Open Access Library Journal
2024, Volume 11, e11319
ISSN Online: 2333-9721
ISSN Print: 2333-9705

A Systematic Review of the Effects of Soil Stabilization on Soil Mechanical Properties: A Comparative Study of Fly Ash, Cement and Lime

Duke Magara, Haicheng She

School of Urban Construction, Yangtze University, Jingzhou, China
Email: dmagara23@gmail.com, shehaicheng@126.com

How to cite this paper: Magara, D. and She, H.C. (2024) A Systematic Review of the Effects of Soil Stabilization on Soil Mechanical Properties: A Comparative Study of Fly Ash, Cement and Lime. *Open Access Library Journal*, **11**: e11319.
http://doi.org/10.4236/oalib.1111319

Received: February 16 2024
Accepted: March 25, 2024
Published: March 28, 2024

Abstract

The main purpose of this research was to systematically review studies on the effects of soil stabilization on the mechanical properties of soil using lime, cement, and fly ash. The systematic review was conducted following the systematic literature review methodology based on the PRISMA guidelines. The review was limited to articles published between 2013 and 2023. From the outcomes of the systematic review, it was found that soil stabilization using either lime, cement or fly ash has significant positive effects on the mechanical properties of soil. Precisely, the results indicated that cement, lime, and fly ash can significantly improve soil mechanical properties such as strength, permeability, and stability. Overall, fly ash was found to be the most effective soil stabilizing agent compared to lime and cement. However, it was concluded that whilst fly ash alone can be more effective in soil stabilization, a combination of cement, lime and fly ash can be more effective. Overall, the research highlighted the potential of different soil stabilizing agents in enhancing the mechanical properties of soils and hence providing valuable insights for geotechnical and civil engineers and practitioners. However, further experimental or field studies are required to comprehensively compare the short-term and long-term impacts of fly ash, cement and lime on soil mechanical properties.

Subject Areas

Soil Science

Keywords

Soil Stabilization, Lime, Cement, Fly Ash, Mechanical Properties

1. Introduction

Soil is the most abundant construction or engineering material of nature. Nevertheless, the limited availability of appropriate subgrade soil for constructing infrastructure facilities has necessitated the enhancement of the characteristics of the existing soil through soil stabilization. Sinha and Iyer (2020) [1] state that soil stabilization has emerged as a highly advantageous method for the development of infrastructure and other significant geotechnical and civil engineering projects. Also, Vinai *et al.* (2022) [2] found that constructing any kind of structure on unsuitable soil can pose difficulties because of the soil's high potential for swelling and/or low strength properties. Therefore, soil stabilization has become increasingly popular due to the limited availability of suitable soil for infrastructure projects and the substantial enhancement of soil properties attained through soil stabilization (Arias-Jaramillo *et al.*, 2023 [3]; Okonkwo and Kennedy, 2023 [4]). Soil stabilization refers to the modification of soil properties, either through chemical or mechanical methods, in order to produce a more enhanced soil material with certain engineering characteristics (Dias-Miguel *et al.*, 2021 [5]; Hamzah *et al.*, 2015 [6]). According to Babu and Paulose (2018) [7], soil stabilization is crucial for maintaining the stability of soil, particularly in cases when the soil is extremely active, to properly bear the weight of superstructures.

The primary objectives of soil stabilization are to enhance the soil's load-bearing capacity, resistance to weathering, and permeability (Babu and Paulose, 2018 [7]; Jawad *et al.*, 2014 [8]). Accordingly, the durability of any construction or engineering work is contingent upon the stability of the underlying soil, as unstable soil can give rise to substantial issues (Babu and Paulose, 2018 [7]; Zuber *et al.*, 2013 [9]). According to Shah and Ahmad (2020) [10] and Singh *et al.* (2018) [11], soil stabilization is typically required when the soil strength is inadequate. Soil stabilization methods are essential to ensure the stability of soil, particularly in cases when the soil is extremely active (Arias-Jaramillo *et al.*, 2023 [3]; Saleem, Kumar and Singh, 2020 [12]; Utami, 2014 [13]). Also, soil stabilization is a time and cost-effective alternative to the traditional process of removing and replacing unstable soil (Mahedi, Cetin and White, 2020 [14]; Shekhar and Saxena, 2018 [15]; Zuber *et al.*, 2013 [9]).

Various stabilizers are employed for soil stabilization, with Lime, Cement, and Fly ash being the commonly utilized agents or binders (Makusa, 2013 [16]; Shah and Ahmad, 2020 [10]). Researchers have conducted comprehensive laboratory, field, and experimental studies, which have demonstrated diverse effects of soil stabilizing additives, such as cement, lime, and fly ash on various soil parameters. Although several soil stabilization methods have been proposed to improve soil properties, there is a lack of comparative studies to find out the most effective soil stabilizing agent (Salimah *et al.*, 2021 [17]; Singh *et al.*, 2018 [11]; Vinai *et al.*, 2022 [2]). Previous studies have found inconclusive results where some found fly ash significantly improves soil mechanical properties (Dayalan and Dayalan, 2016 [18]; Turan *et al.*, 2022a; 2022b [19]; Vinai *et al.*, 2019) [2] whilst other studies found that lime significantly improves soil mechanical properties (Jin and Li, 2019 [20]; Salimah *et al.*, 2021 [17]; Utami, 2014 [13]) and others found cement to have significant effects on soil mechanical properties (Nazari, Tabarsa and Latifi, 2021 [21]; Shooshpasha and Shirvani, 2015 [22]). From this, it remains unclear on the most effective soli stabilizing agent among fly ash, cement, and lime. Engineers have therefore been concerned about the selection of the most efficient binders for soil stabilization, which is a well-known issue in civil and geotechnical engineering where the goal is to identify the appropriate type and proportion of stabilizing agents to enhance soil properties (Arias-Jaramillo *et al.*, 2023 [3]; Lindh and Lemenkova, 2023 [23]).

More so, there is a lack of a systematic review of the studies to provide a summary of the outcomes of the previous studies on soil stabilization. This systematic review therefore aimed to analyse and compare the effects of soil stabilization on soil mechanical properties using cement, lime and fly ash as case studies. Over the past years, several studies on the effects of soil stabilization have been done such that there are varying results regarding the subject in the existing body of literature. As acknowledged by Makusa (2013) [16] and Tripathi (2020) [24], the knowledge of soil stabilization in geotechnical and civil engineering has been well documented in existing literature. However, the effects of soil stabilization have been found to vary by admixtures used such as cement, lime, bitumen emulsion and fly ash and the findings are scattered across the body of knowledge. In this regard, the experimental research has not yet been summarised to guide engineers towards effective soil stabilization. Additionally, while the results presented in existing research are consistent across scholars, it is still unclear regarding the most effective soil stabilizing agent.

