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REVIEW PAPER

The Utilization of Plastic Waste for Stabilizing Expansive Soil Subgrade: A Critical Review

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ABSTRACT: In developing countries like India, plastic waste has become a menace to the environment and civilization. Moreover, it challenges the sustainable waste management practice since plastic waste is non-biodegradable. The reuse and recycling of plastic are the best way to handle it and can be used as a good construction material. Researchers have explored potential applications of plastic waste in civil engineering construction. In this context, it is worth mentioning that efforts have been made to utilize plastic waste as reinforcement material in ground improvements. However, the suitability of plastic strips as a reinforcing material for various types of soil remains a concern. Different studies have been conducted to explore the potential of plastic waste as a reinforcing material for ground improvement. This paper presents a review of the scope and applicability of plastic waste for reinforcing expansive soils and its other impacts.

Keywords: Plastic Waste, Soil Reinforcement, Ground Improvement, Expansive Soil.

1. Introduction

From paper clips to space crafts, from cell phones to computers, and various other items in our daily use, plastic products have found their use in a variety of applications.

In the last 60 years after its invention, plastic has taken center stage in our daily life due to its favorable attributes such as low weight, durability, reliability, easy adaptability, highly convenient to use, and easy availability (Fadhil et al., 2021). Due to these qualities of plastic, its demand increased substantially from 0.5 million tons in 1950 to above 260 million tons by 2008, and similar growth is expected in the future (Fadhil et al., 2021). Plastic is non-biodegradable, and its increased use leads to some adverse effects on the environment by littering roadsides, clogging sewer lines, and filling land. The CPCB India has undertaken a study on plastic trash production in 60 different Indian cities, predicting that it will be 15342.5 tons per day, or about 5.6 million tons per year. In addition, almost 6000 tons of trash remain

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uncollected and littered (Peddaiah et al., 2018). During the survey, it was also found that one of the most important reasons for the Mumbai city flood in 2005 was the choking of sewer drains by plastic waste materials thrown indiscriminately by the people (Peddaiah et al., 2018). One of the efficient methods to limit plastic waste is to recycle or reuse it by blending it with various products under high pressure and temperature. During an investigation, it was found that reinforcing the soil with plastic waste strengthens the soil; hence, it can be used as a reinforcing material. Improving the strength of soil by plastic waste reinforcement is a meaningful and efficient way, and is cost-effective.

Some examples of utilizing such materials for civil engineering applications include soil stabilization of the base, sub-base courses of pavements, strengthening of earthen embankments, and reducing soil settlements in foundations. (Peddaiah et al., 2018). The growth of cities and industrial areas implies that the land available for buildings of sufficient capacity and occupancy is exhausted to a certain extent.

Geotechnical engineers have to construct structures like foundations, embankments, and pavements at a given site with given soil conditions available to them. In such situations, different ground improvement techniques are available to be utilized for the improvement of poor soil conditions.

Soil modification through the addition of admixtures and the use of soil reinforcement techniques are popular ground improvement techniques among engineers. Fly ash, pond ash, Rice Husk Ash (RHA), Ground Granulated Blast Furnace Slag (GGBS), stone dust, terrazyme, etc., can be utilized as an admixture to improve the soil properties (Aswar et al., 2023; Gautam et al., 2022; Priyadarshee et al., 2021). Since soils are susceptible to differential settling due to their low shear strength, heavy loads from civil engineering structures on soft or weak soils can lead to failure if not properly handled (Correia and Rocha, 2021). Certain needs, such as loading capacity, shear strength, and permeability, may be addressed by using ground enhancement techniques such as prefabricated vertical drains or soil stabilization (Abdel-Rahman, 2021). Many studies on soil strengthening have been conducted in recent years utilizing randomly distributed natural and synthetic fiber material (Mirzababaei et al., 2013).

Compaction with randomly distributed fiber-reinforced soil has several advantages. Previous research has shown that the strength properties of randomly distributed fiber-intensified soil are a function of the fiber concentration and fiber-surface interaction (Bahrami and Marandi, 2020).

Random reinforcement of soil with High-Density Polyethylene (HDPE) plastic strips obtained from waste bags or bottles may be a simple and cost-effective method to enhance the engineering properties of existing soil (Vijayan and Parthiban, 2020).

The main emphasis of many researchers is on the usage of plastic strips as fiber materials in the construction of different geotechnical structures. In addition to the recycling of plastic and rubber waste fiber, this will allow fiber to be reused for the stabilization of soils. The large terrain of the world is covered with expansive soil. There is a great change in volume after wetting and drying, which is the main problem associated with expansive soils. Due to its volume change behavior, damages to structures have been observed extensively. Hence, it makes expansive soil problematic. Thus, in the regions with pronounced wet and dry seasons, it poses a great hazard. In a large number of such cases, vertical or horizontal cracks develop, and due to this damage in pavement, buildings, canals, and conduits in basement walls take place. The proper technique to improve the soil condition by reducing estimated structural damage from expanding soil has been the point of focus of many investigations carried out by various researchers. The main purpose of techniques used for soil improvement is to prevent or limit moisture ingress, change of properties of the soil, and super movement with overburden. Materials used recently for the improvement of soil conditions are geosynthetics, including geotextiles, geogrids, geomembranes, plastic waste bottles, carry bags, and many such objects.

By using geotextiles, plastic waste bottles, and carry bags with lateral resistance, tensile diaphragm, support, and build-up capacity, it may be able to increase the expanding terrestrial subgrade's capacity. It is economical to use plastic waste bottles and carry bags in any type of structure, such as buildings, pavements, canals, and conduits (Kumar et al., 2022; Mahajan et al., 2022). This paper provides a comprehensive overview of the intricate relationship between plastic waste and soil stabilization, with a primary focus on expansive soils. The initial section succinctly outlines the prevalent issue of plastic waste and conducts a literature review on soil stabilization techniques, setting the stage for a more focused discussion on expansive soils. The literature review critically evaluates existing methods, establishing a foundation for understanding the complexities associated with stabilizing soils. Subsequently, the paper delves into an in-depth analysis of expansive soil behavior, elucidating the challenges posed by its unique characteristics. The state-of-the-art approaches to enhancing the engineering properties of expansive soils are thoroughly examined, offering a comprehensive understanding of current methodologies and their effectiveness. The paper concludes by identifying a research gap in the current body of knowledge, indicating a need for further investigation into specific aspects of improving expansive soil engineering behavior. By synthesizing existing research, critiquing methodologies, and pinpointing gaps in knowledge, the paper contributes to the academic discourse on soil stabilization, particularly in the context of expansive soils. This fosters a deeper understanding of this multifaceted and crucial environmental challenge. The flow chart of this review article is shown in Figure 1.

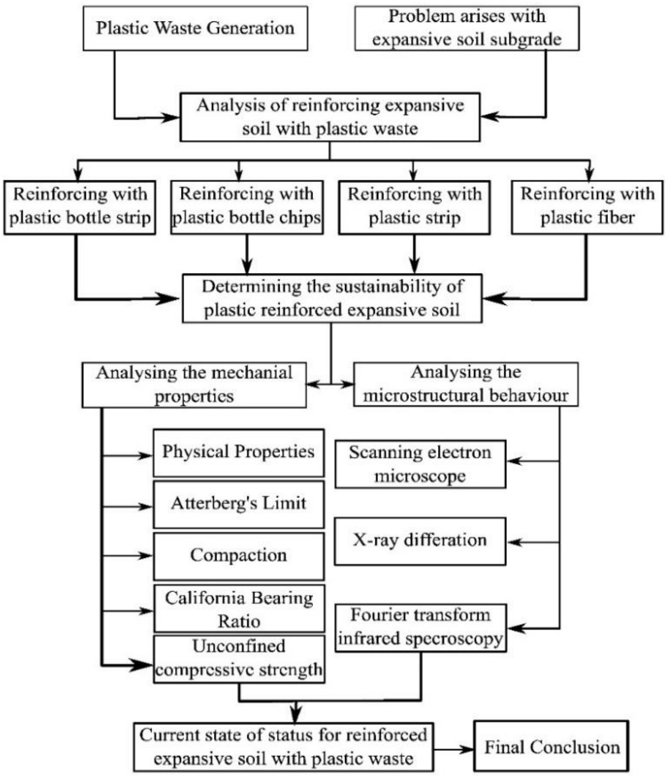


Fig. 1. Overview of stabilization of expansive soil with plastic waste

2. Plastics

Plastics, derived from lighter fractions of natural gas or oil, consist of polymers or resins. The term 'plastics' encompasses a diverse array of resins, each possessing unique capabilities and properties. Also, the properties of every resin can be changed with the addition of substances. Various resin types and added substances permitted a wide scope of item production that meets a variety of specifications. Polymers are large synthetic particles composed of repeating chemical units called monomers which combine to form polymers or long chains. Polymers are pure materials formed through the polymerization procedure; however, they cannot be utilized individually, yet. Additional substances are added for plastic shape. Such added substances comprise of reinforcements, fire retardants, fillers, coupling operators, antistatic specialists, oils, shades, plasticizers, and stabilizers. Unadulterated polymer might incorporate cellulose, cotton, wood, cowhide, elastic, shellac, fleece, bitumen, and silk (Khalid and Alshawmar, 2023).

