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Application of Geosynthetics and Pond Ash in Subgrade Improvement: A Comprehensive Review

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Abstract

Subgrade improvement is crucial for the performance and longevity of road infrastructure. Clayey subgrades, characterized by low strength and high compressibility, present significant challenges in road construction, necessitating innovative solutions for enhancement. Pond ash, an abundant by-product of coal-based thermal power plants, and geosynthetics, such as geotextiles, have emerged as cost-effective and sustainable alternatives to traditional materials. This paper provides a comprehensive review of the application of these materials in subgrade improvement. The review highlights the geotechnical properties of pond ash and its effectiveness in enhancing California Bearing Ratio (CBR) values. It also examines the role of geosynthetics in reinforcing weak subgrades, focusing on their tensile properties and load distribution capabilities. A combined application of pond ash and geosynthetics demonstrates a synergistic effect, further improving subgrade performance. Gaps in existing research, including the lack of long-term field studies and standardized design methodologies, are identified. This review aims to contribute to the development of sustainable and cost-efficient road construction practices, emphasizing the potential of integrating industrial by-products with advanced geosynthetic materials.

Keywords: Subgrade Improvement, Clayey Subgrades, Geosynthetics, Geotextiles, Pond Ash, California Bearing Ratio (CBR), Soil Reinforcement,

1 Introduction

Transportation infrastructure serves as the backbone of socio-economic growth, facilitating connectivity, trade, and regional development. It plays a pivotal role in bridging the gap between rural and urban areas, fostering industrial growth, and ensuring the equitable distribution of resources. The quality of road networks significantly influences a country's development trajectory, with robust transportation systems driving economic productivity and improving access to essential services such as education, healthcare, and markets (World Bank, 2020). Despite its significance, the construction and maintenance of road networks face numerous challenges, particularly in regions characterized by challenging soil conditions. One of the most persistent issues is the poor strength and high compressibility of clayey subgrades, which are often prevalent in expansive or soft soil regions. These subgrades exhibit low California Bearing Ratio (CBR) values, which adversely affect the load-bearing capacity and performance of flexible pavements, leading to frequent failures and costly maintenance cycles (Chen et al., 2021). Addressing these deficiencies requires innovative and sustainable methods for improving subgrade properties. Traditional approaches to subgrade enhancement, such as using natural aggregates or lime stabilization, have been widely practiced due to their proven effectiveness in increasing strength and reducing compressibility. However, these methods are increasingly scrutinized for their environmental implications, including the depletion of natural resources and high carbon emissions associated with material extraction and processing (Muntohar et al., 2022). The rising cost of natural aggregates and lime further accentuates the need for alternative solutions that are both cost-effective and environmentally friendly. With the depletion of natural reserves and growing environmental concerns, research has shifted towards the utilization of industrial byproducts and advanced materials. Pond ash, a byproduct of coal-based thermal power plants, has emerged as a viable alternative due to its abundance and favourable geotechnical properties, such as low unit weight, adequate shear strength, and pozzolanic activity. When appropriately processed and stabilized, pond ash can significantly improve subgrade strength while reducing the dependency on natural materials (Gupta et al., 2020).

In parallel, geosynthetics, including geotextiles and geogrids, have gained prominence as effective reinforcements for weak subgrades. Geosynthetics function by distributing loads more evenly, reducing differential settlements, and enhancing the bearing capacity of subgrades. These materials are not only lightweight and durable but also relatively easy to install, making them a practical choice for a wide range of soil conditions (Koerner, 2012). The integration of geosynthetics with subgrades has demonstrated significant improvements in pavement performance and service life.

This paper reviews the application of pond ash and geosynthetics in subgrade improvement, focusing on their individual and combined effects on enhancing subgrade strength and stability. The objectives of this review are to:

Analyze the geotechnical properties of pond ash and its suitability for subgrade applications: Previous studies have highlighted the potential of pond ash as a partial or full replacement for traditional subgrade materials, with significant cost savings and environmental benefits.

Investigate the role of geosynthetics in reinforcing weak subgrades: Research has demonstrated that geosynthetics can mitigate issues related to differential settlements and provide a stable foundation for pavement layers.

Highlight the synergistic benefits of combining pond ash with geosynthetics: Combining these two materials can leverage the complementary properties of each, resulting in enhanced subgrade performance and reduced environmental impact.

Identify gaps in existing research and propose future directions: While significant progress has been made, more field studies and long-term performance evaluations are needed to establish standardized guidelines for the combined use of pond ash and geosynthetics

2 Ground Improvement Techniques

Ground improvement encompasses a diverse range of techniques aimed at enhancing the engineering properties of soil to meet the structural and geotechnical requirements for construction projects. These techniques are employed to address issues such as low strength, high compressibility, and poor drainage, which often render native soils unsuitable for supporting infrastructure. Ground improvement not only ensures the stability and durability of structures but also minimizes settlement-related issues, reducing the need for costly and time-consuming maintenance (Mitchell and Soga, 2005).

