Performance Evaluation of Ground Improvement Using River Silt and Pond Ash for Sustainable Geotechnical Applications: A Review

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How to Cite this Article:

SINGH, N. (2026). Performance Evaluation of Ground Improvement Using River Silt and Pond Ash for Sustainable Geotechnical Applications: A Review. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(7). https://doi.org/10.55041/ijcope.v2i7.092

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Abstract

Ground improvement techniques play a significant role in enhancing weak soil characteristics to support infrastructure development and improve construction performance. Conventional stabilizing agents such as cement and lime are widely used; however, their production contributes substantially to carbon emissions and environmental degradation. In recent years, increasing attention has been directed toward sustainable alternatives through the utilization of industrial and natural waste materials. Among these materials, river silt and pond ash have emerged as promising resources for soil stabilization and ground improvement applications. River silt, generated through sediment deposition processes, and pond ash, produced from thermal power plants, are available in large quantities and often create disposal and environmental challenges. Their beneficial utilization in geotechnical engineering offers a sustainable solution for waste management and resource conservation. This review paper presents a comprehensive assessment of previous studies related to the application of river silt and pond ash in ground improvement. The review examines the physical, chemical, and engineering characteristics of these materials and their influence on soil behavior. Key geotechnical properties including compaction characteristics, unconfined compressive strength, shear strength, California Bearing Ratio (CBR), permeability, consolidation behavior, and durability performance are critically discussed. The effects of varying replacement percentages and curing periods on stabilized soils are also evaluated. Furthermore, the environmental and economic benefits associated with the use of these waste materials are highlighted. The review concludes that river silt and pond ash can significantly improve engineering performance while reducing dependence on traditional stabilizers, thereby promoting sustainable and eco-friendly geotechnical construction practices. Future research directions focusing on long-term field performance and large-scale implementation are also identified.

Keywords: Ground Improvement, River Silt, Pond Ash, Soil Stabilization, Sustainable Geotechnical Engineering, Waste Utilization, Soil Strength, Environmental Sustainability, Compaction Characteristics, Geotechnical Applications

Introduction

Ground improvement has become an essential geotechnical practice for enhancing weak soil properties to support infrastructure development while reducing environmental impacts. Conventional stabilizers such as cement and lime are effective but contribute significantly to carbon emissions and resource depletion. Consequently, recent research has focused on the utilization of industrial and natural waste materials such as river silt and pond ash as sustainable alternatives for soil stabilization and ground improvement. River silt is a naturally deposited fine-grained material accumulated through river sedimentation processes. Large quantities of river silt are generated during dredging and flood management operations, creating disposal and environmental challenges. Due to its mineralogical composition, primarily silica and alumina, river silt has attracted attention as a potential engineering material for embankments, road subgrades, and ground improvement applications. Studies indicate that untreated river silt generally exhibits poor load-bearing capacity, high compressibility, and moisture sensitivity; however, these limitations can be mitigated through blending with stabilizing agents and mechanical treatment methods.

Recent investigations have demonstrated that activated or modified river sediments can contribute to strength enhancement and microstructural densification of soil systems. Mechanical grinding, thermal activation, and chemical stabilization improve the pozzolanic activity of river silt and enhance bonding among soil particles. Moderate replacement and blending strategies have shown improvements in compressive strength, durability, and permeability characteristics while reducing dependence on natural aggregates.

Pond ash, a by-product of coal-based thermal power plants generated through slurry disposal of Pond ashand bottom ash, has emerged as another promising sustainable geomaterial. Large-scale disposal of pond ash occupies substantial land areas and creates environmental concerns. However, its low density, silt-sized particles, and compatibility with other binders make it suitable for geotechnical applications including embankment fills, subgrade stabilization, backfill material, and foundation improvement.

