A Systematic Review of Subgrade Soil Stabilised with Natural and Synthetic Fibres

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Abstract:
Introduction: The stability of subgrade soil is crucial for the longevity and performance of pavements. Subgrade soil, the in-situ soil underlying the pavement, provides support and influences the overall pavement behaviour. However, subgrade soils can be susceptible to various challenges, such as erosion, swelling, and shrinkage, which can lead to pavement distress and failure. To enhance the stability and mitigate these challenges, subgrade soil can be stabilised using various techniques, including the incorporation of fibres. Fiber-reinforced subgrade soil has gained significant attention in recent years due to its ability to improve soil strength, reduce rutting and erosion, and minimize moisture sensitivity. This systematic review aims to provide a comprehensive overview of the research on subgrade soil stabilisation using natural and synthetic fibres. The review will focus on the types of fibres used, their benefits and limitations, and the methodologies employed in fibre-reinforced subgrade soil studies. Additionally, the review will discuss the performance of fibre-reinforced subgrade soil focusing on the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS). Through this review, we aim to provide valuable insights into the effectiveness of fibre-reinforced subgrade soil and identify areas for further research and development.

Aims: The objective of this paper is to provide a comprehensive overview of the research on subgrade soil stabilisation using natural and synthetic fibres focusing on the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS).

Methods: A systematic literature review was conducted to identify and assess the state of knowledge on the use of natural and synthetic fibres to stabilise subgrade soil. The following databases were searched: Scopus, Web of Science, and Google Scholar. The following search terms were used: “subgrade soil stabilisation,” “natural fibres,” “synthetic fibres,” and “soil reinforcement.” The extracted data was then analysed to identify trends and patterns in the use of natural and synthetic fibres to stabilize subgrade soil. The findings of the analysis were then synthesized to provide a comprehensive overview of the state of knowledge on this topic.

Results: The review found that incorporating fibres into subgrade soil can significantly enhance its strength such as California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS), reduce susceptibility to rutting and erosion, and mitigate moisture-related challenges.

Conclusion: The findings of this review demonstrate that fibre-reinforced subgrade soil offers a promising approach to enhancing pavement performance and durability, making it a valuable tool for infrastructure development.

Keywords: Natural Fibre, Synthetic fibre, Stabilised subgrade, Subgrade stabilisation, Subgrade treatment, California bearing ratio (CBR), Unconfined compressive strength (UCS).
1. INTRODUCTION

The main structural function of the pavement is to support the wheel loads acting on the pavement and ultimately distribute them to the subgrade layer [1]. The strongest material (least flexible) is in the top layer, and the weakest material (most flexible) is in the bottom layer [2]. The lower layer of the pavement is called the pavement foundation or subgrade [3-5]. General geotechnical aspects of pavements are demonstrated in Fig. (1).

The subgrade is a compacted soil layer that provides lateral support to the road surface [1, 4, 5]. Soft soil is easy to damage and has low bearing capacity, which poses a great danger to traffic safety [7]. Furthermore, construction on weak or soft soil affects pavement performance and leads to pavement instability [1, 3, 7-9].

Therefore, roads must be maintained to ensure the safety and durability requirements of pavement [3, 7, 10]. Some of the causes of flexible pavement failure include inadequate drainage, lack of acceptable pavement design, and lack of road maintenance by the responsible entity. Furthermore, excessive subgrade water levels and poor subgrade soil also contribute to subgrade failure [1-3, 7, 10].

Soils are generally classified into four basic types: gravel, sand, clay, and silt [11]. Coarse-grained soils (gravel and sands) work well as a load-bearing platform, while fine-grained soils (silt and clays), particularly clayey soils, present problems for pavement. Some clayey soils with expansive properties characterized by significant volume changes with fluctuations in water content, resulting in severe damage and deformation of overlying structures [1, 3, 7, 9, 11, 12].

Consequently, the strength and stiffness of the subgrade are very important for the design, construction, and performance of road surfaces [3, 13]. The strength and stiffness properties of the subgrade can be expressed as California Bearing Ratio (CBR), R-value or resilient modulus [3]. If the mechanical properties of the subsoils are lower than required, a soil stabilisation method may be an option to improve the soil properties of the weak subsoil [10, 14].