These therefore represent significant gaps in knowledge which this research sought to address by carrying out a systematic review on the comparative study on the effects of soil stabilization on soil mechanical properties focusing on cement, lime, and fly ash. Although several experimental studies have investigated the effects of these different soil stabilization methods on soil mechanical properties, a comprehensive comparative analysis of lime, fly ash and cement as soil stabilizing agents is lacking in existing literature. This systematic review therefore aimed to fill this knowledge gap by examining and synthesizing results of relevant experimental studies in order to assess the effectiveness of these three common stabilization agents. By synthesizing findings from existing knowledge in the field of soil stabilization, this review contributes to a better understanding of the most suitable and effective soil stabilization technique for geotechnical and civil engineering applications.

For comparison purposes, the study reviewed the effects of soil stabilization on soil mechanical properties such as plasticity, swelling, and strength using unconfined compressive strength (UCS) and California Bearing Ratio (CBR), maximum dry density (MDD) and optimum moisture content (OMC). The outcomes of this systematic literature review would be of value to practice and theory. Most importantly, the outcomes would be of great value to geotechnical engineers and civil engineers in soil stabilization. This systematic review of the literature was carried out using articles published from 2013 to 2023 accessed from numerous electronic databases. The time scale (2013-2023) was selected to gather a wide range of recent and relevant articles as possible. The systematic review therefore aimed to achieve the following research objectives:

1) To analyse the effects of fly ash, lime, and cement as soil stabilizing agents on soil mechanical properties.

2) To compare and determine the most effective soil stabilizing agent among fly ash, lime and cement.

2. Materials and Methods

This research followed the systematic literature review methodology elaborated in the following sections.

2.1. Materials

Search Strategy

This systematic literature review was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Based on the PRISMA checklist, the research was conducted making use of articles from several databases. The main databases utilised include Elsevier, Scopus, Science Direct, MDPI, Springer, the American Society of Civil Engineers (ASCE) library as well as Google Scholar. Additional articles included peer-reviewed journal articles available from various journal publishers such as the International Journal of Geotechnical Engineering, the International Journal of Engineering, and the International Journal of Geo-Engineering. The search strategy was delineated to the period from 2013 to 2023 however articles published in the last five (5) years were prioritized to get more current evidence. Additionally, no geographical limits guided the article search.

The search of articles was executed in accordance with the PRISMA checklist where a preliminary search was carried out to find out the proper keywords as well as checking feasibility of the systematic literature review. The search keywords employed include "soil stabilization", "soil mechanical properties", "soil mechanical characteristics", "soil mechanical behaviours", "cement", "fly ash", "lime", "comparative study", "geotechnical properties", "engineering properties" and "effects of" For a comprehensive search, Boolean operators namely as "OR" and "AND" were utilised to join the keywords. In addition, the author conducted manual searches of reference lists for the identified articles.

2.2. Methods

2.2.1. Inclusion Criteria

The following inclusion criteria were employed for this systematic literature review:

1) Articles written and published between 2013 and 2023 inclusive.

2) Articles written and published using the English language.

3) Articles based on experimental, field studies or laboratory tests.

4) Articles on soil stabilization using either lime, cement or fly ash or a combination.

5) Articles published as both abstract and full text.

2.2.2. Exclusion Criteria

The exclusion criteria for the research were as follows:

1) Articles published in other languages other than English language.

2) Articles published prior 2013 and after 2023.

3) Scoping, systematic and/or narrative review research articles.

4) Non-experimental research articles.

5) Articles only published as abstracts.

6) Newspapers, institutional reports, and other "grey" literature.

2.2.3. Quality Assessment of Articles

For quality assessment and rigor of articles, the "Quality Assessment Tool for Diverse Design Studies" (QATSDD) tool. On the other hand, the articles that satisfied the inclusion criteria underwent a thorough evaluation of their quality by two independent reviewers. Based on the outcomes from the independent reviewers, articles were therefore considered of good quality if both independent reviewers agreed.

2.2.4. Data Extraction and Analysis

Before conducting the data analysis, the author collected information about the article, such as the author(s) names, publication year, region, or country, focus or aim, methodology and/or research design, key findings, as well as conclusions. This information was organized in a table format, as shown in **Table 1**. Thereafter data from the systematic literature review were analysed using the content analysis approach. Utilizing the content analysis technique, the primary themes from each article were integrated into data summary Excel sheets. To clarify, the process of extracting data was carried out utilizing Microsoft Excel spreadsheets. Thereafter, the PRISMA flowchart diagram was developed to summarize the article selection and screening process.

2.2.5. Ethical Considerations

For this systematic literature review, ethical approval for the research was sought. Thereafter, efforts were made rigorous efforts to circumvent search biases in conducting the systematic literature review. Additionally, citation and outcome reporting biases were prevented by not only selecting articles with results that suit the author's personal perspectives and expectations. Moreover, database bias was prevented by not limiting the search to a single database.

3. Theory

The challenge of soil stabilization remains a significant issue for engineers due to

Table 1. Summary of included articles.

Author (s)	Country/ Region	Aim/Focus	Research Design/ Methodology	Key Findings/ Conclusions
Mahedi *et al.* (2020) [14]	United States	Effectiveness of fly ash, cement, and lime in improving soil engineering properties	Experimental study	Cement proved to exhibit higher strength and low swelling compared to lime and fly ash.
Sharma *et al.* (2018) [28]	India	Examination of the independent roles of cement and lime soil stabilization	Comparative experimental study	Cement has relatively higher effects on the mechanical properties of soil compared to lime. Cement and lime increased OMC and shear strength and reduced MDD
Lindh and Le-menkova (2023) [23]	Sweden	Geo-technical properties of stabilized soil using blended binders (cement, fly ash, lime, and slag) for sustainable road construction	Experimental design using laboratory tests	Best performance in terms of soil workability and strength was demonstrated by blending fly ash, lime and cement compared to pure binders
Rank *et al.* (2019) [33]	India	Comparison of soil properties for soil stabilized with lime, fly ash and cement	Experimental study	Lime fly ash significantly reduce liquid limit, water content and improve improve shear strength compared to cement
Sharma and Hymavathi (2016) [28]	India	A comparative study on the effects of fly ash, lime and construction demolition waste on geotechnical properties of clayey soil	Experimental study	Lime is the best soil stabilizer given increased UCS and CBR compared to fly ash and construction demolition waste
Asgari, Baghebanzadeh and Bayat (2015) [34]	Iran	Effects of lime/cement on the engineering and geotechnical properties of soil	Laboratory experiments	Improvements in soil mechanical behaviors (UCS and plasticity index) were noticeably higher for cement than lime treatment. However, the effects of lime were more than that of cement on MDD and OMC
Bayat, Asgari and Mousivand (2014) [35]	Iran	Effects of cement and lime on soil geotechnical properties	Experimental study	Improvements in UCS and plasticity index were noticeably higher in cement treatment compared to lime treatment.
Ali and Yousuf (2019) [36]	Oman	Effects of lime and cement on index properties of clayey soil	Experimental study	Lime stabilization is more efficient compared to cement stabilization in terms of MDD, plasticity and OMC
Teerawattanasuk and Voottipruex (2019) [37]	Thailand	Comparison between fly ash and cement for soil stabilization	Experimental study using field CBR tests	Fly ash stabilized soil had higher CBR values compared to cement-stabilized soil