Vilasini P.P et al (2025) pond ash, a byproduct generated during coal combustion in thermal power plants, poses significant environmental and geotechnical challenges due to its large-scale disposal through wet methods, which occupy extensive land areas and may lead to groundwater contamination. Although pond ash has potential for use as an economical and sustainable construction material in geotechnical applications, its direct utilization is restricted because of low shear strength, poor gradation, and inadequate load-bearing capacity. This study evaluates and compares the long-term effectiveness of lime and cement stabilization for improving the engineering properties of pond ash by integrating mechanical testing, microstructural analysis, and statistical optimization techniques. Different proportions of lime and cement ranging from 2% to 10% were mixed with pond ash and cured for periods of 7, 30, and 120 days. The strength performance was assessed through Unconfined Compressive Strength (UCS) tests, which identified optimum stabilization levels of 6% cement and 8% lime, achieving maximum UCS values of 2412 kPa and 2719 kPa, respectively, after 120 days of curing. The observed strength enhancement was attributed to the formation of cementations compounds such as Calcium Silicate Hydrate (C–S–H) and Calcium Aluminate Hydrate (C–A–H), confirmed through Fourier Transform Infrared Spectroscopy (FTIR), indicating improved particle bonding and reduced pore spaces. Additionally, Response Surface Methodology (RSM) was employed to model and optimize UCS outcomes, revealing that additive content and curing duration were the most influential parameters affecting strength development. The findings demonstrate that stabilized pond ash can serve as a cost-effective and environmentally sustainable alternative material for geotechnical and infrastructure projects while encouraging large-scale utilization of industrial waste and reducing dependence on conventional natural resources.

Aamir ahsan et al (2024) the long-term performance and service life of pavement structures largely depend on the strength, stability, and load-bearing capacity of the sub-base and base layers. These layers act as the foundation of the pavement and are responsible for distributing traffic loads safely to the underlying soil. If the supporting soil is weak or unstable, the pavement may develop defects such as cracking, rutting, settlement, and premature failure. Therefore, improving the engineering properties of soil through stabilization becomes an essential step in pavement construction.

Soil stabilization is a process in which the physical and mechanical properties of soil are modified to increase its strength, reduce compressibility, control volume changes, and improve durability. Stabilization can be achieved through mechanical methods or by adding stabilizing agents such as lime, cement, fly ash, industrial by-products, or recycled construction materials. The primary objective is to make weak soils suitable for engineering applications while reducing maintenance requirements and increasing pavement lifespan. In India, black cotton soil is one of the most challenging soil types used in civil engineering projects and represents the fourth largest soil group in the country. It is predominantly found in states such as Maharashtra, Madhya Pradesh, Gujarat, Karnataka, Andhra Pradesh, and parts of Tamil Nadu. Black cotton soil contains a high percentage of expansive clay minerals, particularly montmorillonite, which causes the soil to undergo significant volume changes with variations in moisture content. The major problem associated with black cotton soil is its high swelling and shrinkage characteristics. During the rainy season, the soil absorbs water and expands, while in dry conditions, it loses moisture and shrinks. These repeated expansion–contraction cycles create cracks and uneven settlement in pavement structures. Black cotton soil also possesses relatively low bearing capacity, high plasticity, low shear strength, and poor drainage characteristics, making it unsuitable for direct use in road subgrades without treatment. To overcome these limitations, stabilization of black cotton soil becomes necessary. One sustainable and economical approach is the utilization of construction and demolition (C&D) waste as a stabilizing material. Construction and demolition waste consists of discarded materials generated from building construction, renovation, maintenance, and demolition activities. These materials commonly include crushed concrete, bricks, mortar, ceramic tiles, stone aggregates, and other mineral-based debris.

When processed and mixed with black cotton soil, construction and demolition waste improves the soil structure by filling void spaces and creating a denser and more stable matrix. The granular particles present in C&D waste increase interlocking between soil particles, which enhances compaction characteristics and reduces excessive swelling and shrinkage behavior. This modification leads to improved strength and deformation resistance of the stabilized soil.