![Fig. (1). Geotechnical aspects of pavements [6].](image-url)
Soil stabilisation can be defined as the modification of one or more soil properties to improve the engineering properties and performance of soil [9, 14, 15]. Furthermore, soil stabilisation aims to improve soil strength and increase resistance to water softening by bonding the soil particles together and making them waterproof, or a combination of both [9, 11, 14-18].

Soil stabilisation can be achieved in a variety of ways, including soil preloading, application of high energy impacts, use of sand drains and sand filters, prefabricated wick drains, and chemical additives [10, 14, 15, 17-20]. The most common method for improving the physical and mechanical properties of soils is stabilisation with binders such as cement and lime [9, 21-23].

Cement is the best stabiliser for sand to gravel-sized soil mixes (well-graded), while lime is mainly used for moist, heavy clay soil mixes [22, 24]. However, during cement production, around 0.8 tons of carbon dioxide are released into the atmosphere per ton of cement. Furthermore, it is now reported that approximately 2-8% of global electricity consumption is attributed to the cement manufacturing process [25-28].

Therefore, there is a need to look for an alternative soil stabiliser, such as fibre. Although it is not a new technique, adding fibre is a very practical alternative for soil stabilisation [9, 18]. Various types of fibres, such as natural fibres and synthetic fibres have been used as stabilising agents to improve the strength and durability of subgrade soils [9, 18, 29].

Natural fibre sources such as coconut palms, kenaf and banana plants are commonly grown in Malaysia and are easy to obtain due to the tropical weather. In addition, these natural fibers are biodegradable and do not cause environmental pollution [30, 31]. Natural fibers are also cost-effective, have high tensile strength, have environmentally friendly properties and are readily available in Malaysia [30, 32-35].

In contrast, synthetic fibres are fibres made through various chemical processes and are not derived directly from natural sources. These fibres are designed to mimic the properties of natural fibres, but often offer specific benefits such as greater durability, strength, and resistance to environmental influences [36, 37].

This comparative review aims to provide insights into the advantages, limitations, and optimal applications of stabilisation techniques for natural and synthetic fibres. Factors such as fibre type, content, distribution, and interaction with soil particles are discussed in the context of their impact on soil performance. By analysing the diverse properties of these fibre types and their effect on soil behaviour, this paper aims to contribute to the knowledge base that enables effective decision-making in soil stabilisation projects.

2. METHOD AND MATERIAL

2.1. Necessity of Subgrade Soil Stabilisation

Subgrade soil stabilisation is often required to improve the properties of the subsoil and make it suitable for the construction of pavements or roads. Subsoil stabilisation techniques may include adding additives such as lime, cement, or other materials to the soil to improve its strength, durability, and other engineering properties [9, 11, 14, 16-18, 22, 24]. Here are some conditions where subgrade soil stabilisation might be necessary.

2.2. Low Bearing Capacity and Shear

Bearing capacity is the ability of the soil to support the weight of structures and vehicles safely and without shear failure in the event of deformation or severe settlement. If the natural soil has low bearing capacity and shear strength, it may not be able to support the loads of pavements or roads [4, 12, 27, 38-40]. An example of the situation of soil with low bearing capacity and low shear strength is demonstrated in Fig. (2).

Fig. (2). Rural road conditions in Sarawak, Malaysia, due to the low bearing and shear capacity of the soil [41].
2.3. High Plasticity

In highly plastic soils such as clays, significant volume can occur with changes in moisture content. This can lead to settlement, heaving and other forms of deformation that can affect the stability of subgrade pavements [5, 23, 42].

2.4. Erosion Susceptibility

Soils that are easily eroded by wind or water can cause instability and long-term maintenance problems in construction projects. Uncontrolled erosion can result in the loss of topsoil, destabilisation of slopes, sedimentation in water bodies, and damage to nearby structures and infrastructure [40]. Fig. (3).
2.5. Unstable Slopes

Slopes with unstable or loose soils can pose a risk of landslides and slope failures. Hence stabilisation is required to improve their stability. Subgrade soil stabilisation techniques can help strengthen the slope, increasing its stability and reducing the risk of slope failure [12, 38, 43]. An example of the situation of an unstable slope is demonstrated in Fig. (4).

