified, rather than assumed, in the calculations that follow.

4.2.2 Design philosophy, assumptions and parameters

The design philosophy, limit-equilibrium framework and geometric parameters — wall height, surcharge, foundation safe bearing capacity, base friction coefficient, reinforcement length and geogrid vertical spacing — are retained exactly as set out in Section 4.1.3, so that the pond ash case differs from the conventional case only in the material properties of the backfill placed within the reinforced block. This is essential to a fair comparison: any difference in the calculated stability outcomes can then be attributed solely to the properties of the backfill material itself.

The pond ash backfill is assigned a unit weight (γ_{pa}) of 13.18 kN/m³, an angle of internal friction (ϕ_{pa}) of 31.5°, and zero cohesion ($c = 0$ kPa). Unlike the representative values adopted for conventional soil, these figures were established through laboratory testing of the sourced material, carried out in accordance with the applicable IS 2720 procedures. The friction angle of 31.5° and zero cohesion were obtained from a direct shear test (IS 2720, Part 13). The unit weight of 13.18 kN/m³ is derived from the maximum dry density of 1.344 g/cc obtained from a heavy compaction test — IS 2720 (Part 8), the Modified Proctor procedure, rather than the Standard Proctor (light compaction) procedure referred to elsewhere in this thesis, a distinction addressed further in Chapter 3 — multiplied by the acceleration due to gravity: $\gamma_{pa} = 1.344 \times 9.81 \approx 13.18$ kN/m³. This is treated here as the compacted field unit weight of pond ash for design purposes.

4.2.3 Active earth pressure and external stability

Applying the same Rankine expression used in Section 4.1.5 to the pond ash friction angle,

$$K_a = \tan^2(45^\circ - 31.5^\circ/2) = 0.315 \quad (9)$$

The marginally higher friction angle of pond ash relative to conventional soil (31.5° against 30.0°) produces a correspondingly lower active pressure coefficient, which reduces the lateral thrust generated per unit of vertical stress even before the effect of the lower unit weight is considered.

The weight of the reinforced block is recalculated using the pond ash unit weight:

$$W_{pa} = 13.18 \times 6.0 \times 5.5 = 434.94 \text{ kN/m} \quad (10)$$

This represents a substantial reduction of just over 30 percent relative to the 627.00 kN/m calculated for conventional backfill, a direct consequence of pond ash's lower unit weight. The factor of safety against sliding follows the same expression as before:

$$\text{FoS sliding} = (434.94 \times 0.577) / 155.84 = 1.61 \quad (11)$$

This still satisfies the conventional minimum requirement of 1.5, confirming that the pond ash design remains safe against base sliding; the margin above the minimum is, however, noticeably narrower than the margin obtained for conventional backfill, a point returned to in the discussion in Section 4.4.

The resisting moment about the toe, using the same simplified rectangular-block assumption as Section 4.1.5, is $\text{MR}_{\text{pa}} = W_{\text{pa}} \times (L/2) = 434.94 \times 2.75 = 1196.09 \text{ kN-m/m}$, giving a factor of safety against overturning of

$$\text{FoSoverturing} = 1196.09 / 359.63 \approx 3.32 \quad (12)$$

which comfortably exceeds the conventional minimum requirement of 2.0, and remains well above the sliding-governed margin, indicating that overturning is not the controlling stability mode for either backfill option.

4.2.4 Internal stability: geogrid tension

At the same critical depth ($z = 6.0 \text{ m}$) considered in Section 4.1.6, the vertical stress generated by the pond ash backfill is

$$\sigma_v = (13.18 \times 6.0) + 24 = 103.08 \text{ kPa} \quad (13)$$

a reduction of approximately 25 per cent relative to the 138.00 kPa calculated for conventional backfill, arising directly from the lower unit weight of pond ash. Applying the pond ash active pressure coefficient to this vertical stress gives the horizontal stress transmitted to the reinforcement:

$$\sigma_h = 0.315 \times 103.08 = 32.47 \text{ kPa} \quad (14)$$

and the corresponding maximum geogrid tension is

$$T_{\max} = 32.47 \times 0.6 = 19.48 \text{ kN/m} \quad (15)$$

This represents a reduction of approximately 29 per cent relative to the 27.57 kN/m calculated for conventional backfill. The reduction arises from two compounding effects acting together: the lower unit weight of pond ash reduces the vertical stress at every depth, while its marginally higher friction angle simultaneously reduces the proportion of that vertical stress converted into horizontal thrust.

4.2.5 Reinforcement requirements and engineering behaviour

The reduced geogrid tension demand calculated in Section 4.2.4 means that, for a pond ash backfill, a lower-tensile-strength geogrid could in principle satisfy the internal stability requirement at each level, or alternatively the same geogrid grade could be extended to a wider vertical spacing without exceeding its rated capacity. Either option represents a genuine design optimisation made possible by the measured properties of pond ash, rather than an assumed or aspirational benefit. This advantage must, however, be read together with the narrower sliding safety margin noted in Section 4.2.3: pond ash reduces demand on the reinforcement and on the foundation, but it does not increase the frictional resistance available at the base beyond what its own, only marginally higher, friction angle provides, and the base sliding check should accordingly continue to be treated as the governing external stability criterion for this material.

4.2.6 Construction feasibility and environmental advantages

Construction with pond ash follows a broadly similar sequence to conventional backfill — layered placement, compaction at or near the laboratory-established optimum moisture content, and reinforcement installation at each designated level — but requires closer moisture control given

the moisture sensitivity typical of ash materials, discussed further in Chapter 3. Handling and placement of a lighter material can also ease equipment and compaction demands on site, though this must be weighed against the need for consistent quality control given the inherent variability of ash sourced from a hydraulically deposited pond.

The environmental case for pond ash rests on two related effects demonstrated by this chapter's calculations: first, its use as backfill directly diverts an industrial by-product away from long-term ash-pond storage and into a beneficial engineering application; second, this diversion correspondingly reduces the extraction of natural borrow soil that would otherwise be required for the same volume of backfill. Both effects support the broader case for pond ash as a sustainable construction material, in addition to the structural optimisation demonstrated above.

The cost implications of using pond ash — arising from reduced material procurement, reduced reinforcement demand and altered transportation requirements — are quantified in detail in the cost analysis presented in Chapter 5, building directly on the design outcomes established in this section.

4.3 Comparative Analysis

Table 4.1 consolidates the design parameters and stability outcomes derived in Sections 4.1 and 4.2 for the conventional and pond ash backfill cases, alongside a qualitative comparison of the constructional, economic and environmental factors discussed in those sections. Numerical values are reported exactly as calculated above; rows without an established numerical value are compared qualitatively rather than assigned an estimated figure.

