Transforming Soil Stabilization: Paving the way for Sustainable Development

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Abstract:

The history of soil stabilization techniques unveils a narrative dominated by a pursuit of immediate development gains, often at the expense of environmental considerations. In its nascent stages, conventional methods employing lime, cement, and similar agents were championed for their efficacy in achieving structural objectives, relegating environmental concerns to the periphery. Over time, the continued reliance on these methods led to an eye seeing escalation in environmental impacts, painting a sombre picture of unintended consequences. As years passed, the unrelenting use of these conventional techniques intensified the environmental toll, demanding a critical re-evaluation of the status quo. However, the allure of rapid achievement continued to overshadow the imperative for sustainable alternatives. The environment bore the brunt of this persistent inertia, as degradation became more pronounced. In the wake of technological advancements, a promising model shift has emerged in the realm of soil stabilization. The focus now lies in forging pathways that balance the imperatives of development with the imperative of safeguarding our fragile ecosystems. Central to this evolution are the advent and refinement of sustainable techniques, including the utilization of biopolymers, geo-polymers, bio-cementation, and natural fibres. These innovations signify a departure from the environmentally taxing conventional agents, promising a more harmonious coexistence with nature. This paper summarizes the trans-formative journey of soil stabilization techniques, predicting a shift towards a more sustainable and environmentally considerate approach. Through the adoption of these nature-friendly methodologies, we embark on a trajectory where development and environmental preservation are no longer dissimilar goals, but rather easily intertwined work.

Keywords: Soil stabilization; Environmental considerations, Geopolymers, Biopolymers.

1 INTRODUCTION

Soils with low strength and low bearing capacity exist from time immemorial. The development in science and medicine has certainly benefited the humanity with improved lifespan and accessibility. As the coin, the benefits also have its drawbacks. The rising population need homes and roads for their ease of living. Understanding the arising issues, soil stabilization became prominent to build structure on poor strength soils. Soil stabilization dates to 5000 yrs. Lime was historically used by the Greeks and Romans to stabilize soils, and ancient civilizations like Egypt and Mesopotamia developed stabilized earth roads. However, sulfate-rich subgrades treated with cement and lime had issues because the calcium in these stabilizers reacted with the sulfates and alumina in the soil to generate the expansive mineral ettringite. Due to their propensity to expand, collapse, scatter, experience excessive settlement, clearly lack strength, or be soluble, soils can be troublesome in nature [Fattah et al., 2014]. Problematic soils can be broadly classified as expansive, dispersive, and collapsible soils [Rezaei et al., 2011]. When clay particles in a soil reject one another more than they attract one another, dispersion occurs. When there is water present, this leads to the particles separating and forming tiny, suspended particles. There is a certain water flow velocity in non-dispersive soils below which the soil is stable and water erosion doesn't take place. Only water flowing with a specific amount of force can separate the particles since they are attracted to one another. Dispersive soil erosion is influenced by several variables, such as the type of clay minerals present, pH levels, organic matter, temperature, moisture content, thixotropy (the quality of becoming less viscous when moved or agitated), and the kind and concentration of ions in the water and soil Collapsible soils are sensitive to changes in moisture, and an increase in moisture content is the primary reason why they lose volume [Gali et al.,2020]. These soils, including loess and some wind-blown silts, are capable of collapsing, although there are other varieties as well. Collapsible soils are usually quite light and have a porous structure with lots of empty areas. They can store a substantial quantity of water in their unaltered native condition. These soils appear sturdy while dry, but they can quickly contract and grow denser when they get wet. In other words, as the connections between the soil particles break because of moisture, the soil particles reorganize themselves into a more compact shape [Rezaei et al., 2011]. Expansive soils are problematic due to their property for shrink-well phenomenon. The deformation in expansive soil causes massive problems in lightweight engineering construction. It faces worldwide geotechnical and structural challenges [Zada et al.,2023]. The other problematic soil is peat soil, it comes under organic soil. Organic soil is problematic in nature. However, the amount of organic content defines whether the soil is peat or not. Peat soil are form due to the partial decomposition of plant material at anaerobic water saturated condition. The type of peat is defined according to their humification level. Soils namely peat, black cotton soil, loess etc. are some of highlighted problematic soils for this paper. Thus, stabilization plays a role in improvement of their engineering properties. The use of cement and lime is common due to their effectiveness. However, the contender for best suitable stabilizer depends on the type of soil and its location. Stabilization in broad sense can be done in 2 ways , either by mechanical or chemical stabilization. Blending of different soils, compaction, soil replacement, soil reinforcement, pre-wetting and wetting drying cycles are types of mechanical soil stabilization. As for chemical soil stabilization, cement and lime is consider as traditional stabilizer [Abdila et al.,2022]. The use of GGBS(Ground granulated blast furnace slag), bottom ash, fly ash, silica fume is term as non-traditional chemical stabilization[Lee et al.,2011]. With the advancement of research, industrial by-product like fly ash, ggbs, kaolinite clay etc. are used to produce geopolymer which results in geopolymer stabilization of problematic soil. Bio polymer, bio enzyme and bio-cementation are some of the latest ways to stabilize a problematic soil.

2 PROGRESS OF SOIL STABILIZATION

2.1 Advent of cement and lime

The first recorded soil stabilization using cement or lime was done in early 1900s. In the United States, tests on soil stabilization started in 1904. In Sarasota, Florida, a road was built in 1915 using cement to fortify the soil, and in 1924, lime was used for the first time to widen roadways to accommodate the rising number of automobiles [Zada et al.,2023]. Weak soil stabilization using lime and cement are effective as it increases the unconfined compressive strength of the soil, which is one of the important engineering properties of soil. Lime and cement were used by adding 10% and 20% of lime and cement respectively with peat. It has been observed that a large increase in the content of cement and lime increases the angle of shear resistance and cohesiveness of peat. When it comes to the shear strength of peat soil, lime performs better than cement [Zambri and Ghazaly, 2018]. Impact of lime, cement, combinations of both, and Sarooj (an artificial pozzolan) on expansive soil was examined. Atterberg limit and swelling tests were conducted to assess changes in treated soil compared to untreated soil. Swell pressure and swell percent reduced significantly in most cases, except for Sarooj, which exhibited increased swell pressure with 6% and 9% additions. The addition of 6% lime resulted in a complete reduction of both swell pressure and swell percent [Al-Rawas et al., 2005]. Curing period also plays a main role in soil stabilization. Peat stabilized with OPC are analyzed for different curing styles. Moist curing with 50% OPC and surcharge load was found to be most effective. Most of the research on peat soil stabilization improve the strength of peat soil when lime and cement were added into the soil at varying quantity. The optimum amount which produces the best result differs from soil to soil and depends on the stabilizer. Peat soil stabilization are most done by using other additives/admixtures other than cement or lime. Cement hydration increases the bearing capacity of clayey soil while simultaneously reducing permeability for the soil at room temperature [Yu et al., 2022]. The influence of cement content on the strength of the cement-stabilized weak clayey soil samples was investigated using the UCS test, soaking CBR test, third point loading test, and plate load test