2.6. Organic Content

Organic soils, such as peat and muck, have poor engineering properties and can settle over time. Organic soils have unique properties that make them challenging for construction projects, as they tend to have low shear strength, high compressibility, and poor bearing capacity. Stabilisation may be required to increase their strength and reduce settlement [45].

2.7. High Compressibility

Soils with high compressibility, also called soft or compressible soils, are subject to significant changes in volume under load, leading to settlement and deformation. Significant settlements can occur under loading in compressible soils, which is problematic for structures and pavements. Stabilisation techniques can help reduce compressibility and increase the bearing capacity of these soils [4, 5, 12, 43].

2.8. Permeability

Soils with low permeability, such as clays, silts, and other fine-grained materials, might have poor drainage properties, leading to water accumulation and potential instability [4, 5, 39, 40, 45, 46].

2.9. Environmental Considerations

Soil stabilisation might be needed in environmentally sensitive areas to prevent soil erosion, sediment runoff and other forms of environmental damage [39, 45].

2.10. Cost Saving

Investments in subsurface soil stabilisation can result in significant cost savings over the lifespan of the infrastructure. Reduced maintenance, fewer repairs and a longer lifespan contribute to an overall more economical project (Nilimaa, 2023). In addition, subgrade stabilisation is an alternative method to reduce the thickness of the pavement layer thereby reducing construction costs (Arshad et al., 2021).

The specific conditions that are require subsurface soil stabilisation vary depending on the project, location, and intended use of the constructed infrastructure. Engineers and geotechnical experts evaluate soil properties and project requirements to determine whether subgrade soil stabilisation is required and which techniques are most appropriate.

Fig (4). Unstable slope that led to a landslide in batang kali [44].
3. SUBGRADE SOIL STABILISATION METHODS

Subgrade stabilisation is the process of improving the properties of the natural soil or material beneath a road, pavement, foundation, or other infrastructure to increase its bearing capacity, reduce settlement, and provide a stable foundation for construction [4, 5, 47, 48]. Some common soil stabilised methods are listed in Table 1.

3.1. Mechanical Soil Stabilisation Method

Mechanical soil stabilisation methods involve physically changing the properties of the soil to improve its strength, stability, and bearing capacity. Mechanical stabilisation is also carried out by mixing or blending soils with two or more grain sizes to obtain a material that meets the required specifications. The focus of these methods is on changing the physical structure of the soil through compaction, mixing, or other mechanical techniques [14, 19, 49].

3.2. Chemical Soil Stabilisation Methods

Chemical soil stabilisation is a method of improving soil properties through the introduction of chemical agents that interact with soil particles, changing their behavior and improving overall stability. Common chemical soil stabilisation methods include bitumen stabilisation, cement stabilisation, fly ash stabilisation, and lime stabilisation [4, 5, 14, 19, 24, 48, 49].

3.2.1. Bitumen Soil Stabilisation Method

Mixing bitumen or asphalt with the subgrade soil to improve its strength and reduce its susceptibility to water. This method is commonly used in road construction [4, 5, 14, 20, 50]. Bituminous soil stabilisation is usually carried out using asphalt cement, cutback asphalt, or asphalt emulsions. The type of bitumen to be used depends on the soil to be stabilised, the construction method, and the weather conditions [14, 19, 20].

3.2.2. Cement Soil Stabilisation Method

Cement stabilisation involves three processes: cement hydration, the cation exchange reaction, and carbonation through the pozzolanic reaction [14, 20, 51, 52]. Incorporating cement into the subsoil creates a stronger and more durable material. This is because cement reacts with the soil particles and water to form a cement-like matrix [5, 48]. An example of soil stabilisation with cement is shown in Fig. (5).

<table>
<thead>
<tr>
<th>Methods of Soil Stabilisation</th>
<th>Mechanical Stabilisation</th>
<th>Chemical Stabilisation</th>
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<tr>
<td></td>
<td></td>
<td>Traditional stabilisers (e.g.: cement stabilisation, lime stabilisation, cement and lime stabilisation, fly ash)</td>
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<td></td>
<td></td>
<td>Non-traditional stabilisers (e.g.: cement kiln dust, lime kiln dust, ground granulated blast furnace slag, bottom ash, gypsum, silica fume, bitumen emulsion, calcium-based stabiliser materials)</td>
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</table>

Table 1. Mechanical and chemical soil stabilisation methods.