3. Soil Stabilization with Reinforcing Materials

It is standard practice to use a range of ground improvement additives (for example, calcium, cement, and fly ash) to deal with poor shear strength and soil capabilities when constructing on weak ground. Henry Vidal of France created a new and improved method later to decrease the risk of stability in slopes, enhance the capacity to carry the load, and reduce lateral deformation by reinforcing tensile materials (geo-synthesis, etc.) into deficient soils. direct shear tests were performed on dry sand reinforced with various fiber types. Natural and synthetic fibers, as well as metal wires mixed with soil, were subjected to rigorous testing. A theoretical model, based on a force equilibrium for fiber-reinforced sand, has been developed. Theoretical predictions of the model for fiber-reinforced sand were compared with the experimental results. It was also obtained that the shear strength of the reinforced soil was improved. An increase in the peak shear strength and a reduction in post-peak strength were found. The important parameters that affect the results were the concentration and orientation of fibers in the sand-fiber mix, irrespective of the density of the sand.

These findings are directly applicable to the protection of slopes of weathered granite rocks and sand dunes formed along coastal beaches. The mechanical properties of kaolinite soil and fiber composite were examined. The results of various laboratory tests such as unconfined compression test, splitting tension, three-point bending, and hydraulic conductivity, indicated appreciable enhancement in the all-round strength of the composite. The additional strength was found to be a function of fiber length, fiber content, and soil-fiber water content. The more the fiber content, the higher is the compressive strength, the tensile strength, and the toughness index.

The influence is more at low water content. It is also noted that the higher fiber length provides less increase in tensile and compressive strength but makes the composite more ductile. Though there is a slight increase in the hydraulic conductivity of the composite, it remains low enough to be used as a liner in landfills. It was mentioned in an experimental study on the evaluation of the strength of reinforced sand with small strips of recycled HDPE. The strength tests used included California Bearing Ratio (CBR), secant modulus, robust modulus, and shear strength. Experiments were carried out to examine the interactions between portage sand and HDPE strips. According to the results, the addition of waste plastic to the soil enhances its strength and stiffness. The effects of characteristics of fiber (e.g., weight, aspect ratio, and surface friction), its density, and confining stress on the shear strength of fiber-reinforced soils are evaluated. The results of several triaxial compression tests on reinforced soil have been used to develop a mathematical model through regression analysis. This model can find the shear strength of soils reinforced with any other type of fiber for a given confining stress. The model results compare well with the many other experimental studies reported in the literature. This introduces the concept of "critical confining stress", which means that the failure envelope of soil fiber composite is curvilinear with the transition at critical confining stress, and below which the fibers may slip in the soil matrix on loading. It was also reported that the critical confining stress is dependent upon the aspect ratio of the fiber. The shear strength of the soil was found to increase considerably by fiber insertion, and the rise in strength depended on the fiber weight, the aspect ratio, and the size of the grain. Kumar et al. (2022) provided the findings of laboratory experiments on expansive soil reinforced with randomly dispersed polyester fibers.

The addition of fiber to soils improved the maximum compressive strength, CBR value, peak friction angle, and ductility of the specimens, as shown by the test results. The fiber content and pond ash content are found to be optimal at 0.3% to 0.4% of dry weight. It was described the benefits of using randomly distributed polyethylene terephthalate fiber, obtained from the recycled waste plastic bottles (as reinforcement) to uniform fine sand as well as cemented sand. The various tests conducted for the study were unconfined compression tests, splitting tensile tests, and saturated drained triaxial compression tests with local strain measurements. The strength and deformation characteristics of soil, reinforced soil, and reinforced cemented soil were studied separately through regression analysis of experimental data. It is concluded that the peak strength of cemented and non-cemented soil improves with the inclusion of fiber; however, the ultimate strength is a little bit reduced. Further, the inclusion of fiber makes the cemented soil somewhat ductile, but the initial stiffness remains unaltered. The results of drained triaxial compressive tests on fiber-reinforced sand specimens were provided. After adding a small amount of synthetic fiber, the composite's failure stress has been found to increase. A reduction in early stiffness and an increase in stress, on the other hand, are related to strain at failure. Steel fibers have little effect on the composite's initial stiffness. The failure phases increase up to 70% when the fiber structure is 2% (by volume) and the aspect ratio is 85. Increases in fiber concentration and aspect ratio enhance the reinforcing advantage, but it also depends on relative grain size and fiber length. Fine sand produces more shear strength than coarse sand, and the maximum benefit is attained at low fiber content (0.5%).

However, with a greater fiber concentration, this trend is reversed (1.5%). Under triaxial compression, a model has been developed to predict failure stress. There are two segments in the failure envelope: linear segment with fiber and non-linear segment with respect to fiber material generation. The results indicate that the fiber yield is much higher than the stress range seen in experimental results. To explain the failure criteria of fiber-reinforced sand, the concept of a microscopic internal friction angle was created. This idea is a simple method of integrating fiber reinforcement in the stability analysis of earthen constructions.

Later, after a few years, the mechanical behavior of sand reinforced with strips of waste plastic was reported. Consolidated drained tests were conducted on sand and reinforced sand with strips of waste carry bags and packing materials (HDPE plastic).

The analysis of the experimental results shows improvement in the engineering behavior of reinforced sand. The dilation of reinforced sand is restricted, and the shear strength parameter, i.e., angle of shearing resistance, is increased. It is also established that the improvement is more at low confining pressure as compared to that of high confining pressure. According to the findings of the study, the behavior of polypropylene reinforced sand under high shear strain has been investigated through a ring shear test. Shear testing was performed on sand with and without reinforcement.

The reinforcement used was randomly dispersed fiber. Under high distortional strains, the influence of the fiber was investigated by looking at the impact of the length of the fiber, the content of the fiber, and the effective normal stress at differing relative densities of the sand. Higher fiber content and denser fiber-reinforced sand components have been studied specifically to demonstrate the effects of longer fibers more clearly. The results showed that this kind of fiber strengthening has a tremendous amount of promise since the enhanced strength does not diminish even when subjected to quite high strain. The fibers were taken out after failure to observe their status. It is concluded that the long fibers are broken after large plastic deformation, and short fibers are created. It is also found that the denser sands acquire more shear strength on reinforcement, and the shear strength enhancement is more with higher fiber content. It was considered that the distribution of fiber strips in the fiber-sand mix creates anisotropy. Keeping this in view, an anisotropic yield condition is developed for fiber-reinforced sand with the ellipsoidal distribution of fibers. The maximum shear stress, in an anisotropic yield condition, is dependent on the direction of principal stress and in-plane mean stress.

The anisotropic shear strength can be found from the plot of the yield condition on the plane of maximum shear stress and the shear stress on the z-plane. This yield condition has been used for limit equilibrium analysis employing a kinematic approach. As the fiber-reinforced sand is anisotropic, the angle of internal friction will vary with the direction of the major principal stress.

However, for boundary value problems, the unique value of the angle of internal friction can be determined. The proposed approach has been used to evaluate the performance of fiber-reinforced sand with a retaining wall and a strip foundation. It is concluded that the inclusion of fibers in sand reduces the load on the retaining wall and improves the bearing capacity of the strip footing. Dutta et al. (2016) presented a study on stone dust reinforced with waste plastic strips overlying the soft clay. The experimental study is limited to the impact of reinforcement on the CBR value of the stone dust above soft clay (commercial grade of kaolinite). Three lengths of low-density polyethylene waste plastic strips (12 mm, 24 mm, and 36 mm) with strip content (0.1%, 0.2%, 0.4% and 0.8% by weight) were used. The results were interpreted in terms of CBR value and secant modulus. It is concluded that the inclusion of waste plastic in stone dust above soft clay results in little improvement of CBR value and secant modulus, and the improvement is more with plastic strip content and length of the strips. Kumar et al. (2022) developed a novel shape of plastic strips termed disciplined HDPE by reinforcing it with locally available soil to enhance the engineering performance of sub-grade soil. HDPE strips of various concentrations (0.25, 0.5, 0.75, 1, 2, and 4%), as well as lengths and sizes, were put into the sandy soil with random orientation. It was noted that an increase in HDPE strip content and size, improves CBR values and significantly reduces sub-grade thickness. It is assumed that the confining pressure is so high that the fibers get broken before reaching to pull-out condition. The simple force equilibrium model was used to predict the shear behavior of reinforced soil, which depends on factors like fiber content, aspect ratio, specific gravity, elastic modulus of fiber material, skin friction, the orientation of fiber concerning shear plane, confining stress, void ratio, angle of internal resistance, and specific gravity of soil. This introduces the existence of apparent cohesion due to the presence of fibers in the soil that increases the shear strength. The shear strength improvement is found to be proportional to fiber content and its aspect ratio. However, the validation of the model has not been done with any experimental results. Landfill closure essentially requires a cover barrier for the safety of the surrounding environment. A suitable cover barrier was provided that is somewhat ductile, impermeable, and good for site safety as required. The silty clay cover barriers of landfills are subjected to differential settlement due to the non-uniform settlement of the garbage mass in the landfills. This causes cracks in the cover material, and the purpose of protecting the pollution from the closed landfills is lost.

For this reason, it has been proposed to use polypropylene fiber-reinforced silty clay as a cover material. Authors have reported the results of direct tensile and compression tests of reinforced silty clay and have shown that the composite material is improved in compression as well as in tension. The rigidity and ductility of the proposed composite material become quite good to improve the mechanical performance of the reinforced clay. This leads to a better solution to the problems of covering barriers of landfills. The shear strength of fiber-reinforced soils is evaluated by the test results of triaxial compression on the specimens of the composite soil. For rational designing of a fiber-reinforced soil structure, it is essential to develop the mechanics of reinforcement as well as failure of this composite material.