[Pongsivasathit et al., 2019]. However, as cement use grows, several environmental problems are beginning to arise. Cement production is a very energy-intensive process that releases a lot of CO2, depleting natural resources and producing dust [Ghadir and Ranjbar, 2018]. In order to improve structural qualities, the compressive strength and longevity of Red Soil, also referred to locally as "Hamrah," which was collected from two distinct locations in Al-Hofuf, Eastern Saudi Arabia, was stabilized using Portland cement and lime at varying percentages (0, 2.5, 5, 7.5, 10, 15% of dry soil weight). The Red Soils were successfully stabilized with just 5% cement content, as demonstrated by the 28-day strength of 2.59 MPa, which met the required 2 MPa strength. However, a 10% lime concentration only managed to reach 1.46 MPa, indicating the little strength gain that hydrated lime could provide. Microstructural analysis through SEM and XRD revealed that cement treatment generated more fibrous formations, significantly enhancing strength compared to lime treatment [Zami et al., 2022]. The consciousness of human leads to the consideration of use of different materials in cement or lime based soil stabilization. The exact starting year for addition of pozzolanic material into cement or lime based stabilization differ according to region. The addition of pozzolanic materials in cement or lime based stabilization was started around mid-20th century. There are many materials which can be added in conventional method of soil stabilization. This includes industrial waste materials, aggregates, chemicals, pozzolans etc. The use of filler material in cement or lime based stabilization showed good result in stabilization. The use of additional material with cement or lime in soil stabilization has shown better results and effective in most of the research.

2.2 Geopolymer

Geopolymers, formed through the reaction of an alkaline reagent with alumina (Al2O3) and silica (SiO2)-rich aluminosilicate sources, are semi-crystalline and amorphous materials known for their strength, attributed to the N–A–S–H gel [Castillo et al.,2022]. These materials, created at low temperatures, involve natural aluminosilicates (clays) or aluminosilicate waste (e.g., fly ash, blast furnace slag) and alkalis or acids, a term coined "Geopolymer" by Davidovits in 1988. Geopolymer stabilization has found applications worldwide, including peat soil, with a focus on utilizing various materials and analyzing the impact of curing. The concentration of the alkaline activator significantly enhances soil stabilization. Various industrial waste materials like fly ash, GGBS, metakaolin, rice husk ash, silica fume, and burned trash can be converted into geopolymers [Parthiban et al.,2022]. One study explored enhancing Indian peat properties using rice husk ash geopolymer and examined the influence of additives on organic content. Geopolymer production involved varying the molarity of the alkaline solution, with optimal peat soil stabilization achieved at a 6M concentration of the alkaline solution [Khanday et al.,2021]. The alkaline activator, critical for geopolymerization, is created by combining sodium silicate and sodium hydroxide (NaOH). The study observed no discernible pattern in the compressive strength development of kaolin geopolymers with varying NaOH concentrations (6, 8, 10, 12, and 14 mol/L) and curing times [Heah et al., 2012]. Metakaolin-based geopolymer, utilizing a 2:1 ratio of metakaolin to alkali activator and a 1:1 ratio of quicklime to sodium bicarbonate, yielded optimal results at 10% metakaolin and 5% alkaline activator [Wang et al.,2021]. In a comparative study on riverside soft soil, geopolymer with 80% slag and 20% fly ash outperformed cement stabilization. The best results were achieved with 15% geopolymer content, with uniform CSH gel and NASH components visible as curing progressed. The optimum alkaline activator content was observed at 30%, showing a proportional relationship with NASH production and the amount of fly ash [Zhengdong, L. et al.,2022]. Stabilization of black cotton soil using GGBS-based geopolymer demonstrated its effectiveness, with the highest unconfined compressive strength achieved by adding 40% GGBS and an 8M NaOH solution for alkaline activation. The durability of GGBS-based geopolymer was tested through wetting-drying cycles, with only a 9.2% reduction in strength after 12 cycles [Noolu et al.,2021]. Metakaolin-based geopolymer proved effective in stabilizing high-plasticity clay (CH) and low-plasticity clay (CL). It significantly improved the unconfined compressive strength for CH and reduced the swelling potential for both soil types, ensuring stability [Samuel et al.,2021]. In summary, geopolymers offer a versatile and sustainable solution for soil stabilization, with varying materials and conditions affecting their performance in construction and environmental applications.

2.3 Biopolymer

Biopolymers, which naturally occur and are sourced from renewable resources, often exhibit non-toxic and biodegradable properties. They encompass polypeptides, polynucleotides, and polysaccharides, with polysaccharides readily derived from various plants such as cassava, maize, rice husk, and guar seeds (Ojuri et al., 2022; Kalia and Avérous, 2011). Biopolymers find a diverse array of applications spanning agriculture, biomedical engineering, food processing, the chemical industry, the energy sector, and environmental protection and remediation (Biju and Arnepalli, 2019). These versatile biopolymers possess the ability to bind metals, soil particles, and other biopolymers. They can encapsulate contaminants and effectively control soil erosion (Etemadi et al., 2003). The incorporation of biopolymers into soil leads to a reduction in Maximum Dry Density (MDD), an increase in Optimum Moisture Content (OMC), decreased hydraulic conductivity, higher CBR values, improved Unconfined Compressive Strength (UCS), enhanced shear resistance, and reduced permeability (Zada et al., 2023; Humza et al., 2022; Vydehi and Moghal, 2022; Ayeldeen et al., 2016). The specific outcomes with respect to MDD, OMC, CBR, and hydraulic conductivity vary depending on soil type, the type of biopolymer, dosage, and moisture content (Chang et al., 2020). Biopolymers hold great promise as an innovative technology for economically remediating hazardous soil sites, offering a carbon-neutral, sustainable, and environmentally friendly alternative to traditional materials like cement and lime (Rashid et al., 2017; Dehghan et al., 2018; Anandha et al., 2021; Ayeldeen et al., 2017; Sujatha and Saisree, 2019).