Fig. (5). Process of soil cement stabilisation with heavy equipment [19].
3.2.3. Fly Ash Soil Stabilisation Method

Mixing fly ash, a byproduct of coal combustion, with the subsoil to improve its properties. Fly ash stabilises the soil through pozzolanic reactions [5, 14, 48, 53, 54]. An example of soil stabilisation with fly ash is demonstrated in Fig. (6).

3.2.4. Lime Soil Stabilisation Method

The method of mixing lime with the subsoil to increase its strength and reduce plasticity is called lime stabilisation. The lime reacts with clay minerals and forms stable compounds through pozzolonic reaction, thereby improving the soil’s engineering properties of the soil [5, 14, 19, 48].

3.3. Thermal Soil Stabilisation Method

Thermal soil stabilisation is a method of improving the engineering properties of soils through the effects of heat. This technique involves increasing the temperature of the soil to increase its strength, reduce its compressibility, and alter its water retention properties. Furthermore, thermal soil stabilisation can be particularly useful in cold weather conditions, on certain soil types, and on projects where traditional stabilisation methods may not be as effective [51, 56].

3.4. Geosynthetic and Geogrid Soil Stabilisation Method

Geosynthetics, geotextile made from synthetic polymers (such as PP, PE, PET, and PVC) produced in the form of fibres, are used in particularly large quantities because the polymer production is ineffective, and the corresponding fibres are easily available. The placement of geosynthetic materials such as geotextiles or geogrids within the subgrade serves to reinforce and separate soil layers, thereby increasing bearing capacity and reducing settlement [14, 19, 57, 58].

3.5. Biotechnical Soil Stabilisation Method

Soil stabilisation using biotechnical methods, also called bioengineering or biogeotechnical methods, uses living plants and natural materials to strengthen and stabilise soils. This approach combines ecological principles with engineering techniques to create stable and sustainable solutions for erosion control, slope stabilisation, and soil improvement [59, 60].

4. FIBRE SOIL STABILISATION

Fibre soil stabilisation, also called Fibre-Reinforced Soil (FRS), is a method of improving soil properties by incorporating synthetic or natural fibres into the soil matrix. The addition of fibres improves the mechanical properties of the soil and makes it more resistant to deformation, cracking, and erosion [9, 61-64]. Fibre-Reinforced Soil (FRS) methods are divided into two classes depending on the application method: Oriented Distributed Fibre Reinforced Soil (ODFRS), and Randomly Distributed Fibre Reinforced Soil (RDFRS) as shown in Fig. (7) [15, 65, 66].
4.1. Oriented Distributed Fibre Reinforced Soil (ODFRS)

In this method, fibres are strategically aligned or placed in the soil to provide increased reinforcement in specific directions. The orientation of the fibres can be aligned with the expected stress paths or loading directions. This approach aims to optimize the mechanical performance of the soil in a target region. For this reason, the probability of failure surfaces is relatively higher in unreinforced regions [15, 65, 66].

4.2. Randomly Distributed Fibre Reinforcement Soil (RDFRS)

With this method, the fibres are randomly distributed in the soil. Unlike the Oriented Distributed Fibre Reinforced Soil (ODFRS) method, the fibres do not follow a specific orientation pattern or direction of tension. Instead, they are mixed evenly throughout the soil matrix. The aim of Randomly Distributed Fibre Reinforcement Soil (RDFRS) is to improve the overall mechanical properties of the soil by providing strength and cohesion in different directions. This approach is useful when the stresses acting on the soil can come from multiple directions or when the stress distribution is unpredictable [15, 65, 66].

5. NATURAL FIBRE AND SYNTHETIC FIBRE IN SOIL STABILISATION IN ASIA

5.1. The History of Usage

The use of natural and synthetic fibres to stabilise soil has a long, centuries-old history in Asia. Natural fibres, such as jute, coir, and bamboo, are used to reinforce soils for various purposes, including erosion control, road construction, and slope stabilisation [64, 67, 68, 69]. Natural fibres are sustainable and biodegradable, making them an environmentally friendly option for soil stabilisation. However, they can be susceptible to rot and degradation, which can shorten their lifespan.

