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Stabilization of Expansive Soils using Slag Cement

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ABSTRACT

The expansive nature of certain soil types poses severe and potential risks in the field of geotechnical engineering because of their propensity to swell and retain water. This often results in the detrimental structural damage of pavements, retention systems, and even the foundations of the systems themselves. In the last several decades, the use of soil stabilization to minimize the negative aspects of expansive soils has gained prominence. The use of conventional binders like lime, fly-ash, and cement has been predominant due to the staggering improvement in compressibility, shear strength, and bearing capacity of the stabilized soil. However, the more concerning issues caused by these materials in sulfate-rich conditions and the CO2 emissions have motivated the world to research and find more sustainable options. GGBS (Ground Granulated Blast-furnace Slag) was the first stabilizer to be truly ‘green’, and it has surpassed all other stabilizers, be it lime, cement, or any other blended additive, in performance. GGBS has fantastic performance. There has been an increase in research on sulfate attack and heave, and the reason is clear. Its stabilizing properties as a CSH (Calcium Silicate Hydrate) and ettringite, durable and sustainable, are admirable. The incorporation of strategic hybrid binders or nanomaterials has further advanced microstructural soil engineering.

This review integrates the most recent and pertinent advances in the field of expansive soil stabilization. It evaluates the mechanisms, effectiveness and the drawbacks of lime, cement and slag systems. The systems are further evaluated and compared on the basis of their engineering values and environmental costs. The lime, cement, and slag systems will be compared in engineering values and the environmental costs. The works then highlight the gaps in the field and suggest areas for further research, in particular the improvement of slag-based binders and the use of nanotechnology for treating expansive soil.

1. Introduction

Soils classified as expansive are regarded as some of the most problematic materials in geotechnics and construction, mainly due to the high shrink-swell potential these soils have. Expansive soils are responsible for the development of heave, cracks, and differential settlements in foundations, pavements, and embankments[7][8]. The great concern for geotechnical engineering practice in enhancing the methods of stabilization arises due to their widespread occurrence, particularly in the arid and semi-arid regions is a vital process in the development of The use of lime, cement, and fly ash binders on expansive soils plasticity and associated swelling behavior has been undertaken investments on for decades. These, besides on-plastic clay, fly ash also improves shear strength corresponding to shear and bearing capacities. However, scratches and dents remain, such as the sulfate climate problem, sulfate levels where one forms sulfate ettringite, and the 'dirty' dilemma of cement industry emissions[9].

GGBS has been gaining popularity as a waste byproduct binder with increased stability that surrounds cement waste production, while

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hybrid systems alongside nanomaterials continue to provide numerous possibilities for microstructural augmentation. In light of these issues, this review identifies the research gaps, discusses the stabilization mechanisms, analyzes the efficacy of these systems, and describes the barriers as well as the limitations to aid future geo-materials research[10][11]

2. Stabilization with Lime

Lime stabilization has always been one of the best methods of treating the engineering characteristics of expansive Soils. Lime improves the pliability and workability of soils through cation exchange and subsequent flocculation. Ultimately, with the passage of time, pozzolanic reactions take place in the presence of lime whereby calcium combines with the silica and alumina present in clay minerals to form calcium silicate and calcium aluminate hydrates. Their combinations in soil increase compressive strength with time, and also increase long-term shear strength along with consolidation[12].

The ability to reduce swelling of soils while improving their bearing capacity has been documented both experimentally and numerically with the addition of lime. For instance, Khalil et al. (2019) proved that the addition of 4% lime to expansive clay, with adequate curing time, drastically redefined the swelling ratio and increased unconfined compressive strength. For PLAXIS–2D finite element modeling, lime-treated layers still exhibited better stress–settlement behavior and increased footing capacity overall in comparison to the untreated soils within the model[13].

The effectiveness of lime stabilization still has its bounds. For instance, the addition of expansive minerals, like ettringite, in soils with high concentrations of sulfates drastically reduces overall strength. In situ restrictions and long curing times that slow pozzolanic reactions are practical challenges that also still need to be resolved. In any case, lime remains inexpensive and still widely used for lightly loaded foundations and road subgrades.

3. Stabilization with Ground Granulated Blast Furnace Slag (GGBS)

Ground Granulated Blast Furnace Slag (GGBS) is a steel industry by-product that has come to be recognized as a sustainable and effective stabilizer for expansive soils. Its high concentration of silica and alumina participates in pozzolanic reactions in the presence of calcium sources (lime or cement) to form calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH), and ettringite as cementitious by-products. These products of hydration strengthen the soil and reduce swelling, and increase the durability of the soil for a prolonged period[14].

Wild et al. (1996) were one of the first to show that the combination of lime and GGBS improved compressive strength and significantly reduced the swelling potential of soils saturated with sulfate.

GGBS improves mechanical properties and also reduces the risk of sulfate attack through free lime and ettringite expansion. Other works, such as Al-Dakheeli et al. (2021), also noted that 7% of standalone GGBS increased the compressive strength of sulfate-bearing soils five times during 28 days compared to untreated soils. Microstructural studies also showed the development of CSH, ettringite, and calcite that contributed to strength gain and sulfate expansion control[15].

