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Stabilization of Black Cotton Soil Using Industrial Waste: A Review

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Abstract- Black cotton soil is challenging for construction due to its high shrink-swell behavior and low load-bearing capacity, making stabilization essential for durable infrastructure. Traditional methods like cement and lime stabilization, though effective, are costly and environmentally taxing. As a sustainable alternative, industrial waste has gained attention for soil stabilization due to its low cost and environmental benefits. This study examines using industrial waste, such as fly ash, blast furnace slag, rice husk ash, and glass waste, with a specific focus on stone powder waste like granite dust, marble dust, and kota stone dust. These by-products from the construction and stone processing industries possess favorable chemical and physical properties for soil improvement. The paper critically evaluates existing research on stone powder waste for stabilizing black cotton soil, highlighting its impact on reducing soil plasticity, improving compressive strength, and mitigating swell-shrink properties. Comparative analyses and case studies show the effectiveness of stone powder waste relative to other industrial by-products. The findings conclude that stone powder waste, particularly granite, marble, and kota stone dust, significantly enhances soil stability, promoting sustainable construction practices. However, the study calls for further research to optimize the use of these materials and address long-term performance considerations.

Key Words: Black cotton soil, Construction, Stabilization, Stone powder waste

1. Introduction

A key component of geotechnical engineering is soil stabilization, especially in areas with a preponderance of expansive soils like black cotton soil. Because of its expansive character, black cotton soil is categorized as a very problematic soil, making it difficult to build roads, foundations, and other infrastructure. Shrink-swell behaviour is caused by the soil's high clay content and propensity to experience significant volumetric changes during wetting and drying cycles. As a result, structures become unstable, which eventually results in uneven settlements, cracks, and structural failure. Therefore, it is essential to stabilize black cotton soil effectively in order to enhance its geotechnical qualities and guarantee the durability of construction.

1.1 Overview of Black Cotton Soil

Vertisol, another name for black cotton soil, is a common soil type in tropical and subtropical areas, especially in Australia, India, and some portions of Africa. The dark hue of the soil, which is ascribed to the occurrence of minerals high in iron and magnesium, gives it its name. Its expansive aspect, which is mostly caused by its high montmorillonite clay concentration, is what makes it unique. When moisture levels change, the smectite clay mineral montmorillonite, which has a high affinity for water, undergoes notable volume variations. Black cotton soil swells when it absorbs water during the rainy season and contracts when the moisture evaporates during the dry season. When structures and pavements are constructed on such soil, the cyclical swelling and contraction causes instability [1].

Black cotton soil's harmful behavior extends beyond its expanding qualities. It is also unsuited for carrying big loads without modification due to its low shear strength and bearing capacity. Its poor drainage qualities and excessive flexibility also make building more difficult [2]. Because of these variables, black cotton soil must be stabilized in order to increase its load-bearing capacity, decrease swelling, and improve overall performance.

1.2 Industrial Waste as a Stabilizer

Sustainable building techniques have gained popularity in recent years, with a particular focus on lessening the negative environmental effects of conventional soil stabilizing techniques. Despite their effectiveness, traditional stabilizers like cement and lime have a large carbon footprint and substantial environmental costs [3]. As a result, alternative stabilizers that are not only efficient but also economical and ecologically benign are becoming more and more popular. Using industrial waste products to stabilize soil is one such option.

Large amounts of industrial waste are produced as a by-product of several manufacturing operations. In addition to contributing to environmental contamination, disposing of this garbage in landfills results in the loss of potentially valuable resources. Reusing industrial waste for soil stabilization has two benefits: it improves soil qualities at a reasonable cost while lessening the environmental impact of waste disposal. Numerous industrial wastes have been investigated for their potential as stabilizers in geotechnical applications, including fly ash, blast furnace slag, rice husk ash, foundry sand, glass waste, ceramic waste, and tile waste [4].

One of the most popular industrial wastes for stabilizing soil is fly ash, which is a by-product of burning coal in thermal power plants. Because of its pozzolanic qualities, it combines with calcium hydroxide to create cementitious compounds that increase soil stability and strength. Fly ash has been shown in recent years to be effective in stabilizing expansive soils, especially black cotton soil, by increasing their bearing capacity and lowering their swelling properties [5]. The durability and load-bearing capability of soils have also been found to be improved by blast furnace slag, a by-product of the manufacturing of iron and steel. In addition to enhancing soil qualities, these substances provide a sustainable substitute for conventional stabilizers like cement and lime [6].

Rice husk ash, which is produced when rice husks are burned in agricultural waste, is a good stabilizer for increasing the compressive strength of expanding soils because it is high in silica. According to research, adding rice husk ash to black cotton soil greatly enhances its geotechnical qualities by making it stronger and more rigid [7]. Black cotton soil's flexibility and swell potential have also been effectively decreased by using foundry sand, a by-product of the casting industry. Both minerals are inexpensive choices for stabilizing soil because they are easily accessible in large amounts, especially in agricultural and industrial areas [8].

Black cotton soil stability may benefit greatly from the use of stone powder waste, such as granite dust, marble dust, and kota stone dust, among other industrial wastes. These materials are by-products of the construction and stone processing industries, which produce large quantities of fine powder trash. For instance, marble dust has a high calcium carbonate content, but granite dust is rich in feldspar and silica. Because of these mineral compositions, stone powders are quite successful at enhancing the geotechnical characteristics of soils, especially when it comes to decreasing swelling and plasticity [9].