At the beginning of the 20th century, synthetic fibres were introduced as an alternative to natural fibres. Synthetic fibres, such as polypropylene, polyester, and nylon, are stronger and more durable than natural fibres. They are also resistant to rot and decay, making them a more durable solution for soil stabilisation [67, 18, 70].

Synthetic fibres are now widely used in Asia for soil stabilisation. They are particularly suitable for use in high-traffic areas and areas with harsh environmental conditions. For example, synthetic fibres are often used to reinforce embankments along highways and railways. They are also used to stabilise slopes and prevent erosion in areas prone to landslides [31, 71, 72].

In Malaysia, the use of natural and synthetic fibres for soil stabilisation has increased significantly in recent years. This is partly due to the growing awareness of the environmental benefits of using natural fibres. It is also due to the development of new technologies that facilitate the use of synthetic fibres in soil stabilisation projects.

The use of natural and synthetic fibres in soil stabilisation is a valuable tool for improving the stability and durability of soils. This technology has the potential to help reduce erosion, protect infrastructure, and improve the quality of life for people in Asia.

5.2. Future of Natural and Synthetic Fibre in Soil Stabilisation

The use of natural and synthetic fibres for soil stabilisation is expected to continue to grow in the future. The reason for this is the increasing demand for sustainable and environmentally friendly solutions for soil stabilisation. This is also due to the development of new technologies that facilitate the use of natural and synthetic fibres in soil stabilisation projects. In Asia, the use of natural and synthetic fibres to stabilise soil is expected to play an important role in reducing erosion, protecting infrastructure, and improving people’s quality of life.
In summary, the use of natural and synthetic fibres for soil stabilisation is a valuable tool for improving the stability and durability of soils. This technology has the potential to help reduce erosion, protect infrastructure, and improve the quality of life of people in Asia.

6. RESULT

6.1. Classification of Fibres

Fibres are generally divided into two categories: natural and synthetic fibres. Natural fibres are obtained directly from plants, animals, or minerals without any significant synthetic or chemical processing. Examples of natural fibres are listed in Table 2. The use of natural fibres for soil stabilisation offers several advantages, including high tensile strength, low cost, light weight, high rigidity, sustainability, and environmental friendliness [9, 11, 37, 65, 73-75].

In contrast, synthetic fibres are typically made from polymers, which are long chains of repeating molecular units. These polymers can be derived from petrochemicals, coal, natural gas, or other sources. During the polymerisation process, these smaller units are linked into long chains, which are then processed into fibres using methods such as spinning, extrusion, or drawing [11, 36, 37]. The general classifications of synthetic fibres and their subclassifications are shown in Table 3.

7. NATURAL FIBRE SOIL STABILISATION

Soil stabilisation with natural fibres is a technique in which natural fibres are incorporated into the soil to improve its engineering properties and overall stability. The objectives of this method are to improve soil-bearing capacity, reduce erosion, control moisture content, and mitigate problems associated with shrinkage and swelling. Reinforcing the soil matrix with natural fibres makes it more resilient and more suitable for various construction and infrastructure [9, 78, 79]. Various types of plant-based natural fibres are used to stabilise soil, including coconut (coir) fibre, sisal, jute, flax, and bamboo fibre.

7.1. Coconut (Coir) Fibre

Coconut coir fibre, often simply referred to as coir, is a natural fibre oriented from the husk of coconuts (Cocos nucifera). The fibres are obtained from the husk through several methods such as traditional retting, decortications, use of bacteria and fungi, and mechanical and chemical processes. Coconut coir is a renewable resource, and its various applications contribute to sustainable construction practices such as soil stabilisation [80-82]. The chemical composition of coconut fibre is demonstrated in Table 4.

Mohith Datta & Achuthan (2023) conducted a study on the strength and permeability properties of black cotton soil or expansive high plastic clay (CH) soil by combining soil with coir and Terrasil additives. The percentages of Terrasil and coir used in this study are 0.5% Terrasil and 0.5%, 1.0%, 1.5% and 2.0% coir respectively, based on the weight of the soil. Atterberg Limit Test, Standard Proctor Compaction Test, California Bearing Ratio (CBR) Test, Unconfined Compressive Strength (UCS) Test and Permeability test were conducted on the unstabilised and stabilised soil.

Table 2. Classifications of natural fibres [37, 76].

Table 3. Classifications of synthetic fibres [77].