2.4 Bio - enzyme and Bio - cementation

Bio enzymes emerge as ecologically sustainable and economically viable alternatives to conventional soil improvement methodologies, promising sturdier and more sustainable construction solutions [Taha et al., 2013; Navale et al., 2019]. These revelations underscore the transformative potential of bio enzymes in the realm of soil enhancement, particularly in challenging soil types like Black Cotton Soil. Various studies spotlight promising outcomes of bio enzymes in soil amelioration. For instance, Terrazyme demonstrates a remarkable 200% increase in UCS for Black Cotton Soil, with optimal results achieved after a 7-day treatment period. The study recommends a Terrazyme dosage of 1 ml per 5 kg of soil for a balanced blend of effectiveness and cost-efficiency, positioning it as an environmentally conscious choice for bolstering soil strength. Furthermore, Dz-1X, highlighted by Sinha et al. (2018), showcases notable increases in shear strength and CBR values, even under soaked conditions. These outcomes substantiate the potency and budget-friendliness of bio enzymes, presenting significant advantages for construction ventures and infrastructure development. The eco-friendly and cost-effective attributes of bio enzymes emanate from their natural origins and their capacity to fortify soil for construction, resulting in substantial financial savings and reduced maintenance requirements [Navale et al., 2019]. In a study by Gomez et al. (2018), native ureolytic microorganisms were stimulated for Microbially Induced Calcite Precipitation (MICP) in granular soils from Woodland, California. Deeper soil layers showed higher ureolysis rates due to increased water and nutrient availability, significantly improving soil properties with Vs values reaching 1,020 m/s and unconfined compressive strengths up to 1.9 MPa, demonstrating the potential of native ureolytic microorganisms for geotechnical ground improvement. Fattahi et al. (2020) utilized Bacillus megaterium to create bio-cemented crusts on Minqin Desert sand, reducing erosion rates, emitted particles, and sand erodibility indicators, especially with airflow-induced erosion. Oliveira et al. (2019) harnessed ureolytic bacteria for soil stabilization via Microbially Induced Carbonate Precipitation (MICP). Pressure injection treatment delivered treatment solutions into deep soil regions, minimizing ammonium formation and calcium carbonate, addressing environmental concerns and enhancing economic sustainability, particularly for erosion control and soil improvement in road construction. applications.

2.5 Waste Material in soil stabilization

The review of literature on soil stabilization with various waste materials encompasses a range of studies. Ashiq et al. (2022) investigated the use of Industrial Waste Glass Powder (IWGP) for clay soil stabilization, finding that 20% IWGP addition significantly improved unconfined compressive strength (UCS) and California bearing ratio (CBR) while reducing swelling. Dang et al. (2021) focus on Bagasse ash (BA) for Queensland Road soil stabilization, achieving remarkable strength improvements, bearing capacity enhancement, and reduced compressibility with BA, lime, and their combination. Zhang et al. (2016)

explore lignin for silty soils, finding its mechanical properties superior to quicklime. Iravanian and Ahmed (2021) utilize plastic waste strips to enhance medium plasticity clay soil, achieving substantial improvements in CBR and UCS with plastic additions. Renjith et al. (2021) study the combination of fly ash, enzymes, and lime, achieving remarkable strength gains and reducing pavement wearing layer thickness. Rababah et al. (2020) use mill scale and cementitious materials for subgrade soil, achieving suitable strength for subbase application. Jaber et al. (2023) focus on recycled chips from discarded plastics and cement kiln dust (CKD), with CKD enhancing California bearing ratio (CBR) values. Choobbasti et al. (2019) investigate nano calcium carbonate and carpet waste fibers for clay soil reinforcement, significantly improving soil strength. Muntohar et al. (2013) use rice husk ash and lime in combination with plastic waste fibers, achieving substantial improvements in compressive strength, CBR, and shear strength. Consoli et al. (2002) aim to enhance fine sand with polyethylene terephthalate (PET) fibers and cement, achieving significant improvements in deformation and strength characteristics. Sudhakaran et al. (2018) stabilize soil with bottom ash and natural areca fibers, achieving notable increases in unconfined compressive strength (UCS) and California bearing ratio (CBR). Niomukiza et al. (2023) utilize waste glass powder (WGP) for expansive soil stabilization, finding significant enhancements in gradation, consistency limits, and strength. Sharma and Sivapullaiah (2016) employ ground granulated blast furnace slag (GGBS) and rice husk ash (RHA) for expansive soil stabilization, achieving improved strength. Zorluer and Guse (2014) use marble dust and fly ash for clay soil stabilization, demonstrating improved strength and reduced swelling. Razgozar et al. (2018) investigate rice husk ash (RHA) and Portland cement for clayey sand stabilization, achieving increased strength. Aamir et al. (2019) utilize alum sludge for soil stabilization, achieving higher unconfined compressive strength (UCS) with optimal moisture content. Fauzi et al. (2013) use High-Density Polyethylene (HDPE) and Glass for clayey soil stabilization, achieving improved California Bearing Ratio (CBR) values. Tiwari et al. (2021) employ treated Bottom Ash (BA) and coir fibers for expansive soil stabilization, significantly enhancing unconfined compressive strength and split tensile strength. Firat et al. (2017) use waste materials, including fly ash (FA), marble dust (MD), and waste sand (WS) for soil stabilization, demonstrating improved unconfined compressive strength (UCS) and CBR values. Hassan et al. (2021) aim to stabilize soil with waste plastic products, obtaining substantial improvements in UCS and CBR values with plastic fibres. These studies collectively demonstrate the potential of waste materials to enhance soil stability, improve engineering characteristics, and reduce environmental impact in various geotechnical applications.

3 INFLUENCE ON SUSTAINABILITY

3.1 Cement related impact on environment

The production of cement results in the emission of substantial amounts of CO_2 and NO_x into the atmosphere, as highlighted by Rashid et al.(2017). This process is highly energy-intensive, leading to significant CO_2 emissions and the generation of airborne particulates, as observed by Ghadir and Ranjbar(2018). The long-term environmental impact of cement is exacerbated by its low degradability, with cement used in soil treatment remaining in place for extended periods. This presence of cement-treated soil leads to ecological disturbances and an increased risk of desertification, as discussed by Chang et al.(2015). Furthermore, the overconsumption of raw materials in cement production has raised concerns about sustainability. This has prompted the civil engineering industry to seek alternative soil stabilizers, as noted by Hamzah et al.(2015). Currently, the global annual production of Portland cement stands at an estimated 4.6 billion tonnes, with projections indicating a rise to 6 billion tonnes by 2050. Notably, the cement industry is a significant source of global CO_2 emissions, accounting for approximately 7-8% of the total emissions. Around 50% of these emissions are categorized as indirect emissions, resulting from the use of fossil fuels such as natural gas and coal to heat kilns during cement manufacturing. These indirect emissions are akin to those produced when generating electricity from the same fossil fuels. Specifically, the combustion of these fuels for kiln heating contributes to nearly 40% of the emissions associated with cement production. Furthermore, there are additional indirect emissions, ranging from 5-10%, arising from the energy consumption of plant machinery and the transportation of cement. In summary, the entire cement production process, including fossil fuel use, equipment energy requirements, and transportation, plays a substantial role in global greenhouse gas emissions, a point emphasized by Amran et al.(2022).