Granite dust is a useful substance for stabilizing expansive soils because it has been demonstrated to improve the load-bearing capacity and decrease the shrink-swell potential of black cotton soil [10]. However, because marble dust contains a lot of calcium, it improves the workability and compressive strength of soils. Similar advantages have been discovered for kota stone dust, a regional waste product from the Indian subcontinent that stabilizes soil sustainably while lessening the environmental impact of disposing of stone debris [11].

An economical and sustainable substitute for conventional techniques is the stabilization of black cotton soil using industrial waste. Given its chemical makeup and physical characteristics, stone powder waste in particular, granite, marble, and kota stone dust stands out among them as a potentially useful commodity. Reviewing these stone powder waste's potential for stabilizing black cotton soil, contrasting their effectiveness with that of other industrial wastes, and emphasizing their advantages for the environment and the economy are the objectives of this paper.

1.3 Characteristics and Challenges of Black Cotton Soil

Due to its troublesome behaviour, black cotton soil is a major worry in many areas, especially in tropical and subtropical zones. If the soil is not stabilized, its expansive nature causes significant structural damage. This section covers the basic characteristics of black cotton soil, including its tendency to swell and contract, its effects on infrastructure, and the urgent need for stabilization to avoid damaging roads, buildings, and other structures.

1.3.1 Properties of Black Cotton Soil

Typically found in Australia, Africa, and India, black cotton soil is primarily clayey and rich in montmorillonite, a form of smectite clay. The expansive aspect of the soil is caused by its high clay concentration, especially that of montmorillonite. The soil's high plasticity index indicates that it is malleable and susceptible to volume changes over a wide range of moisture content. Its strong cation exchange capacity, poor drainage qualities, and dark hue from iron and magnesium minerals are some of its key characteristics. The main cause of this soil's strong shrink-swell potential is its montmorillonite component, which fluctuates significantly in volume in response to changes in moisture.

1. Plasticity and Permeability: Due to its great flexibility, black cotton soil frequently becomes difficult to work in damp conditions. It is one of the most troublesome soils for building projects because of its plasticity index, which normally runs between 30% and 70%. Because of its relatively low permeability, the soil retains water and drains slowly, which makes the swelling behaviour during wet seasons worse [12].
2. Shear Strength and Bearing Capacity: In its natural form, black cotton soil has a poor shear strength because of its high clay content and susceptibility to moisture. The bearing capacity, which is an essential component of foundations, is also insufficient, which presents a major building challenge. The soil is not appropriate for massive constructions without stabilization because its bearing capacity is typically between 100 and 150 kN/m^2 [13].
3. Swelling and Shrinkage Behaviour of Black Cotton Soil: The extreme reactivity of black cotton soil to variations in moisture is one of its most troublesome features. The soil expands when it collects water during the wet season and contracts when the liquid evaporates during the dry season. Structures constructed on such soils have severe instability as a result of this periodic swelling and shrinkage. Depending on the composition, moisture content, and external loadings of the soil, the swelling pressure might vary from 100 kPa to 500 kPa.
4. Swelling Mechanism: Montmorillonite, which has the capacity to absorb water between its layers, is the main cause of the expansive behaviour of black cotton soil. The soil expands when it becomes wet because the clay in the montmorillonite absorbs water. Due to the increased volume of dirt, the ground becomes disturbed and pressure is placed on walls, foundations, and other structures. In severe circumstances, the swelling potential of black cotton soil might go to 200% [14].

5. Shrinkage Mechanism: Black cotton soil shrinks and loses moisture during dry spells. Cracks, which can be a few millimeters to several centimeters broad, are the result of this. Structure settling can result from these cracks, which can reach considerable depths typically 1 to 2 meters. The foundation may lose stability due to soil shrinking, which could lead to differential settlement and ultimately superstructure damage [15]. Cracks in walls, foundations, and roadways are the result of differential movement brought on by alternating swelling and shrinking. These fissures have the potential to spread over time and seriously harm the structure.

1.3.2 Impact on Infrastructure and the Need for Stabilization

Infrastructure is significantly impacted by the behavior of black cotton soil, hence stabilization is required to lessen these problems. The cyclical shrink-swell tendency causes serious issues for pavements, roads, and buildings built on untreated black cotton soil.

Damage to Buildings and Foundations: Building foundations experience upward and downward forces due to the alternating expansion and contraction of black cotton soil, which results in uneven settlement. These vibrations frequently cause foundations constructed on untreated black cotton soil to tilt, crack, or even collapse. Research has indicated that in areas with expansive soils, insufficient stabilization of black cotton soil is directly responsible for over 20% of construction collapses [16]. For example, many rural and urban buildings in India, where black cotton soil is common, have severe wall and foundation cracking, especially in places with inadequate drainage systems [17].

Road and Pavement Distress: Black cotton soil presents additional difficulties for road building because of its cyclic swelling and shrinking, which can cause potholes, rutting, and pavement cracking. This shortens the roads lifespan in addition to raising maintenance expenses. According to studies, roads constructed on black cotton soil without adequate stabilization frequently show failure symptoms a few years after they are completed [18]. While shrinking during the dry season leads to cracks that erode the road surface, swelling during the monsoon season creates pavement instability.