Li and Zornberg (2013) presented a methodology by which the equivalent shear strength of fiber-reinforced soil can be predicted by knowing the shear strength of the soil matrix and the pull-out tensile capacity of the fiber through the soil. It is proposed to evaluate the shear strength in a discrete framework, which requires experimental assessment of shear strength parameters of soil by triaxial compression test and results of fiber pull-out test through soil, which indicates the tension mobilized at various shear strain levels. The shear strength of reinforced soil is governed by strain compatibility at peak failure or post-peak residual shear strength of the unreinforced soil. The study concludes that the fiber-induced tension is mobilized at the high strain stage, high fiber content provides shear strength by the use of residual shear strength of the soil, and low fiber content gives shear strength with peak shear strength of the soil. However, the equivalent shear strength of the reinforced soil should be calculated corresponding to the strain level at peak failure and residual shear strength of the soil, and the maximum of the two values may be taken as equivalent shear strength. Bahrami and Marandi (2020) gave the formulation of failure criteria of fiber-reinforced sand considering the isotropic and anisotropic distribution of fiber in the soil matrix. A concept of cross-anisotropy concerning three planes (x, y, and z) has been followed to define the anisotropy due to the distribution of fibers in the soil. This defines an anisotropic variable 'A' as a joint invariant of the deviator stress tensor and deviator fiber distribution tensor. The value of 'A' ranges from -1 to 1, and for the isotropic fiber distribution, its value is zero.

The strength of the composite sand is also influenced by the degree of anisotropy of fiber distribution. It is assumed that the host soil alone is isotropic, and anisotropy in the composite is contributed by the reinforcing fibers only. One of the failure criteria developed and presented for the isotropic distribution of fibers considers the major, intermediate, and principal stresses. The criteria can predict the shear strength of the composite at a given confining pressure and can also predict the strength of unreinforced soil. The other expression gives the shear strength of the composite with the anisotropic distribution of fibers.

This criterion may assess the shear strength of the reinforced soil, which is tested under true triaxial compression under the three-dimensional (3D) loading, where the intermediate and minor stresses differ in magnitude. It has been noted that the predictions made by the proposed criteria match well with the test results. The study is applicable for analyzing the stabilized slopes with reinforcement of soil by synthetic fibers, plant roots, and soil nails, etc. Correia and Rocha (2021) described an experimental study on the effect of plastic fibers on the compressibility behavior of soils. Materials used were waste HDPE plastic bottle fibers and silty sand with clay content. A series of odometer tests were conducted on specimens of compacted composite soil at Optimum Moisture Content (OMC) reinforced with plastic strips of aspect ratios (2, 4, and 8) and varied plastic content (0.0%, 0.25%, 0.5%, and 1% by weight). The test results reveal that the Maximum Dry Density (MDD) reduces with an increase in fiber content, but the OMC remains almost the same. The compression index (C_c) and coefficient of volume change (m_v) decrease up to 0.5% and these are increased thereafter. The coefficient of consolidation (C_v) increases with an increase in aspect ratio of fibers. It is eventually found that 96% consolidation gets completed within 96 seconds with the inclusion of 1% fibers of aspect ratio 8, which shows the potential of plastic fibers in achieving early consolidation settlement of soil. Mirzababaei et al. (2013) reported the rise in the amount of residential, commercial, and industrial carpet waste that may be used to control the swelling characteristics of compacted expansive soils. Two different soil samples with plasticity indices (17.0% and 31.5%) were taken for the study. Two different types of carpet waste fibers were mixed with the soil. The fiber contents in the sample soils were kept at 1%, 3% and 5% by the dry weight of soil. The MOCs and maximum dry unit weights of reinforced and unreinforced samples were determined.

The two types of fibers used were GBF (synthetic carpet shred) and ABF (short fibers from shearing processes). It was ensured that fiber and water distribution remained uniform. Many compaction tests and swelling tests were done. The results show that the maximum dry unit weights decrease with an increase in the fiber content, and the OMC is increased with the rise in fiber content.

The specimens prepared with fiber content at MDD and OMC have shown a reduction in swelling pressure values. The highest drop in swelling pressure has been found with 1% GBF fiber content. It has also been noted that minimum swelling pressure is attained at 1% ABF fiber content. Vijayan and Parthiban (2020) present the use of plastic waste as a reinforcing material for improving the strength of clayey and sandy soil. It was found that reinforcing the soil with waste plastic pieces strengthens and improves the stability of the soil. The plastic waste pieces are mixed with clayey and sandy soil. The shear strength parameters of reinforced and unreinforced samples were investigated by a direct shear test. A significant improvement is shown in terms of soil strength. The internal friction angle is increased more in sandy soil, but it is improved marginally in the case of clayey soil. The influence of reinforcement on cohesion is negligible. The compaction tests on reinforced and unreinforced clay revealed that the MDD and OMC of reinforced soil are decreased due to the use of those plastic pieces, which obviously have low specific gravity. Fadhil et al. (2021) investigated experimentally the performance of local sand reinforced with HDPE strips. Here, two sandy soils, i.e., Klipheuwel sand and Cape Flats sand, were used, and the tests conducted were direct shear tests and plate load tests. Shredded plastic material strips were mixed at concentrations up to 0.3% by weight. The dimensions of the plastic strips were varied, and the effect of variation in strip sizes was also studied. The strip lengths were between 15 mm and 45 mm, and the width was between 6 mm and 18 mm. To find the extent of soil improvement, soil strength parameters were obtained for the composite specimen. The results obtained from the tests suggest that in the case of sandy soils, the induction of plastic strips is an effective reinforcement. It was considered that the reactive soils exhibit volume changes due to climatic variations, which cause damage to pavements and foundations of various structures. The specimens were prepared by mixing slag, construction wastes (crushed masonry, tiles, etc.), and commercial bentonite in different proportions and cured for 28 days. The specimens were tested for shear strength by a direct shear test. The test results and microstructural study of specimens showed considerable improvement in the shear strength and stability of the proposed mix. It is also mentioned that the microstructural study supports the test results, as the slag has cementing properties.

Mahajan et al. (2022) reported the research with the objective of exploring the underlying challenges of expanding soils and providing realistic economic solutions for expanded Sudanese soil development. The concern was the field performance of expanding soils with a focus on design requirements and construction safeguards for large-scale buildings. The results indicated that high swelling pressure led to the heaving of soil below the foundations of structures and was the main cause of failure.

Correia et al. (2015) worked on the mechanical impact of the soft soil "Baixo Mondego" on the amount of binder and fiber used in the production of a chemically stabilized concrete mix that is reinforced or not with short polypropylene fibers. One test was for determining compressive strength (unconfined compressive strength test), while the other three were for determining tensile strength. There were four distinct kinds of tests (direct tensile strength test, split tensile strength test, and flexural strength test). Increased binder concentration increased stiffness, compressive strength, and resistance in fiber-reinforced specimens, but had less effect on nanofiber-reinforced specimens, according to the findings. Stiffness, compressive force, and direct tensile force are reduced, strength losses after the peak are minimized, and the soil's behavior transforms from fragile to ductile by adding a tiny number of fibers to soft soil that has been stabilized. The research also discovered that the effect of fiber addition on strength varied based on the straining mechanism used in each test. Therefore, the impact of the fiber on bending strength testing is considerable, while the presence of fibers in direct strength tests is insignificant. The relationship between compressive strength and tensile strength, as well as the relationship between the tensile strengths, are presented at the end of the trial, as well as the relationship between the tensile strengths, as determined by direct tensile strength testing, split strength testing, and flexural tests. Abdel-Rahman (2021) described the soil at construction sites which is not suitable for bearing heavy loads as needing to be improved to enhance bearing capacity and decreased the effective settlement. An overview and concept of major ground improvement techniques and their practical applications were described.

As a result, the techniques may be used in a variety of soil types, from coarse to fine-grained soils. A large portion of India's red soil is typically covered by water. These soils are found in low-precipitation areas and are not capable of absorbing moisture from the atmosphere. Because of the high concentration of iron in these soils, they are red. Because of the porous structure of the red soil, it has a lower strength than other soils. Soil stabilization is accomplished via the application of certain chemicals to soils to improve their engineering and strength properties.

Peddaiah et al. (2018) globally stated that since the non-biodegradable plastics are being incinerated because the hazardous gases are thrown into the atmosphere, it is causing a major environmental problem. Research on the compliance and usage of waste plastics in soil enhancement is shown here. Experimentally, it was investigated that reinforced plastic soil resulted in effective stabilization to encounter waste disposal problems and to provide economic solutions for soil stabilization. The compaction test, direct shear test, and CBR test are all used in this study to explore the effect of plastic bottle strips on silty sand. According to the results, the maximum dry weight of the plastic unit, shear strength parameters, and CBR values increased. With each passing day, the usage of plastic items such as plastic bags, bottles, chairs, toys, and many other plastic products is increasing. Therefore, the environmental problems caused by plastic waste are becoming more severe. Therefore, the use of waste plastics as a soil stabilizer is an effective use of waste, since suitable soil is missing for a variety of technical applications. In Table 1, the summary of different studies is presented.