One of the important indicators used to evaluate pavement subgrade performance is the California Bearing Ratio (CBR). The CBR value measures the load-bearing capacity of soil under standard penetration conditions. Higher CBR values indicate stronger soil with greater resistance to deformation under traffic loads. The addition of construction and demolition waste generally increases the CBR value of black cotton soil, making it more suitable for pavement applications. An increase in CBR value directly benefits pavement design because stronger subgrade soil allows engineers to reduce the thickness of pavement layers while maintaining structural performance. Reduced pavement thickness results in lower consumption of construction materials, decreased project costs, and faster construction. Furthermore, improved soil stability enhances pavement durability and reduces maintenance expenses over the service life of the road. From an environmental perspective, utilizing construction and demolition waste for soil stabilization supports sustainable engineering practices. Instead of disposing of demolition debris in landfills, these waste materials are reused as valuable construction resources. This approach minimizes environmental pollution, conserves natural aggregates, reduces waste generation, and promotes circular economy principles in infrastructure development. Therefore, stabilization of black cotton soil using construction and demolition waste provides both engineering and environmental benefits by improving soil strength, increasing CBR values, enhancing pavement performance, reducing construction costs, and encouraging sustainable management of construction waste.

Vipul Kerni et al (2022) soil stabilization is one of the most important processes in highway construction because the performance, durability, and service life of a pavement largely depend on the strength and stability of the subgrade soil. The subgrade is the natural soil layer that supports all upper pavement layers and transfers traffic loads to the ground. If the subgrade soil possesses low bearing capacity, high compressibility, or poor resistance to moisture, pavement failures such as cracking, rutting, settlement, and uneven surfaces may occur. Therefore, improving weak soils through stabilization techniques becomes essential. The study described focuses on utilizing fines obtained from demolished concrete structures as a stabilizing material for clay subgrade soil. These fines are the very small particles of crushed concrete that pass through a 1.18 mm IS sieve. Instead of disposing of demolished concrete as construction waste, the study explores its reuse as a sustainable and economical ground improvement material.
Clay soils are generally considered problematic for highway construction because they exhibit high water absorption capacity, swelling and shrinkage behavior, low shear strength, and poor drainage characteristics. These properties reduce the load-carrying capacity of the pavement foundation. Introducing concrete fines into clay soil can modify its engineering behavior and improve overall performance. The effectiveness of stabilization was evaluated using the California Bearing Ratio (CBR) test. The CBR test is one of the most widely used laboratory methods for determining the strength of subgrade soils and assessing their suitability for pavement design. It measures the resistance of soil against penetration under controlled loading conditions. Higher CBR values indicate greater soil strength and better load-bearing capacity.

Vinod Kumar Reddy et al (2022) studied soil stabilization as a method of improving soil properties so that the soil can meet construction and engineering requirements. The study focused on clay soil, which has a high swelling potential and often causes uneven settlement and damage in roads and foundations. Since the use of construction and demolition (C&D) waste in soil stabilization is still an emerging research area, the authors investigated its effectiveness in improving soil performance. Different percentages of C&D waste were mixed with soil and tested for engineering properties. The results showed that increasing the C&D waste content improved the interaction between water and soil, leading to better compaction characteristics, with optimum moisture content (OMC) and maximum dry density (MDD) reaching favorable values at 8% C&D addition. The unconfined compressive strength (UCS) and California Bearing Ratio (CBR), which indicate soil strength and load-bearing capacity, also increased, while the plastic limit showed no major variation. Additionally, the liquid limit decreased at 5% C&D content and remained nearly constant with further addition. Overall, the study concluded that incorporating C&D waste up to 8% effectively enhances the engineering properties of clay soil, but further increases beyond this optimum level reduce the improvement effect.

Sudeepta Pran Baruah et al (2020) the study focuses on evaluating the engineering properties of Brahmaputra silt collected from the Nimati Ghat area on the south bank of the Brahmaputra River in Jorhat district, Assam and improving its performance for use in civil engineering applications. The collected soil sample was initially tested to understand its natural behavior. The soil was identified as non-plastic, meaning it does not show significant plastic deformation when mixed with water. The Liquid Limit (LL) of 33.80% indicates the moisture content at which the soil changes from a plastic state to a liquid state and reflects moderate water sensitivity. The Maximum Dry Density (MDD) of 1.504 g/cc at an Optimum Moisture Content (OMC) of 20.40% shows that the soil achieves its highest compacted density when mixed with approximately 20.40% water. However, the original soil exhibited weak engineering performance, as indicated by a California Bearing Ratio (CBR) value of 3.80%, which signifies low load-bearing capacity and poor suitability for pavement subgrades. The permeability value of 1.29×10^{-4} cm/sec suggests moderate water movement through the soil, while the Unconfined Compressive Strength (UCS) of 0.082 kg/cm² indicates very low compressive resistance and poor structural stability.