1.3.3 The Need for Stabilization

Soil stabilizing procedures are essential to preventing such harm. Black cotton soil's physical and chemical characteristics are altered during stabilization in order to increase its strength, decrease its flexibility, and regulate its behaviour of swelling and shrinking. For this, a variety of techniques have been used, such as the use of industrial waste materials, mechanical stabilization, and chemical stabilization.

Chemical Stabilization: The most widely utilized stabilizers for black cotton soil historically have been cement and lime. Calcium silicate hydrates (CSH), which are created when lime combines with the clay minerals in the soil, increase the soil's strength and decrease its flexibility. Similarly, by forming a cementitious matrix inside the soil, cement stabilization raises the soil's bearing capacity. However, because of the carbon emissions involved in the manufacturing of cement and lime, these techniques are linked to high costs and environmental issues [19].

Industrial Waste Stabilizers: Utilizing industrial waste products like fly ash, blast furnace slag, and stone powder has become more popular recently as an environmentally responsible substitute for conventional stabilizers. In addition to enhancing the geotechnical characteristics of black cotton soil, industrial waste materials provide a long-term answer to waste management issues. For instance, it has been demonstrated that fly ash, a by-product of burning coal, greatly lowers the possibility for black cotton soil to swell while increasing its strength and longevity [20].

In order to improve black cotton soil's technical qualities and make it appropriate for building, stabilization is necessary. The shrink-swell tendency of the soil will continue to harm infrastructure in the absence of proper stabilization, resulting in higher maintenance expenses and shorter building, road, and other construction lifespans.

Black cotton soil's expansive character, low bearing capacity, and cyclic swelling and shrinkage behavior make it extremely difficult to work with. Effective stabilization solutions are necessary because of the extensive damage that these characteristics inflict to infrastructure. Notwithstanding their effectiveness, traditional chemical stabilizers like cement and lime have financial and environmental disadvantages. One viable way to overcome the issues with black cotton soil is through the increasing interest in stabilizing soil with industrial waste materials. Stabilization improves the soil's geotechnical qualities, which helps with sustainable building methods and increases the longevity of infrastructure.

2. Overview of Soil Stabilization Techniques

A basic method used in civil engineering to enhance the mechanical and physical characteristics of weak soils, especially expansive soils like black cotton soil, is soil stabilization. If left untreated, the swelling and shrinking characteristics of black cotton soil cause significant structural damage, hence stabilization is crucial to the long-term viability of infrastructure. To lessen the expansive character of black cotton soil, a variety of techniques have been used, from the use of industrial waste to conventional stabilizers. Furthermore, new and creative methods are becoming more popular due to their financial and environmental advantages. An overview of conventional soil stabilization techniques, industrial waste stabilization, and cutting-edge new techniques for stabilizing black cotton soil are given in this section.

2.1 Traditional Stabilization Methods

The qualities of expansive soils have long been altered using conventional soil stabilization techniques. These techniques usually entail the use of chemical additives that interact with soil particles to limit swelling, decrease flexibility, and increase strength.

1. Lime Stabilization: One of the most popular substances for stabilizing expansive soils, such as black cotton soil, is lime. Lime strengthens and decreases the flexibility of soil by reacting with clay minerals, especially montmorillonite, to produce cementitious compounds such calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH). Additionally, lime raises the soil's pH, which encourages pozzolanic reactions that improve stabilization even more. Because lime stabilization greatly lowers BCS's swelling potential, it can be used for road construction and foundations [21]. However, the energy-intensive nature of lime production results in carbon emissions.

2. Cement Stabilization: Another conventional stabilizer that is used to improve the geotechnical characteristics of poor soils is cement. By binding soil particles together, cement creates a cementitious matrix that increases the soil's compressive, shear, and load-bearing capacities. Black cotton soil's swell-shrink tendency can be significantly reduced by cement stabilization, which increases the soil's stability across a range of moisture conditions [22]. However, the manufacture of cement is linked to significant energy consumption and environmental issues, much as the production of lime.
3. Bitumen Stabilization: Using bituminous materials to lessen the permeability and flexibility of expansive soils is known as bitumen stabilization. By reducing the soil's capacity to absorb water, bitumen produces a waterproof coating that helps minimize swelling. When building roads, this technique is frequently employed, especially when building pavements over black cotton soil. Additionally, bitumen increases the stabilized layer's elasticity, which lessens cracking during dry seasons [23]. Despite its effectiveness, bitumen stabilization is not frequently utilized because of its high cost and the availability of less expensive alternatives.

2.2 Use of Industrial Waste in Stabilization

Because of its benefits for the environment and the economy, using industrial waste to stabilize soil has become more popular in recent years. By keeping significant amounts of trash out of landfills, industrial waste products not only enhance the geotechnical characteristics of soils but also offer a sustainable waste management option.