Continued

Zhou *et al.* (2019) [38]	China	Physical-mechanical behaviours of stabilized expansive soil using lime and fly ash	Experimental research	Fly ash showed better UCS compared to lime
Nguyen and Phan (2021) [39]	Vietnam	Engineering properties of stabilized soil using fly ash and cement for sustainable road construction	Experimental study	Fly ash demonstrated higher UCS compared to cement
Kalyane and Patil (2020) [25]	India	Experimental study of black cotton soil stabilization by lime and fly ash	Experimental study	Combination of lime and fly ash proves to very effective as it results in improved soil strength, reduced MDD and increased OMC though fly ash is more effective compared to lime. 15% of fly ash reduced plastic limit by 28%
Krithiga *et al.* (2017) [40]	India	Soil stabilization using lime and fly ash	Experimental study	Soil stabilization using fly ash is more effective in soil strengthening compared to lime
Arias-Jaramillo *et al.* (2023) [3]	Colombia	Evaluation of mixture of fly ash and lime as stabilizers compared to cement and lime	Experimental study	Mixture of lime and fly ash demonstrated increased bearing capacity compared to cement and lime. However, fly ash is more effective compared to lime
Rai *et al.* (2021) [27]	Pakistan	Effects of cement and fly ash on engineering characteristics of stabilized subgrade soils.	An experimental study	Fly ash and cement decreases OMC, reduce swelling, increases MDD and increased CBR where Fly ash is more effective compared to cement
Andavan and Pagadala (2020) [41]	India	An examination of soil stabilization by addition of lime and fly ash	Experimental study with laboratory tests	Fly ash resulted in considerable increments in CBR compared to lime
Okonkwo and Kennedy (2023) [3]	Nigeria	Effects of lime and cement on mechanical properties for sub-grade soils	Experimental study with laboratory tests	Cement is the most effective in reducing OMC, increased MDD, reduced plasticity index and increased CBR and UCS compared to lime. However, when used together, cement and lime offer significant effectss in terms of durability, strength and stability.
Talabi, Awodiji and Balogun (2019) [42]	Indonesia	Comparative study of effects of lime and cement on engineering properties of subgrade soils	Experimental study	Lime was more effective in improving strength and stability of soil compared to cement
Saleem *et al.* (2020) [12]	India	Comparative analysis of soil stabilization using cement and lime	Experimental study	CBR values for lime stabilized soil were higher compared to cement stabilized soils

Continued

Shekhar and Saxena (2018) [15]	India	Comparative study for soil stabilization using fly ash, cement, and lime	Experimental investigation	CBR values for lime-stabilized soil were higher followed by those for soils stabilized using cement and fly ash
Mir (2015)	India	Effect of lime and fly ash mechanical and physical properties of expansive clay	Experimental study	Fly ash is more effective compared to lime in terms of improved permeability and strength
Navale *et al.* (2016) [43]	India	Soil stabilization using lime and fly ash	Experimental study	Lime showed very high CBR values compared to fly ash

the growing need for construction of infrastructure and engineering structures in places with inadequate or low-quality soils (Kalyane and Patil, 2020) [25]. Although soil stabilization can be traced back to more than 500 years ago, its application mostly in developing countries is still at its infancy stages (Archibong *et al.*, 2020 [26]; Makusa, 2013 [16]; Rai *et al.*, 2021 [27]). As per Sharma *et al.* (2018) [28], in recent decades, engineers have introduced a new technique for soil stabilization designated as chemical stabilization where chemicals such as cement and lime are used. In accordance with Singh *et al.* (2018) [11], soil stabilization is a method used to enhance the properties of natural soil or granular material for the purpose of constructing pavement layers. From Jawad *et al.* (2014) [8], soil stabilization refers to the modification of geotechnical parameters to meet engineering specifications.

Soil stabilization is necessary when the road alignment passes through a sub-grade of poor soil quality that does not meet the engineering qualities specified in any standard specifications such as the ASTM international standards (Taki and Bhattacharya, 2020) [29]. According to Jawad *et al.* (2014) [8], soil stabilization can enhance shear strength, enhance bearing capacity, stabilize slopes, minimize structural settling, and increase soil density. On the other side, soil stabilization is used to alter the characteristics of soil to enhance its engineering performance, including its durability and strength (Babu and Poulose, 2018 [7]; Jin and Li, 2019 [20]). Firoozi *et al.* (2017) [30] argued that soil stabilization not only improves strength but also improves permeability and compressibility. From Salimah *et al.* (2021) [17], soil stabilization refers to the process of altering the characteristics of soil by either physical or chemical methods to enhance its engineering performance. Babu and Poulose (2018) [7] contend that soil stabilization offers significant time and cost savings compared to the approach of removing and replacing unstable soil.

As summarized by Singh *et al.* (2018) [11], there are several effects that may take place in a soil-stabilized mixture. The widely documented effects include 1) increased strength in terms of any standard test values such as CBR value, R-value and k-value, 2) decrease of plastic and liquid limit values, 3) important physical properties due to reactions with cementation agents mixed with soil, 4) decrease in water film thickness around each soil particle due to flocculation/agglomeration following addition of lime/cement, 5) decreased swelling and shrinkage rates and 6) improvement in overall pavement structural integrity (Archibong *et al.*, 2020 [26]; Singh *et al.*, 2018 [11]; Sinha and Iyer, 2020 [1]). The effects differ depending on the admixture used, which includes various soil stabilization methods such as soil-cement, soil-lime, soil-fly ash and soil-bitumen stabilization (Afrin, 2017 [31]; Archibong *et al.*, 2020 [26]; Huang *et al.*, 2021 [32]; Tripathi, 2020) [24]. Currently, all construction of roads or engineering projects include either one or both of these soil-stabilizing approaches (Tripathi, 2020) [24]. In addition, as stated by Archibong *et al.* (2020) [26], Vinai *et al.* (2022) [2], and Tripathi (2020) [24], the different approaches to soil stabilization can be categorized into the proportioning techniques, cementing, moisture/waterproofing, modifying, water-repelling, moisture-retaining, heat treatment, as well as chemical stabilization agents.

However, existing experimental studies have shown varying effects for soil stabilizing agents such as cement, lime, and fly ash on soil mechanical properties. There is a lack of comparative studies to find out the most effective soil stabilizing agent among cement, lime, and fly ash. More so, there is lack of systematic review studies to provide a summary of the outcomes of the previous studies on soil stabilization effects on soil mechanical properties. This systematic review therefore aimed fill the existing gap in knowledge by examining and synthesizing results of relevant experimental studies to assess the effectiveness of these three common stabilization agents on soil mechanical properties.

4. Results and Discussion

4.1. Results

Following the comprehensive search of relevant articles and quality assessment, twenty-two (22) articles were included in the systematic review as demonstrated in **Figure 1**.