To improve these properties, stabilization experiments were conducted by mixing the silt with different percentages of lime and bentonite. Lime stabilization involved adding 5% lime alone and combinations of 1.5%, 3%, 6%, and 9% lime with bentonite, whereas bentonite stabilization was tested independently at 2%, 5%, 7%, 10%, and 12% additions. After mixing, laboratory tests were repeated to evaluate changes in Atterberg limits (Liquid Limit and Plastic Limit), compaction characteristics (OMC and MDD), strength (CBR and UCS), and permeability. Lime generally improves soil through chemical reactions that reduce plasticity and increase strength by forming cementitious compounds, but in this study, the improvement was limited. Bentonite, a highly absorptive clay mineral, showed better performance because it filled soil voids, increased particle bonding, reduced permeability, and enhanced compaction and strength characteristics. As bentonite content increased, the soil demonstrated improved bearing capacity and compressive strength while reducing water flow through the soil mass.

The study concluded that bentonite stabilization alone was more effective than lime stabilization or lime–bentonite combinations for improving Brahmaputra silt. The stabilized material became stronger, denser, and more suitable for engineering use. Therefore, after proper stabilization, Brahmaputra silt can be utilized as a sustainable construction material in road subgrades, embankments, foundation fills, and other geotechnical applications, reducing dependence on conventional borrow soil and supporting environmentally beneficial reuse of river sediments.

Shivakumar Chakure et al (2020) the study investigates the stabilization of black cotton (BC) soil using fines of concrete cube waste (FCCW) and fines of brick demolition waste (FBDW) to improve its engineering performance and suitability for construction applications. Black cotton soil is known for its high swelling and shrinkage characteristics, low bearing capacity, and poor strength, which create challenges in pavement and foundation construction. The incorporation of FCCW and FBDW demonstrated significant improvements in the compaction and strength behavior of the soil. The addition of FBDW resulted in an increase in maximum dry density (MDD), indicating better soil compaction and denser particle arrangement due to the filling of void spaces and improved interlocking among soil particles. However, FCCW exhibited a more pronounced impact on strength characteristics, particularly in enhancing the California Bearing Ratio (CBR) and shear strength of BC soil. Among different replacement levels, the optimum performance was observed at 20% FCCW content, where the soil showed substantial improvement in load-bearing capacity and resistance to deformation. The higher CBR values indicate increased suitability for pavement subgrades and structural foundations, while enhanced shear strength contributes to greater stability and durability under loading conditions. Overall, the findings suggest that both FCCW and FBDW can serve as sustainable and cost-effective stabilizing materials by utilizing construction and demolition waste, reducing environmental impact while improving the geotechnical properties of expansive black cotton soil for engineering applications.

S.P.Kanniyappan et al (2019) the long-term performance and service life of pavement structures are highly dependent on the stability and load-bearing capacity of the underlying soil layers, particularly the sub-base and base layers. These layers transfer traffic loads from the pavement surface to the natural ground (subgrade). If the soil possesses poor strength, excessive compressibility, or volume instability, the pavement may develop defects such as rutting, settlement, cracking, and premature failure. Therefore, soil stabilization is commonly adopted to improve the engineering behavior of weak soils and enhance pavement durability.

