An Overview on Innovative Approaches for Soil Stabilization

Abdul Wahab Tehami [1, *], and Majid Ali [1]

[1] Capital University of Science and Technology, Pakistan; email4wahab@gmail.com; majid.ali@cust.edu.pk
* Correspondence: email4wahab@gmail.com

Abstract

Soil stabilization forms one of the main solutions to the weak soil strength or stability, especially as it occurs during construction and development of infrastructures in the focus of geotechnical engineering. There are Fourier conventional stabilization methods that often take advantage of using chemical additives, which may be quite costly and damaging to the ecosystem. Studies indicate that waste plastic after treatment or after recycling can be used in construction as in a variety of forms. However, the same is not the case with regard to its use in soil stabilization or more particularly, in soil stabilization. The current research thus conducts a systematic review of waste plastic as a new material in soil stabilization, its advantages, shortcomings, and general viability concerning geotechnical practice. In the current review, the scholarly literature of well-established periodicals about both the historical breakthroughs and latest advancements was questioned. The focus of the study was to incorporate so-called sustainable materials i.e., plastic fibers, and wood dust into soil-based matrices to obtain improved mechanical performance. Laboratory experiments, including Unconfined Compressive Strength (UCS), Direct Shear Tests, and Proctor Compaction Tests, were conducted to evaluate the efficacy of these materials. Results indicated significant improvements in strength and cohesion, suggesting their potential as eco-friendly alternatives for soil stabilization.

Keywords: Geotechnical engineering, landfill instability, plastic fibers, soil stabilization, wood dust

1. Introduction

The introduction should briefly place the study in a broad context and highlight why it is important. The stability of soil plays an essential part in project success in constructing or development of infrastructure, assuring structure and building stability and durability. The natural soils especially cohesive soils, that generally do not satisfy the required strength, cohesion and loads, are improved in such projects. This explains why soil stabilization is a necessary procedure in geotechnical. especially in the areas of problem soils (weak or expansive), engineering. Traditional soil stabilizing methods like lime and cement have been largely used to improve soil increase strength, decrease plasticity, limit drop in shrink-swell properties. These methods have however been proven to work with great costs in the environment and economy over time. Non-renewable materials such as cement and lime are widely used to make a tremendous contribution to the emission of carbon, depletion of resources, and energy waste to the detriment of sustainability objectives in the contemporary world of construction. [1,2]. These drawbacks have sparked interest in exploring more eco-friendly alternatives that can maintain the required soil stability without compromising environmental or economic sustainability.

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The recent developments in the field of soil stabilization have been directed towards the use of waste material and the geopolymers as stabilizing agents instead of using conventional types. The newer techniques come with the potential of improving the soil properties combined with the ability to overcome the environmental problem related to the older methods. As an example, one should talk about using plastic fibers and wood dust which have become more noticeable now since they may help to strengthen soil and reduce waste simultaneously [3,4]. These consist of industrial by-products and are a safer way of approaching soil stabilization in a more sustainable and cost-efficient manner. Using waste materials is means the environmental impact of traditional stabilization techniques is minimized because waste is diverted out of landfills, and little non-renewable resources are required [5,6]. Nevertheless, there are some challenges associated with those new methods, like the question of long-term stability, even spread of additives, and the possibility of scaling them in large projects. In spite of them, there is a high possibility of incorporating green resources such as plastic fibers and wood dust due to their advantageous factors of geotechnical engineering in the future.

Use of sustainable soil stabilisation methods especially through recycled products such as plastic fibers as well as wood dust is also a great opportunity where such practices could be undertaken massively in civil engineering. Scaling such innovative techniques does however bring a number of issues, such as material availability is variable, quality of wastes is inconsistent and standardized testing procedures are needed [1,7]. It is important to find a balance between cost, performance, and the environmental effect, which are also different region by region, different soil, and project requirements of geosynthetics materials, which determines the success of these materials. Moreover, research and development is also necessary so that these procedures could be enhanced and made to have reliable results in various settings of the environment and on diverse soils [4]. On a large scale, the integration of these materials should also take into consideration logistical issues related to supply of waste materials, processing these materials and mixing them properly with soil. Such hurdles may be overwhelming but the long-term benefits associated with adoption of waste-based stabilizers may be very significant as compared to the initial challenge especially in the light of the benefits that such stabilizers offer in terms of sustainability and cost benefits in building industry [5,2].