Design Parameter	Case A: Conventional Soil	Case B: Pond Ash	Variance / Observation
Unit Weight (γ)	19.00 kN/m ³	13.18 kN/m ³	~31% reduction
Angle of Internal Friction (ϕ)	30.0°	31.5°	Marginally higher for pond ash
Cohesion (c)	0 kPa	0 kPa	No difference
Active Earth Pressure Coefficient (K_a)	0.333	0.315	Lower for pond ash
Base Vertical Pressure (σ_v at $z = 6.0$ m)	138.00 kPa	103.08 kPa	~25% reduction
Horizontal Stress (σ_h at $z = 6.0$ m)	45.95 kPa	32.47 kPa	~29% reduction
Weight of Reinforced Block (W)	627.00 kN/m	434.94 kN/m	~31% reduction
FoS – Sliding	2.32	1.61	Both satisfy > 1.5; narrower margin for pond ash
FoS – Overturning	4.79	3.32	Both satisfy > 2.0; not the governing mode for either
Maximum Geogrid Tension (T_{max})	27.57 kN/m	19.48 kN/m	~29% reduction
Reinforcement Requirement	Higher-capacity geogrid required at lower levels	Lower-capacity geogrid, or wider spacing, feasible	Design optimization possible with pond ash
Material Requirement	Natural borrow soil (sand / gravelly soil / moorum)	Industrial by-product (pond ash)	Pond Ash more sustainable
Construction Feasibility	Well-established practice; dependent on borrow availability	Feasible; requires closer moisture control	Pond Ash more feasible
Initial Cost	Governed by borrow excavation and transport	Governed by ash and procurement transport	Pond Ash more economical
Long-Term Cost	Reinforcement demand scales with higher stress	Reduced reinforcement demand	Pond Ash is cheaper

Design Parameter	Case A: Conventional Soil	Case B: Pond Ash	Variance / Observation
Maintenance Requirement	Standard for granular RE wall backfill	Expected comparable, subject to field verification	Almost same
Environmental Impact	Continued extraction of natural soil	Reduced natural resource extraction	Favours pond ash
Industrial Waste Utilisation	None	Diverts pond ash from ash-pond disposal	Favours pond ash
Natural Resource Conservation	Not applicable	Conserves borrow material	Favours pond ash
Overall Suitability for RE Wall Construction	Established, higher-demand solution	Technically viable; narrower sliding margin	Both satisfy code minima

Table 4.1: Comparative design and engineering assessment – conventional soil versus pond ash backfill

(H = 6.0 m)

4.4 Discussion

The comparison in Table 4.1 shows a consistent pattern across every quantitative stability check: the lower unit weight of pond ash, reinforced by its marginally higher friction angle, reduces the vertical stress, the horizontal thrust and the resulting geogrid tension relative to conventional backfill, while both materials continue to satisfy the conventional minimum safety factors for sliding and overturning. This pattern, rather than any single figure in isolation, is what supports the case for pond ash as a technically viable alternative backfill.

The reduction in base vertical pressure — from 138.00 kPa to 103.08 kPa, a decrease of approximately 25 per cent — follows directly from substituting a lighter material into the same overburden depth and geometry. This reduction is potentially significant wherever the founding soil is of only moderate bearing capacity, since a lower applied pressure widens the margin against foundation-related distress without requiring any change to the assumed foundation safe bearing

capacity of 250 kPa used in this chapter. The reduction in maximum geogrid tension — from 27.57 kN/m to 19.48 kN/m, a decrease of approximately 29 per cent — follows from the combined effect of lower unit weight and lower active pressure coefficient, and translates into a genuine design optimisation: a lower-capacity geogrid, or a wider reinforcement spacing, becomes feasible without compromising the internal stability requirement established in Section 4.1.6.

This advantage should, however, be read alongside a less favourable outcome that the same calculations reveal: the factor of safety against sliding falls from 2.32 for conventional backfill to 1.61 for pond ash. Both values satisfy the conventional 1.5 minimum, and the pond ash design is not, on this basis, unsafe; but its margin above the minimum is markedly narrower, leaving less tolerance for uncertainty in the assumed base friction coefficient, construction quality, or long-term degradation of the sliding interface. A balanced reading of this chapter's results is therefore that pond ash offers genuine and quantifiable relief on internal stability and foundation loading, while offering comparatively little relief — and in relative terms, a reduced margin — on the base sliding check, which continues to warrant careful attention in detailed design and construction quality control.

The overturning check is satisfied comfortably by both materials, with factors of safety of 4.79 and 3.32 respectively against a minimum requirement of 2.0, and is not the governing stability mode for either case; it is included here for completeness rather than because it distinguishes meaningfully between the two backfill options.

Beyond the stability calculations themselves, pond ash offers advantages that are qualitative in this chapter but are quantified later in the thesis. Its use directly diverts an industrial by-product from long-term ash-pond storage into a structural engineering application, in line with circular-economy principles of extending the useful life of a material that would otherwise be treated as

waste. This displacement of natural borrow soil by an industrial by-product simultaneously reduces the extraction pressure on natural resources associated with conventional backfill sourcing. The extent to which these environmental advantages are matched by a genuine reduction in construction cost — through reduced material procurement, reduced transportation and the reduced reinforcement demand established in Section 4.2.4 — is examined quantitatively in the cost analysis presented in Chapter 5.

Taken together, the calculations in this chapter support a measured conclusion rather than an unqualified one: pond ash satisfies the standard geotechnical safety requirements evaluated here and offers demonstrable engineering benefits in internal stability and foundation loading, but its narrower sliding safety margin means that its adoption as RE wall backfill should be accompanied by attentive construction quality control and, where practicable, by field performance monitoring, rather than being treated as an unconditional improvement over conventional practice.

CHAPTER 5

RESULTS & DISCUSSION

5.1 Physical Properties

The physical properties of a backfill material govern its behaviour during handling, placement, compaction and long-term service. For RE wall backfill, the properties of greatest relevance are grain size distribution, specific gravity, natural moisture content, Atterberg limits where applicable, and unit weight, since these jointly determine drainage capacity, compactability, achievable density and the mobilisation of shear strength within the reinforced zone. Pond ash is compared throughout against conventional soil, the reference material against which any candidate replacement backfill must ultimately be judged.

5.1.1 Grain size distribution

Grain size distribution was established by sieve analysis, giving percentages passing of 100% at 75 mm, 99.12% at 4.75 mm, 62.25% at 0.425 mm and 6.75% at 0.075 mm. The corresponding conventional soil gradation is sandy soil remains to be inserted as once that testing is complete. Gradation is examined first among the physical properties because it governs particle interlock, void structure and the ease with which water can drain through the compacted mass properties that bear directly on both compaction behaviour and long-term drainage performance behind the facing.