Red soil is one of the major soil groups found in India and is widely distributed in states such as Tamil Nadu, Karnataka, Andhra Pradesh, Odisha, and parts of northeastern India. It is generally formed through weathering of crystalline rocks and is characterized by a porous structure, relatively low cohesion, and moderate bearing capacity. Depending on its mineral composition and moisture conditions, red soil may exhibit lower strength and increased deformation under loading. These characteristics make untreated red soil less suitable for direct use as pavement subgrade material in road construction. Soil stabilization refers to the process of modifying soil properties to achieve improved strength, stiffness, durability, and resistance to moisture variation. Conventionally, stabilizing agents such as lime, fly ash, cement, and ground granulated blast furnace slag

(GGBS) are used to improve weak soils. These additives react physically and chemically with soil particles, resulting in enhanced compaction characteristics and increased bearing capacity. However, due to increasing environmental concerns and the need for sustainable construction practices, researchers are focusing on alternative waste materials for soil improvement. Construction and Demolition (C&D) waste has emerged as a promising sustainable stabilizing material. C&D waste includes crushed concrete, bricks, mortar, tiles, aggregates, and other debris generated during construction, renovation, and demolition activities. Large quantities of such waste are generated annually, and improper disposal creates environmental challenges. Reusing C&D waste in geotechnical applications reduces landfill burden and conserves natural resources. In this project, C&D waste is utilized to stabilize red soil by mixing it in different proportions. Initially, the engineering properties of untreated red soil are determined through laboratory tests such as grain size analysis, Atterberg limits, specific gravity, Standard Proctor compaction test, and California Bearing Ratio (CBR) test. Subsequently, C&D waste is added to the soil at varying percentages (for example, 5%, 10%, 15%, 20%, and 25% by weight), and the modified soil mixtures are tested again. One of the most important parameters evaluated in this study is the California Bearing Ratio (CBR), which measures the load-carrying capacity of soil and is extensively used in pavement design. A higher CBR value indicates improved resistance to penetration and greater bearing strength. When C&D waste particles are mixed with red soil, they improve particle interlocking, reduce compressibility, and increase density, resulting in higher CBR values. The increase in CBR value directly influences pavement thickness design. According to pavement design principles, stronger subgrade soil requires a thinner pavement layer to carry the same traffic load. Thus, if stabilization significantly improves the CBR value of red soil, the required thickness of sub-base, base, and overall pavement structure can be reduced. This reduction lowers construction costs and material consumption while maintaining pavement performance. Therefore, this project investigates the effectiveness of C&D waste in enhancing the engineering properties of red soil and evaluates its impact on pavement thickness reduction. The study supports sustainable waste management practices and provides an economical alternative for road construction by converting construction debris into a useful ground improvement material.

Dr. Ramakrishna Hegde et al (2018) in this studied work, we have collected the demolition waste from our college work site where the column in the top floor of our college building was demolished for the purpose of renovation. The demolished column is of M20 grade concrete and the age of concrete is 10 years. Construction of any concrete structures requires huge amount of natural coarse aggregate. So by using the demolition waste, we can reduce the cost o purchasing natural coarse aggregate. Our project deals with replacing of coarse aggregate by demolished column waste in various proportions of 10, 20,30,40,50 and 100. Cubes, cylinder, beams were casted for different mix proportions and kept curing for 7, 14and28 days. After the curing the cubes, cylinder and beams were tested to find the compressive strength, split tensile strength and flexural strength of concrete. The results were discussed and conclusions were made accordingly.

Alessandra Mobili et al (june 2018) in this study, natural calcareous aggregates used in mortar production were partially replaced with recycled aggregate fines at a proportion of 12.5% by volume to evaluate the feasibility of sustainable construction practices and reduce dependence on natural resources. The produced mortars were assessed through mechanical, microstructural, and durability tests to determine their engineering performance. The results demonstrated that complete replacement of natural calcareous aggregates with recycled aggregates is technically feasible without significantly compromising overall functionality. Although the recycled aggregate mortars exhibited higher porosity and greater water absorption through capillary action due to the presence of attached old mortar and a more irregular internal structure, these characteristics also provided certain advantages. The increased porosity reduced the stiffness of the mortar, allowing it to accommodate deformation more effectively and decreasing the likelihood of crack formation under stress. Additionally, the mortars showed improved water vapor permeability, enabling better moisture movement and reducing the accumulation of internal pressure that can damage structures over time. Another significant observation was the enhanced resistance to sulphate attack, which is a common durability issue in cement-based materials exposed to sulphate-rich environments. The recycled aggregate mortars were less susceptible to chemical deterioration, suggesting improved long-term durability under such conditions. Overall, the findings indicate that recycled aggregates can serve as an environmentally sustainable alternative to natural aggregates while maintaining acceptable mechanical and durability performance for construction applications.