Table 1. Literature review with critical remarks

Author	Soil location	Country	Type of soil/work	Remarks
Machado et al. (2024)	Salvador	Brazil	• Sand • Reinforced with randomly distributed polypropylene fibers, 0.5% by weight, 12.5-51 mm in length.	• Improvement in the isotropic compression test, triaxial test • Reinforced with polypropylene fibers under isotropic compression.
Amena and Chakeri (2022)	Jimma town	India	• Expensive soil • Used plastic water bottles that are easily available, economical and a waste substance posing a problem for safe disposal.	• 0.75% improvement in the shear strength, cohesion, and loads settlement. • 1% improvement in the CBR. • Poorly graded sand added with shredded plastic strips.
Kumar et al. (2022)	Sasaram, India	India	• Black Cotton Soil (BCS) • Waste plastic strip • Soil was stabilized with waste plastic strips of three different aspect ratios in varying proportions (i.e., 0.4%, 0.7% and 1%)	• Find a significant improvement in CBR and shear strength characteristics. • Soaked CBR significantly increased by 223%. • Slight increase in MDD and significant decrease in OMC.
Abukhettala and Fall (2021)	Ottawa-Gatineau area in Ontario	Canada	• BCS reinforced with plastic waste.	• Plastic Fiber is used. • MDD reduced due to the addition of plastic waste • CBR value is improved, and the thickness of pavement is reduced.
Bozyigit et al. (2021)	Kaolin clay, Bornova	Turkey	• Kaolin clay. • Waste plastic fibers used for the improvement of soil for its geotechnical parameters.	• 1% improvement in the angle of shear strength and cohesion. • Waste plastic fibers are used. • Geotechnical parameter improvement of soil in terms of its parameters.
Fadhil et al. (2021)	Mustansiriyah University, Baghdad	Iraq	• Sand • Two selected sandy soils: • Utilizing polyethylene shopping bags waste to reinforce soils.	• 0.75% improvement in the angle of friction, plate load test. • Inclusion of discrete polypropylene fibers in soil as reinforcement material.
Hassan et al. (2021)	Hawshki area, Iraq	Iraq	• Clayey soil • Plastic bottle strip • Plastic bag strip • Both strips were mixed with soil to improve the mechanical properties of the soil	• Modulus resilient of soil was improved with an increase in fiber content. • MDD was improved significantly • CBR was also increased with an increase in fiber content.

Yang et al. (2021)	Hunana	China	• Granular Soil • This scientific paper explains how to use a simple analytical model to estimate the shear strength of granular soils reinforced with fibers. The model is intended to be basic and simple.	• Because of the existence of fibers in the granular soil, cohesion contributes to the soil's increased shear strength, but it contributes very little to the increased shear resistance due to increased stress.
Kassa et al. (2020)	Bole, Ethiopia	Ethiopia	• Expansive soil • Rectangular PET bottle strip • Mixing plastic strip in three different aspect ratios in 0.5, 1, and 2 % with expansive soil to improve its strength	• MDD and OMC are reduced. • Swelling is reduced by using a plastic strip. • Huge improvement in Uniaxial Compressive Strength (UCS). • Angle of internal friction and cohesion increases with an increase in reinforcement material.
Peddaiah et al. (2018)	Patna Ganga alluvial soil	India	• Silty sand • Use of waste • Plastic soil improvement. • Plastic may be utilised as an efficient waste stabiliser as well as a cost-effective option for stabilising poor soils.	• 0.4% improvement in the CBR value, MDD and shear strength. • Plastic bottle strips are used. • Improvement in the engineering properties of soil for its stabilization.
Naeini and Rahmani (2017)	Silty soil, Qazvin	Iran	• Silty soil • Laboratory CU tri-axial tests on randomly plastic waste bottle chips.	• 1.25% improvement in the angle of internal friction, cohesion, pore water pressure, OMC, and MDD. • Silty soils are used. • The influence of different fiber length and different fiber content on the shear strength is detected.
Dutta et al. (2016)	Koradi thermal power plant, Nagpur	India	• Fly ash • This article raises concerns about two types of industrial waste: old plastic water bottles and fly ash. • It emphasizes the repurposing of old, discarded plastic water bottles in the field of civil engineering.	• 13% improvement in the tensile strength-strain, deformation. • Waste plastic water bottles and plastic bags are used. • Reinforcement materials in the field of geotechnical engineering.
Dutta et al. (2016)	Badarpur sand	India	• Sand • For consolidated three-axial compression testing, a mixture of sand-waste plastic strips was used.	• 0.15% improvement in the stress-strain behavior by the neural network method. • Neural network architectures are used.
Mirzababaei et al. (2013)	Clayey soil, Balton	United kingdom	• Clay soil • Utilization of carpet waste fibers. • In order to improve the swelling characteristics of compacted cohesive soils.	• 3% improvement in the swelling condition • Investigated the effect of adding two carpet waste fibers on the swelling characteristics of two clay soils.

4. Behavior of Expansive Soil

4.1. Mechanism of Expansive Clay

Clay particles have superficial negative charges due to isomorphic substitution. This happens due to the chemistry of exchangeable cations, which depends on the electrostatic forces between the pore fluid medium in the clay and the negatively charged clay surface. To preserve neutrality within the fluid media of the clay pore, normal affinity draws counter ions to the surface of clay particles, distancing them from the clay surface by reducing their concentration.

The diffuse double layer is produced because of variations in concentration caused by the electrostatic surface characteristics and cation exchange capacity of the clay, i.e., the number of cations needed to permeate the clay surfaces (Aswar et al., 2023; Yadav and Tiwari, 2017). The dual layer employs an inflammatory reaction to separate minerals and expandable minerals such as montmorillonite from particles. Diffuse double layers significantly affect the technical characteristics of clay soils, most notably hydraulic conductivity. Hydraulic conductivity should be decreased because of the diffuse thickness expansion of the dual layer, and vice versa when the dual layer has been reduced. In fact, this forms the basis for the swell-shrinking behavior of varying moisture on expansive soils.

Because of its expandable clay mineral, for example, montmorillonite, the morphology of which is characterized by an expanding clay lattice. Volume variations in expansive soil are inherent because of the behavior of the diffuse dual layer.

Expandable clay minerals have low intermolecular attraction forces among adjacent unit cells; however, major isomorphic substitution shows negative surface charges, significant capability for cation exchange, and large specific surface during clay mineral formation.

4.2. Identification of Clay Minerals

Two methods, mineralogical identification and the inferential testing method, have been introduced for evaluating the presence of expandable clay lattice. The inferential testing procedure consists of the indirect methods used for calibrating index characteristics like liquid limit, limit of shrinkage, and distribution of particle size, and direct methods including odometer testing and free swell testing (free swell ratio, free swell value, and differential free swell) (Aswar et al., 2023). The method of mineralogical identification is comprised of differential thermal analysis, X-ray diffraction analysis, Scanning Electron Microscopy (SEM), dye adsorption, and chemical analysis. Though mineralogical identification methods are good enough in expansive soils to identify clay minerals, their use to classify swelling behavior is limited due to a few shortcomings. Because of higher-level tools, complexity, as well as expert review of findings, mineralogical detection procedures were not cost-effective as suggested in the literature. Mineralogical detection approaches become unfeasible for an extensive variety of applications. The inferential testing approaches appear useful to identify and classify the swelling behaviors of clay minerals because they depend on index properties, and direct approaches when testing the swell potential, it is neither costly nor advanced. Though, for literature, the free swell ratio technique (the most encouraging method used to identify the dominant clay mineral in expansive soil) was introduced because it tends to be compatible with the methods used recently for the identification of mineralogical soils (Soltani et al., 2018). The ratio of free swell, in combination with the fluid limit test, is used to assess the dominant clay mineral using a cone approach with carbon tetrachloride and water as pore fluids, due to its inherent nature of certain soils, which consist of a combination of montmorillonite and non-expansible kaolinitic clay mineral. This knowledge derives from the non-polarity of carbon tetrachloride, which prevents the development of a diffusing dual-layer and allows flocks to form, resulting in high liquid limits for kaolinite-rich soils. Expansive soils are categorized using the free swell ratio technique, as given in Table 2. Figure 2 shows the plasticity chart classification of Black Cotton Soil (BCS), which is collected from different locations of India (Reddy et al., 2020).

4.3. Identification of Clay Minerals

BCSs are the black clays generated by the breakdown of simple igneous rocks because of very severe seasonal weather variation. It is called BCS as it is suitable for cotton cultivation. The colors vary from light grey to dark grey and black. BCS are limited to the tropical and temperate climate zones of semi-arid regions and are plentiful in the regions where the yearly evaporation is greater than the precipitation. BCSs have been documented to exist as superficial deposits in continuous stretches and are typical of the low drainage flat terrain. The lack of quartz for clay's mineralogy helps to establish impermeable and waterlogged fine-grained soil material.

4.4. BCS's General Characteristics

During any road construction project, expansive soils generally appear as sub-grade material, and these sub-grades can vary from highly expansive to expansive.

The soil is very clayey and is very hard like the clods, often measuring 70 mm wide and 1.0 m thick, which cannot to be quickly pulverized for treatment to use in constructing a road due to the formation of cracks. This raises serious problems with subsequent road performance. Besides, the softened subgrade tends to rise to the top layers of the pavement, especially when there are many voids in the stone soling of the subsurface. Invariably, the incremental infiltration of wet BCS contributes to road collapse.