Because pond ash is a hydraulically deposited by-product rather than a manufactured aggregate, its gradation cannot be assumed constant across sources, or even within a single ash pond, and

must instead be verified for the specific sample under evaluation. Measured against the gradation envelope specified in IRC:SP:102-2014 (Table 1), the tested pond ash satisfies every band checked: 100% passing the 75 mm sieve against a specified 100%, 99.12% passing 4.75 mm against a specified range of 85–100%, 62.25% passing 0.425 mm against a specified range of 60–90%, and 6.75% passing 0.075 mm against a specified upper limit of 15%. The comfortable margin on the fines content in particular well below the 15% ceiling — is a favourable indicator for drainage and reduces the likelihood of moisture-sensitive behaviour developing within the reinforced zone.

Sieve Size (mm)	% Passing (Result)	IRC:SP:102 Spec (%)	Compliance
75 mm	100.00%	100	PASS
4.75 mm	99.12%	85 - 100	PASS
0.425 mm	62.25%	60 - 90	PASS
0.075 mm	6.75%	<15	PASS

Table 5.1: Sieve analysis compliance summary for pond ash

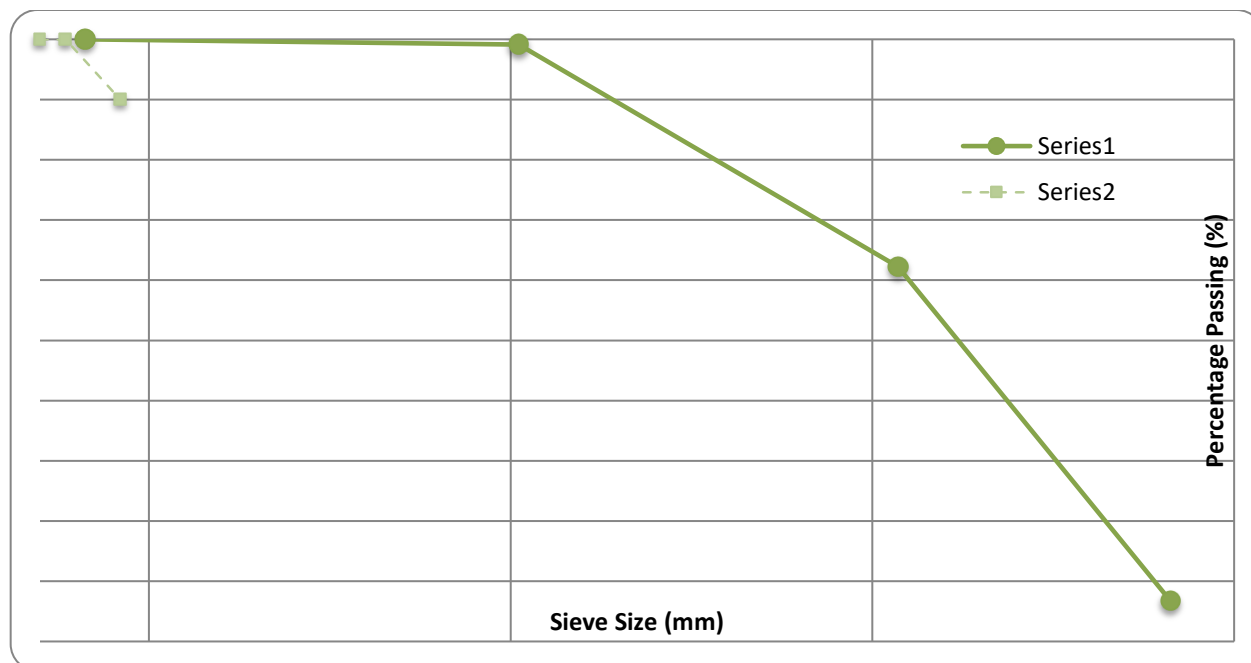


Figure 5.1: Particle size distribution curve for pond ash

The gradation is further characterised by a uniformity coefficient (C_u) of 4.00, determined in accordance with IS 1498:1970 and exceeding the specified minimum of 2. A C_u value of this magnitude indicates a moderately well-graded material spanning a reasonable range of particle sizes, though a complete gradation assessment would additionally require the coefficient of curvature (C_c), which was not available from the present testing and is not asserted here.

Description	Technical Details
D60 (60% Passing)	0.400 mm
D10 (10% Passing)	0.100 mm
Uniformity Coefficient (Cu)	4.00
IRC:SP:102 Specification	Greater than 2.0
Compliance Status	PASS

Table 5.2: Uniformity coefficient assessment for pond ash

5.1.2 Specific gravity, unit weight and moisture condition

Specific gravity values for pond ash 2.12 and conventional soil 2.68 respectively. Specific gravity governs the density of the solid particles themselves and, through the phase relationships of the compacted mass, influences achievable dry density and void ratio; given the partly hollow, cenospheric character of ash particles discussed in Chapter 3, pond ash would be expected to record a lower specific gravity than conventional soil, with a correspondingly lower compacted unit weight.

The maximum dry density of pond ash, established by heavy compaction testing (Section 5.2.1), was 1.344 g/cc, equivalent to a design unit weight of approximately 13.18 kN/m³ ($\gamma = \rho_d \times g$). For the design comparison in Chapter 4, the conventional soil unit weight was taken as 19.00 kN/m³, a representative value for well-compacted granular backfill rather than a laboratory result for the specific conventional soil sample. The resulting difference in unit weight pond ash roughly

31% lighter than conventional soil — is the single property with the widest-reaching design consequence, since it reduces vertical stress, active thrust and reinforcement demand simultaneously, as demonstrated in Chapter 4.

Natural moisture content of pond ash is 12% the soil is 6%. The optimum moisture content for compaction 25.30% from the laboratory heavy compaction test, and 25.5% from the field compaction trial discussed in Section 5.6 — which together indicate the moisture level field placement should target; the small difference between the two figures is well within the scatter expected between a laboratory determination and a field compaction trial performed on a bulk sample, and both point to the same practical conclusion that pond ash requires deliberate moisture conditioning before placement.

5.1.3 Atterberg limits and plasticity behaviour

The liquid limit of pond ash was recorded as 19.8%, while the plastic limit could not be determined the material is designated non-plastic (NP), meaning no plasticity index can be computed. The corresponding conventional soil values remain to be inserted as. Low plasticity is a favourable indicator for RE wall backfill: plastic fines retain water, resist drainage and can develop volume-change behaviour under wetting and drying that a granular, non-plastic material does not.