As demonstrated in **Figure 1**, the comprehensive search of articles from various databases yielded 539 research publications on soil stabilization. Out of these, 513 articles were directly obtained through database search whilst 26 were identified following manual scanning reference lists of the 513 articles. Among the 539 research articles, a total of 88 duplicates were discovered and subsequently discarded from screening such that only 451 went through the article screening process. Out of the remaining 451 articles, 378 articles were excluded due to issues of either the abstract or title or both. Resultantly, a total of 73 full-text articles were assessed for eligibility whilst 51 articles were excluded as they lacked relevance. Subsequently, only twenty-two (22) articles met the inclusion criteria and quality assessment such that they were included in this systematic literature review. A summary of the 22 included articles is presented in **Table 1**.

The findings summarised in **Table 1** provide an analysis on the effects of soil

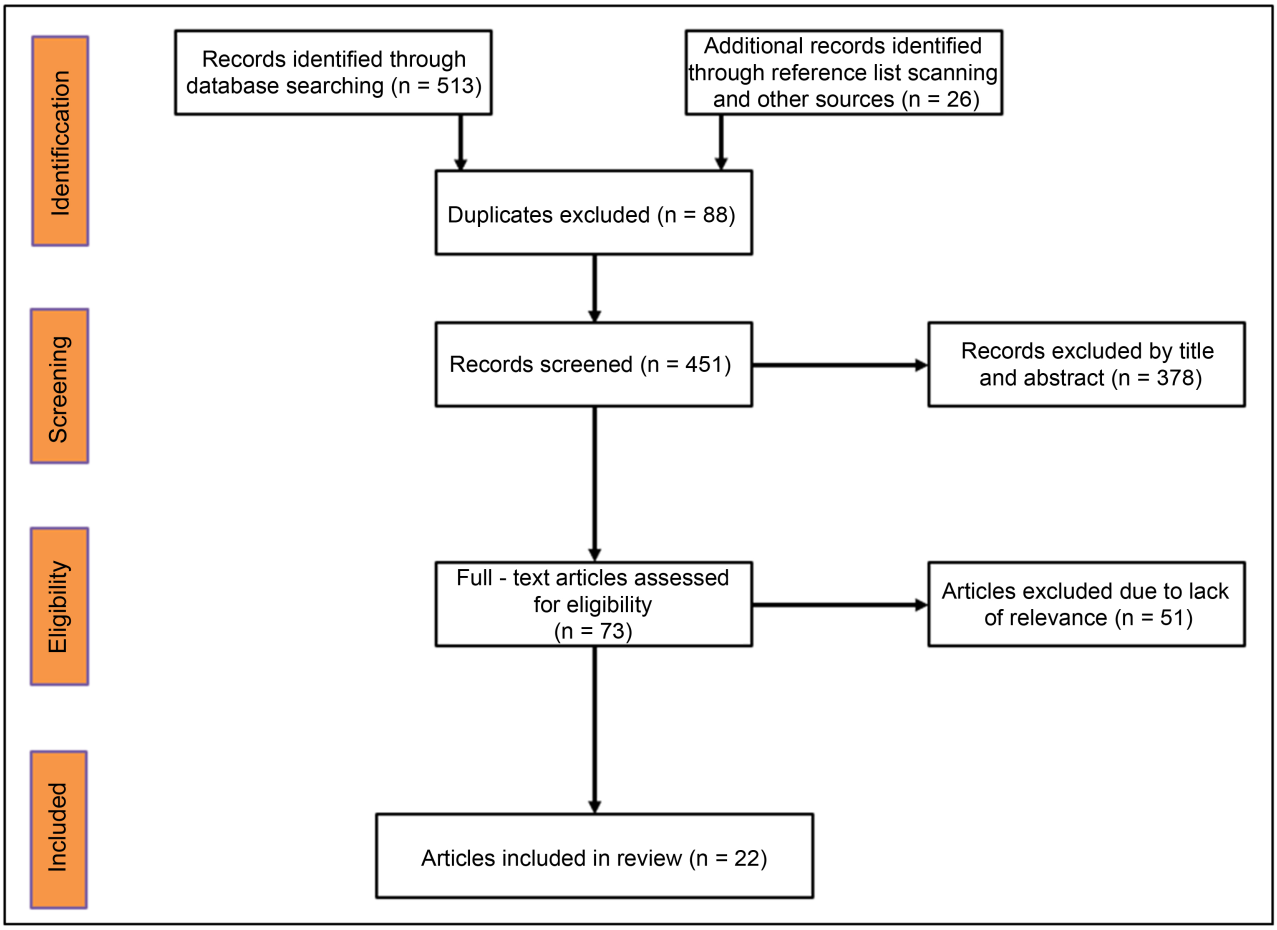

Figure 1. PRISMA flowchart.

stabilization on different soil mechanical properties through the application of lime, fly ash and cement. From the findings presented in **Table 1**, lime, cement, and fly ash have significant effects on different mechanical properties such as plasticity, swelling, UCS, CBR, OMC and MDD. The effects of the three stabilizers (fly ash, cement, and lime) on soil mechanical properties as cited in the reviewed articles summarised in **Table 1** are further shown in **Table 2**.

From the results in **Table 2**, a significant number of studies found that lime soil stabilization significantly improves the mechanical properties of soil such as plasticity, CBR, UCS, OMC and MDD and reduce swelling (Ali and Yousof, 2019 [36]; Andavan and Pagadala, 2020 [41]; Asgari *et al.*, 2015 [34]; Krithiga *et al.*, 2017 [40]; Navale *et al.*, 2016 [43]; Sharma and Hymavathi, 2016 [28]; Shekhar and Saxena, 2018 [15]; Talabi *et al.*, 2019 [42]; Zhou *et al.*, 2019 [38]). However, a few studies (Okonkwo and Kennedy, 2023 [4]; Rai *et al.*, 2021 [27]) found that soil stabilization using lime reduces plasticity and OMC. In overall, soil stabilization using lime has proved to have a significant improvement on the mechanical properties of soil. The findings are consistent with those of previous studies (Jin and Li, 2019 [20]; Salimah *et al.*, 2021 [17]; Taki and Bhattacharya, 2020 [29]; Utami, 2014 [13]) which found that lime significantly improve soil

Table 2. Summarised effects of fly ash, cement and lime soil stabilization.