Finally, the approach towards sustainable methods of soil stabilization can be discussed as another important improvement in geotechnical engineering. Incorporation of waste products such as plastic fibres and wood dust by the engineers enables them to enhance soil, improving its functions, at the same time taking care of the environment, and less dependence on conventional techniques which use many resources and are resource-intensive [1,7]. Despite the setbacks that exist concerning scalability and efficiency in the long run, research and development on this topic will continue improving the industry and making concrete measures that will define the future of soil stabilization [3,6]. As they are continually developing, these sustainable practices portray a positive prospect of creating more environmentally-friendly, financially viable practices that will go towards the formation of the future of construction and infrastructure projects in the future in line with the recent theme of construction being more sustainable in the built environment. Further incorporation of waste materials products in soil stabilization has the ability to change the industry, making it more sustainable and robust in the future generations [4,5].

2. Need for soil stabilization and limitations of conventional methods

Soil stabilization has played a greater role in geotechnical engineering where a lot of research has concentrated in making weak or expansive soil physically and mechanically stable to prevent unrest like settling, erosion and instability of structures. Old age techniques such as the addition of lime or cement to enhance load bearing capacity, minimize plasticity and or containment of shrink-swell effect, have been employed; thus soils have met the standards of performance by construction activities [8,9]. Such materials have been proved not just to improve soil characteristics but also solve the burning environment issues due to decreasing wastes [10,11]. Formulation of geopolymers, which are made of aluminosilicate supplies, has also become more popular as a likely replacement to conventional stabilizers. Generating great strength, chemical resistance, reduced environmental impact, these materials are considered one of the central units of the contemporary and sustainable engineering practice [11,6]. The soil stabilization has also taken a turn to become sustainable, where it entails the use of waste materials, and geopolymers. They are eco friendlier alternatives to conventional techniques, which enhance the quality of soil.

The combination of these alternative stabilization ways is today redefining the environment of geotechnical engineering. Eco-friendly materials have appeared and provided the engineers with diverse options that enhance the performance of soils and reduce the environmental impact of construction initiatives. The developments enable more economical, durable and green solutions to the soil stabilization problems, further enhancing the trend of a green engineering practice. With the continued growth of research, it only becomes obvious that the future of soil stabilization will be more focused on sustainable resources, providing an effective ratio in terms of performance and environmental sustainability [2]. The invention of other forms of stabilization is changing geotechnical engineering through green and economical resources. Going green is not only increasing the functionality of the soil but minimizing its consequences on the environment.

The further study based on sustainable methods of soil stabilization has resulted in introduction of other having additional effect of improved soil characters that have less effect on the environment. An example is that natural fibers, including coir, jute and hemp are increasingly being used, on account of them being biodegradable and capable of enhancing soil binding capacity and shear strength. Researches have indicated that inclusion of these fibers in a certain optimum percentage could greatly enhance the strength and stability of soils not forgetting to give them an eco-friendlier alternative to conventional chemical stabilizers [15,16]. Those materials (enzymatic stabilizers and the use of polymer composites) have been promising both in laboratory and field experiments, to a more sustainable treatment of the soil, and in line with the emerging focus on lowering the carbon footprint of the construction industry. Besides increasing the durability and resilience of soil, incorporating these eco-friendly soil stabilizers satisfies the desire to provide cheaper and more environmentally-friendly construction products. Alternative stabilizers can be considered even more viable in large-scale operations in the future, given further investigation, which is also likely to move the field of geotechnical engineering further towards a more environmentally friendly construction industry. Natural fibers and enzymatic stabilizers are some examples of methods under sustainable soil stabilization that enhance soil properties and minimize environmental effect. The innovations also present cost-efficient, environment-friendly construction in large areas, which complies with the objectives of green infrastructure.