1. Fly Ash: Fly ash is one of the most extensively researched industrial wastes for soil stabilization. It is a by-product of burning coal in thermal power plants. Because of its pozzolanic qualities, it works well as an additive to increase the stability and strength of expanding soils. Cementitious compounds are created when fly ash and calcium hydroxide in the soil combine, decreasing the soil's capacity to swell and become malleable. Fly ash is a cost-effective substitute for conventional stabilizers like cement and lime because it dramatically increases the load-bearing capacity of black cotton soil, according to numerous studies [24].
2. Blast Furnace Slag: Another potential stabilizer for black cotton soil is ground granulated blast furnace slag (GGBS), a by-product of the iron and steel sector. GGBS improves the strength and durability of the soil when combined with cement or lime. By encouraging cementitious processes, it also aids in lowering the shrink-swell behavior of black cotton soil. Because blast furnace slag can improve soil qualities while lowering the environmental effects of waste disposal, its use in soil stabilization is becoming more and more popular [25].
3. Rice Husk Ash and Foundry Sand: Burning rice husks yields rice husk ash, which is silica-rich and possesses pozzolanic qualities akin to fly ash. It is an appropriate stabilizer since it increases the compressive strength and decreases the plasticity of black cotton soil. Another industrial waste product that has been utilized in soil stabilization is foundry sand, which is a by-product of the metal casting industry. Foundry sand increases the load-bearing capacity of expansive soils and lowers their shrink-swell potential [26].
4. Stone Powder Waste: One promising industrial waste material for soil stabilization is stone powder waste, such as granite dust, marble dust, and kota stone dust. These materials, which are abundant in minerals including feldspar, calcium carbonate, and silica, are by-products of the stone processing industry. It has been demonstrated that granite and marble dust, in particular, enhance the strength, flexibility, and swelling behavior of black cotton soil, making them a sustainable substitute for conventional stabilizers [27].

A crucial step in enhancing the qualities of weak soils, especially expansive soils like black cotton soil, is soil stabilization. Although they have been utilized extensively, traditional stabilizing techniques like cement and lime are linked to environmental issues. An economical and environmentally friendly substitute for soil stabilization is the use of industrial waste products including fly ash, blast furnace slag, and stone powder waste. By lessening the environmental impact of soil stabilization, these techniques not only enhance the qualities of the soil but also support sustainable building methods.

2.3 Mechanisms of Soil Stabilization Using Industrial Waste

The use of industrial waste materials for soil stabilization has drawn a lot of interest lately since it can both improve the engineering qualities of troublesome soils and encourage environmentally friendly building methods. The methods by which different industrial wastes, especially stone powder waste, stabilize black cotton soil (BCS) and improve its performance for building applications are examined in this section.

Several processes, such as pozzolanic activity, particle size modification, and chemical reactions that improve the soil's strength and durability, are involved in stabilizing soil using industrial waste. These processes are facilitated by many forms of industrial waste, each of which has a positive impact on the characteristics of the soil.

1. Pozzolanic Activity: Pozzolanic activity is a key process via which industrial waste stabilizes soil. Cementitious compounds are created when silica and alumina from pozzolanic materials, including fly ash and blast furnace slag, combine with calcium hydroxide when water is present. By decreasing the soil's fluidity and swelling potential, this response improves the soil's binding properties.
2. Particle Size Modification: Adding industrial waste materials to soil can change its physical properties and enhance the distribution of particle sizes overall. A denser and more cohesive combination can be produced, for instance, by adding finely ground waste materials to fill in the spaces between bigger soil particles. This is especially important when thinking about waste from stone powder.
3. Chemical Reactions: Many chemical components found in industrial waste materials have the ability to react with soil particles and change their behavior. This chemical reaction can decrease unwanted characteristics like swelling and increase soil firmness.
4. Chemical Composition of Stone Powder Waste: Depending on where the stone came from, stone powder waste might have a different chemical makeup, but it usually contains silica, calcium, and magnesium. Improved binding and stabilization may result from these

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substances interactions with the clay minerals in black cotton soil. In particular, a high silica content can help the soil matrix develop silicate connections, which will improve the soil's structural integrity [28].

5. Hydraulic Activity: Certain industrial wastes have hydraulic qualities that can help stabilize the soil even more. For example, combining lime with stone powder can result in a mixture that has hydraulic qualities, which enable it to solidify and become stronger when water is present. This gives the soil an extra layer of stability, which is especially advantageous in areas with high moisture content [29].
6. Long-Term Performance Enhancement: Another crucial component of soil stabilization is the long-term performance of soil treated with industrial waste. The soil matrix's bonding strength strengthens as the pozzolanic reactions proceed, improving the soil's resilience to environmental influences and durability.
7. Durability Against Erosion and Weathering: Stone powder and other industrial waste can stabilize soil, making it more resistant to weathering and erosion. Infrastructure constructed on treated soils lasts longer because of the improved bonding and decreased porosity, which shield the soil from the damaging impacts of moisture and temperature changes [30].

Specific Focus on Stone Powder Waste: Because of its special physical and chemical characteristics, waste stone powder is an especially suitable industrial by-product for stabilizing black cotton soil. Because of its small particle size, it may efficiently fill in the gaps in the soil matrix, increasing density and decreasing plasticity. Additionally, the chemical makeup of stone powder influences the soil's binding qualities.

Research Findings: Stone powder waste has been shown in recent research to be an efficient way to improve the geotechnical characteristics of black cotton soil. For example, adding 10% stone powder has been demonstrated to lower the plasticity index of BCS while increasing its unconfined compressive strength by more than 25% [31].

Sustainability Benefits: By lowering trash production, using leftover stone powder not only solves issues with soil stabilization but also encourages environmentally friendly building methods. An inventive way to manage trash and improve the performance of troublesome soils is demonstrated by the incorporation of an industrial by-product into soil stabilization techniques.

The engineering qualities of black cotton soil can be effectively improved by employing the processes of soil stabilization using industrial waste materials, such as pozzolanic activity, particle size modification, and chemical reactions. In particular, using leftover stone powder offers a sustainable way to improve soil performance, lower the possibility of swelling and shrinking, and guarantee long-term durability. The use of industrial waste in soil stabilization initiatives will be essential in tackling the problems caused by expanding soils as the demand for environmentally friendly building techniques keeps rising.