	Plasticity	Swelling	CBR	UCS	OMC	MDD	Reference
Lime	Increase/ Reduce	Reduce	Increase	Increase	Increase/ Decrease	Increase	Ali and Yousof, 2019 [36]; Andavan and Pagadala, 2020 [41]; Asgari *et al.*, 2015 [34]; Krithiga *et al.*, 2017 [40]; Navale *et al.*, 2016 [43]; Okonkwo and Kennedy, 2023 [4]; Rai *et al.*, 2021 [27]; Sharma and Hymavathi, 2016 [28]; Shekhar and Saxena, 2018 [15]; Talabi *et al.*, 2019 [42]; Zhou *et al.*, 2019 [38]
Cement	Increase	Reduce	Increase	Increase	Increase/ Decrease	Increase	Bayat *et al.*, 2015 [35]; Mahedi *et al.*, 2020 [14]; Nguyen and Phan, 2021 [39]; Okonkwo and Kennedy, 2023 [4]; Rai *et al.* [27]., 2021; Sharma *et al.*, 2018 [28]; Shekhar and Saxena, 2018 [15]; Talabi *et al.*, 2019 [42]
Fly ash	Increase	Reduce	Increase	Increase	Increase	Increase	Andavan and Pagadala, 2020 [41]; Krithiga *et al.*, 2017; Mir, 2015; Navale *et al.*, 2016 [43]; Nguyen and Phan, 2021 [39]; Shekhar and Saxena, 2018 [15]; Teerawattanasuk and Voottipruex, 2019 [37]; Zhou *et al.*, 2019 [38]

mechanical properties.

Similarly, from the reviewed experimental studies, it has been noted that just like lime, cement soil stabilization significantly improves most of the mechanical properties of soil. From the results in **Table 1** and **Table 2**, stabilization of soil using cement improve mechanical properties of soil such as plasticity, CBR, UCS, OMC and MDD whilst reducing soil swelling (Bayat *et al.*, 2015 [35]; Mahedi *et al.*, 2020 [14]; Nguyen and Phan, 2021 [39]; Sharma *et al.*, 2018 [28]; Shekhar and Saxena, 2018 [15]; Talabi *et al.*, 2019 [42]). Contrastingly, a few studies by Okonkwo and Kennedy (2023) [4] and Rai *et al.* (2021) [27] found that cement soil stabilization reduce OMC. In overall, the results indicate that cement soil stabilization significantly improves the mechanical properties of soil. The findings are in line with the findings of previous studies such as Nazari *et al.* (2021) [21] and Shooshpasha and Shirvani (2015) [22] which found that cement soil stabilization has significant positive effects on soil mechanical properties such as permeability, strength, and stability of soil.

Furthermore, from the included articles, the majority of the experimental studies (Andavan and Pagadala, 2020 [41]; Krithiga *et al.*, 2017 [40]; Mir, 2015; Navale *et al.*, 2016 [43]; Nguyen and Phan, 2021 [39]; Shekhar and Saxena, 2018 [15]; Teerawattanasuk and Voottipruex, 2019 [37]; Zhou *et al.*, 2019 [38]) revealed soil stabilization using fly ash improved soil strength as measured by CBR and UCS. These results clearly indicate that fly ash-soil stabilization significantly improves the mechanical properties of soil such strength. The findings agree with the findings of previous studies (such as Dayalan and Dayalan, 2016 [18]; Turan *et al*., 2022a; 2022b [19]; Vinai *et al*., 2019 [2]) which found fly ash significantly improves soil mechanical properties such as strength and stability.

Besides, the reviewed studies have shown that among the three stabilizers (fly ash, cement, and lime), there are some more effective compared to others. In terms of cement, the study by Mahedi *et al.* (2020) [14] found that cement is more effective in soil stabilization compared to lime and fly ash. Similarly, Sharma *et al.* (2018) [28] revealed that cement has relatively higher effects on mechanical properties of soil compared to lime. Supporting evidence was also obtained from the studies by Asgari *et al.* (2015) [34], Bayat *et al.* (2014) [35] and Okonkwo and Kennedy (2023) [4] which revealed that improvements in soil mechanical properties were relatively higher in cement treatment compared to lime treatment.

However, studies such as Rank *et al.* (2019) [33] found that fly ash has significant effects on soil mechanical properties compared to cement. Similar to Rank *et al.* (2019) [33], Teerawattanasuk and Voottipruex (2019) [37] found that fly ash stabilized soil had higher CBR values compared to cement-stabilized soil. Rai *et al.* (2021) [27] also established that fly ash is more effective compared to cement. Also, the study by Zhou *et al.* (2019) [38] reported that fly ash showed better soil strength compared to lime. Kalyane and Patil (2020) [25] also found that fly ash is more effective compared to lime. In the context of Vietnam, Nguyen, and Phan (2021) [39] also proved that fly ash had significant effects compared to cement. The experimental studies by Andavan and Pagadala (2020) [41], Arias-Jaramilo *et al.* (2023) [3], Krithiga *et al.* (2017) [40] and Mir (2015) also revealed that soil stabilization using fly ash is more effective in soil strengthening compared to lime.

On the other hand, several studies reported that lime is the most effective soil stabilizing agent. For instance, Sharma and Hymavathi (2016) [28] and Rank *et al.* (2019) [33] concluded that lime is the best soil stabilizing agent compared to fly ash. Consistent with Sharma and Hymavathi (2016) [28], Ali and Yousuf (2019) [36] found that lime stabilization is more efficient compared to cement stabilization. Comparably, Saleem *et al.* (2020) [12] and Talabi *et al.* (2019) [42] revealed that lime is more effective in improving strength and stability of soil compared to cement. In their experimental research, Shekhar and Saxena (2018) [15] found that lime stabilized soil had higher CBR values compared to cement and fly ash stabilized soil. Navale *et al.* (2016) [43] found that lime was more effective compared to fly ash.

From the aforementioned analyses, out of the included articles, majority them proved that fly ash is the most effective soil stabilizing agent compared to alternatives such as cement and lime. However, Shekhar and Saxena (2018) [15] concluded that whilst fly ash alone works much better as a soil stabilizing agent, a combination of cement, lime and fly ash can be more effective and beneficial. In the same view, Lindh and Lemenkova (2023) [23] reported that best performance in soil stabilization can be attained by blending cement, lime, and fly ash. Similarly, Kalyane and Patil (2020) [25] concluded that a combination of lime and fly ash proves to very effective as it results in improved soil strength. Arias-Jaramillo *et al.* (2023) [3] also concluded that mixture of lime and fly ash demonstrated increased bearing capacity compared to cement and lime. The technique of blending admixtures was also supported by Okonkwo and Kennedy's (2023) [4] study which concluded when used together, cement and lime provide significant outcomes in terms of soil strength and stability.

Effects of Combinations of Soil Stabilization on Mechanical Properties

Through out this paper we assesed individual soil stabilizers, however there are situations where they are combined in an attempt to give satisfactory results to engineering. The three stabilizers fly ash, lime and cement analyzed here provide us with 3 combinations: 1) fly ash and cement 2) lime and cement 3) fly ash and lime.

Table 3 below outlines the pros and cons of soil stabilizers combinations.

4.2. Discussion

Firstly, this paper has discussed the effects of soil stabilization on soil mechanical properties using three different materials—fly ash, cement and lime individually. It is explained how each material affects the strength, compressibility, and permeability of the soil. It also compared the effectiveness of each material, and found that fly ash and lime are the most effective when used together. These findings ultimately suggested that lime and fly ash are great in many engineering aspects and even better more when compared.