Read together with the low fines content established in Section 5.1.1, the non-plastic response of pond ash supports its classification as a free-draining, workable backfill rather than a moisture-retentive one, which is a materially different engineering behaviour from a fines-rich, plastic ash that would require considerably more cautious treatment.

Parameter	Test Result	IRC:SP:102 Specification	Compliance
Liquid Limit (LL)	19.8 %	-	-
Plastic Limit (PL)	Non-Plastic (NP)	-	Pass
Plasticity Index (PI)	0 (NP)	≤ 6	Pass

Figure 5.2: Atterberg limits compliance summary for pond ash

5.1.4 Engineering implications of physical properties

Taken together, the physical properties establish the first tier of the suitability assessment: pond ash is not accepted on the strength of its availability or its disposal-reduction benefit, but on the basis that its measured gradation, fines content and plasticity satisfy the functional requirements of RE wall backfill. On this basis — code-compliant gradation, comfortable fines margin, and non-plastic behaviour — the tested pond ash is physically suitable to proceed to the mechanical evaluation presented in Section 5.2.

Table 5.3 consolidates the physical-property results for pond ash alongside the corresponding conventional soil values, where available.

Parameter	Pond Ash	Conventional Soil	Engineering Relevance
Passing 75 mm sieve	100%	100%	Satisfies maximum particle-size requirement for reinforced fill.
Passing 4.75 mm sieve	99.12%	99.23%	Indicates a predominantly sand-sized and finer fraction.
Passing 0.425 mm sieve	62.25%	83.69%	Supports gradation assessment for compaction and drainage.

Parameter	Pond Ash	Conventional Soil	Engineering Relevance
Passing 0.075 mm sieve	6.75%	6.21%	Low fines content favours drainage; reduces moisture sensitivity.
Uniformity coefficient, Cu	4.00	3.40	Satisfies the adopted gradation assessment criterion (> 2).
Liquid limit	19.8%	23.6%	Low value indicates limited moisture sensitivity.
Plastic limit / plasticity	Non-plastic (NP)	Non-plastic (NP)	Non-plastic behaviour is favourable for RE wall backfill.
Specific gravity	2.12	2.68	Required for void ratio, density and compaction interpretation.
Natural moisture content	12%	6%	Controls handling, spreading and field moisture conditioning.
Dry unit weight / design unit weight	13.18 kN/m ³	19.00 kN/m ³	Lower unit weight reduces vertical and lateral stress demand.

Table 5.3: Summary of physical properties of pond ash and conventional soil

5.2 Mechanical Properties

Mechanical properties determine whether the compacted material can resist deformation and sustain stability under load. The present evaluation covers heavy compaction characteristics and direct shear strength parameters, both of which bear directly on RE wall performance since compacted density and frictional resistance jointly govern the stability of the reinforced soil mass.

5.2.1 Compaction characteristics

Compaction testing was carried out to establish the optimum moisture content (OMC) and maximum dry density (MDD) of pond ash. The test followed the heavy compaction procedure of IS 2720 (Part 8) — the Modified Proctor method, using a higher compactive effort than the light compaction (Standard Proctor, IS 2720 Part 7) procedure referred to elsewhere in this thesis — and returned an OMC of 25.30% and an MDD of 1.344 g/cc. Because heavy compaction mobilises greater compactive energy than light compaction, the resulting MDD is correspondingly higher and the OMC correspondingly different from what a Standard Proctor test on the same material would return; this distinction matters for internal consistency and should be carried through wherever compaction terminology appears elsewhere in this thesis.

Proctor Compaction Test – Pond Ash (Chhabra Power Plant)

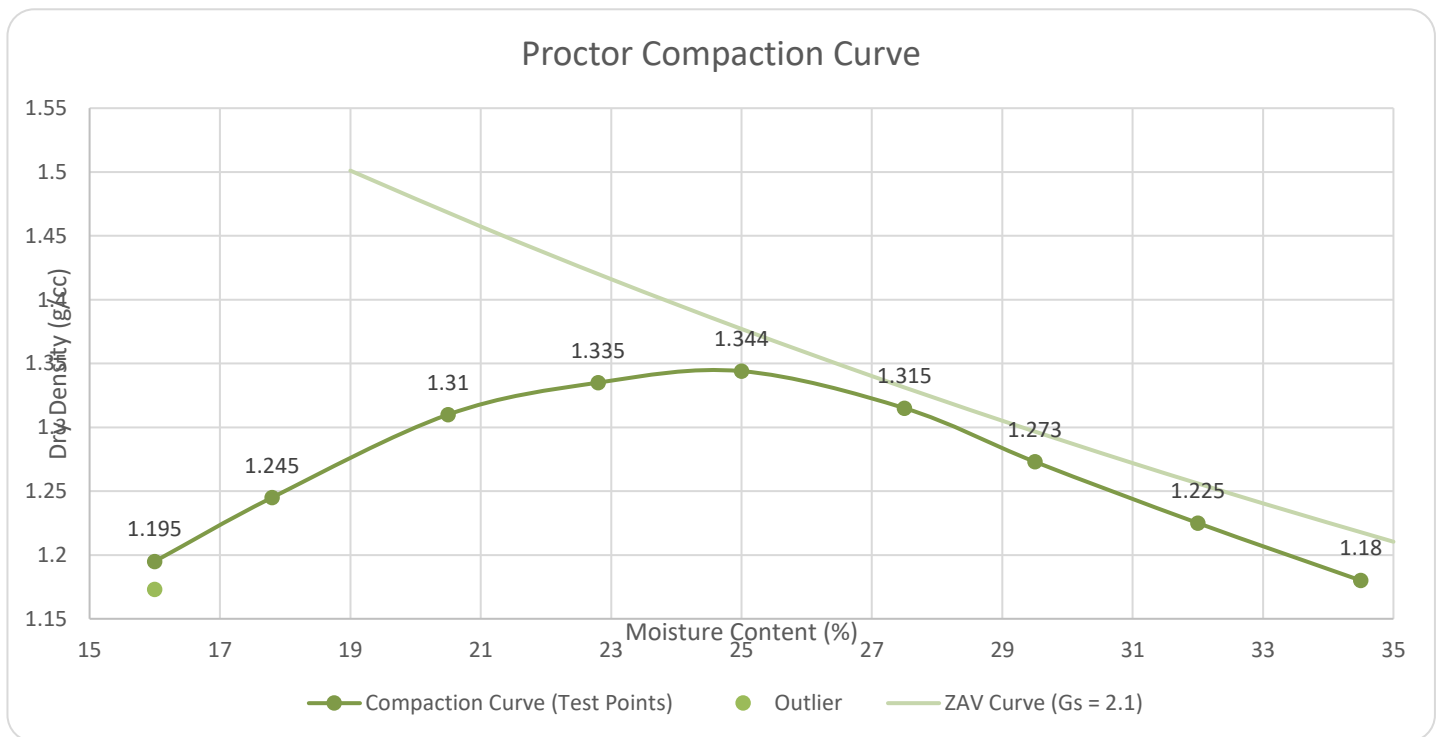


Figure 5.3: Proctor Compaction Curve Graph

Compaction behaviour reflects the interaction between water content, particle rearrangement and compactive effort: at low moisture, insufficient lubrication between particles restricts rearrangement and dry density remains low; as moisture increases toward the optimum, particles rearrange into a denser configuration under the same compactive effort; beyond the optimum, additional water occupies void space at the expense of solids and dry density falls again. This general behaviour applies to both pond ash and conventional soil, though the precise shape of the curve — and hence the field tolerance for moisture variation — depends on gradation, particle morphology and specific gravity, each of which differs between the two materials as discussed in Section 5.1.