3. Review of Previous Studies

In recent years, geotechnical engineering research has focused a lot of attention on stabilizing black cotton soil (BCS) with industrial waste. This study of the literature summarizes earlier research, looks at the many kinds of waste used for soil stabilization, finds gaps in the body of knowledge, and emphasizes case examples, with a special emphasis on the use of waste stone powder.

Numerous industrial wastes have been found through soil stabilization research to efficiently improve the mechanical qualities of troublesome soils like BCS. The majority of early research was on conventional stabilizing techniques, such cement and lime, which significantly enhanced soil performance. However, because sustainability and waste reduction are becoming more and more important, industrial waste products have been included in more recent studies.

3.1 Lime Stabilization

Lime stabilization significantly improves the engineering properties of Black Cotton Soil (BCS), reducing swell-shrink behavior and enhancing workability. It reduces plasticity index, decreasing deformation susceptibility and enhancing structural integrity. The optimal lime content is 3% lime and 20% volcanic ash, which enhances California Bearing Ratio (CBR) values and reduces swell potential. Lime's combination with pozzolans often results in superior performance, making it a viable option for road construction and civil engineering applications [32].

3.2 Cement Stabilization

Cement improves soil stabilization by binding soil particles, increasing strength and durability in granular and low plasticity clay soils. The quantity of cement and curing time significantly impact soil stability. The optimal cement addition ratio is 1% to 5%, determined through laboratory tests. However, the environmental impact of cement production prompts research on alternative materials with lower ecological footprints [33].

3.3 Industrial Waste Stabilization

3.3.1 Fly Ash

Fly ash, a by-product of coal combustion, has been widely investigated for soil stabilization. Research by Priya et al. (2021) demonstrated that the addition of fly ash reduced the plasticity index and swelling potential of black cotton soil [1]. The pozzolanic reactions between fly ash and lime were found to significantly enhance soil cohesion and stability. Additionally, fly ash has been shown to improve the workability of soils, making it a favorable option for construction applications.

India's expansive black cotton soil, covering 51.8 million hectares, presents significant construction challenges due to its contrasting properties: hard when dry but weak when wet. These soil characteristics hinder stability, making stabilization essential for safe foundation and pavement construction. Soil stabilization techniques either involve replacing problematic soil with a better material or adding an additive to enhance soil properties like strength, volume stability, and durability. In this study, fly ash from Balapur was tested as an additive for stabilizing black cotton soil. Added in varying proportions (5%, 10%, 15%, and 20%), fly ash effectively reduced the soil's plasticity index (PI) and swelling, thanks to its non-plastic nature. The inclusion of fly ash changes the soil's grain size and colloidal properties, enhancing workability and strength. Testing revealed that as fly ash content increased, the free swell ratio and PI decreased, confirming its effectiveness in controlling soil expansion. This stabilization method, reducing soil plasticity and increasing structural integrity, highlights fly ash's potential in geotechnical applications. The results demonstrate that fly ash is a viable, sustainable option for improving black cotton soil's engineering properties, suggesting broader applications in construction [34].

3.3.2 Blast Furnace Slag

Blast furnace slag is another widely studied industrial waste material. Mujtaba et al. (2018) reported that incorporating blast furnace slag into BCS resulted in substantial improvements in compressive strength and reduced plasticity [35]. The hydraulic properties of slag contribute to the formation of cementitious compounds, which enhance the soil's binding characteristics.

3.3.3 Stone Powder Waste

The recent focus on stone powder waste, particularly granite dust and marble dust, highlights its potential as a sustainable soil stabilizer. Several studies have indicated that stone powder waste can effectively improve the engineering properties of black cotton soil. For example, a study by Reehana et al. (2018) found that India's vast black cotton soils, covering around 8 million square kilometers, pose challenges for construction due to their shrink-swell behavior caused by the Montmorillonite mineral. These expansive soils damage foundations, buildings, and roads when untreated. This study investigates using granite dust to improve the soil's compaction, strength, and bearing capacity, assessing how these properties vary with different water content levels. Black cotton soil samples, mixed with 0–20% granite dust, underwent tests like liquid and plastic limits, permeability, California bearing ratio (CBR), and unconfined compression tests. Findings show that granite dust addition increases stability: the liquid limit varied between 76–102% and the plastic limit between 36–53% with 30% granite dust, while the plasticity index rose. Granite dust enhances dry density and reduces optimal moisture content, boosting CBR from 2.9% to 9.71% at 25% granite dust. These results indicate that granite dust effectively stabilizes black cotton soils, making it promising for road sub-grade applications and construction, as it notably improves soil strength and suitability for load-bearing purposes. The study highlights granite dust as a practical solution for treating expansive soils, suggesting its broader use in infrastructure projects across areas with black cotton soils [36]. The fine particle size of stone powder fills voids in the soil matrix, enhancing density and stability. This indicates that stone powder waste is not only effective in stabilizing BCS but also contributes to sustainable waste management practices by repurposing by-products from stone processing industries.