3. Innovative soil stabilization techniques

Clay soil stabilization geotechnical engineering has been concerned with design/construction operations of strengthening weak/expansive clayey soil to reduce adverse ground settlements, loss of soil due to erosion, and structural failure risks. The use of lime and cement has been one of the traditional practices to enhance load bearing, reduce plasticity, and control shrink-swell phenomena of soils to enable them satisfy the performance conditions of the endeavors needed in construction uses [12,13]. Conventional practices are often expensive and environmentally degrading and new researches reveal that the extent to which waste material is used in soil, in form of plastic fibers, wood dust, and recycled aggregates improves the soil condition and creates relief with regards to waste disposal issues [10,11]. Also, the concept of geopolymers, which are synthesized using aluminosilicate materials has also attracted interest as the possible solution to the concept of conventional stabilizers which are unsustainable. These geopolymers have high strength and their resistance to chemical attack and their much-reduced environmental impact makes them popular because of the current shift towards eco-friendly engineering techniques [11,6]. New soil stabilization methods include the use of waste products and geopolymers so as to enhance soil behaviour and have reduced effects on the environment. These substitutes are sustainable and are in line with green engineering practices that are cost effective and environmentally friendly.

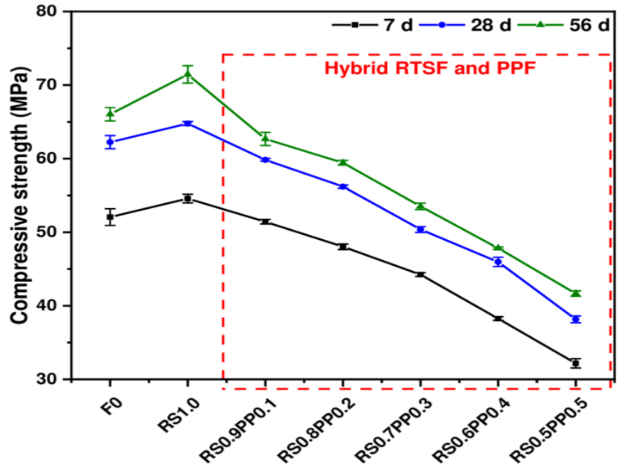

Figure 1: Impact of Plastic Fibers on Compressive Strength

This shift towards sustainable techniques is transforming soil treatment, emphasizing performance and environmental responsibility. As research advances, sustainable materials will drive the future of soil stabilization, promoting greener engineering solutions for the construction industry. This changes of techniques of sustainability is revolutionizing how the soil is treated by the focus being on the performance and environmental responsibility. Sustainability in soil stabilization will become the new paradigm as we improve our research efforts, and the construction sector seeks to embrace greener methodologies to the field of engineering. It is true that the available knowledge in design and construction of these innovative materials is still under development to provide more effective and sustainable soil stabilization practices to the future. The soil stabilization technology is continually enhancing robust and cost-effective applications besides reducing reliance on ecologically damaging chemicals and materials. These innovations follow the general path of green infrastructure and sustainable construction as they incorporate sustainable principles in their operation.

Table 1: Comparison of innovative soil stabilization and shortlisting

Stabilization Technique	Pros	Cons
Chemical Stabilization	Durable, effective for clay, reduces shrink-swell.	Costly, potential leaching, needs expertise.
Biological Stabilization	Eco-friendly, low-cost, improves fertility.	Slow-paced, needs extensive care.