Looking at the effect of fly ash and lime on soil strength. Fly ash is known to increase the strength of the soil by filling in the voids between the soil particles. This reduces the amount of water that can be held by the soil, and also makes the soil more resistant to compression. Lime, on the other hand, works by increasing the pH of the soil and causing the soil particles to flocculate (stick together). This makes the soil more cohesive and resistant to shearing. When fly ash and lime are used together, they work synergistically to increase the strength of the soil even further.

Fly ash and lime combined together were more compatible. Here are several reasons why fly ash and lime are more compatible than the other combinations you mentioned. First, the chemical composition of fly ash and lime is similar, which means they react well together. Second, the pH levels of fly ash and lime are close to each other, so they don't react negatively with each other. Third, the physical properties of fly ash and lime are also similar, which means they can be mixed easily without causing problems. Fourth, fly ash and lime are both abundant compatible combinations than the other options you mentioned. Fly ash and lime have a lower environmental impact than cement, and can also help to reduce

Table 3. Summarised effects of cimbining soil stabilizers.

Combination	Advantages and Disadvantages	Supporting Articles and Papers
Lime and Cement	Advantages: 1) Improved strength and durability: The combination of lime and cement can significantly increase the strength and durability of the stabilized soil, making it suitable for various construction applications. 2) Reduced plasticity: Lime and cement can help reduce the plasticity of the soil, making it less susceptible to volume changes due to moisture variations. 3) Enhanced workability: The addition of lime and cement can improve the workability of the soil, making it easier to handle and compact. 4) Environmental benefits: Stabilizing soil with lime and cement can lead to reduced environmental impact by minimizing the need for importing or exporting soil materials. 5) Reduced swelling potential of the soil as well as faster setting and hardening of the soil. Disadvantages 1) Cost: The use of lime and cement as soil stabilizers can be expensive, especially for large-scale projects. 2) Environmental considerations: Cement production is associated with high carbon emissions, which can have environmental implications. 3) Long-term performance: The long-term performance of lime and cement stabilized soil may be influenced by factors such as environmental conditions and maintenance. 4) Potential for alkali-silica reaction and an increased risk of shrinkage cracking.	- "Stabilization of Clayey Soil Using Lime and Cement" by M. N. Akhtar, S. M. Jamil, and M. A. Khan (Journal of Materials in Civil Engineering) - "Effect of Lime and Cement Stabilization on the Engineering Properties of Expansive Clay Soil" by M. A. Al-Abdul Wahhab and M. A. Basma (Journal of Geotechnical and Geoenvironmental Engineering) - "Strength and Durability Characteristics of Lime and Cement Stabilized Soil" by S. S. Singh and S. K. Kaushik (International Journal of Geotechnical Engineering) [11] - "Environmental Impact of Cement Production: Detail of the Different Processes and Cement Plant Variability Evaluation" by M. I. Martínez and I. M. C. de Guzmán (Journal of Cleaner Production) - "Cost-Effective Soil Stabilization for Sustainable Pavement Construction" by A. K. Pathak and S. K. Shukla (International Journal of Pavement Engineering)
Lime and fly ash	Advantages: 1) Cost-effectiveness: Using lime and ash as soil stabilizers can be cost-effective compared to other stabilizing agents, making it an attractive option for construction projects. 2) Improved workability: The addition of lime and ash can enhance the workability of the soil, making it easier to handle and compact during construction. 3) Environmental benefits: The use of ash, a byproduct of combustion, can provide a sustainable solution for disposing of waste materials while contributing to soil stabilization. 4) Reduced plasticity: Lime and ash can help reduce the plasticity of the soil, making it less susceptible to volume changes due to moisture variations. Disadvantages: 1) Long-term performance: The long-term performance of lime and ash stabilized soil may be influenced by factors such as environmental conditions and maintenance, and may require periodic reapplication. 2) Variability of ash properties: The properties of ash can vary depending on the source and combustion process, which may impact the effectiveness of soil stabilization.	Supporting Journals: - "Utilization of Lime and Fly Ash for Soil Stabilization" by S. K. Singh and A. K. Jain (Journal of Materials in Civil Engineering) [11] - "Effect of Lime and Ash Stabilization on the Engineering Properties of Soil" by A. K. Pathak and S. K. Shukla (International Journal of Geotechnical Engineering) - "Sustainable Soil Stabilization Using Lime and Ash" by M. A. Al-Abdul Wahhab and M. A. Basma (Journal of Sustainable Development) Supporting Journals: - "Assessment of the Engineering Properties of Lime and Ash Stabilized Soil" by M. N. Akhtar, S. M. Jamil, and M. A. Khan (Journal of Geotechnical and Geoenvironmental Engineering) - "Long-Term Performance of Lime and Ash Stabilized Soil in Pavement Construction" by R. K. Trivedi and S. R. Gupta (International Journal of Pavement Engineering)

Continued

Lime and fly ash	3) Limited strength improvement: Lime and ash may not provide as significant strength improvement as other stabilizing agents such as cement	
Fly ash and Cement	Advantages: 1) Environmental benefits: The use of fly ash, a byproduct of coal combustion, as a soil stabilizer can provide a sustainable solution for disposing of waste materials while contributing to soil stabilization. 2) Improved workability: The addition of fly ash and cement can enhance the workability of the soil, making it easier to handle and compact during construction. 3) Reduced plasticity: Fly ash and cement can help reduce the plasticity of the soil, making it less susceptible to volume changes due to moisture variations. 4) Increased long-term strength: The combination of fly ash and cement can lead to increased long-term strength and durability of the stabilized soil, making it suitable for various construction applications. Disadvantages: 1) Cost: The use of fly ash and cement as soil stabilizers can be expensive, especially for large-scale projects, due to the cost of cement and transportation of fly ash. 2) Variability of fly ash properties: The properties of fly ash can vary depending on the source and combustion process, which may impact the effectiveness of soil stabilization. 3) Environmental considerations: Cement production is associated with high carbon emissions, which can have environmental implications.	Supporting Journals: - "Utilization of Fly Ash and Cement for Soil Stabilization" by S. K. Singh and A. K. Jain (Journal of Materials in Civil Engineering) [11] - "Effect of Fly Ash and Cement Stabilization on the Engineering Properties of Soil" by A. K. Pathak and S. K. Shukla (International Journal of Geotechnical Engineering) - "Sustainable Soil Stabilization Using Fly Ash and Cement" by M. A. Al-Abdul Wahhab and M. A. Basma (Journal of Sustainable Development) Supporting Journals: - "Environmental Impact of Cement Production: Detail of the Different Processes and Cement Plant Variability Evaluation" by M. I. Martínez and I. M. C. de Guzmán (Journal of Cleaner Production) - "Cost-Effective Soil Stabilization for Sustainable Pavement Construction" by A. K. Pathak and S. K. Shukla (International Journal of Pavement Engineering)

the amount of carbon dioxide emissions associated with construction projects. This is also seen and proven in studies done on the following researches, Deflection analysis of flexible pavements-Materials and Test Division Report Passuello A. Rodríguez E. D. Hirt E. Longhi M. Bernal S. A. Provis J. L. Kirchheim A. P. Construction and Building Materials (2015), Quantification and micro-mechanisms of CO_2 sequestration in magnesia-lime-fly ash/slag solidified soils Wang D. Zhu J. He F. International Journal of Greenhouse Gas Control (2019), 10.1016/j.ijggc.2019.102827, Improved mechanism of expansive soils by lime and fly-ash Hui H. Q. Hu T. K. Wang X. D. Chang'an Daxue Xuebao (Ziran Kexue Ban)/Journal of Chang'an University (Natural Science Edition) (2006).