Historically, methods such as lime and cement stabilization have been widely employed to improve weak soils. Lime stabilization involves the addition of lime to clayey soils, triggering chemical reactions that enhance their strength and reduce plasticity. Similarly, cement stabilization utilizes cementitious compounds to bind soil particles, significantly increasing the load-bearing capacity. These traditional methods have proven effective over decades and remain in use, particularly in regions where material availability and technical expertise are abundant.

However, the environmental concerns associated with these methods have led to a paradigm shift in ground improvement practices. The production of lime and cement is energy-intensive, contributing to significant carbon emissions and depleting natural resources. Additionally, the extraction and transportation of raw materials for stabilization exacerbate environmental degradation (Van Impe and Bouazza, 2021). In response to these challenges, alternative approaches have been developed, prioritizing sustainability without compromising effectiveness.

Among these alternatives, the utilization of industrial byproducts has emerged as a promising solution. Materials such as fly ash, pond ash, slag, and silica fume, which are byproducts of industrial processes, offer a sustainable and cost-effective option for soil stabilization. Pond ash, a waste product from coal-based thermal power plants, is particularly noteworthy due to its abundance, low cost, and favourable geotechnical properties. When appropriately processed, pond ash can enhance the strength, compaction, and drainage properties of soils, making it a viable substitute for traditional materials (Gupta et al., 2020).

Reinforcement using advanced geomaterials, such as geosynthetics, has also gained prominence (Fig.1). Geosynthetics, which include geotextiles, geogrids, and geomembranes, are synthetic polymer-based materials designed for geotechnical applications. These materials are lightweight, durable, and highly versatile, offering solutions for soil reinforcement, separation, filtration, and drainage. By distributing loads more uniformly and preventing soil deformation, geosynthetics improve the structural integrity of soil systems, particularly in weak or problematic soils (Koerner, 2012).

The incorporation of industrial byproducts like pond ash and advanced geomaterials such as geosynthetics has gained significant attention due to their cost-effectiveness, technical feasibility, and environmental sustainability. These approaches align with global efforts to promote circular economy principles, where waste materials are repurposed into valuable resources. Moreover, combining these techniques can yield synergistic benefits, such as enhanced strength, improved drainage, and reduced environmental impact. For instance, using pond ash in conjunction with geosynthetics can create reinforced soil systems that outperform traditional stabilization methods in terms of both cost and performance (Muntohar et al., 2022).

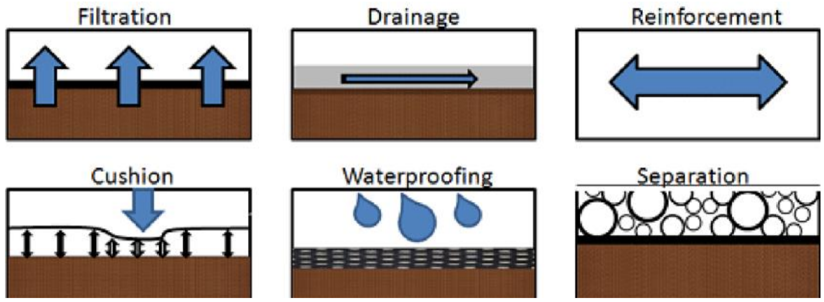

Fig. 1 Function of geotextile

As the construction industry continues to prioritize sustainability, these innovative ground improvement techniques are expected to play a critical role in addressing the challenges of soil stabilization, ensuring the development of resilient and eco-friendly infrastructure.

3 Utilization of Pond Ash

Pond ash, a by-product generated during the combustion of coal in thermal power plants, holds significant potential for application in geotechnical and construction projects. This material is characterized by its low specific gravity, which reduces the overall weight of structures, and pozzolanic properties that contribute to its binding and strength-enhancing capabilities when mixed with other materials. Additionally, its non-plastic nature ensures minimal shrink-swell behaviour, making it particularly advantageous for use in soils prone to volumetric changes under varying moisture conditions (Gupta et al., 2020).

One of the most compelling advantages of pond ash is its abundance and low cost. With millions of tons generated annually as a by-product of energy production, pond ash presents an opportunity to address waste management issues while reducing the dependency on natural aggregates. Its use in construction applications aligns with the principles of sustainable development and circular economy, as it promotes the repurposing of industrial byproducts into valuable engineering materials (Muntohar et al., 2022).

Research has demonstrated that incorporating pond ash into clayey subgrades significantly improves their engineering properties. Key improvements include an increase in California Bearing Ratio (CBR) values, which directly translates to enhanced load-bearing capacity. The reduction in plasticity and compressibility further enhances the stability of subgrades, reducing the likelihood of deformation under traffic loads. Studies have shown that optimized mixtures of pond ash with local soils can achieve substantial strength gains, making them suitable for various road construction projects (Raut et al., 2018).