The maximum dry density of pond ash (1.344 g/cc, equivalent to 13.18 kN/m³) is lower than would be expected for a conventional granular soil compacted under the same effort, consistent with the lower specific gravity anticipated for ash particles in Section 5.1.2. This is not, in itself, an unfavourable outcome: a lower unit weight reduces pressure on both the foundation and the reinforcement, as shown in Chapter 4, provided the corresponding shear strength remains adequate — which is examined next — and provided field compaction can reliably achieve this density in practice, which is examined separately in Section 5.6.

5.2.2 Shear strength parameters

Direct shear testing, carried out in accordance with IS 2720 (Part 13), gave an angle of internal friction of 31.50° and a cohesion of 0.00 kg/cm² for pond ash. For the design comparison in Chapter 4, the conventional soil friction angle was taken as 30.0° with zero cohesion. Shear strength is the governing mechanical property for RE wall backfill because the reinforced soil mass must resist internal shear deformation and sliding tendencies and must transfer stress reliably

around each reinforcement layer; a higher friction angle directly improves resistance to shear deformation and supports both internal and external stability.

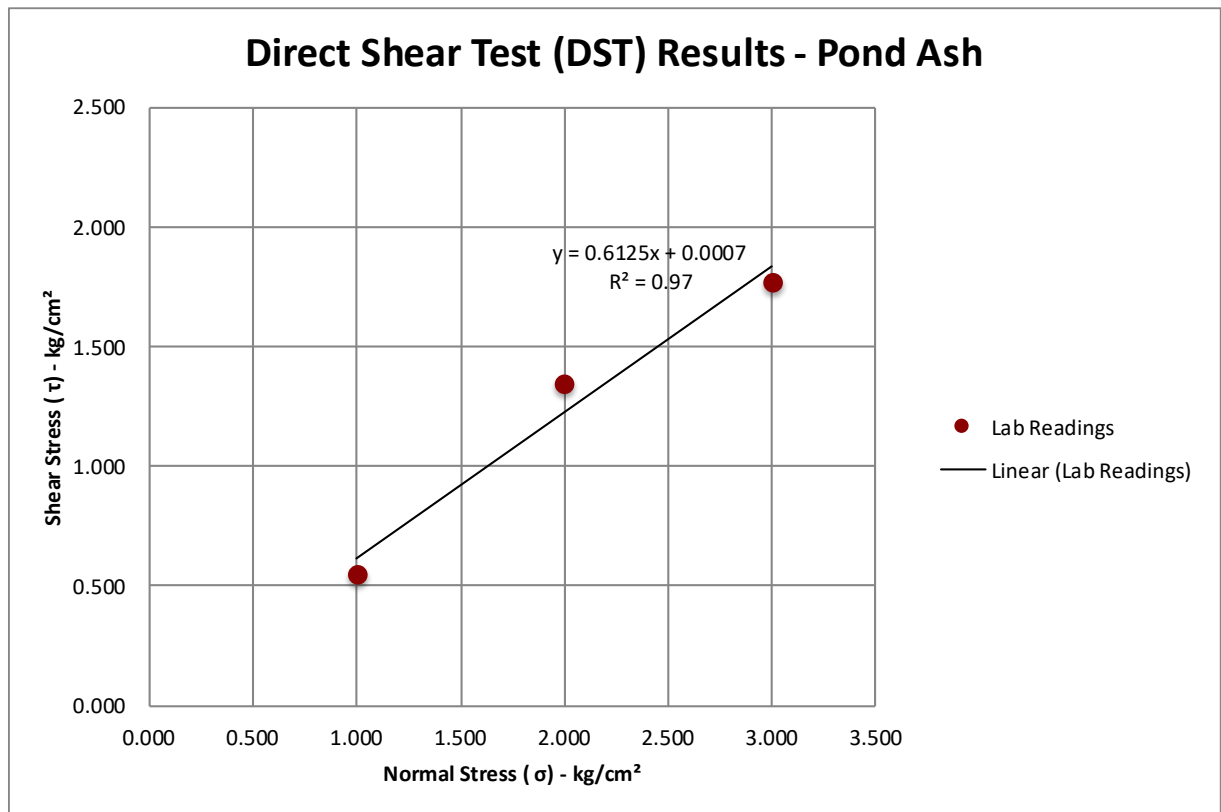


Figure 5.4: Direct shear failure envelope for pond ash

The measured friction angle of pond ash, at 31.50°, is marginally higher than the 30.0° adopted for conventional soil and comfortably exceeds the specified minimum requirement of 30°. The zero cohesion value is consistent with the expected behaviour of a granular, non-plastic material — confirmed independently by the Atterberg-limit results in Section 5.1.3 — and supports a design approach that relies on frictional resistance alone rather than any assumed cohesive contribution, which is the more conservative and defensible basis for design. On the strength of this friction angle, pond ash is mechanically comparable to, and marginally better than, conventional soil under the parameters adopted for this comparison.

Table 5.4 summarizes the mechanical properties relevant to RE wall backfill performance.

Parameter	Pond Ash	Conventional Soil	Interpretation
Optimum moisture content (OMC)	25.30%	15.23%	Defines target moisture condition for field compaction.
Maximum dry density (MDD)	1.344 g/cc	2.24 g/cc	Controls achievable compacted density and unit weight.
Angle of internal friction, ϕ	31.50°	30.00°	Pond ash provides frictional resistance comparable to, and marginally exceeding, conventional soil.
Cohesion, c	0.00 kg/cm ²	0 kPa	Design should rely mainly on frictional behaviour.
Compaction control requirement	Moisture conditioning required near OMC	Layer-wise control required	Both materials require controlled placement and compaction.