3.2 Geopolymerization

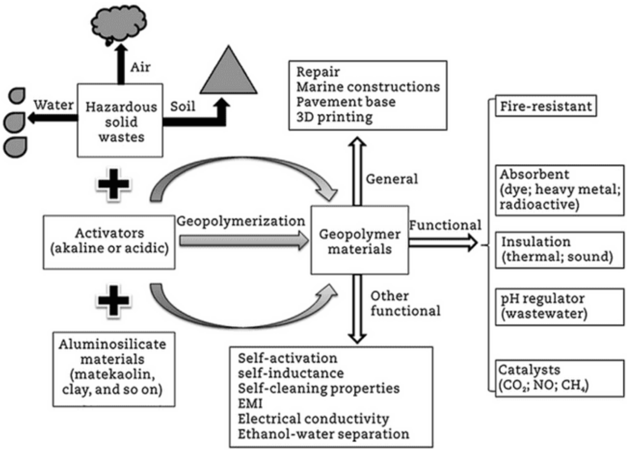

Fig 1 - Flowchart for geopolymerisation. Source - [Cong and Cheng.,2021]

The process of geopolymerisation consist of 3 parts in broad sense. The contribution of geopolymer in sustainable future from civil engineering perspective is that it can be made from different raw materials. Fig 1 shows the flowchart of geopolymerisation and usage of geopolymer in today's world. Geopolymers can be produce by using naturals materials like clay minerals, laterite soil etc. The benefit of geopolymer is the use of industrial by-product namely fly - ash, red mud, blast furnace slag etc. and biomass waste including incineration bottom ash. The raw material should be aluminosilicate in nature.

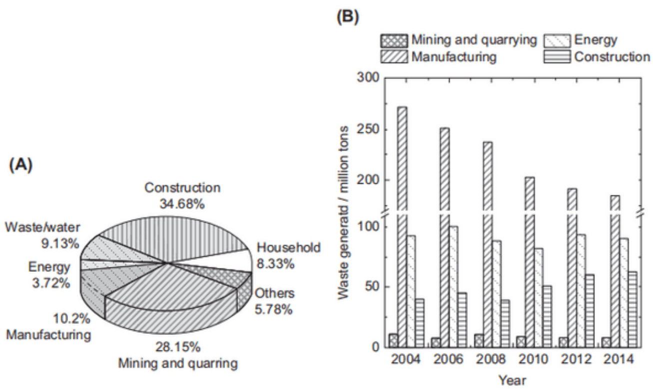

Fig 2 - a) Waste generation for Europe in 2024; b) Major industrial activity per year in Europe excluding mineral waste. [Source- Ria M et al, 2019].

Industrial Sector	Description	Typical Waste
Mining and quarrying	Extraction, beneficiation, and processing of minerals	Solid rock, slag, phosphogypsum, muds, tailings
Energy	Electricity, gas, steam, and air-conditioning supply	Fly ash, bottom ash, boiler slag, particulates, used oils, sludge
Manufacturing	Chemical	Spent catalyst, chemical solvents, reactive waste, acid, alkali, used oils, particulate waste, ash, sludge
	Food	Plastic, packaging, carton
	Textile	Textile waste, pigments, peroxide, organic stabilizer, alkali, chemical solvents, sludge, heavy metals
	Paper	Wood waste, alkali, chemical solvents, sludge
Construction	Construction, demolition activity	Concrete, cinder blocks, gypsum, masonry, asphalt, wood shingles, slate, metals, glass, and plaster
Waste/water services	Water collection, treatment, and supply	Spent adsorbent, sludge

Fig 3 - Characteristics of waste. [Source - Ria M et al, 2019]

The production industrial by-product and biomass waste is one of the leading effects of solid waste production. After obtaining the raw material, the raw material is mix with alkaline solution to produce the free silica and the alumina tetrahedron unit. The next process is the condensation process which results in the formation of inorganic geopolymer gel. The last process is the hardening part in which results in formation of a three-dimensional network of silicoaluminate. Soil stabilization is necessary for different geotechnical engineering purposes. Production of industrial by-products and biomass waste is continuous in nature. The approximate amount of agriculture waste produced every year is around 998 million tons of Agri-residue waste [Agamuthu P et al.,2009]. Fig 2 shows the amount of waste generated from energy sector as shown in Fig 3. The huge amount of waste generated from energy & mining and quarrying sector can be used for many civil engineering related works and geopolymer production. The total reuse of this waste products in different ways is the most efficient way to combat pollution and degradation of the environment.

3.3 Process of Bio - enzyme and Bio - cementation

The collective findings from several studies underscore the substantial potential of bio enzymes in revolutionizing soil improvement techniques. Notable bio enzymes such as Alkazyme and Terrazyme have demonstrated significant enhancements in soil strength metrics, including California Bearing Ratio (CBR) values and Unconfined Compressive Strength (UCS), when applied at optimal dosages. Lengthier treatment duration and precise dosage control were found to amplify their efficacy, establishing them as invaluable tools for both environmentally conscious and cost-effective soil stabilization practices. While the research highlights the pivotal role of laboratory assessments in comprehending bio enzyme performance, it also emphasizes the necessity of striking a balance between controlled experiments and real-world applications.

Bio-cementation is an eco-friendly approach to strengthen and protect soils by emulating nature's way of binding soil particles. These studies highlight the potential of bio-cementation for eco-friendly soil management and geotechnical applications.

3.4 Environmentally friendly Biopolymer

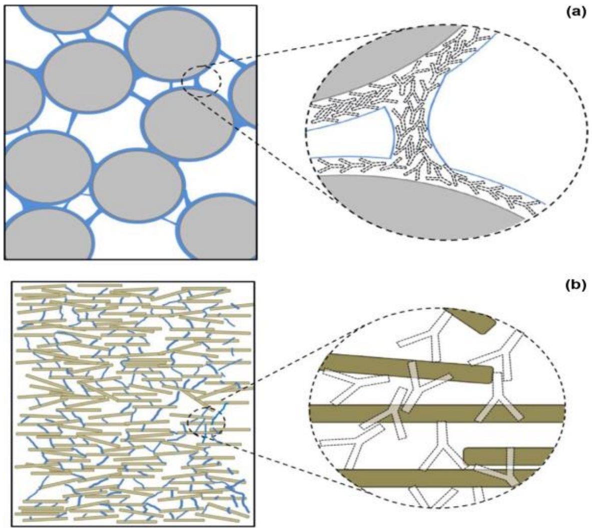

Fig 4 - a) Biopolymer gel forming a thread like structure to bind the soil particles, b) The biopolymer fiber directly interacts with the fine particle in micro scale level. [Source - Chang et al.,2015]

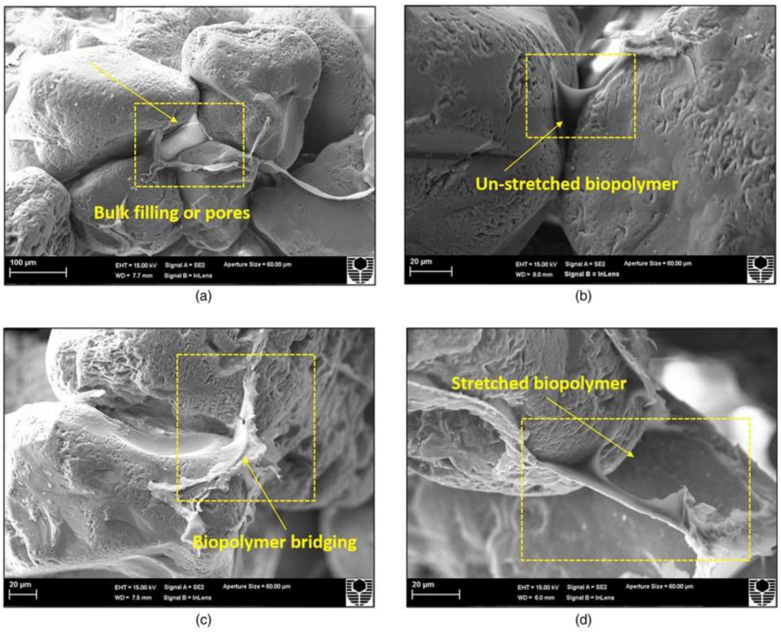

Fig 5 - a) Biopolymer gel forming a thread like structure to bind the soil particles (100µm); b) Biopolymer binds the soil particles together by forming a sheet (20µm); c) Formation of bridge by the biopolymer between the grains (20µm); d) Bridge between the particles get stretched at loading (20µm). [Source - Ramachandran et al.,2021]