Owing to the loss of the subgrade strength through softening during the rainy season, roads laid on BCS bases build undulations on their surfaces. A low concentration of titanium oxide induces the black color of the BCS. There may be a high percentage of clay in the BCS, which is mainly the composition of montmorillonite that is black or blackish grey. The physical characteristics of BCS vary from location to location. As a result, the bearing capacity of BCS is low and it may depict high shrinkage/swelling characteristics. The physical characteristics of BCS vary from position to location. It is estimated that approximately 40-60% of BCS in grain has a size of less than 0.001 mm. In general, these soils have a higher liquid and plasticity limit index and an extremely low CBR value. Swelling pressure as high as 785-981 kN/m^2.

Table 2. Free swell ratio expansive classification of soils (Asuri and Keshavamurthy, 2016)

Odometer expansion (%)[a]	Type of clay	Free swell ratio	Shrinkage limit	Soil expansively
< 1	Non-swelling	≤ 1	<5	Negligible
1-5	Mixture of swelling and non-swelling	1-1.5	5-13	Low
5-15	Swelling	1.5-2	8-18	Moderate
15-25	Swelling	2-4	30-60	High
>25	Swelling	>4	>60	Very high

Note: [a]with 7 kPa surcharge from air-dried to saturated.

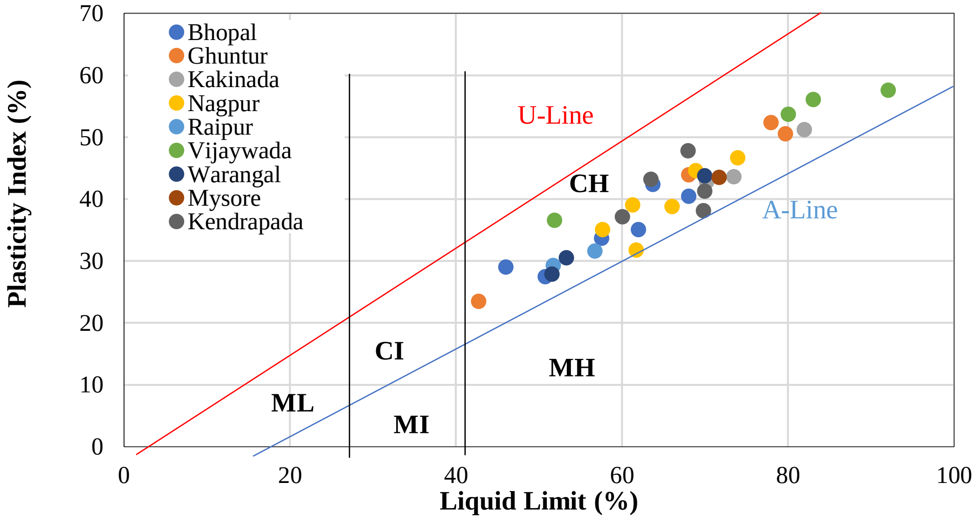


Fig. 2. Plasticity chart classification of BCS (Reddy et al., 2020)

Because of the extremely low CBR values of this soil, pavement construction becomes expensive.

4.5. State of the Art in the Stabilization of Expansive Soil

Over the years, advancements in understanding expansive soil behaviour have yielded numerous outcomes in the realm of soil stabilization. Geotechnical engineers, employing scientific principles, have dedicated substantial efforts to comprehend how expansive soils behave under various loading conditions. The latter half of the 20th century witnessed a plethora of experiments conducted by the geotechnical community, aimed at elucidating and classifying the fundamental behaviour of expansive soils. A method was developed to determine the swelling pressure of the BCS, revealing an increase in swelling pressure despite incomplete relationship maturation. In the pursuit of comprehending the heave phenomenon, odometer tests were conducted to procure data. Subsequent research endeavours sought to determine the swell capacity of expansive clays through predictive, field, and laboratory observations. The concept of soil suction, associated with a negative pore water pressure resulting from the humidity demand of hydro-mechanical clays, was introduced and correlated with swelling in sub-grade clay during moisture occurrence.

Researchers have contributed to the development and application of definitions and methods for quantifying characteristics of expansive soil, including swelling and resilient modulus. Laboratory experiments, such as Atterberg limits, particle size distribution (sieve investigation and hydrometer), dry density, and humidity content, have been instrumental in identifying key properties of expansive clays. In summary, these research endeavours offer valuable insights into expansive soil behaviour and various laboratory identification methods.

4.6. Utilizations of Waste Plastic in the Field of Civil Engineering

Plastics find diverse applications across various sectors, including development, packaging, automotive, furniture, sports, electrical and electronics, health and safety, consumer goods, and household appliances.

In the field of civil engineering, plastics play a crucial role in the construction of bridges, buildings, water-retaining structures, landfills, terminals, ports, roads, railways, and landscaping, among others (Kumar et al., 2022; Khalid and Alshawmar, 2023). Construction-related plastic components encompass materials for partitions, erosion control, foundation inlays, bike racks, walkways, boardwalks, docks, bulkheads, curbs/wheel stop, pallets, railroad ties, piles, piers, guardrails, and sound walls. For a material to qualify as an effective construction material in structural engineering, it should possess qualities such as durability, strength, flexibility, ease of installation, fire resistance, and cost-effectiveness. However, this research focuses on reinforced soil using PET (Polyethylene Terephthalate) waste plastics, as outlined in Table 2, which compares the characteristics of plastic with other construction materials.

5. Mechanical Technique

Mechanical techniques for soil modification encompass compaction, vibration (utilizing various methods), and blasting. The mechanical enhancement of soil through compaction involves densifying the soil by imparting mechanical energy. This process entails adjusting the water content and the gradient of the soil.

Cohesionless soils are compacted by confining the soil and applying vibration energy. Hand-operated vibratory plates and motor-powered vibratory rollers of various sizes prove highly effective in compacting sand and gravel soils. Dynamic compaction of loose granular fills is achieved using substantial dropping weights. In areas with fine-grained cohesive soils, common compaction devices such as sheep foot rollers, rubber tire rollers, and others are employed. Mechanical compaction is directed towards enhancing the engineering properties of the soil mass. This includes reducing settlement through decreased void ratios, bolstering soil strength, and minimizing shrinkage (Ikeagwuani and Nwonu, 2019).

5.1. Reinforcement

Utilizing fibrous materials like waste plastic strips and geosynthetics, along with composites such as geotextiles, geocomposites, geocells, geogrids, and geonets, represents a strategy for stabilizing weak soils and enhancing soil strength (de Azevedo et al., 2021). This approach creates a 3D spatial strengthening network that interweaves or interlocks soil grains into a cohesive mass with improved mechanical efficiency. Typically, these materials are introduced into the soil system, either randomly or with specific engineering, before components are integrated. Table 3 illustrates various forms and configurations of natural and synthetic fibers used for reinforcing soil. de Azevedo et al. (2021) extensively analysed the technical effects of randomly dispersed fibers on soil properties, encompassing both natural and synthetic soil reinforcement fibers.

Notably, the analysis did not delve into the stabilization effects of waste rubber fibers or carpet waste fibre (de Azevedo et al., 2021). The influence of waste rubber fibers on the geotechnical properties of clay was studied by Yadav and Tiwari (2017).

The rubber fibers were added between 0% and 10% content, with a constant increase of 2.5% by weight of the dry soil. Progressive decreases in both MDU: "Maximum Dry Unit weight" and OMC from 16.35 kN/m3 to 14.78 kN/m3 and from 20.1% to 18.25% were due to the result of the humidity density relationship. The Uniaxial Compressive Strength (UCS) in the soil has improved slightly from 60.59 kPa to 62.69 kPa with a rubber fiber content of 2.5%. However, additional rubber fiber decreased the maximum axial stress by a maximum decrease of approximately 21.7% with 10% of the rubber fiber material. The results of the test for split tensile strength of the soil demonstrated a steady rise in split tensile stress with a volumetric strain until a total of 2.5% rubber fiber was reached for all percentages; the peak strength of the tensile has increased by 8.6% but has decreased at high content of rubber fibers with the highest drop of around 7.3% with a maximum level of 10%. The soaked CBR decreased steadily with rubber fiber content, whereas the unsoaked CBR reached around 38.6% with 2.5% rubber fiber addition. The swelling pressure in the soil was steadily decreased by the rise in fiber from 70.12% for natural soil to 39.58% with a 10% content of rubber fiber.

Table 3. Description of the natural/synthetic fibers used in soil reinforcement

Information source	Type of fiber	Dosage/Optimal content (%)	Fiber configuration (length)/Optimal length (mm)
Chompoorat et al. (2023)	Palm fiber	0-1	20-40
Ekinci et al. (2022)	Carbon and polypropylene fiber	0.3	10-30
Kumar et al. (2022)	Waste plastic strip	0-1	10-20
Ma et al. (2022)	Polyethylene fiber	4-5	Pellets
Hassan et al. (2021)	Plastic bottle strip	1-4	10-20
Lv et al. (2021)	Polypropylene fiber	1[a]	12[a]
Kassa et al. (2020)	Pet bottle strip	0.5-2	15-20
Wang et al. (2017)	Jute fiber	0.3-0.9	6-18
Yadav and Tiwari (2017)	Waste rubber fiber	0-10	≤ 15
Jayasree et al. (2015)	Natural coir fiber	0.2-1	> 4.5
Jayasree et al. (2015)	Coir pith	0.5-3	< 4.75
Mirzababaei et al. (2013)	Synthetic carpet waste fiber	1-5	2-20

Note: [a]The optimal values

Mirzababaei et al. (2013) presented the analysis of the impact of the swelling properties of two forms of carpet waste fibers from various sources. Type 1 consisted of short nylon fibers derived from shearing piles of carpets, while Type 2 consisted of a mixture of polyester, polypropylene, and wool derived from trim carpet edges. The addition of the additives into dry soil was at 1%, 3%, and 5% by weight. The results indicate that the swelling pressure for compacted clay, with an activated content of sodium bentonite at MDU and OMC, has reduced to around 20% with 1% of type 1 fiber content, and strengthened by 10% at other fiber content. On the other side, the soil swelling pressure has risen exponentially for type 2 fibers, with a rise of approximately 83% with a fiber content of 3%. The impact of different moisture levels at a fixed dry unit weight and different dry unit weights at constant moisture levels has been studied. The findings demonstrate that the swelling pressure declines with the rise of the moisture level in constant dry unit weight, but the rise of dry unit weight in a fixed moisture content is raised. The same findings for fiber-reinforced soils have also been recorded (Mirzababaei et al., 2013).