The lightweight nature of pond ash is another critical factor that contributes to its suitability for road construction, particularly in areas with soft or highly compressible soils. By reducing the overall weight of the embankment or subgrade, pond ash minimizes the risk of settlement, which is a common issue in soft soil regions. This characteristic makes it an ideal material for infrastructure projects in floodplains, coastal areas, and other challenging environments where traditional materials may lead to excessive settlements (Singh et al., 2021).

Beyond its geotechnical benefits, the use of pond ash in construction also has significant environmental implications. Utilizing this industrial by product helps reduce the accumulation of ash in disposal sites, which are often associated with environmental hazards such as groundwater contamination and air pollution. By repurposing pond ash for infrastructure development, the construction industry can contribute to the mitigation of these environmental challenges while reducing its reliance on finite natural resources (Van Impe and Bouazza, 2021).

The integration of pond ash into clayey subgrades and other construction applications represents a sustainable and cost-effective solution that addresses both geotechnical challenges and environmental concerns. Its widespread adoption has the potential to revolutionize construction practices, particularly in regions with abundant thermal power plant byproducts and challenging soil conditions.

4 Principles of Geotextile-Reinforced Soil

Geotextile reinforcement in soil is based on the principle of introducing tensile strength to weak soils, which inherently lack it. This reinforcement works through several primary mechanisms. First, tensile reinforcement is achieved as geotextiles resist tensile forces within the soil, thereby enhancing overall stability. Second, frictional resistance occurs due to the interlocking between soil particles and the fibres of the geotextile, which helps in distributing loads more uniformly. Lastly, drainage enhancement is facilitated by geotextiles, allowing water to move through the soil, thereby reducing pore pressure and improving shear strength.

These properties make geotextiles highly versatile and effective in various geotechnical applications. They are widely used to stabilize soft subgrades in road construction, providing a solid foundation for pavements. Geotextiles also reinforce slopes and embankments, preventing erosion and maintaining structural integrity. Additionally, they are used to support retaining walls and foundations, where their strength and drainage capabilities contribute to the stability and longevity of the structures. The integration of geotextiles in these applications underscores their importance in modern construction practices, particularly in challenging soil conditions.

5 Literature Review

Numerous studies have demonstrated the potential of pond ash and geosynthetics in improving the engineering properties of clayey soils, addressing issues such as low strength, high plasticity, and excessive settlement. Research by Bera (2010) highlighted the significant benefits of incorporating pond ash into clayey soils, including notable reductions in plasticity and substantial increases in California Bearing Ratio (CBR) values. These improvements enhance the load-bearing capacity and stability of weak subgrades, making pond ash a viable alternative to natural aggregates. Kumar and Mahla (2015) further supported these findings by demonstrating enhanced load-bearing capacity and reduced settlement in compacted pond ash beds, emphasizing its suitability for road construction and other geotechnical applications.

6 Geosynthetics in Soil Reinforcement

In parallel, geosynthetics have emerged as an effective solution for reinforcing clayey subgrades. Kamalzare and Moayed (2011) investigated the role of geogrids in soil reinforcement, observing significant enhancements in tensile strength and reductions in settlement under load. Their findings underscored the utility of geogrids in distributing loads more evenly and preventing deformation in weak soils. Singh (2013) studied the use of jute geotextiles, a natural and cost-effective material, in reinforcing clayey soils. His research highlighted improvements in shear strength and stiffness, demonstrating the versatility of geotextiles in geotechnical applications.

6.1 Combined Use of Pond Ash and Geosynthetics

The combined application of pond ash and geosynthetics has recently gained attention as a synergistic approach to subgrade improvement. Pradhan and Pothal (2023) explored this integration, reporting significant enhancements in subgrade performance. Their study revealed higher CBR values and reduced settlements compared to the use of either material alone. The complementary properties of pond ash and geotextiles were identified as the key factor driving these improvements. Pond ash contributes to improved soil properties through its pozzolanic activity and low weight, while geosynthetics provide tensile reinforcement and effective load distribution.

7 Gaps in Existing Research

Despite these advancements, gaps remain in the current understanding of the combined use of pond ash and geosynthetics. While individual applications of these materials are well-documented, studies on their combined performance are limited, particularly under varying field conditions and long-term loading scenarios. Comprehensive investigations into the durability, environmental impact, and cost-efficiency of these integrated approaches are essential to establish standardized practices for their use in geotechnical engineering.