Biopolymer molecules accumulate and align, forming thread-like structures and textiles. The strength of the biopolymer-coarse soil mixture predominantly relies on the robustness of the biopolymer gels. Given that fine soil particles carry electric charges on their surfaces, they engage directly with biopolymer fibers on a microscale level, as depicted in Figure 4. Furthermore, biopolymer fibers serve as threads, reinforcing the connections between soil clods. The biopolymer matrix bolsters the soil by enhancing interactions between particles, resulting in increased strength, higher stiffness, and a more brittle structure when dehydration occurs. This transformation resembles the hardening of plastic. Considering the backdrop of environmental degradation, global warming, and climate change, researchers are actively exploring alternatives to chemical stabilizers like cement and lime [Vydehi and Moghal, 2022; Rimbarngaye et al., 2022]. While chemicals like cement are effective, durable, and cost-efficient for soil stabilization, their detrimental environmental impacts include a substantial carbon footprint, disruption of vegetation, pH alterations, and soil contamination [Ojuri et al., 2022; Biju and Arnepalli, 2022]. In light of these adverse effects associated with chemical additives, the feasibility and environmental advantages of biopolymers make them a viable alternative to traditional chemicals. Figure 5 provides a microstructural view of biopolymer reinforcement in soil stabilization.

3.5 Reuse of waste material in soil stabilization

The findings from the research papers relating to waste material shows that proper use of waste material is possible for different waste materials, offering innovative and sustainable solutions to longstanding soil-related challenges. The use of Industrial Waste Glass Powder (IWGP) into clay soil proved promising. The studies determined that an optimum dosage of IWGP offered the suitable balance between strength enhancement and cost reduction. Bagasse Ash (BA) can be seen as a valuable stabilizing agent for expansive soils. With studies demonstrating its potential to significantly enhance bearing capacity and reduce soil compressibility, crucial factors in road construction. Lignin, a byproduct of the timber and paper industry, showcased its effectiveness in stabilizing silty soils in highway subgrades. Although it fell slightly short in strength compared to quicklime stabilization, its advantages included cost savings and potential sustainability benefits. Further studies encompassed diverse waste materials, including recycled chips from discarded plastic bottles and cement kiln dust (CKD). Optimal blends for subbase construction were identified, providing valuable insights for road infrastructure projects. Clay soil was strengthened using nano calcium carbonate and carpet waste fibers, which almost doubled the undrained cohesion, enhancing soil stiffness and stability. In addition, a combination of rice husk ash, lime, and plastic waste fibers demonstrated significant improvements in compressive, tensile, and shear strength, as well as California Bearing Ratio (CBR). The application of PET fibers from recycled plastic bottles and rapid-hardening Portland cement is another success story, resulting in noteworthy increases in unconfined compressive strength and tensile strength. Bottom ash (BA) and areca fibers showed great promise in enhancing expansive soil stability. The optimal combination resulted in a substantial boost in unconfined compressive strength and reduced upward swelling pressure, addressing a critical issue in geotechnical engineering. Waste glass powder (WGP), Fly-ash, Ground Granulated Blast Furnace Slag (GGBS) and rice husk ash (RHA) were used as stabilizing binder to produce significant improvements in soil strength. Another study employed marble dust (MD) and fly ash (FA) as soil stabilizers. These materials not only improved soil strength but also reduced swelling potential, enhanced California Bearing Ratio (CBR), and increased durability. Plastic bags, polyethylene (PE) bottles and polypropylene (PP) fibers proved to be a substantial breakthrough in soil stabilization. These materials significantly enhanced soil strength and bearing capacity at different research with different ways of usage.

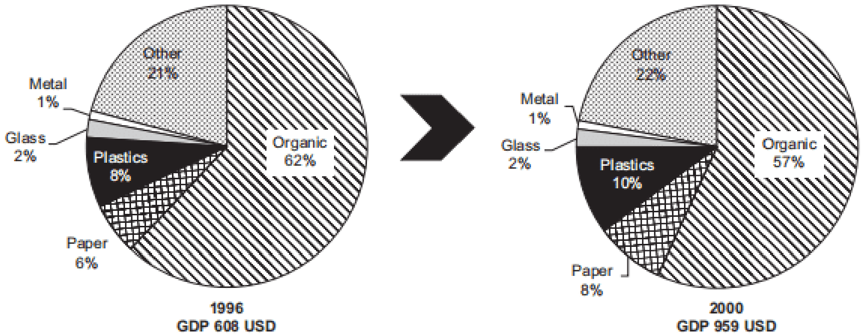

Fig 6 - Change in physical composition of municipal solid waste due to lifestyle and prosperity.
[Source - Ria M et al., 2019]

Fig 6 shows the increase in plastic waste generation from 1996 to 2000. The current percentage of plastic waste production is much more than the shown date. In summary, these research studies collectively highlight the immense potential of waste materials in soil stabilization. They offer cost-effective, sustainable, and innovative solutions to address a wide range of soil-related challenges, opening new avenues for the construction and geotechnical engineering industries. The key takeaway is that the right blend of waste materials can be tailored to specific soil types and project requirements, yielding substantial benefits.

4 CONCLUSION

The environmental impact of traditional soil stabilization methods, such as cement, has spurred a quest for more sustainable alternatives in civil engineering. The studies presented here showcase promising innovations that prioritize sustainability and environmental responsibility. Geo-polymerization offers a versatile approach, utilizing various raw materials, including industrial by-products and biomass waste, to create durable and eco-friendly soil stabilization agents. The incorporation of waste materials into soil stabilization practices further enhances sustainability. Materials like Industrial Waste Glass Powder (IWGP), Bagasse Ash (BA), Lignin, and even recycled plastics have demonstrated their potential in improving soil properties, offering a cost-effective and Eco-conscious solution.

