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Sustainable Stabilization of Expansive Soils Using Lime, Cement, and Bottom Ash: A Review

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Abstract:

Expansive soils, particularly those containing montmorillonite minerals, pose significant challenges in geotechnical engineering due to their high swelling and shrinkage characteristics. These behaviors often lead to structural distress such as cracking and differential settlement. Conventional stabilization techniques using lime and cement have been widely adopted to mitigate these issues; however, their environmental impact and cost have encouraged the exploration of alternative materials. This paper presents a comprehensive review of lime and cements stabilization mechanisms and evaluates the effectiveness of bottom ash (BA) as a sustainable additive. The review synthesizes findings from previous studies on strength development, durability, and micro structural behavior. Results indicate that the combined use of BA with lime or cement improves engineering performance while reducing environmental impact. The study also identifies gaps related to long-term performance and variability in BA properties, suggesting directions for future research.

Keywords —**Lime stabilization; Cement stabilization; Bottom ash; Sustainable geo-techniques; Soil improvement**

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I. INTRODUCTION

Expansive soils are highly problematic due to their tendency to undergo significant volume changes with moisture variation. These soils, typically rich in montmorillonite clay minerals, exhibit swelling upon wetting and shrinkage upon drying. This leads to severe damage in pavements, foundations, and earth structures.

Chemical stabilization using lime and cement has long been recognized as an effective technique to improve soil properties. Lime stabilization primarily reduces plasticity and swelling, whereas cement stabilization enhances early strength and durability. However, both methods are associated with high energy consumption and carbon emissions.

In recent years, the use of industrial by-products such as bottom ash (BA) has gained attention as a sustainable alternative. BA, a residue from coal combustion, possesses pozzolanic characteristics that can enhance soil strength when combined with lime or cement. This paper reviews existing literature on the stabilization of expansive soils using lime, cement, and BA, focusing on mechanisms, performance, and sustainability aspects.

II. LITERATURE REVIEW

The swelling behavior of expansive soils is mainly governed by mineral composition, particularly montmorillonite, along with soil fabric, density, and moisture conditions. Water absorption between clay layers causes volume expansion, influenced by exchangeable cations and pore water chemistry. Standard classification methods such as Atterberg limits and swelling pressure tests are widely used to evaluate these soils [1]. Lime stabilization involves immediate and long-term reactions. Initially, cation exchange leads to flocculation and reduced plasticity. Over time, pozzolanic reactions produce cementitious compounds such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), improving strength and durability [1,2].

Studies report significant improvements in unconfined compressive strength (UCS) and California Bearing Ratio (CBR), with optimum lime content typically ranging from 4% to 8% [2]. Strength gain is rapid within the first 28 days and continues gradually over time due to ongoing pozzolanic reactions.

Microstructural studies using XRD and SEM reveal that lime treatment alters ionic concentrations, particularly calcium ions, which play a key role in strength development [2]. Long-term studies also confirm improved durability under environmental conditions such as wet-dry cycles [4]. Cement stabilization relies on hydration reactions that produce binding compounds such as C–S–H and ettringite, resulting in improved strength and reduced compressibility [6]. Compared to lime, cement provides faster strength gain and better early-stage performance. Typical cement contents range from 3% to 8%, with strength increasing with curing time and cement dosage [6]. However, higher water content negatively affects strength, making the water–cement ratio a critical factor [7].

Recent studies highlight that soil type and chemical environment significantly influence cement stabilization performance [8]. While cement offers superior mechanical properties, its environmental impact necessitates partial replacement with sustainable materials such as BA. Bottom ash is a coarse-grained by-product of coal combustion, containing silica, alumina, and calcium compounds [11]. Due to its porous nature, BA increases optimum moisture content and may reduce maximum dry density when used alone [12]. When combined with lime or cement, BA acts as a pozzolanic material and micro-aggregate, enhancing strength and durability. Studies suggest optimal BA content between 10% and 20% when used with 3% to 6% binder [12].Several studies demonstrate that combining BA with lime or cement significantly improves soil properties. Optimal mixes such as 5% lime with 15–20% BA or 3% cement with 20% BA yield substantial improvements in UCS and CBR [13]. Strength development occurs in two stages: early strength due to binder hydration and long-term strength due to pozzolanic reactions involving BA. Particle size distribution and curing conditions significantly influence performance [14]. Durability studies indicate improved resistance to wet-dry and freeze-thaw cycles, making combined stabilization suitable for pavement applications [15]. The use of bottom ash reduces the demand for conventional binders, thereby lowering cost and carbon emissions. It also promotes waste utilization, contributing to sustainable construction practices [18].

However, BA properties vary depending on source, requiring proper characterization before use. Standard laboratory testing procedures such as UCS, CBR, and compaction tests are commonly employed to evaluate stabilized soils [19].

III. METHODOLOGY

This study adopts a systematic literature review approach by analyzing published research on soil stabilization using lime, cement, and bottom ash. Data from various studies were compared based on key engineering parameters, including Atterberg limits (LL, PL, PI), Compaction characteristics (MDD, OMC), Strength parameters (UCS, CBR), Durability performance, Microstructural properties (XRD, SEM, EDAX).

IV. RESULTS AND DISCUSSION

The reviewed studies indicate that both lime and cement significantly improve the engineering properties of expansive soils. Lime is effective in reducing plasticity and swelling, while cement provides higher early strength.

The incorporation of bottom ash enhances the performance of both stabilizers by contributing reactive silica and improving particle packing. Combined stabilization results has presented increased UCS and CBR values, reduced plasticity, and improved durability.

However, the effectiveness of BA depends on its chemical composition, particle size, and curing conditions. Variability in BA properties and limited long-term performance data remain key challenges.

V. CONCLUSIONS

. This review highlights the effectiveness of lime and cements stabilization in improving expansive soil behavior and emphasizes the potential of bottom ash as a sustainable additive. Combined stabilization using BA with lime or cement offers improved engineering performance while reducing environmental impact.

Future research should focus on long-term performance evaluation, field-scale validation, and the development of standardized mix design procedures considering BA variability.

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