8 Methodologies for Evaluating Subgrade Improvement

The evaluation of subgrade improvement involves a comprehensive approach that combines laboratory testing, field performance assessments, and advanced numerical modeling to analyze soil behavior and the effectiveness of improvement techniques. Laboratory tests provide fundamental insights into the engineering properties of subgrades (Table.1). The California Bearing Ratio (CBR) test simulates loading conditions to evaluate the strength and load-bearing capacity of subgrades, which is critical for pavement design (Kumar and Mahla, 2015). The unconfined compression test measures the soil's compressive strength, determining its ability to withstand axial loads without lateral confinement. Similarly, the direct shear test assesses the shear strength parameters of soil and soil-geosynthetic interfaces, which are essential for understanding the stability of reinforced systems (Kamalzare and Moayed, 2011).

Field performance tests complement laboratory assessments by offering real-time evaluations under actual site conditions. The plate load test is widely used to determine the bearing capacity and settlement characteristics of subgrades, providing essential data for foundation design. The in-situ CBR test offers a quick and reliable assessment of subgrade strength directly at the site, facilitating immediate decision-making for construction activities (Singh, 2013). These field tests bridge the gap between controlled laboratory conditions and the complex realities of construction sites, ensuring that subgrade improvement techniques are practical and effective in real-world scenarios.

In addition to laboratory and field tests, numerical modelling has become a vital tool in modern geotechnical engineering. Finite Element Analysis (FEA) using software such as PLAXIS and SEEP/W enables the simulation of subgrade behaviour, including stress distribution, deformation, and seepage.

TABLE:1 Laboratory tests and relevant codes for experiments of materials

Name of laboratory tests	**Names of Codes**
Engineering Properties of Soil and Pond ash 1) Free swell index 2) Grain Size analysis 3) Specific Gravity Test by Density Bottle 4) Proctor Compaction Test (Light and Heavy compaction) 5) Atterberg Limit (LL and PL) 6) California Bearing Ratio Test	IS: 2720 (Part 40) IS: 2720 (Part 4) IS: 2720 (Part 3/Sec 1) IS: 2720 (Part 7 and Part 8) IS: 2720 (Part 5) IS: 2720 (Part 16)
Determination of different properties of Geotextile 1)Weight per square meter 2)CBR Punch Strength Test (N) Static CBR Puncher Resistance 3) Garb strength and Elongation Garb Tensile Strength (N) Machine Direction Cross Machine Direction Max. Elongation (%) Machine Direction	(ISO 9864 :2005) (ISO 12236-2006) (ASTM- D 4632:2015) (ASTM D 4533-2015)

Cross Machine Direction 4)Trapezoid Tear strength Trapezoid Tear strength Machine Direction Cross Machine Direction	(ASTM 4491-2021)
5)Water Permeability Water Permeability WH 50mm ($1/m^2/s$) Water Permittivity, S-1 6)Characteristic Opening Size	(ISO -129586-2010)

These models help optimize designs and provide a deeper understanding of material interactions under various loading conditions (Pradhan and Pothal, 2023). Moreover, the integration of Artificial Intelligence (AI) and Machine Learning (ML) has revolutionized predictive analysis by identifying patterns in soil behavior from large datasets. These advanced technologies enhance the accuracy of performance forecasts and facilitate the development of efficient, data-driven solutions for subgrade improvement (Van Impe and Bouazza, 2021). This multidimensional approach ensures that traditional and innovative methods for subgrade improvement are thoroughly evaluated, paving the way for reliable and sustainable geotechnical designs.

9 Conclusions:

The integration of pond ash and geosynthetics in subgrade improvement presents several challenges that must be addressed to maximize their potential. One of the primary obstacles is the logistics and transportation costs associated with pond ash, particularly in remote areas where thermal power plants are not in proximity. Additionally, compatibility issues between pond ash and geosynthetics, such as chemical interactions and bonding efficiency, can affect the overall performance of the reinforced subgrade system. Regulatory barriers and environmental concerns regarding the utilization of industrial byproducts further complicate their widespread adoption, necessitating thorough assessments and compliance with environmental standards.

Despite these challenges, there are promising avenues for future research and development. Establishing standardized design guidelines for the combined application of pond ash and geosynthetics would provide a framework for engineers and practitioners, ensuring consistency and reliability in their use. Further exploration of other industrial byproducts, such as slag and silica fume, could expand the range of sustainable materials available for subgrade improvement. Advances in geosynthetic materials, focusing on enhanced durability, performance under extreme conditions, and eco-friendly production methods, offer additional opportunities to optimize their application in geotechnical engineering.

In conclusion, the integration of pond ash and geosynthetics represents a sustainable and cost-effective solution for subgrade improvement. By addressing current challenges, filling research gaps, and leveraging advancements in material science, the construction industry can develop more resilient and environmentally friendly infrastructure. These innovative approaches align with the global shift towards sustainable development, offering practical solutions to the dual challenges of weak subgrades and environmental sustainability.

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