Black cotton soil, an expansive soil prone to failure due to water-induced swelling, can be stabilized using admixtures. This study explores enhancing black cotton soil's engineering properties by combining 20% marble stone slurry with varying percentages of wooden sawdust (SDA). Tests such as Atterberg limits, standard Proctor, and unconfined compressive strength were conducted on soil specimens with these admixtures. The addition of marble slurry shifts black cotton soil from an Intermediate Compressibility (CI) to Low Compressibility (CL) state, improving stability. The highest maximum dry density (MDD) achieved was 1.84 g/cm³, with 5% SDA and 20% marble slurry at 9% optimal moisture, yielding an 8.37% increase in MDD over the reference mix. In terms of strength, a maximum shear strength of 169 kPa was recorded using 15% SDA and 20% marble slurry—an increase of 106.9%, 64%, and 34.12% over combinations of 0%, 5%, and 10% SDA with 20% marble slurry, respectively. These findings demonstrate that blending marble slurry and sawdust with black cotton soil effectively enhances its compressibility, density, and shear strength, making it more suitable for construction applications [37].

The soil layer beneath road pavements plays a crucial role in supporting vehicle loads, and its stability directly impacts pavement durability. Clay-rich soils, such as black cotton soil (BCS), often exhibit poor performance and require stabilization for road construction. This study focuses on improving BCS by adding marble dust (MD) and silica fume. Tests conducted include soil characterization, density and moisture content analysis (Proctor test), unconfined compressive strength (UCS), and California bearing ratio (CBR) tests. Results show that BCS gains significant strength after stabilizing with marble dust and silica fume. Specific gravity of BCS increased with marble dust but decreased with silica fume. Liquid limit (LL) dropped from 67% to 54% with marble dust, to 55% with silica fume, and to 55% when both were combined. The plastic limit (PL) decreased from 37% to 28% with marble dust, to 29% with silica fume, and to 30% with the blend. The plasticity index also improved, reducing from 30% to 26% with either marble dust or silica fume, and to 25% with the blend. These findings confirm that using marble dust and silica fume enhances BCS properties, making it more suitable for road pavement applications [38].

Recent research has introduced innovative materials such as biopolymers and nano-materials for soil stabilization. Biopolymers, derived from natural sources, exhibit promising results in enhancing soil cohesion and strength. Meanwhile, the application of nano-materials, such as nano-silica, has shown potential for improving the mechanical properties of black cotton soil, enhancing its resistance to swelling and shrinkage.

3.4 Gaps in Literature

Despite the progress made in soil stabilization using industrial waste, several gaps remain in the existing literature:

1. Long-Term Performance Studies: Many studies focus on short-term effects, with limited research on the long-term durability and performance of stabilized soils. Understanding the behavior of stabilized soil over extended periods is crucial for practical applications.
2. Optimal Dosage Determination: While various studies have examined the effects of different types of industrial waste, there is still a lack of consensus on the optimal dosage for effective stabilization. More research is needed to determine the ideal proportions of industrial waste that yield maximum benefits.
3. Field Studies: Much of the existing research is based on laboratory experiments. There is a need for more field studies to validate laboratory findings and assess the effectiveness of industrial waste stabilization in real-world conditions.
4. Comparative Studies: Limited comparative studies exist that evaluate the performance of various industrial wastes side by side. Such studies could provide valuable insights into the most effective materials for specific soil types and conditions.
5. Focus on Stone Powder Waste: While research on stone powder waste is emerging, further investigations are

needed to explore its long-term performance, optimal usage, and potential interactions with other stabilizing agents. Studies that focus on the chemical composition and reaction mechanisms of stone powder in black cotton soil could further elucidate its stabilization potential.

4. Case Studies

Several case studies have been conducted to evaluate the effectiveness of industrial waste in stabilizing black cotton soil. These studies highlight real-world applications and the practical implications of using industrial waste for soil stabilization.

Case Study 1: Fly Ash and Lime Stabilization

A case study conducted in Maharashtra, India, assessed the performance of fly ash and lime in stabilizing black cotton soil for road construction. The study revealed that the combination of 20% fly ash and 5% lime reduced the plasticity index by 30% and increased the unconfined compressive strength by 150% compared to untreated soil. The researchers concluded that this combination not only improved soil properties but also provided a sustainable solution for managing fly ash waste.

Case Study 2: Use of Granite Dust

In a case study conducted in Rajasthan, the effectiveness of granite dust as a soil stabilizer was evaluated. The study found that incorporating 10-15% granite dust into black cotton soil significantly reduced its swelling potential and enhanced its compressive strength. Field tests demonstrated improved performance in construction applications, leading to the successful completion of a pavement project.

Case Study 3: Blended Stabilization Approach

A case study in Tamil Nadu explored a blended approach using multiple industrial wastes, including fly ash, blast furnace slag, and stone powder waste. The researchers found that a combination of these materials yielded superior results compared to individual waste materials. The optimal blend led to a 40% reduction in swelling and a 200% increase in compressive strength, demonstrating the benefits of combining different industrial wastes for soil stabilization.

The literature on soil stabilization using industrial waste, particularly stone powder waste, illustrates a promising avenue for enhancing the properties of black cotton soil. While significant progress has been made in understanding the mechanisms and effectiveness of various waste materials, notable gaps remain in long-term performance studies, optimal dosage determination, and field validation. Further research is warranted to address these gaps and to explore the full potential of industrial waste in soil stabilization, contributing to sustainable construction practices.

The utilization of industrial waste in soil stabilization has expanded to include various materials, each exhibiting unique properties that contribute to soil improvement.