Bio-enzyme and bio-cementation techniques, as exemplified by Alkazyme and Terrazyme, have proven to be valuable tools in soil improvement, showcasing increased strength metrics. These methods underscore the importance of striking a balance between controlled laboratory experiments and real-world applications for optimal results. Bio polymers, with their ability to form threads and textiles that interact with soil particles, offer an environmentally friendly approach to soil stabilization. This method, as demonstrated in various studies, leads to greater strength, stiffness, and improved inter-particle interactions. The best benefit being usage of only naturally available material in producing biopolymer, bio-enzyme and bio-cementation. The reuse of waste materials, from plastic bottles to byproducts like Fly Ash and Ground Granulated Blast Furnace Slag (GGBS), represents a groundbreaking approach to soil stabilization. These materials have shown significant improvements in soil strength, durability, and bearing capacity, providing sustainable and cost-effective alternatives. In a world facing mounting environmental challenges, the incorporation of waste materials, biopolymers, bio-enzymes, and geopolymers in soil stabilization practices offers an environmentally responsible and economically viable path forward for the construction and geotechnical engineering industries. By harnessing the potential of these sustainable alternatives, we can address soil-related challenges while minimizing our ecological footprint and contributing to a greener, more sustainable future.

REFERENCES

Aamir M, Mahmood Z, Nisar A, Farid A, Ahmed Khan T, Abbas M, Ismaeel M, Shah SAR, Waseem M (2019) Performance evaluation of sustainable soil stabilization process using waste materials. Processes, 7(6), pp.378.

Abdallah HM, Rabab'ah SR, Taamneh MM, Taamneh MO, Hanandeh S (2023) Effect of Zeolitic Tuff on Strength, Resilient Modulus, and Permanent Strain of Lime-Stabilized Expansive Subgrade Soil. *Journal of Materials in Civil Engineering*, *35*(5), 04023081.

Abdila SR, Abdullah MMAB, Ahmad R, Burduhos Nergis DD, Rahim SZA, Omar MF, Sandu AV, Vizureanu P, Syafwandi (2022) Potential of soil stabilization using ground granulated blast furnace slag (GGBFS) and fly ash via geopolymerization method: A Review. Materials, 15(1), p.375.

Agamuthu P, Khidzir KM, Hamid FS (2009) Drivers of sustainable waste management in Asia. Waste Management & Research, 27(7), pp.625-633.

Agarwal P, Kaur S (2014) Effect of bio-enzyme stabilization on unconfined compressive strength of expansive soil. International Journal of Research in Engineering and Technology, 3(5), 30-33.

Aher PD, Patil YD, Waysal SM, Bhoi AM (2023) Critical review on biopolymer composites used in concrete. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2023.07.212

Al-Rawas AA, Hago AW, Al-Sarmi H (2005) Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman. Building and environment, 40(5), pp.681-687.

Al-Rawas AA, Hago AW, Al-Sarmi H (2005) Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman. Building and environment, 40(5), pp.681-687.

Amran M, Makul N, Fediuk R, Lee YH, Vatin NI, Lee YY, Mohammed K (2022) Global carbon recoverability experiences from the cement industry. Case Studies in Construction Materials, 17, p.e01439.

Anandha Kumar S, Sujatha ER, Pugazhendi A, Jamal MT (2021) Guar gum-stabilized soil: A clean, sustainable and economic alternative liner material for landfills. Clean Technologies and Environmental Policy, pp.1-19. https://doi.org/10.1007/s10098-021-02032-z

Ashiq SZ, Akbar A, Farooq K, Mujtaba H (2022) Sustainable improvement in engineering behavior of Siwalik Clay using industrial waste glass powder as additive. Case Studies in Construction Materials, 16, p.e00883.

Athira S, Safana BK, Sabu K (2017) Soil stabilization using TerraZyme for road construction. International Journal of Engineering Research & Technology, 6(03), 547-549.

Ayeldeen M, Negm A, El-Sawwaf M, Kitazume M (2017) Enhancing mechanical behaviors of collapsible soil using two biopolymers. Journal of rock mechanics and geotechnical engineering, 9(2), pp.329-339. http://dx.doi.org/10.1016/j.jrmge.2016.11.007

Ayeldeen MK, Negm AM, El-Sawwaf MA (2016) Evaluating the physical characteristics of biopolymer/soil mixtures. Arabian Journal of Geosciences, 9, pp.1-13. DOI 10.1007/s12517-016-2366-1

Begum AS, Prasada Raju GVR, Prasad DSV, Anjan Kumar M (2020). Influence of TerraZyme on compaction and consolidation properties of expansive soil. In Problematic Soils and Geoenvironmental Concerns: Proceedings of IGC 2018 (pp. 525-535). Singapore: Springer Singapore.

Biju MS, Arnepalli DN (2019) Biopolymer-modified soil: prospects of a promising green technology. In Geotechnical Characterisation and Geoenvironmental Engineering: IGC 2016 Volume 1 (pp. 163-169). Springer Singapore.

Biju MS, Arnepalli DN (2020) Effect of biopolymers on permeability of sand-bentonite mixtures. Journal of Rock Mechanics and Geotechnical Engineering, 12(5), pp.1093-1102. https://doi.org/10.1016/j.jrmge.2020.02.004

Castillo H, Collado H, Droguett T, Vesely M, Garrido P, Palma S (2022) State of the art of geopolymers: A review. e-Polymers, Vol. 22 (Issue 1), pp. 108-124. https://doi.org/10.1515/epoly-2022-0015

Chang I, Im J, Prasidhi AK, Cho GC (2015) Effects of Xanthan gum biopolymer on soil strengthening. Construction and Building Materials, 74, pp.65-72. https://doi.org/10.1016/j.conbuildmat.2014.10.026

Chang I, Lee M, Tran ATP, Lee S, Kwon YM, Im, J, Cho GC (2020) Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices. Transportation Geotechnics, 24, p.100385. https://doi.org/10.1016/j.trgeo.2020.100385

Choobbasti AJ, Samakoosh MA, Kutanaei SS (2019) Mechanical properties soil stabilized with nano calcium carbonate and reinforced with carpet waste fibers. Construction and Building Materials, 211, pp.1094-1104.

Cong P, Cheng Y (2021) Advances in geopolymer materials: A comprehensive review. Journal of Traffic and Transportation Engineering (English Edition), 8(3), pp.283-314.

Consoli NC, Montardo JP, Prietto PDM, Pasa GS (2002) Engineering behavior of a sand reinforced with plastic waste. Journal of geotechnical and geoenvironmental engineering, 128(6), pp.462-472.

Dang LC, Khabbaz H, Ni BJ (2021) Improving engineering characteristics of expansive soils using industry waste as a sustainable application for reuse of bagasse ash. Transportation Geotechnics, 31, p.100637.

Dehghan H, Tabarsa A, Latifi N, Bagheri Y (2019) Use of xanthan and guar gums in soil strengthening. Clean Technologies and Environmental Policy, 21, pp.155-165. https://doi.org/10.1007/s10098-018-1625-0

Etemadi O, Petrisor IG, Kim D, Wan MW, Yen TF (2003) Stabilization of metals in subsurface by biopolymers: Laboratory drainage flow studies. Soil and Sediment Contamination, 12(5), pp.647-661. DOI: 10.1080/10588330390246215

Fattah MY, Al-Ani MM, Al-Lamy MT (2014) Studying collapse potential of gypseous soil treated by grouting. Soils and Foundations, 54(3), pp.396-404.