Table 5.4: Summary of mechanical properties relevant to RE wall backfill performance

5.3 Performance Evaluation

Performance evaluation integrates the physical and mechanical results established above to judge the practical suitability of pond ash as RE wall backfill. A material may possess one favourable property — a low unit weight, for instance — and still be unsuitable overall if its drainage, compaction response or shear strength are inadequate; suitability must therefore be assessed from the combined response of gradation, plasticity, moisture condition, compaction and shear strength considered together.

The tested pond ash presents suitable gradation, non-plastic behaviour, an OMC of 25.30%, an MDD of 1.344 g/cc and a direct shear friction angle of 31.50°. Together these support its technical viability as RE wall backfill within the laboratory and analytical scope of this study, subject to the

qualification, repeated throughout this thesis, that pond ash is source-dependent and that field use requires moisture control, layer-wise compaction, drainage attention and project-specific verification rather than reliance on a single characterisation exercise.

Applying these properties to the 6.0 m high RE wall section analysed in Chapter 4, the base vertical pressure reduces from 138.00 kPa for conventional soil to 103.08 kPa for pond ash, and the maximum geogrid tension reduces from 27.57 kN/m to 19.48 kN/m. The factor of safety against sliding for pond ash is 1.61, satisfying the minimum requirement of 1.5, and the factor of safety against overturning is 3.32, satisfying the minimum requirement of 2.0. Both factors are lower than the corresponding conventional soil values — a direct consequence of the reduced self-weight discussed in Section 5.1.2 — but both remain within the accepted limits, with the sliding check in particular retaining a narrower margin that warrants continued attention in detailed design and construction quality control, as already noted in Chapter 4.

Table 5.5 compares the principal design and performance indicators for conventional soil and pond ash backfill.

Parameter	Conventional Soil	Pond Ash	Performance Implication
Unit weight	19.00 kN/m ³	13.18 kN/m ³	Pond ash acts as a lightweight backfill.
Active earth pressure coefficient, K_a	0.333	0.315	Lower value reduces lateral pressure tendency.
Backfill weight per metre run	627.00 kN/m	434.94 kN/m	Lower dead load improves foundation response.
Base vertical pressure	138.00 kPa	103.08 kPa	Approximately 25% reduction with pond ash.
Maximum geogrid tension	27.57 kN/m	19.48 kN/m	Approximately 29% reduction in tensile demand.

Parameter	Conventional Soil	Pond Ash	Performance Implication
Factor of safety against sliding	2.32	1.61	Both satisfy the minimum requirement of 1.5; narrower margin for pond ash.
Factor of safety against overturning	4.79	3.32	Both satisfy the minimum requirement of 2.0.

Table 5.5: Design performance comparison for conventional soil and pond ash backfill

Parameter	Test Result	IRC:SP:102	Compliance
Internal Friction Angle	31.50 Degree	>30 Degree	Pass
Cohesion	0.0 kg/cm ²	-	Pass
MDD	1.344 g/cc	-	N/A
OMC	25.30%	-	N/A
Uniformity Coefficient (CU)	4.00	>2	Pass
Liquid Limit	19.8%	-	N/A
Plastic Index	Non-Plastic	<=6	Pass
Passing 0.075mm Sieve	6.75%	<15%	Pass

Table 5.6: IRC:SP:102-2014 compliance summary for pond ash

5.4 Cost Assessment

Cost Analysis

The cost comparison shows that the use of pond ash as a backfill material can significantly reduce the overall cost of an RE wall. For this comparison, the major cost components considered are material procurement/royalty, transportation, geogrid reinforcement, and compaction/rolling.

Material Procurement / Royalty

For conventional soil backfill, the material procurement and royalty cost is INR 350.00/m³,

whereas for pond ash it is only INR 60.00/m³. This results in a saving of INR 290.00/m³, corresponding to approximately 82.86% savings in the material procurement cost. This is the most significant saving observed among all the individual cost components.

Transportation

The transportation cost of conventional soil is INR 250.00/m³, while the corresponding cost for pond ash is INR 190.00/m³. Therefore, a saving of INR 60.00/m³ (24.00%) is achieved. The relatively lower transportation cost of pond ash contributes further to its economic advantage, although the actual saving may vary depending on the source and transportation distance.

Geogrid Reinforcement

For geogrid reinforcement, the cost associated with conventional soil backfill is INR 300.00/m³, whereas the pond ash-based system requires INR 216.67/m³. This gives a saving of approximately INR 83.33/m³, or 27.78%. The difference is associated with the reinforcement requirement adopted in the respective design conditions.

Compaction / Rolling

The compaction or rolling cost is also lower for pond ash. The cost decreases from INR 96.97/m³ for conventional soil to INR 69.70/m³ for pond ash, giving a saving of approximately INR 27.27/m³ (28.12%). This indicates that pond ash can be compacted economically under the adopted field conditions.

Overall Cost Comparison

Overall, the total estimated cost for conventional soil is INR 996.97/m³, whereas the total cost for pond ash is approximately INR 536.36–536.37/m³. Thus, the use of pond ash results in an overall saving of approximately INR 460.61/m³, corresponding to an overall cost reduction of about 46.20%.

Practical Interpretation

The results indicate that material procurement/royalty is the major contributor to the overall cost saving. Although transportation, reinforcement, and compaction also contribute to the reduction, the substantial difference in material procurement cost makes pond ash particularly attractive as an alternative backfill material.

From a practical construction perspective, this cost reduction becomes more significant when the volume of backfill is large, as is generally the case in reinforced earth wall construction. For every 1 m³ of backfill, approximately INR 460.61 can be saved based on the adopted rates. Therefore, for a large RE wall project involving several thousand cubic metres of backfill, the cumulative economic benefit can be considerable.

Overall, the cost analysis supports the use of pond ash as a cost-effective alternative to conventional soil backfill, provided that its engineering properties, availability, drainage requirements, and field compaction are adequately controlled.

Cost Component	Conventional Soil (INR/m ³)	Pond Ash (INR/m ³)	Saving (INR/m ³)	Saving (%)
Material procurement / royalty	350.00	60.00	290.00	82.86
Transportation	250.00	190.00	60.00	24.00
Geogrid reinforcement	300.00	216.67	83.33	27.78
Compaction / rolling	96.97	69.70	27.27	28.12
Total	996.97	536.36	460.61	46.20

Table 5.7: Component-wise cost comparison per cubic metre of RE wall backfill

5.5 Sustainability Assessment

The sustainability assessment considers the environmental significance of replacing conventional backfill with pond ash. Its use can reduce demand for natural aggregates, put an industrial by-

product to productive use, and reduce the volume of material requiring long-term ash-pond storage — benefits that are particularly relevant for transportation infrastructure, where RE walls consume large quantities of compacted backfill.