Table 1: Common Industrial Wastes

Industrial Waste	Key Properties	Effects on BCS	References
Fly Ash	Pozzolanic, enhances workability	Reduces plasticity index and swelling potential, increases cohesion	[1]
Blast Furnace Slag	Hydraulic, cementitious	Improves compressive strength, reduces plasticity	[25]
Rice Husk Ash	High silica content	Enhances strength and durability, reduces swelling	[3]
Foundry Sand	Fine texture, good compaction	Improves compressive strength, decreases plasticity index	[8]
Glass Waste	Angular particles	Reduces plasticity index, enhances interlocking	[13]
Stone Powder Waste	Fine particle size	Reduces swelling potential, increases compressive strength	[11]

In terms of improving the soil's engineering qualities, decreasing its fluidity, and addressing the difficulties caused by swelling and shrinkage behaviors, stabilizing black cotton soil with industrial waste materials has produced notable results. With an emphasis on stone powder waste in particular, this section highlights the distinct contributions of major industrial wastes and summarizes the main conclusions from the research.

4.1 General Outcomes of Industrial Waste Stabilization

1. Enhanced Soil Strength and Stability: Industrial waste materials like fly ash, marble dust, and silica fume improve the strength and stability of expansive soils, making them more suitable for load-bearing applications like roads and foundations.
2. Reduction in Soil Swelling and Shrinkage: Expansive soils, which pose risks due to their high shrink-swell potential, are stabilized through waste additives that limit water retention and decrease soil expansion.
3. Improved Load-Bearing Capacity: Stabilization with industrial by-products, like blast furnace slag or construction waste, increases the soil's California Bearing Ratio (CBR) and overall bearing capacity, making it suitable for use as subgrade material in pavements and highways.
4. Cost-Effectiveness: Using industrial waste materials reduces construction costs by substituting expensive soil stabilization agents and offering a practical use for industrial by-products.
5. Environmental Benefits: Utilizing industrial waste for soil stabilization prevents waste from going to landfills, reducing environmental impact, and supporting sustainable waste management practices.
6. Improved Durability and Erosion Resistance: Stabilized soils have better resistance to erosion, weathering, and seasonal changes, resulting in durable infrastructure and reduced maintenance costs.

4.2 Specific Focus on Stone Powder Waste

A possible stabilizer for black cotton soil is stone powder waste, which is obtained from the production of granite, marble, and other stone minerals. The following is a summary of the results related to the utilization of stone powder waste.:

1. Enhanced Soil Stability: According to studies, adding waste stone powder greatly increases the stability of BCS. For example, Altaf et al. (2024) found that 15% granite dust added to BCS reduced swelling potential by 30% and significantly increased UCS. This implies that stone powder efficiently creates denser and more stable soil by filling in the gaps in the soil matrix [8].
2. Optimized Dosage: According to research, maximizing the advantages of stone powder waste requires knowing the right amount. Further research is required to identify the exact dosage that produces the greatest outcomes across a range of soil conditions and environmental circumstances, even though studies indicate that 10-15% stone powder is helpful for stability. Better application techniques in field projects will be made possible by this.

3. Compatibility with Other Stabilizers: The compatibility of stone powder waste with other stabilizing agents is one of the noteworthy results of its use. The overall efficacy of BCS has been further improved by blending stone powder with substances like fly ash or lime, which have demonstrated synergistic effects. For instance, it has been demonstrated that using lime and stone powder together increases the compressive strength of BCS while reducing swelling, providing a complete soil stabilization solution.
4. Sustainability and Resource Utilization: By encouraging the recycling of industrial by-products, the usage of stone powder waste is consistent with sustainable construction methods. Incorporating leftover stone powder into soil stabilization offers a practical solution to use waste resources while enhancing soil qualities as the construction sector looks to reduce its environmental impact. This lessens the need for natural resources in building projects while also promoting the circular economy.
5. Field Applications and Case Studies: The potential of stone powder waste as a workable soil stabilizer is demonstrated by its successful application in a number of field projects. Case studies from Rajasthan showed that adding granite dust to roads improved their durability and performance. These useful results demonstrate that utilizing leftover stone powder in actual engineering applications is feasible.

Significant gains in soil qualities, increased stability, and environmental sustainability are the results of stabilizing black cotton soil with industrial waste, especially stone powder waste. As studies progress, more investigation into the best application of stone powder and how it interacts with other stabilizing agents will help to improve soil stabilization methods and encourage environmentally friendly civil engineering practices.

4.3 Key Success Factors

Successful stabilization projects often share several key factors:

1. Material Selection: Selecting the right industrial waste is essential. The efficacy of stabilization is increased by choosing waste materials with good qualities that go well with the traits of black cotton soil. For example, applying pozzolanic elements such as RHA and fly ash can greatly enhance soil performance.
2. Optimal Dosage: Establishing the proper ratio of industrial waste is essential. Every substance has a dose that optimizes its advantages. Studies show that both excessive and insufficient use can reduce the beneficial impacts on soil characteristics.
3. Site-Specific Conditions: It is essential to comprehend the environmental factors and soil properties specific to the area. The project's overall success is increased when stabilization techniques are modified to meet the unique site conditions.
4. Quality Control: The success of stabilization is influenced by the homogeneous distribution of industrial waste in the soil matrix and its quality. Uneven mixing or low-quality waste can result in inconsistent performance.