Fauzi A, Rahman WMNWA, Jauhari Z (2013) Utilization waste material as stabilizer on kuantan clayey soil stabilization. Procedia engineering, 53, pp.42-47.

Fertahi S, Pistocchi C, Daudin G, Oukarroum A, Zeroua, Y, Barakat A, Bertrand I (2022) Experimental dissolution of biopolymer-coated phosphorus fertilizers applied to a soil surface: Impact on soil pH and P dynamics. Annals of Agricultural Sciences, 67(2), pp.189-195.

Firat S, Khatib JM, Yilmaz G, Comert AT (2017) Effect of curing time on selected properties of soil stabilized with fly ash, marble dust and waste sand for road sub-base materials. Waste Management & Research, 35(7), pp.747-756.

Gali ML, Rao PR (Eds.) (2020). Problematic Soils and Geoenvironmental Concerns: Proceedings of IGC 2018 (Vol. 88). Springer Nature.

Ghadir P, Ranjbar N (2018) Clayey soil stabilization using geopolymer and Portland cement. Construction and Building Materials, 188, pp.361-371.

Hamza M, Nie Z, Aziz M, Ijaz N, Ijaz Z, Rehman ZU (2022) Strengthening potential of xanthan gum biopolymer in stabilizing weak subgrade soil. Clean Technologies and Environmental Policy, 24(9), pp.2719-2738. https://doi.org/10.1007/s10098-022-02347-5

Hamzah HN, Al Bakri Abdullah MM, Heah CY, Arif Zainol MRR, Kamarudin H (2015) Review of soil stabilization techniques: Geopolymerization method one of the new technique. Key engineering materials, 660, pp.298-304.

Hassan HJA, Rasul J, Samin M (2021) Effects of plastic waste materials on geotechnical properties of clayey soil. Transportation Infrastructure Geotechnology, 8(3), pp.390-413.

Heah CY, Kamarudin H, Mustafa Al Bakri AM, Bnhussain M, Luqman M, Khairul Nizar I, Ruzaidi CM, Liew YM (2013) Kaolin-based geopolymers with various NaOH concentrations. International Journal of Minerals, Metallurgy, and Materials, 20, pp.313-322.

Iqbal N, Agrawal A, Dubey S, Kumar J (2020) Role of decomposers in agricultural waste management. In Biotechnological Applications of Biomass. IntechOpen.

Iqbal N, Agrawal A, Dubey S, Kumar J (2020) Role of decomposers in agricultural waste management. In Biotechnological Applications of Biomass. IntechOpen.

Iravanian A, Ahmed IUD (2021) Geo-environmental solution of plastic solid waste management using stabilization process. Environmental Earth Sciences, 80, pp.1-7.

Jaber NH, Radhi MS, Alsaad AJ (2023) Sustainable Potentials of Plastics Waste-cement Kiln Dust Blends on Strength Properties of Subbase Soil. Periodica Polytechnica Civil Engineering, 67(2), pp.596-602.

Joseph EJ, Saiyada MK (2017). Stabilization of Kaolinite clay by using TerraZyme. In Indian Geotechnical Conference

Kalia S, Avérous L (2011) Biopolymers: biomedical and environmental applications (Vol. 70). John Wiley & Sons.

Khanday SA, Hussain M, Das AK (2021) Rice husk ash–based geopolymer stabilization of Indian peat: Experimental investigation. Journal of Materials in Civil Engineering, 33(12), p.04021347.

Khanna V, Beriha B, Sahoo UC (2019) Mechanical characterization of a bio-enzyme treated granular lateritic soil for application in low volume roads. In *Indian Young Geotechnical Engineers Conference* (pp. 185-193). Singapore: Springer Nature Singapore.

Lee SS, Song HY, Lee YS, Lee KP (2011) A Study on the strength and flowing properties of the non-cement inorganic composite by using blast furnace slag and red mud. Advanced Materials Research, 261, pp.491-495

Luo Z, Luo B, Zhao Y, Li X, Su Y, Huang H, Wang Q (2022) Experimental Investigation of Unconfined Compression Strength and Microstructure Characteristics of Slag and Fly Ash-Based Geopolymer Stabilized Riverside Soft Soil. Polymers, 14(2), p.307.

Michael G Gomez, Charles M R Graddy, Jason T DeJong, Douglas C Nelson, Michael Tsesarsky (2018) Stimulation of Native Microorganisms for Biocementation in Samples Recovered from Field-Scale Treatment Depths. J. Geotech. Geoenviron. Eng., 2018, 144(1): 04017098. ASCE

Michael G Gomez, Jason T DeJong (2017) Engineering Properties of Bio-Cementation Improved Sandy Soils. Grouting 2017 GSP 288.ASCE

Millati R, Cahyono RB, Ariyanto T, Azzahrani IN, Putri RU, Taherzadeh MJ (2019) Agricultural, industrial, municipal, and forest wastes: an overview. Sustainable resource recovery and zero waste approaches, pp.1-22.

Mittal A 2020 Soil Stabilization Using Bio-Enzyme: A Review.

MS Swathi R (2020) STABILIZATION OF BLACK COTTON SOIL USING TERRAZYME.

Muntohar AS, Widianti A, Hartono E, Diana W (2013) Engineering properties of silty soil stabilized with lime and rice husk ash and reinforced with waste plastic fiber. Journal of materials in civil engineering, 25(9), pp.1260-1270.

MV Sravan, HB Nagaraj (2018) PRELIMINARY STUDY ON USE OF TERRAZYME AS A BIO STABILIZER ALONG WITH CEMENT AND LIME IN COMPRESSED STABILIZED EARTH BLOCKS

Niyomukiza JB, Eisazadeh A, Akamumpa J, Kiwanuka M, Lukwago A, Tiboti P (2023) Use of waste glass powder in improving the properties of expansive clay soils. Global nest journal, 25(3), pp.139-145.

Noolu V, Rao GM, Chavali RVP (2021) Strength and durability characteristics of GGBS geopolymer stabilized black cotton soil. Materials Today: Proceedings, 43, pp.2373-2376.

Ojuri OO, Ramdas V, Aderibigbe EA, Williams CG, Ramchuran, Al-Nageim H, (2022) Improving strength and hydraulic characteristics of regional clayey soils using biopolymers. Case Studies in Construction Materials, 17, p.e01319. https://doi.org/10.1016/j.cscm.2022.e01319

Parthiban D, Vijayan DS, Koda E, Vaverkova MD, Piechowicz K, Osinski P, Van Duc B (2022) Role of industrial based precursors in the stabilization of weak soils with geopolymer–A review. Case Studies in Construction Materials, 16, p.e00886.

Paulo J Venda Oliveira, João PG Neves (2019) “Effect of Organic Matter Content on Enzymatic Biocementation Process Applied to Coarse-Grained Soils”. J. Mater. Civ. Eng., 2019, 31(7): 04019121.ASCE.

Pongsivasathit S, Horpibulsuk S, Piyaphipat S (2019) Assessment of mechanical properties of cement stabilized soils. Case Studies in Construction Materials, 11, p.e00301.