Asphalt Stabilization	Durable, dust control, water- resistant.	Relatively expensive, has environmental impact.
Geosynthetics Stabilization	Versatile, quick, low maintenance.	Costly, UV degradation.
Compaction	Simple, cost-effective, and improves load-bearing capacity.	May not be effective in soils with poor cohesion, like sandy or loose soils.
Lime Stabilization	Improves workability, enhances strength, and is suitable for clay-rich soils.	Limited effectiveness in sandy soils and potential environmental concerns regarding lime leaching.
Cement Stabilization	Suitable for a wide range of soil types, highly effective for road construction and foundations.	Higher cost and environmental impact due to cement production.
Geosynthetics	Effective in weak soils, reduces erosion, and increases load distribution.	Initial cost of materials, may require regular maintenance depending on soil conditions.
Polymer Stabilization	Effective in reducing erosion, environmentally friendly in some cases, and improves soil durability.	Can be more expensive and may not be as widely applicable to all soil types.

During the past decades, the trend of soil stabilization research has shifted, so the more conventional approaches based on cement and lime have been superseded with more sustainable methodologies, which include the introduction of plastic fibers, geopolymers and enzymatic stabilizers. The alternative methods are as strong and offer similar benefits to their forbearers, and at the same time offer a smaller environmental impact than the original versions [1,10,12]. The results of empirical studies point to the fact that although conventional aggregates increase the unconfined compressive strength (UCS) of mortar by around 30-40 %, waste-derived stabilisers such as PET fibres and wood ash have an influence resulting in UCS gains of or around 25-35 %. In addition, use of these alternatives reduces reliance on non-renewable input [4,14]. Addition of biodegradable fibers namely coir, jute, and hemp to geotextiles has also been proved to increase soil cohesion and promote increased sustainability. The fibers use renewable sources, which give them the significant offerings as compared to the conventional nonwoven geotextiles that largely consist of polymers that are derived by petroleum products [5,7]. In the context of the scientific verbiage, one is constantly faced with the realization that recently developed set of high throughput methodologies of analysis has managed to do well in replacing the resource intensive methods and overcoming a step today towards the era of more sustainable and cost-efficient infrastructures [2].

The discipline of soil stabilization has been advanced over the recent decades owing to the increase in the needs within the geotechnical-engineering field. The old solutions like chemical stabilization using lime and cement are the conventional solution and especially in cohesions where all that matters is to mitigate the phenomenon of shrink-swell and to increase strength [12]. By using mechanical stabilization practices such as compaction, traditionally granular soils have been used in order to increase the load bearing capacity as well as reducing settlement. The increasing popularity of the demand of sustainable measures has however led to considerations of more eco-friendlyÂ ways. In this regard, the idea of using waste-derived products, including plastic fibers, wood dust, and a range of geosynthetic products, as alternatives has appeared as a rather promising option, as it would simultaneously enhance soil properties and eliminate waste-management issues [18]. Consideration of the stabilization technique has to be specific to the situation at hand depending on the existing soil environments, environmental limitations and goals of the project. Traditional remedial plans are often ineffective in attaining the current sustainability goals and this impetus has prompted the academic establishment to seek the more futuristic theories [12]. The modern soil-stabilization techniques are also trending towards incorporation of green materials (or waste to resource) within the method such as soils, cement and lime become just part of the solution as it is possible to promote natural soil treatments in addition to preventing the environmental loss.