Other studies also showed that GGBS-based systems offer higher durability. GGBS soil is stabilized at a slower rate, which reduces the risk of delayed expansion. In addition to these benefits, GGBS is a waste which helps reduce industrial CO_2 emissions and fits the framework of modern sustainable construction.

These benefits aside, these advances still leave room for improving on the use of GGBS as a single binder. For example, the concern for any application requiring a quick stabilization system is the initial strength gain without the presence of lime or cement. Consequently, the focus of the research is blending systems of lime-slag, cement-slag, or their combinations for optimized early strength gain and sustained durability[16].

Figure 4. (a) Schematic of soil response around a pile cross-section under lateral loading (normal stress $Q$and

4. Hybrid and Nano-Material Stabilizers

4.1 Hybrid Binders

Recent studies have highlighted the benefits of combining traditional binders (lime, cement) with supplementary materials such as fly ash, slag, or silica fume to create hybrid stabilization systems. These systems exploit the rapid strength development of lime and cement while leveraging the long-term durability of pozzolanic additives. Sharma et al. (2015) showed that combining cement with fly ash significantly improved the unconfined compressive strength and California Bearing Ratio of expansive clays

Similarly, lime–slag blends have been reported to reduce swelling more effectively than lime alone, as GGBS consumes free calcium hydroxide and reduces the risk of ettringite formation in sulfate-bearing soils

Hybrid binders are particularly useful in aggressive environments where single additives may fail. For example, Raviteja et al. (2014) demonstrated that lime–cement–fly ash combinations improved footing performance under strip loading, enhancing bearing capacity by over 150% compared with untreated soil

These results suggest that hybrid systems offer a balanced approach, combining early mechanical improvements with long-term durability[17].

4.2 Nano-Materials

The application of nanotechnology to soil stabilization has further sophisticated the mechanical behavior of materials on the micro-level. Nano-silica (NS), nano-alumina, and nano-clay stand out among the most researched materials. Their enormously high predominating surfaces quicken the …

Results from various tests demonstrate that the micro-silica possesses the ability to increase the compressive strength and decrease the swelling potential to…

In tandem, nano materials complement the nano mixed binders as well. For example, the combination of lime or cement and the nano-silica binder results in the unprecedented increase in the early strength and durability of the cementitious material when compared to the sole use of macroscale additives, as well as improved interparticle bonding of the material at the nano scale.

In a scanning electron microscope (SEM), there is then, evidence from the transverse microstructures that the nano-sized additives condition the soil pore structure, and subsequently minimize pore-pore structure associated with pore water and vadose water.

The use of nano materials, however, can still be improved for use in geotechnical engineering. Cost, as well as the health and safety issues surrounding the handling of nanoparticles, and the ability to apply laboratory work at a field scale, still remain an obstacle. Nonetheless, nano materials, mixed with other binder systems, have great potential for the stabilization of expansive soil[18].

5. Comparative Analysis of Lime, Cement, and Slag Systems

A comparative evaluation of lime, cement, and slag-based stabilization systems highlights both their engineering performance and sustainability considerations.

Lime is widely recognized for its cost-effectiveness and efficiency in reducing plasticity and swelling potential. It is particularly effective for low-plasticity clays and road subgrades where long curing times are acceptable. However, its performance declines in sulfate-rich soils due to ettringite formation, which can lead to excessive expansion and reduced durability[19].

Cement stabilization provides rapid strength gain and improved bearing capacity, making it suitable for time-sensitive projects. It has been shown to increase both compressive strength and California Bearing Ratio significantly. Nevertheless, cement-based systems are more prone to durability issues in aggressive sulfate environments and contribute heavily to CO_2 emissions, raising environmental concerns.

GGBS, whether used alone or in combination with lime or cement, provides superior long-term durability and mitigates sulfate-induced heave. It offers a more sustainable solution by recycling industrial by-products and reducing greenhouse gas emissions. However, the slower early strength development of standalone GGBS may limit its immediate application in field projects requiring quick stabilization[20].

Hybrid systems, combining lime or cement with slag or fly ash, strike a balance between early strength and long-term performance. They reduce reliance on cement, lower CO_2 emissions, and mitigate sulfate attack risks. Incorporating nano-materials further refines soil microstructure, enhancing both mechanical strength and durability.

Overall, lime is best suited for low-cost, large-scale applications, cement for projects demanding rapid improvement, and GGBS for long-term sustainable stabilization. The choice of stabilizer should therefore consider not only the geotechnical properties of the soil but also environmental, economic, and durability aspects as shown in Table 4-1[21].