Rabab’ah S, Al Hattamleh O, Aldeeky H, Aljarrah MM, Al_Qablan HA (2020) Resilient response and permanent strain of subgrade soil stabilized with byproduct recycled steel and cementitious materials. Journal of Materials in Civil Engineering, 32(6), p.04020139.

Rahgozar MA, Saberian M, Li J (2018) Soil stabilization with non-conventional eco-friendly agricultural waste materials: An experimental study. Transportation Geotechnics, 14, pp.52-60.

Ramachandran AL, Dubey AA, Dhami NK, Mukherjee A (2021) Multiscale study of soil stabilization using bacterial biopolymers. Journal of Geotechnical and Geoenvironmental Engineering, 147(8), p.04021074. 10.1061/(ASCE)GT.1943-5606.0002575.

Rashid ASA, Latifi N, Meehan CL, Manahiloh KN (2017) Sustainable improvement of tropical residual soil using an environmentally friendly additive. Geotechnical and Geological Engineering, 35, pp.2613-2623. DOI 10.1007/s10706-017-0265-1.

Rashid ASA, Latifi N, Meehan CL, Manahiloh KN (2017) Sustainable improvement of tropical residual soil using an environmentally friendly additive. Geotechnical and Geological Engineering, 35, pp.2613-2623. DOI 10.1007/s10706-017-0265-1

Renjith R, Robert D, Setunge S, Costa S, Mohajerani A (2021) Optimization of fly ash-based soil stabilization using secondary admixtures for sustainable road construction. Journal of Cleaner Production, 294, p.126264.

Renjith R, Robert DJ, Gunasekara C, Setunge S, O'Donnell B (2020) Optimization of enzyme-based soil stabilization. Journal of Materials in Civil Engineering, 32(5), 04020091.

Rezaei M, Ajalloeian R, Ghafoori M (2012) Geotechnical properties of problematic soils emphasis on collapsible cases. International Journal of Geosciences, 3(1), pp.105-110.

Rimbarngaye A, Mwero JN, Ronoh EK (2022) Effect of gum Arabic content on maximum dry density and optimum moisture content of laterite soil. Heliyon, 8(11). https://doi.org/10.1016/j.heliyon.2022.e11553

Rimbarngaye A, Mwero JN, Ronoh EK (2022) Effect of gum Arabic content on maximum dry density and optimum moisture content of laterite soil. Heliyon, 8(11). https://doi.org/10.1016/j.heliyon.2022.e11553

Samuel R, Puppala AJ, Banerjee A, Huang O, Radovic M, Chakraborty S (2021) Improvement of strength and volume-change properties of expansive clays with geopolymer treatment. Transportation Research Record, 2675(9), pp.308-320.

Sen J, Singh JP (2015). Stabilization of black cotton soil using bio-enzyme for a highway material. International Journal of innovative Research in science, engineering and technology, 4(12), 12453-12459.

Seyed Mohammad Fattahi, Abbas Soroush, Ning Huang (2020) Biocementation Control of Sand against Wind Erosion. J. Geotech. Geoenviron. Eng., 2020, 146(6): 04020045.ASCE.

Sharma AK, Sivapullaiah PV (2016) Ground granulated blast furnace slag amended fly ash as an expansive soil stabilizer. Soils and Foundations, 56(2), pp.205-212.

SODHI PS, OCEAN YK (2018) Stabilization of soil using alkaline bio-enzyme (Alkazyme). International Research Journal of Engineering and Technology, 5(8), 1681-1685.

Sudhakaran SP, Sharma AK, Kolathayar S (2018) Soil stabilization using bottom ash and areca fiber: Experimental investigations and reliability analysis. Journal of Materials in Civil Engineering, 30(8), pp.04018169.

Sujatha ER, Saisree S (2019) Geotechnical behaviour of guar gum-treated soil. Soils and Foundations, 59(6), pp.2155-2166. https://doi.org/10.1016/j.sandf.2019.11.012

SWATHI R, ANUSHA TP, BABITHA DAS, RAMYA R (2020) “STABILIZATION OF BLACK COTTON SOIL USING TERRAZYME”

Taha MR, Khan TA, Jawad IT, Firoozi AA, Firoozi AA (2013) Recent experimental studies in soil stabilization with bio-enzymes–a. Electronic Journal of Geotechnical Engineering, 18, 3881-3894.

Tiwari N, Satyam N, Puppala AJ (2021) Strength and durability assessment of expansive soil stabilized with recycled ash and natural fibers. Transportation Geotechnics, 29, p.100556.

Vydehi KV, Moghal AAB (2022) Effect of biopolymeric stabilization on the strength and compressibility characteristics of cohesive soil. Journal of Materials in Civil Engineering, 34(2), p.04021428. 10.1061/(ASCE)MT.1943-5533.0004068.

Wang H, Wu H, Xing Z, Wang R, Dai S (2021) The effect of various Si/Al, Na/Al molar ratios and free water on micromorphology and macro-strength of metakaolin-based geopolymer. Materials, 14(14), p.3845.

Yu H, Yi Y, Romagnoli A, Tan WL (2022) Cement soil stabilization for underground liquid natural gas storage. Cold Regions Science and Technology, 194, p.103438.

Zada U, Jamal A, Iqbal M, Eldin SM, Almoshaogeh M, Bekkouche SR, Almuaythir S (2023) Recent advances in expansive soil stabilization using admixtures: current challenges and opportunities. Case Studies in Construction Materials, p.e01985. https://doi.org/10.1016/j.cscm.2023.e01985.

Zada U, Jamal A, Iqbal M, Eldin SM, Almoshaogeh M, Bekkouche SR, Almuaythir S (2023) Recent advances in expansive soil stabilization using admixtures: current challenges and opportunities. Case Studies in Construction Materials, p.e01985.

Zambri NM, Ghazaly ZM (2018) Peat soil stabilization using lime and cement. In E3S Web of Conferences (Vol. 34, p. 01034). EDP Sciences.

Zami MS, Ewebajo AO, Al-Amoudi OSB, Al-Osta MA, Mustafa YMH (2022) Compressive Strength and Wetting–Drying Cycles of Al-Hofuf" Hamrah" Soil Stabilized with Cement and Lime. Arabian Journal for Science and Engineering, 47(10), pp.13249-13264.

Zhang T, Cai G, Liu S (2017) Application of lignin-based by-product stabilized silty soil in highway subgrade: A field investigation. Journal of Cleaner Production, 142, pp.4243-4257.

Zorluer I, Gucek S (2014) The effects of marble dust and fly ash on clay soil. Science and Engineering of Composite Materials, 21(1), pp.59-67.

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Ethical Approval: I hereby confirm that this research project has received ethical approval from [Institution/Organization] Ethics Committee, ensuring compliance with ethical standards in accordance with established guidelines.

Consent to participate: I voluntarily consent to participate in the Environmental Science and Pollution Research and agree to abide by the terms and conditions outlined.

Consent to Publish: I, Jeelek Rigia (corresponding author) hereby grant consent to publish the paper.

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