Table 4. Chemical composition of coir fibre [83].

According to Mohith Datta & Achuthan (2023), the results show that the addition of Terrasil and coir up to 0.5% and 1.5% respectively, reduced the optimum moisture content (OMC) while increasing the maximum dry density (MDD). Additionally, clay subsoil stabilised with 0.5% Terrasil and 1.5% coir shows improvement in California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS).

Therefore, a thinner subgrade layer is required for the pavement as the California Bearing Ratio (CBR) is improved by the addition of coconut fibre and Terrasil. Furthermore, adding the chemical additive Terrasil to the soil had no negative or harmful effects. Mohith Datta & Archuthan (2023) conclude that the cohesion of the clay soil was significantly improved by adding Terrasil.

Lawer et al. (2021) conducted a study on the effects of coir fibre (fibre lengths of 30 mm, 60 mm, and 90 mm) and palm fibre on some geotechnical properties of a weakly lateritic subsoil. The lateritic soil is mixed with fibres that make up between 0.1 and 1.0% by weight of the dry soil. The blended materials were then subjected to a Proctor compaction test, an Unconfined Compressive Strength (UCS) test and a 4-days-soaked California Bearing Ratio (CBR) test.

Lawer et al. (2021) report that the maximum dry density (MDD) and optimum moisture content (OMC) of lateritic soil dropped and rose respectively, with an
increase in fibre content. The inclusion of fibres also increased the soaked California Bearing Ratio (CBR) and unconfined compressive strength (UCS) of the soil sample, as shown in Figs. (8 and 9). Based on the data obtained, the peak values of California Bearing Ratio (CBR) & Unconfined Compressive Strength (UCS) were achieved at an optimal fibre content of 0.2% [84].

Fig. (8). Graph of CBR versus fibre content [85].

Fig. (9). Graph of UCS versus fibre content [85].
Bawadi et al. (2020) conducted a study to determine the optimal proportion of natural fibres in influencing compaction properties. The X-ray fluorescence (X-RF) test and the standard Proctor compaction test were used to determine the chemical composition of natural fibres and the compaction properties of soil samples, respectively. Natural fibres such as banana, kenaf, and coconut fibres were used as natural soil stabiliser with different weight proportions (0.3%, 0.5%, and 1.0%) of the soil mixture to improve the properties and stability of the soil samples.

Experimental data obtained from the compaction test shows that the appropriate maximum dry density (MDD) and optimum moisture content (OMC) for each natural fibre are 0.5% natural fibres. According to Bawadi et al. (2020), this is because when 1.0% natural fibres were mixed with the soil sample, the fibres absorbed a large amount of water in the soil grains and resulted in a reduction in the maximum dry density (MDD). Therefore, the optimal proportion of natural fibres is 0.5%.

M. Mohan & L. Manjesh (2017) conducted a study on the influence of randomly oriented natural fibre reinforcements on the soil strength parameter. Coconut and jute fibres with different aspect ratios and different fibre dosages of 0.25%, 0.50%, 0.75%, and 1.0% of the dry weight of the soil. The Proctor Compaction Test, California Bearing Ratio (CBR) Test, Fatigue Load Test, and Unconfined Compressive Strength (UCS) Test were conducted to determine the strength properties of natural fibre reinforced soils.

According to M. Mohan & L. Manjesh (2017), the results show that adding coir and jute fibres to the soil improves the strength properties of the soil. The maximum dry density (MDD) of soil decreases with increasing coir and jute content while optimum moisture content (OMC) increases. In addition, the inclusion of fibres also increased the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) of the soil sample. Furthermore, according to M. Mohan & L. Manjesh (2017), the California Bearing Ratio (CBR) of soil stabilised with jute fibres provides higher strength compared to coir. The soil fatigue life also increases with the addition of stabilisers and decreases as the stress ratio increases.

7.2. Sisal

Sisal is a natural plant fibre obtained from the leaves of the Agave Sisalana plant, commonly known as the sisal plant. This plant originally comes from Mexico and is now grown in various parts of the world for its valuable fibre. Sisal fibres are known for their strength, durability, and versatility, and are suitable for a wide range of applications such as soil stabilisation [30, 86-90]. The chemical composition of sisal is demonstrated in Table 5.