5.2. The Relation Between the Microstructural and Engineering Properties

In addition to the volumetric and gravimetric condition variables-void ratio, the content of water, saturation level, and stress (back history) both hydraulic as well as mechanical, various macroscopic soil characteristics can also be seen in terms of microstructural behavior, distribution of pores and connectivity; shape, size, distribution, and arrangement as well as contacts of grain. A typical example is a difference in the permeability of soil at various compaction water content; a compacted soil wet optimal is less than the same compacted soil with an optimal dryness to the same porosity. Initially, it was because of a transition from the flocculated to a dispersed clay particle structure, but the latest research on the permeability of clay aggregates caused by compaction was explained at distinctive water level contents. The inapplicability of the specific connections between macroscopic parameters and hydraulic compressibility, conductivity, and swelling/shrinkage behavior was also explained using clay microstructure imaging. The significance of the size, shape, as well as aggregations of structure, distribution, and connectivity of pores, is illustrated by these studies, along with the behavior of the soil, and how these aggregations and pores would alter throughout. It has also been studied by several variables, such as the type of clay mineral, the rate of drying or wetting, wetting/drying periods, and separating or combining.

Generally, the shape as well as the amount of clay minerals in soils and the interactions with pore water within the soil were illustrated to have a major impact on their strength, compressibility, as well as permeability over time. In the study, it is identified that there may be a relationship between the fabric of natural clays and their engineering properties. A microscopic review of thin parts, prepared by a special technique, in both the undisturbed and remolded specimens of many types of clays at natural water content, has provided direct information on the fabric. It presents various fabric features such as parallel clay orientation and photomicrographs. In terms of the inter-particle forces and the past of the material subsequent deposition or remolding, the fabrics produced in the undisturbed and remolded clays are clarified. To determine the engineering properties of the soil, experiments on micro-analysis of soil particles with regard to micrographs, chemical analysis using energy-dispersive X-ray spectroscopy, fabric orientation, and pores in compacted clay can be used. The effect of using soil enhancement additives can also be effectively determined using microanalysis.

6. Microanalysis of Soil

It was reported that it has always been important to understand the essence of materials/soil and their structures. In deciding the form of environmental processes and in estimating their resistance, the fine soil microscopic structure can be used as an index. During the evaluation of the soil structure on a small scale, some new nanometer research methods and particulate analysis were proposed. SEM: "Scanning Electron Microscopy"; AFM: "Atomic Force Microscopy"; and TEM: "Transmission Electron Microscopy"; are direct methods of nanoscale particle imaging, providing data such as particle size, shape, and morphology. SEM was invented in 1931, Which offers a wider picture of the electron by using specimens.

In this procedure, an electron beam is vertically centered on the specimen. When the beam interacts with the specimen in the vacuum, X-rays and electrons are emitted from the specimen. X-rays are then obtained by the detectors, converted into signals, and passed onto the screen to prepare for the final picture via the interaction between primary electrons and the sample. The nanostructure of soil particles has been widely used by SEM for research. TEM uses the emission of electrons in the direction of the TEM; however, the electrons emitted pass through the specimen and enter a phosphorous detector to reveal a pattern of sample composition.

This unit was also used for imagery of soil nanostructures. AFM has been used in recent years to assess the topography of surfaces and Surface Forces analysis. The surface of a sample is scanned with a sharp tip connected to a cantilever in AFM. In geotechnics, AFM images are also used to analyze soil nanoparticles' surface morphology, calculate the adhesive force between the soil particles, and measure the friction angle between them.

6.1. Determination of Clay Fabric by SEM

A clay fabric (or microstructure of clay) describes the orientation or structure, or spatial solid particle distribution and particle-to-particle relations. Clay variations are primarily associated with mineralogy, consolidation, diagenesis, and the size of a grain. The sediments' mechanical and physical properties are extremely influenced and primarily regulated by the microstructure of clay fabric, which includes its consolidation behavior. Due to greater contact surface area and greater bonding ability, clay fabric with a preferred orientation offers superior sediment integrity and greater shear strength than clay sediments with less shear resistance and random microstructure.

Fabric modification, therefore, tends to be a significant variable affecting both the rise in the core sample's shear intensity as well as the speed of the shear wave. In the early stages of consolidation, the micro-structure of this portion of the sediment will most likely be of sufficient strength to cope with pressure impressed on it by the reduced overload. The soil's micro pores provide valuable information on shear intensity, compressibility, hydraulic conductivity, and soil-water characteristics.

It is difficult to determine the structure of the soil micro-pores, and they are highly variable for one type of soil. The arrangement of micro pores shifts with the stress conditions, water and air movement, temperature, flocculation, gravimetric behavior, and weathering in the long term.

Several experiments were performed on the composition of soil micro-porosity. The intra, as well as inter-aggregate pores, have been studied in compacted clays. This kind of micro-porosity structure was called a double structure or dual structure by subsequent researchers. The findings have shown that the inter-aggregate pores shift quickly during soil compaction, consolidation, and drying.

6.2. Formation of Image in The SEM

SEM images of 3D objects and electron lenses are interpreted. The purpose of the electron lenses on the specimen was to create a focused, small electron probe. SEM produces an electron beam on the surface of a specimen with a spot size having a diameter < 10 nm while still having enough current for forming an appropriate image. Furthermore, the electron beam is usually characterized through the diameter of the probe (d) that ranges from 1nm-1μm, the current of the probe (I)-nA° to μA°, as well as the convergence of the probe (α) - 10^{-4}-10^{-2} radians. The electron beam images are concentrated into a fine probe that is scanned with the aid of scanning coils around the surface of the sample. In the form of electromagnetic radiation, a signal is emitted by every specimen point that has been hit through accelerated electrons.

Also, this radiation's selected portions received by a detector, generally Back Scattered Electrons (BSE) and/or Secondary Electrons (SE), as well as the subsequent signal, are amplified and presented on a computer monitor or TV screen.

6.3. Lenses Within the SEM

The electron lenses aim to achieve the desired crossover diameter of a convergent electron beam. The lenses are cylindrical-hole metal cylinders that work in a vacuum.

The magnetic field is produced within the lenses that vary to concentrate or defocus the electron beam that passes across the lens hole. In the electron gun, the electron-beam crossing diameter is de-magnified to a small size by SEM using one to three condenser lenses. The amount of demagnification is regulated by the first and second condenser lenses. There is typically a resolution, condenser, spot size, or single control mark in the microscopes. The beam-limiting aperture, the stigmator, as well as space for the scanning coil are also included in the design of the lenses.

6.4. Formation of Image

The SEM picture in the analog or digital domain is a two-dimensional (2D) intensity map. In each picture, a pixel on the monitor appears for the same point on the sample that is proportional to the force of the signal collected on each point by the detector. The picture is created and electronically displayed.

Electronic synthesis shapes the images in the SEM; there is no optical transformation, and no virtual optical images are created. The beam is continuously pushed in an analog scanning system; at a predefined number of lines, along the X-axis (line scan), a fast scan is complemented along the Y-axis through a stepwise slow scan. The frame time is given by the time for a single line scanning multiplied by the total frame lines. Only discrete beam positions are permitted in digital scanning systems. The beam is located there for a fixed time in a specific spot, known as dwell time, as well as afterward it is shifted to the next point.

Analog signal strength is determined by the detector while the beam is centered on the specimen. The voltage signals produced through the amplifier from the detector are digitized and stored in the corresponding database registry as a discrete numerical value. By translating the numerical values into an analog signal that is stored in the computer memory for displaying it on a monitor. Thus, the digital image is displayed.

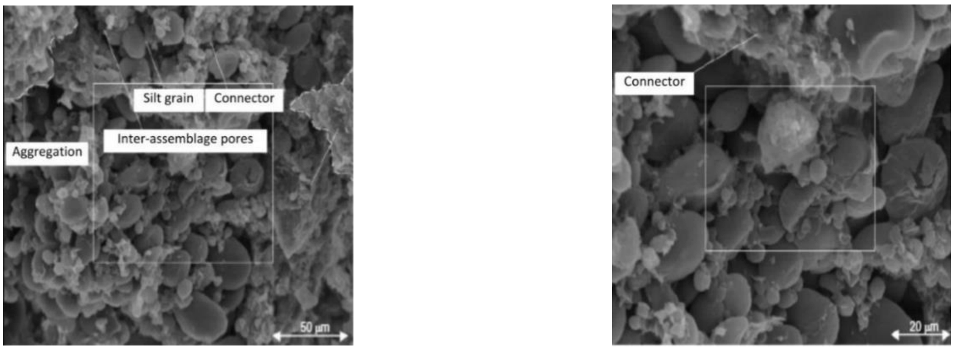
6.5. Focus on Microstructural Interaction

Engineers need to understand the physicochemical changes of the stabilized soil. Therefore, for the physicochemical changes, a convincing explanation is given by the microstructural study. It is possible to present such analysis in the qualitative digital image analysis context, for example, X-Ray Diffraction (XRD), or quantitative charts, SEM.