5. Conclusions

The main purpose of this systematic review was to compare the effects of soil stabilization on mechanical proprieties of soil using lime, cement, and fly ash. From the systematic review conducted focusing on articles published between 2013 and 2023 guided by the PRISMA guidelines, the effects of soil stabilization on mechanical properties were established. From the outcomes of the systematic review, it can be concluded that soil stabilization using either lime, cement or fly ash has significant effects on the mechanical properties of soil. The results of the systematic review indicated that all three stabilizers (cement, lime, and fly ash) can significantly improve soil mechanical properties such as strength and stability. Overall, fly ash was found to be the most effective soil stabilizer in terms of reducing soil plasticity and increasing strength according to the outcomes of the systematic review.

Fly ash showed great results in improving soil mechanical properties compared to lime and cement. Therefore, based on the outcomes, it can be concluded that fly ash represents the most effective soil stabilizing agent for geotechnical and civil engineers. However, whilst fly ash alone can be more effective in soil stabilization, a combination of cement, lime and fly ash can be more effective. We therefore also noted that combinations of lime and fly ash bring satisfactory results. Lastly, it is noteworthy to mention that the effects of soil stabilization by lime, fly ash and cement can also vary with type of soil. Overall, the findings highlighted the potential of soil stabilizing agents in enhancing the mechanical properties of soils and hence provide valuable insights for geotechnical and civil engineers and practitioners. Nevertheless, further experimental or field studies are required to comprehensively compare the short-term and long-term effects of fly ash, cement, and lime on soil mechanical properties.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Sinha, P. and Iyer, K.K.R. (2020). Effect of Stabilization on Characteristics of Subgrade Soil: A Review. In: Prashant, A., Sachan, A. and Desai, C., Eds., *Advances in Computer Methods and Geomechanics*, Springer, Singapore, 667-682. https://doi.org/10.1007/978-981-15-0886-8_54

[2] Vinai, R., *et al.* (2019) Mechanical Properties of Calcareous Fly Ash Stabilized Soil. *Proceedings of the EUROCOALASH Conference*, Dundee, 10-12 June 2019, 2.

[3] Arias-Jaramillo, Y.P., Gómez-Cano, D., Carvajal, G.I., Hidalgo, C.A. and Muñoz, F. (2023) Evaluation of the Effect of Binary Fly Ash-Lime Mixture on the Bearing Capacity of Natural Soils: A Comparison with Two Conventional Stabilizers Lime and Portland Cement. *Materials*, **16**, 3996-4012. https://doi.org/10.3390/ma16113996

[4] Okonkwo, U.N. and Kennedy, C. (2023) The Effectiveness of Cement and Lime as Stabilizers for Subgrade Soils with High Plasticity and Swelling Potential. *Saudi Journal of Civil Engineering*, **7**, 40-60. https://doi.org/10.36348/sjce.2023.v07i03.001

[5] Dias-Miguel, G., Scheuermann Filho, H.C., Festugato, L. and Bellaver Corte, M. (2021) Discussion of Cement, Lime, and Fly Ashes in Stabilizing Expansive Soils: Performance Evaluation and Comparison. *Journal of Materials in Civil Engineering*, **33**, 1-12. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003867

[6] Hamzah, H.N., Al Bakri Abdullah, M.M., Heah, C.Y., Arif Zainol, M.R.R. and Kamarudin, H. (2015) Review of Soil Stabilization Methods: Geopolymerization Me-

thod One of the New Techniques. *Key engineering materials*, **660**, 298-304. https://doi.org/10.4028/www.scientific.net/KEM.660.298

[7] Babu, N. and Poulose, E. (2018) Effect of Lime on Soil Properties: A Review. *International Research Journal of Engineering and Technology*, **5**, 606-610.

[8] Jawad, I.T., Taha, M.R., Majeed, Z.H. and Khan, T.A. (2014) Soil Stabilization Using Lime: Advantages, Disadvantages and Proposing a Potential Alternative. *Research Journal of Applied Sciences, Engineering and Technology*, **8**, 510-520. https://doi.org/10.19026/rjaset.8.1000

[9] Zuber, S.S., Kamarudin, H., Abdullah, M.M.A.B. and Binhussain, M. (2013) Review on Soil Stabilization Methods. *Australian Journal of Basic and Applied Sciences*, **7**, 258-265.

[10] Shah, K.A. and Ahmad, E. (2020) A Study on Alluvial Soil Stabilization Using Bitumen Emulsion. *International Journal of Engineering Research*, **9**, 229-239. https://doi.org/10.17577/IJERTV9IS060213

[11] Singh, R., Ray, D.S., Mehrotra, A. and Mohammad, A.K. (2018) A Review Paper on Comparative Study of Soil Stabilization with Widely Used Admixtures Like Lime, CEMENT, Flyash and Bitumen. *International Journal of Engineering Trends and Technology*, **58**, 1-4. https://doi.org/10.14445/22315381/IJETT-V58P218

[12] Saleem, K., Kumar, A. and Singh, S. (2020) Comparative Study of Soil Stabilization Using Lime and Cement. *International Journal of Scientific Development and Research*, **5**, 111-117.

[13] Utami, G.S. (2014) Clay Soil Stabilization with Lime Effect the Value CBR and Swelling. *ARPN Journal of Engineering and Applied Sciences*, **9**, 1744-1748.

[14] Mahedi, M., Cetin, B. and White, D. J. (2020) Cement, Lime, and Fly Ashes in Stabilizing Expansive Soils: Performance Evaluation and Comparison. *Journal of Materials in Civil Engineering*, **32**, 177-195. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003260

[15] Shekhar, A. and Saxena, N.K. (2018) A Comparative Study of Soil Stabilization Using Cement, Lime and Fly Ash. *International Journal of Science and Research*, **7**, 979-984.

[16] Makusa, G.P. (2013) Soil Stabilization Methods and Materials in Engineering Practice: State of the Art Review. Luleå University of Technology Luleå, Sweden.

[17] Salimah, A., Hazmi, M., Hasan, M.F.R. and Agung, P.A.M. (2021) A Comparative Study of Red Brick Powder and Lime as Soft Soil Stabilizer. *F1000Research*, **10**, 777-786. https://doi.org/10.12688/f1000research.27835.1

[18] Dayalan, J. and Dayalan, J. (2016) Comparative Study on Stabilization of Soil with Ground Granulated Blast Furnace Slag (GGBS) and Fly Ash. *International Research Journal of Engineering and Technology*, **3**, 5-11.