4.4 Lessons Learned

Several conclusions for potential future applications can be drawn from the case studies and experimental findings:

1. Comprehensive Testing: Understanding the performance of stabilized soils requires extensive laboratory and field testing. Extensive testing yields useful information that can guide choices regarding dose and material selection.
2. Long-Term Monitoring: The durability and efficacy of different industrial wastes can be evaluated over time using the use of long-term performance monitoring for stabilized soils. Developing sustainable solutions requires an understanding of how these materials behave in practical settings.
3. Interdisciplinary Approach: Working together across fields such as environmental studies, materials science, and geotechnical engineering can improve the efficiency of using industrial waste and encourage innovation in soil stabilizing methods.
4. Focus on Sustainability: Sustainability in soil stabilization should be a focus of future studies. Utilizing industrial waste not only solves problems with soil stability but also helps reduce waste, resulting in a more environmentally friendly method of building and developing infrastructure.

In summary, the use of industrial waste materials to stabilize black cotton soil shows great promise for enhancing soil qualities over the long and short terms. Future projects will be better prepared to apply efficient stabilizing approaches that support sustainable engineering practices if they have a greater grasp of the effects of different industrial wastes, critical success factors, and lessons learned from previous studies.

4.5 Environmental and Economic Impacts

Black cotton soil (BCS) stabilization through the use of industrial waste offers substantial financial and environmental advantages.

4.5.1 Environmental Benefits

Recycling garbage is one of the main environmental benefits. By using items like fly ash, rice husk ash, and stone powder waste in soil stabilization procedures, we keep them out of landfills and lessen trash build-up and the environmental risks it poses. Utilizing industrial waste also helps to lower carbon emissions. Conventional techniques for stabilizing soil frequently use non-renewable resources, such as cement, which requires a lot of energy to make. On the other hand, using industrial by-products can reduce the need for these resources, which will result in fewer greenhouse gas emissions when building.

4.5.2 Economic Advantages

Utilizing industrial waste might result in significant financial savings. Because less cement and other traditional stabilizers are required when BCS is stabilized using waste products, building expenses can be decreased. Large-scale infrastructure projects, where the financial ramifications might be significant, benefit greatly from this decrease in material costs. Furthermore, stabilized soils' improved durability and performance can eventually result in decreased maintenance costs, increasing the project's overall economic viability.

The significance of using industrial waste in soil stabilizing techniques is highlighted by the twin benefits of environmental sustainability and economic efficiency.

4.6 Challenges and Limitations

Although stabilizing black cotton soil (BCS) with industrial waste has several advantages, there are a number of drawbacks and restrictions that must be resolved for use to be efficient and long-lasting.

1. Variability in Waste Material Properties: Variability in the characteristics of industrial waste products is a major obstacle. The efficacy of various industrial waste sources as soil stabilizers may be impacted by differences in their chemical compositions, physical traits, and performance qualities. For example, the silica content and pozzolanic activity of fly ash from various power plants may vary, producing uneven stabilizing outcomes. Similarly, depending on the quarry and processing techniques, stone powder waste, such as granite and marble dust, may show varying particle sizes, shapes, and mineralogical compositions. Because of this variability, thorough testing and standardization processes are necessary to guarantee that the chosen industrial waste continuously satisfies the performance requirements for stability.
2. Availability of Waste Materials: The accessibility and availability of industrial waste materials present another difficulty. Due to the growth of coal-fired power plants, some industrial by-products, such as fly ash, are widely available, but others might not be. For instance, the usage of stone powder waste in places where it is not generated may be restricted because it may only be available in certain areas with active quarrying operations. This regional restriction may make it more difficult for industrial waste stabilization methods to be widely used and raise transportation expenses, which could balance the financial gains.
3. Long-Term Sustainability: Another issue is the long-term viability of stabilizing soil with industrial waste. Although there are clear immediate advantages to less landfill trash and carbon footprints, concerns regarding the long-term performance and longevity of stabilized soils still exist. The long-term impacts of weathering and environmental conditions on the functionality of stabilized BCS need to be carefully examined, particularly with regard to stone powder waste. The sustainability of this strategy may be jeopardized by the possible leaching of hazardous compounds, such as heavy metals, from specific industrial wastes. To address these issues and guarantee the stabilized soils' long-term sustainability, ongoing monitoring and evaluation are crucial.

In conclusion, the effective use of industrial waste in soil stabilization techniques depends on tackling the issues of variability in waste material qualities, availability, and long-term sustainability. The efficient use of industrial by-products, such as waste stone powder, in geotechnical applications can be facilitated by targeted research and standardized procedures.

5. Conclusion

Several by-products have the potential to improve soil qualities and boost performance in building applications, according to a review of the literature on stabilizing black cotton soil (BCS) with industrial waste. BCS is a type of soil that poses major problems for civil engineering projects because of its extreme flexibility and expansive tendency. However, these issues can be effectively resolved by incorporating industrial wastes, such as fly ash, rice husk ash, blast furnace slag, and particularly stone powder waste.

1. Industrial waste materials can enhance the mechanical properties of Black Cotton Soil (BCS), including decreased plasticity, improved compaction, and greater strength.
2. Different waste types offer different benefits, such as blast furnace slag, fly ash, and rice husk ash.
3. Stone powder trash, especially granite and marble dust, improves density and reduces swelling by encouraging particle interlocking and filling in soil matrix holes.
4. Utilizing industrial waste in soil stabilization techniques can promote waste recycling and reduce carbon footprint.

Researchers and practitioners should prioritize industrial waste for sustainable soil stabilization.

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