Resource conservation follows directly: natural backfill extraction can disturb borrow areas, river systems, local drainage patterns and landforms, and any substitution of pond ash for conventional backfill reduces this extraction pressure.

Beyond resource conservation, pond ash utilisation supports circular-economy principles by keeping an industrial by-product in productive engineering use rather than treating it solely as a disposal burden. This sustainability case is deliberately made to depend on the engineering findings of this chapter, not the reverse: pond ash is recommended here because it satisfies the physical, mechanical, drainage and code-related requirements established in Sections 5.1 to 5.3, with the sustainability benefit following as a consequence of that engineering suitability rather than substituting for it.

Assessment Aspect	Conventional Soil Backfill	Pond Ash Backfill	Sustainability Implication
Natural resource demand	Requires extraction of borrow soil or granular material	Utilises an industrial by-product	Conserves natural aggregates and borrow areas.
Disposal burden	No reduction in ash-pond storage	Diverts pond ash to productive construction use	Reduces long-term ash disposal pressure.
Transportation and handling	Higher material weight in the adopted comparison	Lower compacted unit weight	Can reduce freight and handling demand under suitable logistics.

Assessment Aspect	Conventional Soil Backfill	Pond Ash Backfill	Sustainability Implication
Structural material demand	Higher reinforcement tension in the adopted section	Lower maximum geogrid tension	Supports lower reinforcement demand in the analysed case.
Implementation control	Established construction practice	Requires source-specific testing and moisture control	Sustainable use must remain linked with engineering safety.

Table 5.8: Sustainability comparison between conventional soil backfill and pond ash backfill

Table 5.9: Field dry density determination by the sand replacement method (pond ash, Ch. 118+600, Wall-4) 49

5.6 Field Verification of Compaction Performance

The laboratory heavy compaction test (Section 5.2.1) establishes what pond ash is capable of achieving under controlled conditions; it does not, by itself, confirm that the same density is achievable during actual field placement, where layer thickness, moisture conditioning, roller type and operator practice all introduce variability absent from a laboratory mould. A field density check is therefore the necessary complement to laboratory characterisation, and one was carried out at the RE wall construction site studied for this thesis, at chainage 118+600 (Wall-4), on 18 June 2026.

5.6.1 Sand replacement method

Field dry density was determined by the sand replacement method in accordance with IS 2720 (Part 28). The method works by excavating a small test hole in the compacted backfill, weighing the excavated material, and then determining the volume of the hole by pouring in calibrated sand of known bulk density until the hole is exactly refilled; because the poured sand takes on the precise shape of the excavated cavity, its known bulk density converts the mass of sand used into the volume of the hole, which is otherwise impossible to measure directly in an irregular field

excavation. Dividing the mass of excavated material by this volume gives the bulk density of the compacted fill, which is then corrected for moisture content to yield the field dry density.

The calibration constant for the method is the bulk density of the standard sand used to fill the hole, recorded here as 1.35 g/cc; this is a property of the calibration sand itself, not of the pond ash being tested, and is used purely to convert the measured sand mass into a hole volume.

5.6.2 Field observations and calculation

Two independent observations were taken at the test location. The weight of wet pond ash excavated from the test hole (W_w) was 4,671 g and 4,663 g respectively. The weight of sand and cylinder before pouring (W_1) was 15,000 g in both cases, and after pouring into the hole and cone (W_2) was 9,995 g and 10,120 g respectively; with the sand retained in the pouring cone (W_3) recorded as 1,088 g, the weight of sand occupying the hole itself ($W_4 = W_1 - W_2 - W_3$) works out to 3,917 g and 3,792 g. Dividing each W_4 value by the calibration bulk density of the sand (1.35 g/cc) gives hole volumes of 2,901 cc and 2,809 cc, and dividing the corresponding W_w by these volumes gives bulk densities of 1.610 g/cc and 1.660 g/cc for the two observations.

The moisture content of the excavated material was measured as 23.5% and 26.0% for the two observations — bracketing the laboratory optimum moisture content of 25.30% reasonably closely, and consistent with the field-trial OMC of 25.5% noted in Section 5.1.2 — and applying the standard bulk-to-dry-density correction ($\gamma_d = \gamma_b / (1 + w/100)$) gives field dry densities of 1.303 g/cc and 1.317 g/cc, averaging 1.310 g/cc.

Description	Unit	Observation 1	Observation 2
Weight of wet material from hole, W_w	g	4671	4663
Weight of sand + cylinder before pouring, W_1	g	15000	15000

Description	Unit	Observation 1	Observation 2
Weight of sand + cylinder after pouring, W2	g	9995	10120
Weight of sand in cone, W3	g	1088	1088
Weight of sand in hole, W4 (W1 – W2 – W3)	g	3917	3792
Volume of hole, $V = W4 / \gamma_s$	cc	2901	2809
Bulk density of material, $\gamma_b = W_w / V$	g/cc	1.610	1.660
Moisture content	%	23.5	26.0
Field dry density, $\gamma_d = \gamma_b / (1 + w/100)$	g/cc	1.303	1.317
Compaction obtained, $(\gamma_d / MDD) \times 100$	%	96.95	97.99

Table 5.9: Field dry density determination by the sand replacement method (pond ash, Ch.

118+600, Wall-4)

5.6.3 Degree of compaction and suitability for RE wall construction

The degree of compaction — the field dry density expressed as a percentage of the laboratory MDD of 1.344 g/cc — was 96.95% and 97.99% for the two observations, averaging 97.47%. This exceeds the commonly specified minimum requirement of 95% relative compaction for reinforced soil structures, and the field trial is accordingly assessed as satisfactory.

This result carries engineering significance beyond a simple pass/fail outcome. It confirms that the maximum dry density obtained under laboratory heavy compaction is not merely a theoretical figure but is practically achievable in the field using ordinary compaction equipment and layer control, which in turn lends direct support to the unit weight of 13.18 kN/m³ adopted for the stability calculations in Chapter 4 — a design assumption that would otherwise rest on laboratory data alone. Achieving a degree of compaction close to full MDD also indicates that the void ratio assumed in the density-dependent design parameters is realistic, and that the frictional resistance

measured in the direct shear test (Section 5.2.2) can reasonably be expected to develop in the field, since shear strength in a granular material is itself sensitive to the density at which it is compacted.

Both field moisture contents (23.5% and 26.0%) bracket the optimum reasonably closely, suggesting that moisture conditioning at the site was managed with reasonable care, consistent with the requirement, noted throughout this thesis, that pond ash placement demands closer moisture control than a conventional granular soil. Taken together with the laboratory results in Sections 5.1 and 5.2, this field verification provides the practical evidence that the physical and mechanical suitability demonstrated in the laboratory translates into achievable performance under ordinary construction conditions, which is the standard a backfill material must ultimately meet regardless of how favourable its laboratory properties appear in isolation.