They help in explaining the influence on the pore structure of stabilization, micro fabric, and soil components. Mirzababaei et al. (2013) studied the microstructural investigation of the polymers' impact on soil micro fabrics. The furan polymer, applied to the soil at 3%, 5% and 10% by weight, steadily decreased the three expansive soils' free swell percentage compressed at MDD and OMC having approximately 83.5% average maximum drop. Figures 3-5 represent the alterations in the micro fabric of the soil due to the result of the furan addition at 5% as well as 10%.

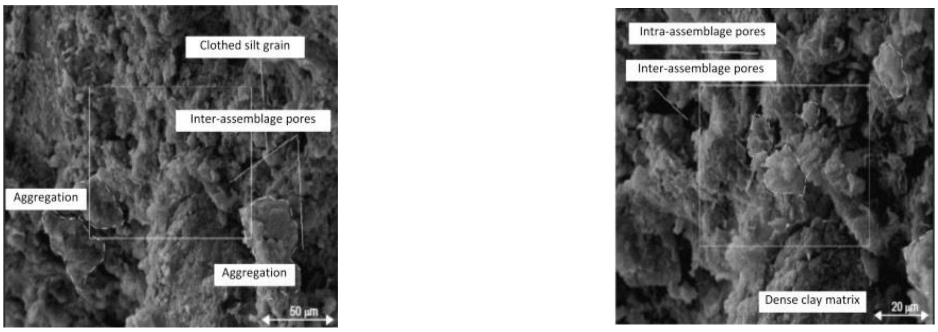
A natural soil, from various magnification ratios picture (500x and 1000x), when combined with a few silt grains, sparse aggregations, and a few connectors consisting of discrete granular soil. There exist clear inter-assemblage pores among scattered and discrete aggregations.

Although, the soil fabric transitions into denser aggregation with intra-assemblage pore creation resulting from the denser aggregations' formation with inter-assemblage pore being less visible, with the addition of furan at 5% and 10%, suggesting a decrease in the size of the pore. Clothed silt grains in the natural soil are even more noticeable than that. In the soil's swelling properties, the observed reduction is responsible for improvements in the pore structure and soil fabric. The microstructural inquiry performed here, however, is only qualitative.



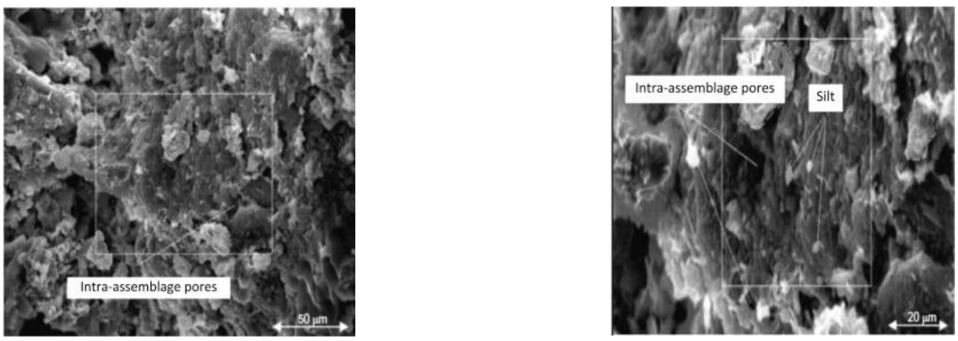
(a) (b)

Fig. 3. Micro fabric of natural soil modified from (Mirzababaei et al., 2013): a) 500x magnification; and b) 1000x magnification



(a) (b)

Fig. 4. Micro fabric of Soil with 5% furan modified from (Mirzababaei et al., 2013): a) 500x magnification; and b) 1000x magnification



(a) (b)

Fig. 5. Micro fabric of clayey soil with 10% furan modified from (Mirzababaei et al., 2013): a) 500x magnification; and b) 1000x magnification

7. Solid Wastes

In municipal areas, the production of solid waste is usually found in large quantities as a common phenomenon. Glass, paper, plastics, wood, rubber scraps, reusable goods, metals, plant debris, and organic materials are the main components of such waste. Depositories and the disposal of waste generated in large amounts involve environmental challenges. However, most of these materials have demonstrated their suitability in recent years for use in soil stabilization. Signes et al. (2016) analyzed the effect of the addition of rubber particle crumbs on the swelling potential for the soil to argillaceous marlstones and observed a decline from 3.71% to 1.37% for the addition of rubber crumb particles at 25%. The impact of cement-modified soft clay on durability has been investigated with solid waste from gypsum wastes (recycled basanite). The soil has lost a slight part of its UCS between cycle 1 and cycle 3, and was almost recovered in cycle 5 with a ratio of basanite-soil of 10% and a cement-to-soil ratio of 5% on the application of 10%, so stabilized soil is confirmed to be sustainable.

7.1. The Transition from State of the Practice to State of the Art

The geotechnical group is carrying out a great deal of work on expansive soil stabilization in the 21st century. However, problems emerging from such practice areas need to be resolved to be more effective and achievable. It's not so very limited, although rather a potential way to maximize the use of available methods for the sustainable and productive implementation of comprehensive soil stabilization. When such problems are solved, expansive soil stabilization becomes a realistic method. The approach will best be implemented in the area without the requirement for strict, time-consuming, and expensive research, which might not be feasible in situ application (Ikeagwuani and Nwonu, 2019).

7.2. Geo Environmental Issue

The soil stabilization technology should be used to avoid adverse environmental effects. Applications involving the use of an additive that contains high-carbon or hydrogen sulfide must be avoided, as emissions of such compounds have proven to be detrimental to the environment. No recommendation is made for products made up of heavy metals that would pollute the groundwater by leaching. The soil value of pH must also be taken into consideration when using any stabilizer. To make the study more sustainable, researchers must conduct geo-environmental assessments, based on the additive used, according to their research (Ikeagwuani and Nwonu, 2019). The use of gypsum waste plasterboard at dosages after evaluation of the soil pH and hydrogen sulfide release after completing the stabilization procedure did not contribute to any adverse effect. Etim et al. (2017) showed the quantity of iron that could be generated from an additive in the groundwater through batch equilibrium analyses and compared it with the prescribed level in drinking water given by the World Health Organization (WHO).

The use of engineered deposits as deposit liners is another approach used to prevent heavy metal dumping into groundwater. This form of liner serves as an obstacle to heavy metals being sorbed and prevents groundwater pollution. A deposit filler was used with a mixture of clay, 17% of RHA, and 2% bentonite. Similarly, the sawdust-resistant clay soil is used to contain cadmium and lead leachate from waste disposal.

7.3. Reuse of Waste

In expansive soil stabilization, waste tire rubber has shown great potential. The Expansive Soil-Rubber (ESR) technique has been used and suggests that it might significantly minimize in situ heaving in soil, particularly where the deposit of sulphate-rich natural soil exists. Also, it can prevent traditional agents of soil use; whereas it has been significantly restricted by ESR, which is not appropriate where material rigidity is necessary.

7.4. Sustainable Practice

For efficient waste management, waste reuse should be tested in soil stabilization to ensure safe disposal of waste material for a green environment. The stabilization studies, therefore, use materials to determine the possible effect of the additives on the environment to make its use safe. However, few researchers regard this as a crucial parameter for applying these in expansive soil stability (Ikeagwuani and Nwonu, 2019). Recycled gypsum from waste plasterboard to improve the soil used as an embankment material and enhance the properties of the stabilized soil, while making sure that the stabilizer has no wrong environmental impact within its administration dosage. The studies were carried out to calculate the effect of recycled gypsum as regards hydrogen sulfide, pH, as well as toxic substances like boron, chromium, and fluorine. Low-carbon sodium silicate liquid was used to enhance the UCS and expansive clay compressibility features. Due to the low carbon additive used, this can be seen as a sustainable enhancement.

7.5. Focus on the Application of Nanotechnology

Using highly fine particles was the other practice that has been embraced in recent years (within the context of nanoparticles).

It was presented for improving the tensile strength as well as its parameters of lime-treated marine clay with nano-modified coir fiber that preserved durability by increasing the wetting cycles of the stabilized soil matrix. Sharo and Alawneh (2016) described a similar analysis to change the expansive clay soil, for the purpose of using nano-clay materials. A regressive pattern has been shown by increasing clay content, which also demonstrates the soil swelling potential, with a peak decline of approximately 65.5% with 3% nano-clay content, and with 0.6% nano-clay content, a peak increase of about 42% is achieved for UCS.

Nanomaterial (nano-z) has been used by Ugwu et al. (2013) to improve the subgrade strength of soil in plastic clay. At varying ratios of nano-z/water at 1:150, 1:200, and 1:300 nanomaterial is applied. The increase in the material ratio shows a monotonous decrease with the change in the tested soil characteristics and the ideal ratio found is 1:150. The additive causes a reduction of about 74.5% in the soil Plasticity Index (PI) and an improvement of about 120% in CBR. The nanomaterial stabilization mechanism has been clearly shown. The nano-z material is a non-functional alkyl organic matter, and silanol (Si-OH) is generated in terms of hydrolyzation (reaction with water).