Table 1**.** Comparative summary of LS, CS, and GGBS stabilization systems for expansive soils

Stabilizer	Main Mechanism	Advantages	Limitations	Best Applications
Lime	Cation exchange, flocculation, and pozzolanic reactions form CSH and CAH	- Reduces plasticity and swelling - Improves workability - Cost-effective	- Long curing time - Poor performance in sulfate-rich soils (ettringite formation) - Limited early strength	Low-cost projects, road subgrades, lightly loaded foundations
Cement	Hydration reactions producing CSH and CAH	- Rapid strength gain - Significant improvement in compressive strength and CBR - Widely available	- Susceptible to ettringite expansion in sulfate soils - High CO_2 emissions - Higher cost than lime	Time-sensitive projects, structural foundations, pavements
GGBS	Pozzolanic reactions in the presence of lime/cement; formation of CSH, CAH, and ettringite	- High long-term durability - Mitigates sulfate-induced heave - Sustainable (industrial by-product, low CO_2 footprint)	- Slow early strength development if used alone - Requires activation (lime or cement)	Aggressive sulfate soils, sustainable construction, blended stabilization systems

6. Research Gaps and Future Directions

Although significant progress has been made in stabilizing expansive soils using lime, cement, slag, and hybrid systems, several research gaps remain that need to be addressed to ensure reliable and sustainable applications.

1. **Standalone performance of GGBS**:
   The outcomes of combining GGBS with lime or cement are quite promising, but its individual application remains rather obscure. The processes involved in activation, the chemistry behind strength gain, and long-term strength and durability in the presence of sulfate and moisture certainly require additional research[22].
2. **Optimization of binder ratios.**
   The systematic optimization of binder proportions suited to variable soil types and particular environmental conditions is a gap in the literature, even though a mix of lime, cement, and slag is considered in most studies. An investigation on performance regarding the optimal balance between mechanical, durable, and sustainability improvements is recommended.

3. **Durability under field conditions**: Laboratory results often differ from field performance due to environmental variability such as wet–dry cycles, freeze–thaw effects, and long-term sulfate exposure. More large-scale field studies are needed to validate laboratory findings and assess the durability of stabilized soils under real-world conditions [23].
4. **Integration of nanotechnology**: Application of nano-silica and other nanoparticles has seen some improvements toward minimizing swelling and strengthening soil. However, their practical utilization is still very limited. Further studies should explore their implementation at scale for mass production, safe handling, and cost-effectiveness [24].
5. **Environmental and life-cycle assessments: -** stabilization techniques' carbon footprint, energy use, and comprehensive environmental effects have been examined only cursorily in the literature. Given the importance of realizing the most sustainable outcomes, life cycle assessments (LCA) have become indispensable [25].
6. **Numerical modeling and prediction tools**: Soil mechanics is an example of an engineering discipline where predictions can be erroneous. Advanced modeling approaches, such as coupled hydro-mechanical models or microstructural simulations, can enhance the predictions of these models. Advanced modeling approaches, such as coupled microstructural simulations or hydro-mechanical models, can enhance the predictions of advanced modeling approaches[26].
7. The predictions of such models require validation against experimental or field data.

Future Directions

Future research should prioritize blended stabilization systems that combine early strength gain with long-term durability, particularly lime–slag and cement–slag mixes. Emphasis should also be placed on the role of nanomaterials in enhancing performance at low dosages. Moreover, interdisciplinary approaches integrating geotechnical engineering, materials science, and environmental engineering will be vital to advancing sustainable soil stabilization practices[27].

7. Conclusion

Geotechnical engineering attempts to tackle the problems associated with expansive soils, considering the ever-increasing moisture associated with sensitivity problems posing heaving problems. These culminate in disproportionate damage being inflicted on the understructures of the pavement's infrastructure that repose within the estuaries and embankment. Over the past two decades, the emergence of binders, namely lime, cement, and their hybrids, has helped to alleviate this problem [28].

Economic efficacy is enhanced with lesser quantities of stabilized lime, yet with marginal success in regions with high concentrations of sulfonates. Bearing and rapidity of a structure are improved with cement as well, all of which serve to enhance the strength of the system. In blended systems, the use of GGBS has been instituted as a stabilizer of mitigated plasticity and swelling, delayed and sulfate heave, and improved durability. With each added set of nanomaterials to more recent hybrid systems, we get that much closer to sustainable construction.

Geotechnical engineering investigates the issues concerning expansive soils. The problems associated with the high swelling potential and moisture sensitivity caused damage to the structure of the foundations, pavements, and embankments. The use of lime, cement, slag, and hybrid binders over the last couple of decades has alleviated some of the issues mentioned previously[29].

Use of lime leads to a decrease in plasticity and swelling. Inexpensive, dominated by plasticity and swelling, but moisture sensitive, and does poorly in high sulphate environments. The structure retains support from the underlying soil, and the bearing capacity of the structure is gained and improved at a very rapid rate. The disadvantages of cement are a lack of durability in aggressive sulphate environments of complex systems. The GGBS in blended systems is a plasticity and swelling stabilizer that is used to prevent sulfate-induced heave and increase long-term durability. The more complex advanced systems, hybrids with higher concentrations of nanomaterials, are a new step in constructive sustainable engineering[30].

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