5.7 Summary of Results and Discussion

The results presented in this chapter show that the suitability of pond ash as RE wall backfill cannot be established from any single test in isolation, but emerges from an integrated framework: physical characterisation establishes whether the material has suitable gradation, density, moisture behaviour and plasticity; compaction testing establishes whether it can be placed at an acceptable dry density under practical moisture conditions; direct shear testing establishes whether it can mobilise adequate shear strength; and the field verification in Section 5.6 establishes whether the density assumed in design is actually achievable on site. Code compliance, cost assessment and sustainability assessment then convert these laboratory and field findings into an engineering decision.

On the basis of the results assembled in this chapter, pond ash performs favourably against conventional soil on nearly every measure examined: its gradation satisfies the IRC:SP:102-2014

requirements with a comfortable margin, its plasticity is non-existent by measurement, its friction angle of 31.50° marginally exceeds that adopted for conventional soil, and its lower unit weight reduces base vertical pressure by approximately 25% and maximum geogrid tension by approximately 29% relative to conventional backfill in the analysed 6.0 m wall section. The field density check confirms that the laboratory-derived maximum dry density is achievable under ordinary site conditions, at 97.47% average compaction against a 95% requirement, lending practical support to the design assumptions carried through Chapter 4. The cost comparison indicates a 46.20% reduction in the considered cost components, and the sustainability assessment identifies genuine benefits in natural resource conservation and industrial waste utilisation.

This favourable picture should, however, be read with the same qualification maintained throughout this thesis: the factor of safety against sliding for pond ash (1.61) satisfies the code minimum of 1.5 but with a substantially narrower margin than conventional soil (2.32), and pond ash's source-dependent variability means that the properties reported here characterise the specific sample tested rather than pond ash as a universal material class. Neither point undermines the overall conclusion, but both mean that adopting pond ash as RE wall backfill should be accompanied by source-specific testing, careful moisture control during construction, and continued attention to the sliding stability check, rather than treated as an unconditional substitute for conventional practice.

Considered together, the physical, mechanical, field-performance, cost and sustainability evidence gathered in this chapter supports pond ash as a technically sound and economically favourable sustainable backfill for Reinforced Earth wall construction, achieved without exaggerating the margins involved or setting aside the specific respects — principally sliding stability and source variability — in which conventional practice still carries an advantage.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

Based on the comprehensive evaluation of pond ash as a sustainable backfill material for Reinforced Earth (RE) wall applications, the following conclusions are drawn:

- **Comparative Engineering Performance:** Comprehensive source-specific laboratory testing confirmed that the engineering properties of the tested pond ash—specifically its compaction characteristics and shear strength—are highly comparable to conventional backfill soil. By evaluating both materials under identical testing procedures, the study establishes pond ash as a structurally sound alternative.
- **Compliance with Standard Specifications:** Geotechnical characterization of the pond ash demonstrates that it fully satisfies the stringent acceptance criteria outlined in the IRC:SP:102-2014 guidelines. This verifies its technical suitability for use as a backfill material in Reinforced Earth (RE) wall applications.
- **Successful Field Validation:** Addressing the critical gap of over-reliance on laboratory-only studies, this project successfully validated the laboratory findings through site-based implementation. The practical evaluation demonstrated high construction feasibility and structural stability of untreated pond ash in real-world RE wall construction scenarios.
- **Cost-Effectiveness and Economic Viability:** The integrated assessment revealed that utilizing pond ash significantly reduces material procurement and transportation costs compared to conventional soil. This makes it a highly economical alternative for large-scale RE wall projects without compromising structural integrity.
- **Promoting Sustainable Infrastructure:** By replacing conventional borrow soil with pond ash, the study highlights a dual environmental benefit: it mitigates the ecological depletion caused by soil mining while simultaneously offering a productive, large-volume disposal solution for thermal power plant waste.

- **Final Recommendation for Field Application:** Integrating the findings of engineering performance, economic analysis, and sustainability, the study conclusively recommends the adoption of untreated pond ash as a primary backfill material in RE walls. This approach bridges the gap between theoretical research and practical industry application, offering a sustainable, cost-effective, and safe engineering solution.

6.2 Scope for Future Research

This thesis has established the physical, mechanical, analytical, field-compaction and cost basis for pond ash as RE wall backfill within a defined laboratory and analytical scope. Several extensions naturally follow from this scope and are recommended for future research.

- Long-term field monitoring: instrumented pond ash-backed RE wall sections should be monitored over an extended service period to track settlement, lateral facing movement, drainage performance and any progressive change in compacted density, extending the single-point field verification reported in this thesis into a continuous performance record.
- Cyclic and traffic loading behaviour: the present analysis considers static design loading only; the response of pond ash backfill to repeated traffic-induced cyclic loading, relevant to highway and bridge-approach applications, merits dedicated laboratory and field investigation.
- Seismic performance: given India's varying seismic zonation, the dynamic response of pond ash-backed RE walls — including pseudo-static and, where warranted, fully dynamic stability analysis — represents an important extension beyond the static case examined here.
- Durability studies: the long-term durability of compacted pond ash under repeated wetting-drying cycles, freeze-thaw exposure where relevant, and prolonged moisture exposure warrants investigation, since this thesis characterises the material only in its initially compacted condition.

- Numerical modelling and finite element analysis: the simplified rigid-block limit-equilibrium approach adopted in this thesis could be extended through finite element or finite difference modelling to examine internal deformation, stress distribution and reinforcement-soil interaction in more detail than a limit-equilibrium method allows.
- Life-cycle assessment: a formal, quantified life-cycle assessment, covering embodied carbon, transportation emissions and resource depletion, would place the qualitative sustainability discussion in this thesis on a more rigorous quantitative footing.
- Optimisation of reinforcement spacing: the reduced tension demand identified in this study suggests scope for a dedicated optimisation study of geogrid spacing and grade selection specifically for pond ash backfill, balancing reinforcement cost against the stability margins identified here.
- Large-scale field validation: construction and monitoring of multiple pilot RE wall sections, ideally using pond ash from more than one source, would validate the laboratory and single-site field findings of this thesis across a broader range of practical conditions.
- Blended and stabilised systems: where a given pond ash source exhibits marginal properties, future work could examine blending pond ash with conventional granular soil or other industrial by-products, or controlled chemical stabilisation, as a means of extending its applicability beyond sources that satisfy the criteria used in this study directly.
- Climate resilience: the performance of pond ash backfill under extreme rainfall and drainage-stress scenarios, relevant to changing climate patterns, would extend the moisture-sensitivity findings of this thesis into an explicitly climate-resilience-focused investigation.

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