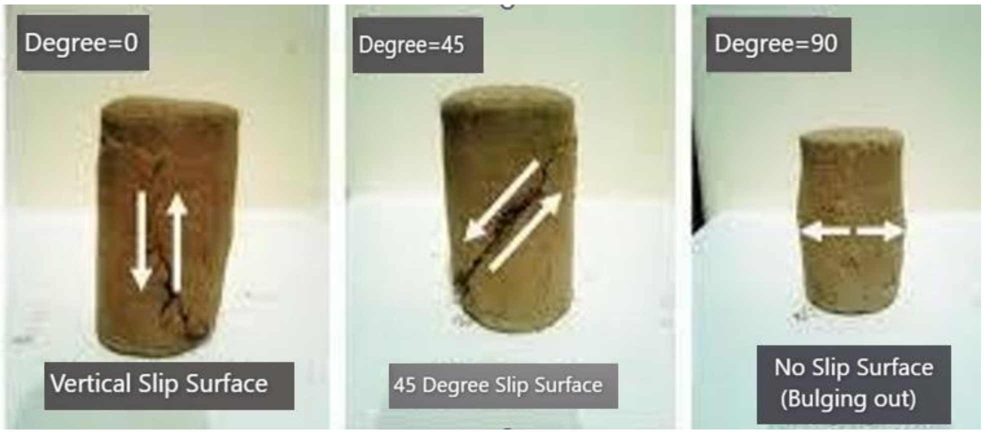

Figure 2: Expected post-failure views of soil samples tested in triaxial

4. Adoption of shortlisted innovative soil stabilization technique at large scale

With regard to the improvement of the load transfer capacity and the deformation resistance, plastic fibers have proven to be rather promising in raising the compressive strength of soils to excellent levels. Through the introduction of the fibers into the soil matrix the reinforcing effect helps to fragment the stresses more evenly by spreading, and also helps to limit the risk of cracks when loading. Experimental tests have shown that under optimum conditions of about 0.5 %-1.5 % by weight addition of plastic fibers, as much as 35 % increase in compressive strength would be realized and through this provide an effective method of stabilizing weak or expansive soils [13,14]. This approach will most definitely provide an eco-friendly solution for waste materials to be recycled in geotechnical applications [15]. This was done through permeability tests aimed at checking whether the amendment had any factor bearing on the permeability of the soil and whether the modification created any excessive water holding capacity or drainage issue that would jeopardize structural integrity. Thereafter, Proctor Compaction Tests were undertaken to determine the optimum moisture content and the maximum dry density of the treated soils thus determining the compaction requirements needed to increase the load-bearing capacity of the soils.

For sample preparation, soil samples were mixed with varying proportions of plastic fibers (0.5%, 1.0%, and 1.5% by weight) and wood dust (2%, 4%, and 6% by weight) to ensure uniform distribution of additives throughout the soil. Homogenization of the test sample was carried out strictly with the intent of making sure that the results remain similar in the later phases of the experiment. Similar proportions of additives were already used previously in the studies to enhance the composition of soils but the specific ratio of plastic fibers and wood dust was not studied extensively before [8,13]. In the laboratory testing programme, a package of typical geotechnical tests were conducted i.e., Unconfined Compressive Strength (UCS) tests, Direct Shear Tests, permeability and Proctor Compaction Tests. This phase was aimed at testing whether the tested additives had the benefit (increased) strength, shear strength, cohesion, permeability and compaction properties of the soils [12,18]. Geotechnical laboratory research included the collection of soil samples and mixing them with plastic fibres at varying proportions and wood dust, and the aim of the experiment was to determine whether the addition of these entities could provide strength, shear resistances, and permeability.

Considering the research done in laboratories, the data obtained were statistically treated in order to examine the percentages of plastic fibers and wood dust needed in order to stabilize the soil well. Comparative evaluation was made as an opposition of untreated samples of the soil to evaluate the gains in the soil features thus ascertaining the effectiveness of the waste-based stabilisers. Previous studies have shown similar approaches for evaluating soil stabilization, but the specific combination of plastic fibers and wood dust was not as thoroughly investigated [4,14]. This paper is based on the numerical simulation that aims at predicting the long-term behaviours and performances of the engineered soils stabilized in the landfill design. The simulations consider basic variables including the load bearing capacity, settlement and the variation of moisture so as to determine the sustainability and strength of the treated soils. This is true to the studies that are conducted to simulate the geotechnical behaviour previously [10]. The findings reveal that unconfined compressive strength (UCS) and shear strength are always improved by chemical stabilization with lime and cement with lime showing 30-40 % improvement as compared with the reference soil. Derived waste materials such as PET fibers and wood ash have registered similar gains with the former showing 25-35 % improvement in UCS and presenting less environmental negative attributes [4,14]. The current research touched the question of the effectiveness of waste products as sustainable soil amendments. An intensive interpretation of data about experimental and numerical simulations probed the fact that polymeric fibers and wood dust contributed to similar improvement in soil mechanical properties.