Siloxane can be formed from reactive silanol (=Si-O-Si=), which attaches to the silanol surface of soil, providing the soil with molecular hydrophobicity and making it water repellent on the treated soil surface.

7.6. Problem Statement

With rapid technological development worldwide, plastic usage, such as waste plastic carry bags, is rising. Every year around the world, about 500 billion bags are used. Used waste plastic carry bags disposal is a major issue, as most plastic waste can no longer be biodegraded and cannot be incinerated, as it emits toxic gases.

The stabilization of soil enhances the mechanical properties of fragile soils, with managed compaction or the use of stabilizers, like asphalt or lime, although these additives in the recent few years have become expensive.

7.7. Solution Statement and Aim

To have a solution for the alternative management of the waste plastic carry bags is their use in soil stabilization, which is cost-effective. The trash is clean; it just needs recycling. Since it is eco-friendly, it will protect the environment and improve soil properties, CBR value, tensile strength, as well as shear resistance by reducing the compressibility of the soil. Advantages of using waste plastic for soil enhancement:

- Reduces the field permeability of the soil.
- Load-bearing capacity improves.
- Soil shear strength increases.
- Soil cracks and swelling are minimized.
- Durability boosts.
- Soil settlement reduction.
- CBR improves.
- The improvement of soil quality is cost-effective and energy-intensive.
- The problem of waste plastic can be solved.
- Abundantly available.

8. Focus on the Economic Implication

Since soil properties need to be improved to achieve some default values while stabilizing poor soil, the engineer’s role is to provide geotechnical soil modification and cost-effectively obtain the desired properties. Besides, researchers have performed comparative research to determine the efficacy and economy of various additives. This is evident from studies in the year 2000, conventional stabilizers are frequently being used for expansive soil stabilization as stand-alone products (Zhao et al., 2015; Dafalla et al., 2015; Soltani et al., 2018). Many problems related to this, however, have provided space for potential alternatives as illustrated by Firoozi et al. (2017). In spite of this, the stabilizing impact of conventional agents appears to exceed other stabilizer effects during comparative studies, unless electrolytic lignin is marginally superior to fly ash, especially as regards soil plasticity.

Even among the conventional agents, although fly ash is a waste product, it appears to beat both lime and cement economically. Some non-traditional agents were also used for comparative research compared to traditional agents. These were commonly used in soil cushions. Soil cushioning strategies are also implemented to avoid moisture content variations in the soil since it is understood that the soil instability is due to the difference in moisture in water content. To alleviate the swelling behavior of expansive clays, the approach utilizes a coherent non-expansive soil cushion. To stabilize the overlapping soil, cushioned materials are typically spread over extensive soil beds in the sheet of mattress formation and are sand beds, geocells, and others, as described in the research carried out by Dutta et al. (2016). Waste for manufacturing by-products, polymeric waste, and geotextiles are the most important substances for cushioning.

Geocell is a rigid geosynthetic product of complicated blended cells with 3D honeycomb structures requiring limited effects. Dutta et al. (2016) recommended that the shear strength of compact products should be substantially enhanced due to the geocell system boundary impact. They also claimed that by using geocell confinement for distributing base load, settlement reduction is superior to other mesh-shaped 2D composites. Other researchers (Sharma and Nallasivam, 2023) endorsed this claim, which found that the geocell reinforcement system delivered greater output than the material quantity equivalence of the planar reinforcement system. The efficacy of the process is illustrated by laboratory experiments performed using soil cushioning techniques for comparative research purposes. GGBSand fly ash were used as cushions on expansive soil treated with lime. Both GGBS and fly ash increased the CBR and, with increasing the cushion thickness, reduced the expansive soil swell potential.

The same results were obtained using Expanded Geofoam Polystyrene (EPS) and sand as cushions. It was found by using sand as a cushion, the cushioning technique performs in the same way as the additive mixing technique. The EPS geofoam, however, worked better in stabilizing the soil than sand. In a 3D geocell mattress and EPS geofoam embankment, a finite element approach was used to test soil cushion and fill materials. The component materials of geocell and geofoam are modeled using elastic models or linear-elastic, excluding the concrete and geogrid layers, by applying the Mohr-Coulomb failure criterion. The findings of the study show a decrease in the geocell-stabilized soil’s vertical displacement and also a decline in the geocell-stabilized soil's vertical and horizontal displacement. To calibrate these results, however, further laboratory work is required. As several of the researchers demonstrate, comparative analyses of the efficacy of one substance over another can be differentiated easily (Dafalla et al., 2015). However, a minor variation is found in the evaluation of comparative stabilizers' efficiency in other situations. Besides, the need for successful and economically sustainable stabilization has led investigators to try to optimize each of these two steps-based information: first, a potential combination of different materials following a comparative analysis, and Second, data obtained using a single material on the outcomes of numerous independent works. It is typically an optimization technique to make good use of the advantages of diverse materials.

9. Issue of Optimization

During expansive soil stabilization, researchers also strived to achieve both economy and efficiency. To optimize the advantages of each, they used different trial approaches to combine different stabilizers.

These findings are consequent as well from the work of individual and their comprehension of the chemistry behind physical-chemical variations caused by a certain stabilizer to achieve such optimal efficiency. Because of cost consequences and time-consuming nature, the conventional trial approach is not so adequate; however, using a combination of stabilizers, the need arose for better approaches to achieving optimum efficiency (Ikeagwuani and Nwonu, 2019).

10. Research Limitations

This article investigates the usefulness of waste plastic carry bags in improving the behavior of expansive soil. Some research limitations in the present review article are listed below.

- The investigation has not been done to stabilize the expansive (BCS) soil using waste carry bags.
- The usefulness of HDPE was investigated to improve all the soil parameters.
- Further studies and research are needed to reduce the cost by using waste plastic carry bags as reinforcing materials for improving all soil parameters. The exploration has not handled the hypothetical parts of soil stabilization, reused waste plastic management, immaculateness, and the type of water. Due to a lack of laboratory facilities, accessible distributed index information and mechanical properties of HDPE (carry bags) plastic strips, a portion of the HDPE (carry bags) strip study (e.g., tensile strength at break, tensile modulus, flexural strength, and elongation at break, heat redirection, and melting point) has not been explored. Besides, water was assumed to be usable during the mixing of the soil and the waste soil HDPE (carry bags) plastic composite during the laboratory equipment program; afterward, no testing was carried out. Additionally, field reinforcement of the soil was not taken care of. Besides, the soil type received for this exploration was cohesionless, a portion of the tests couldn't be conducted on soil-HDPE (carry bags) plastic waste, as well as soil examples such as triaxial shear test, and others.

11. Conclusions

This paper discusses recent advances in soil stabilization technology. The paper aims to analyze the stabilization of expansive soil, emphasizing those critical areas like microstructural interaction for deciding the stabilization process, the economic consequences of comparative research, the topic of sustainability and reuse of waste, and the use of nanotechnology. Many test methods for the analysis of variations in the microstructure of expansive as well as stable soils have been developed in recent years. Changes in soil micro fabrics, pore sizes, and constituents are often concerned with these changes. This is generally achieved by maximizing the use of different additives for achieving economic efficiency. Sustainable practice is also very critical. Efficient methods of waste management and recycling have been provided by soil stabilization technologies, by reusing waste products. Nanotechnology has also shown that it is a viable instrument for expansive soil stabilization. While achieving the stabilization of expansive soil, some insights have been found to resolve some of the issues that impede the applicability of the available soil. Below is the summary of the critical reviews:

- After soil stabilization, geo-environmental problems can occur. To ensure that the stabilization process is sustainable, it is, therefore, important for researchers to conduct the required experiments. Criteria with adverse environmental implications should be checked in accordance with the form and dosage of the additive used. This includes the soil's pH value, the release of hazardous compounds such as carbon, and the leaching of heavy metals into groundwater.
- For the field application of expansive soil stabilization by various additives, the standardization problem has not been resolved. When field experts investigate the potential to establish such a norm based on practice, along with the findings of individual stabilization, and the possible implementation of artificial intelligence techniques, this issue can be resolved.
- When using a mixture of different additives, optimization problems occur in attempting to achieve maximum efficiency.
- The research findings show that the prospect of its usage to improve and stabilize the soil is a good sign.
- The usage of waste plastic carry bags has led to the soil's improvement.
- The use of waste plastic carry bags on the soil is an economic option.
- In the value, there is a significant increase. It can also be suggested to use it to build roads like temporary roads, village roads, or pathways, because the material is waste and non-biodegradable.
- Using waste plastic carry bags in the clay soil allows the overall weight of the dry device to decrease and the ideal moisture content to increase. The ideal humidity content is decreased by an increase in waste plastic carry bags.
- The effect of waste plastic carry bags on the improvement of soil properties depends primarily on the size of the strip, the quality of the plastic, and the form. The plastic strips may be a successful soil enhancement technique.

12. Availability of Data and Material

Data will be made available on request from the corresponding author.

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14. Author’s Contribution

Mantu Kumar: Investigation, Writing-original draft, Bheem Pratap: Writing–review and editing, Md Azhar: Investigation, Writing-review and editing, Somenath Mondal: Writing-review, editing, and Supervision, Rakesh Pratap Singh: Conceptualization, Methodology, editing, and Supervision.

15. Declarations

- Competing interests: The authors declare that there is no conflict of interest regarding the publication of this paper.
- Ethics approval and consent to participate: The survey research directed has received ethical clearance from the ethics committee

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- Consent for publication: not applicable.

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