Vivek S et al (2018) focused on improving the properties of expansive Black Cotton (BC) soil using Construction and Demolition (C&D) waste, which includes concrete and plastering debris. The primary goal was to investigate the effectiveness of C&D waste in stabilizing expansive BC soil and determine the optimal mixture for enhancing soil properties. Known for its expansive nature, which causes significant issues in construction due to its swelling and shrinking behavior. Comprising concrete and plastering debris, used as an additive to the BC soil. Various mixtures were prepared with BC soil plus 10%, 12%, and 14% C&D waste to evaluate the changes in soil properties. Calculated using Terzaghi's equation for different mixtures. This equation helps in determining the bearing capacity of shallow foundations based on soil shear strength parameters. Utilized to determine the cohesion (c) and angle of internal friction (φ) of the soil mixtures. These parameters are crucial for understanding the shear strength of soils, which directly impacts the SBC. The Direct Shear test results showed that the addition of C&D waste improved the cohesion and internal friction angle of the BC soil, contributing to enhanced stability. The research concluded that using C&D waste is an effective method for stabilizing expansive BC soil. The addition of 10% C&D waste to BC soil optimally improved its bearing capacity and shear strength, making it a viable and sustainable solution for construction projects involving problematic soils.This study highlights the potential of recycling construction and demolition materials, not only reducing waste but also providing a cost-effective method to improve soil properties for engineering applications.

Methodology

This review paper was prepared through a systematic collection, evaluation, and synthesis of published literature related to the use of river silt and pond ash for sustainable ground improvement applications. Relevant research articles, review papers, conference proceedings, technical reports, theses, and journal publications were collected from recognized academic databases and scientific sources. The literature selection focused on studies investigating the geotechnical performance of soils stabilized with river silt, pond ash, or their combined utilization. The selected studies were screened based on relevance, publication quality, availability of experimental data, and contribution to sustainable geotechnical engineering.
The collected literature was analyzed to identify the physical, chemical, and engineering characteristics of river silt and pond ash and their influence on soil improvement. Key performance parameters reviewed included compaction behavior, unconfined compressive strength, shear strength, California Bearing Ratio (CBR), permeability, consolidation characteristics, settlement response, and durability performance. Comparative evaluation was carried out to examine the effect of different replacement ratios, curing periods, and stabilization approaches adopted by previous researchers. Environmental and economic aspects associated with the reuse of these waste materials were also assessed to determine their sustainability potential. Based on the synthesized findings, overall trends, advantages, limitations, and future research opportunities for implementing river silt and pond ash in ground improvement applications were identified and discussed.

Conclusion

Ground improvement using alternative and sustainable materials has gained considerable attention in geotechnical engineering due to increasing environmental concerns and the need to reduce dependence on conventional stabilizers. This review examined the application of river silt and pond ash as sustainable materials for improving weak soil performance. Based on the reviewed studies, both materials demonstrate significant potential to enhance geotechnical properties such as compaction characteristics, unconfined

compressive strength, shear strength, California Bearing Ratio (CBR), and settlement behavior while improving the overall stability of soil systems.
The findings indicate that river silt contributes to improved particle arrangement and densification, whereas pond ash enhances soil structure through better gradation and pozzolanic interaction under suitable conditions. The combined utilization of these waste materials not only improves engineering performance but also offers an effective solution for waste management and environmental conservation. Their application can reduce the consumption of traditional stabilizing agents such as cement and lime, thereby lowering carbon emissions and promoting sustainable construction practices. The performance of stabilized soils depends on factors such as material composition, replacement ratio, curing duration, moisture content, and site conditions. Although laboratory investigations have shown encouraging results, additional long-term field studies and standardized design guidelines are required to support large-scale implementation. Overall, river silt and pond ash present a viable and environmentally responsible approach for sustainable ground improvement and can contribute significantly toward future green geotechnical infrastructure development.

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