The experimental programme showed that the significance of plastic fibres and wood dust addition in enhancing some important geotechnical properties of the soil specimens being studied was highly evident. Unconfined compressive strength (UCS) this means that values rose by around 35 % and shear strength rose by around 25 % in comparison with the untreated control specimens. The test conducted on permeability showed that the rates of water infiltration were lower, which proved higher capacity of containment in landfills applications. Both theoretically and empirically attested results suggested that there was an increase in stability with an increment in the number of loads and moisture. The addition of lime or cement applied chemical stabilization due to a consistent improvement in unconfined compressive strength (UCS) and shear strength; lime produced a higher improvement in strength of 30-40 per cent. Similar gains were realized in the purported materials that consist of waste materials such as PET fibers and wood ash, with UCS gains of 25-35%, with fewer environmental penalties [1,19]. Stabilizers derived out of waste have the ability not only to raise the geo-tech qualities but also ensure that environmental issues are addressed: they minimize waste in landfill and mitigate the carbon intensity that is a problem in standard methods of stabilization. Empirical research shows that the incorporation of PET fibers and wood dust can reduce the total cost of the project by 2030% as compared to the conventional solutions, and therefore, the practice is viable at the scale of mass construction both in the urban and rural settings. The current paper supports the idea that waste streams are potential, cost-effective media with proven long-term sustainability benefits. The findings bear out that adding plastic fibers and wood dust to soil substantially increase the soil stability, providing it with the strength that corresponds to the commonly used additives and all this at the same time saves the capital cost and ecological cost. These data combined serve to corroborate the hypothesis that amendments produced by waste are financially and environmentally viable replacements to traditional soil conditioners.

5. Conclusions

The current state of the art paper will study waste material application in the geotechnical soil stabilization, mainly plastic fibers and wood dust. These constituents are green and economically viable alternative to the traditional agents e.g. lime and cement, thereby resolving both performance engineering and environmental factors. The review of scientific works based on the publication of the works in high-quality journals of the past 10 years allows evaluating the impact of plastic fibers and wood dust on soil properties, the subsequent environmental benefits, and the extent to which their use can be considered practically possible. The paper also evaluates the current processes involved in recycling and managing of these materials, especially their abilities of reducing the negative effects on the environment. Based on the research findings, the following conclusions can be drawn:

- Soil-stabilizing conventional methods, that is lime and cement, increase the strength and the load bearing capacity of the soils, but on the same breath, they generate high carbon dioxide emissions, cause degradation of the environment and a lot of financial cost hence hindering the issue of sustainability.
- The waste products, especially the plastic fibers and wood dust, have positive effects on the soil properties in terms of amendment of texture and water holding capacity and thus reduce the environmental damages and serve as a cost-effective alternative of synthetic elements and a solution of waste management.

The acquisition of raw materials of the same grade, high costs of production and use, and solving regulatory barriers are the three major barriers to the broad implementation of carbon-capture technologies in a large scale. The lack of standardization of the industry and the questions about the long-time performance are other, very important barriers.

The empirical data developed in this paper highlights why there is a need to develop sustainable soil stabilizers that will have a less footprint in the environment without compromising the structural properties. The ongoing scientific research and technological optimization are required to streamline these binders to be used at large scale. There needs to be a university, policy and industry cooperation to work towards the development of common safe practices and stimulate the widespread use of waste-based soil stabilisers. By integrating these innovative techniques, the construction industry can move toward more resilient and eco-friendly infrastructure solutions.

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Abbreviations

The following abbreviations are used in this manuscript:

UCS	Unconfined Compressive Strength
PET	Polyethylene Terephthalate
MDPI	Multidisciplinary Digital Publishing Institute
Mintek	Mineral and Metallurgical Technology (South African mineral research organization)
CO2	Carbon Dioxide
UV	Ultraviolet
MW	Megawatt (used for earthquake magnitude in references)
Geotech	Geotechnical
Aluminosilicate	Aluminum Silicate (chemical compound)

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