[19] Turan, C., Javadi, A.A. and Vinai, R. (2022) Effects of Class C and Class F Fly Ash on Mechanical and Microstructural Behaviour of Clay Soil—A Comparative Study. *Materials*, **15**, 1845-1869. https://doi.org/10.3390/ma15051845

[20] Jin, Q. and Li, B. (2019) Effects of Lime Treatment on the Geotechnical Properties of Dredged Mud. *Marine Georesources and Geotechnology*, **37**, 1083-1094. https://doi.org/10.1080/1064119X.2018.1527421

[21] Nazari, Z., Tabarsa, A. and Latifi, N. (2021) Effect of Compaction Delay on the Strength and Consolidation Properties of Cement-Stabilized Subgrade Soil. *Transportation Geotechnics*, **27**, 100495-100510. https://doi.org/10.1016/j.trgeo.2020.100495

[22] Shooshpasha, I. and Shirvani, R.A. (2015) Effect of Cement Stabilization on Geotechnical Properties of Sandy Soils. *Geomechanics and Engineering*, **8**, 17-31. https://doi.org/10.12989/gae.2015.8.1.017

[23] Lindh, P. and Lemenkova, P. (2023) Geotechnical Properties of Soil Stabilized with Blended Binders for Sustainable Road Base Applications. *Construction Materials*, **3**, 110-126. https://doi.org/10.3390/constrmater3010008

[24] Tripathi, P. (2020) Evaluation and Analysis of Soil Stabilisation with Some Non-Conventional Additives. Master's Thesis, Babu Banarasi Das University, Lucknow.

[25] Kalyane, A. and Patil, R. J. (2020) Experimental Investigation of Black Cotton Soil by Lime and Fly-Ash Stabilization. *Acta Technica Corviniensis-Bulletin of Engineering*, **13**, 83-88.

[26] Archibong, G.A., Sunday, E.U., Akudike, J.C., Okeke, O.C. and Amadi, C. (2020) A Review of the Principles and Methods of Soil Stabilization. *International Journal of Advanced Academic Research*, **6**, 89-115.

[27] Rai, P., Qiu, W., Pei, H., Chen, J., Ai, X., Liu, Y. and Ahmad, M. (2021) Effect of Fly Ash and Cement on the Engineering Characteristic of Stabilized Subgrade Soil: An Experimental Study. *Geofluids*, **2021**, Article ID: 1368194. https://doi.org/10.1155/2021/1368194

[28] Sharma, L.K., Sirdesai, N.N., Sharma, K.M. and Singh, T.N. (2018) Experimental Study to Examine the Independent Roles of Lime and Cement on the Stabilization of a Mountain Soil: A comparative study. *Applied Clay Science*, **152**, 183-195. https://doi.org/10.1016/j.clay.2017.11.012

[29] Taki, K. and Bhattacharya, P. (2020) Comparative Study of Expansive and Non-Expansive Soils Stabilized with Lime and Rice Husk Ash (RHA). In: Prashant, A., Sachan, A. and Desai, C.S., Eds., *Advances in Computer Methods and Geomechanics: IACMAG Symposium*, Springer, Singapore, 553-563. https://doi.org/10.1007/978-981-15-0886-8_45

[30] Firoozi, A.A., Guney Olgun, C., Firoozi, A.A. and Baghini, M.S. (2017) Fundamentals of Soil Stabilization. *International Journal of Geo-Engineering*, **8**, 1-16. https://doi.org/10.1186/s40703-017-0064-9

[31] Afrin, H. (2017) A Review on Different Types Soil Stabilization Methods. *International Journal of Transportation Engineering and Technology*, **3**, 19-24. https://doi.org/10.11648/j.ijtet.20170302.12

[32] Huang, J., Kogbara, R.B., Hariharan, N., Masad, E.A. and Little, D.N. (2021) A State-of-the-Art Review of Polymers Used in Soil Stabilization. *Construction and Building Materials*, **305**, 124685-124695. https://doi.org/10.1016/j.conbuildmat.2021.124685

[33] Rank, K., Bhanderi, J., Mehta, J.V., Marsonia, S. and Harshrai, T. (2019) Comparative Study on Effect of Expansive Soil Properties While Using Stabilizer as Lime Fly ash and Cement Dust Manufacturing Waste. *Journal of Emerging Technologies and Innovative Research*, **6**, 269-275.

[34] Asgari, M.R., Baghebanzadeh, A. and Bayat, M. (2015) Experimental Study on Stabilization of a Low Plasticity Clayey Soil with Cement/Lime. *Arabian Journal of Geosciences*, **8**, 1439-1452. https://doi.org/10.1007/s12517-013-1173-1

[35] Bayat, M., Asgari, M.R. and Mousivand, M. (2014) Effects of Cement and Lime Treatment on Geotechnical Properties of a Low Plasticity Clay. *International Conference on Civil Engineering Architecture and Urban Sustainable Development*, Tabriz, Iran, 27-28 November 2013, 376-390.

[36] Ali, S.A. and Yousuf, Y. (2019) Effect of Cement and Lime on the Index Properties of Nizwa Clayey Soil. *International Journal of Innovations in Engineering and Technology*, **14**, 45-52.

[37] Teerawattanasuk, C. and Voottipruex, P. (2019) Comparison Between Cement and Fly Ash Geopolymer for Stabilized Marginal Lateritic Soil as Road Material. *International Journal of Pavement Engineering*, **20**, 1264-1274. https://doi.org/10.1080/10298436.2017.1402593

[38] Zhou, S.Q., Zhou, D.W., Zhang, Y.F. and Wang, W.J. (2019) Study on Physical-Mechanical Properties and Microstructure of Expansive Soil Stabilized with Fly Ash and Lime. *Advances in Civil Engineering*, **2019**, Article ID: 4693757. https://doi.org/10.1155/2019/4693757

[39] Nguyen, D.T. and Phan, V.T.A. (2021) Engineering Properties of Soil Stabilized with Cement and Fly Ash for Sustainable Road Construction. *International Journal of Engineering*, **34**, 2665-2671. https://doi.org/10.5829/ije.2021.34.12c.12

[40] Krithiga, N., Pujitha, D., Palayam, T. and Revathy Sri Muthukumaran, A. (2017) Soil Stabilization Using Lime and Fly Ash. *International Journal of Civil Engineering*, **1**, 510-518.

[41] Andavan, S. and Pagadala, V.K. (2020) A Study on Soil Stabilization by Addition of Lime and Fly Ash. *Materials Today: Proceedings*, **22**, 1125-1129. https://doi.org/10.1016/j.matpr.2019.11.323

[42] Talabi, S.I., Awodiji, O. and Balogun, A.L. (2019) Comparative Analysis of Cement and Lime on the Engineering Properties of Subgrade Soil. *Journal of Materials and Environmental Science*, **10**, 453-462.

[43] Navale, A.V., Gite, B.E., Mundada, M.D. and Kolhe, S.B. (2016) Soil Stabilisation Using Fly-Ash and Lime. *International Journal of Advance Research and Innovative Ideas in Education*, **2**, 4588-4596.