Assefa & Shantveerayya (2022) conducted a study on the strength properties of subgrade soils by reinforcing randomly distributed sisal fibres. The sisal fibres were manually extracted and treated with kerosene to reduce water absorption. Different weight proportions of sisal fibres (0.5%, 1.0%, 1.5%, and 2.0%) for fibre lengths of 10 mm, 15 mm, and 20 mm were mixed with the soil. The Proctor compaction test soaked California Bearing Ratio (CBR) test, and Unconfined Compressive Strength (UCS) test was carried out on the unstabilised and stabilised soil.

Table 5. Chemical composition of sisal [83].

<table>
<thead>
<tr>
<th>Content</th>
<th>Percentage (%)</th>
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</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>43-78</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>10-13</td>
</tr>
<tr>
<td>Lignin</td>
<td>4-12</td>
</tr>
<tr>
<td>Pectin</td>
<td>0.8-2</td>
</tr>
</tbody>
</table>

According to Assefa & Shantveerayya (2022), the finding shows that as the fibre content and fibre length increased, the maximum dry density (MDD) of the reinforced soil decreased while the optimum moisture content (OMC) increased. Furthermore, both the California Bearing Ratio (CBR) and the Unconfined Compressive Strength (UCS) increased significantly with increasing fibre length and content. This increment is optimal with a fibre length of 15 mm and a fibre content of 1.5%. Therefore, it is concluded that a fibre length of 15 mm can be considered as it improves the properties of weak subsoils.

Mughal Y & Singh R (2022) conducted a study on the effects of the addition of bagasse ash and sisal fibre on the maximum dry density (MDD) and optimum moisture content (OMC) of soil. 4% bagasse ash is mixed with sisal fibres of different lengths (2 cm, 4 cm, and 6 cm) and different weight proportions (1.5%, 2.0%, 4.0%) of the soil. The standard Proctor compaction test, California Bearing Ratio (CBR) test and Unconfined Compressive Strength (UCS) tests were carried out on the unstabilised and stabilised soil.

The results show that the optimum moisture content (OMC) increases, and the maximum dry density (MDD) decreases with the addition of 4% bagasse ash. In addition, the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) are increased by adding a mixture of 4% bagasse ash and 1.5% sisal fibre with a length of 4 cm.

Sani J (2022) conducted a study on the effect of lateritic soil stabilised with cement and sisal fibre on the Unconfined Compressive Strength (UCS) of the soil. The soil was treated with a mixture of cement (2%, 4%, 6%, and 8%) and sisal fibres (0.25%, 0.50%, 0.75% and 1%) by dry weight of soil. The sisal fibre was treated with Sodium Borohydride (NaBH₄) (1% wt/vol) at room temperature for 60 minutes at room temperature to remove the cellulose content present in the fibre. Standard Proctor Compaction test and Unconfined Compressive Strength (UCS) test were performed on unstabilised and stabilised soil.
In addition, according to Sani (2022), the results show that Maximum Dry Density (MDD) decreases with increasing cement and sisal fibre content while Optimum Moisture Content (OMC) increases. Furthermore, the Unconfined Compressive Strength (UCS) also increases with the increasing in cement and sisal fibre content, as shown in Fig. (10). Based on the data obtained, it can be concluded that a mixture of 4% cement and 0.50% sisal fibre proved to be the optimum proportion for lateritic soil stabilisation.

### 7.3. Jute Fibre

Jute fibres are natural plant fibres obtained from the stems of the jute plant (Corchorus species). It is one of the most affordable and widely available natural fibres, known for its versatility, durability, and environmental friendliness. Jute plants are mainly grown in regions with warm and humid climates, such as India, Bangladesh, China, and Thailand. Soil stabilisation with jute fibres provides a natural and environmentally friendly solution to the challenges of soil erosion [92-95]. The chemical composition of jute fibre is shown in Table 6.

### Table 6. Chemical composition of jute fibre [83].

<table>
<thead>
<tr>
<th>Content</th>
<th>Percentage (%)</th>
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</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>51-84</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>12-120</td>
</tr>
<tr>
<td>Lignin</td>
<td>5-13</td>
</tr>
<tr>
<td>Pectin</td>
<td>0.2</td>
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</tbody>
</table>

Furthermore, according to Ashok et al. (2023), the results show that both maximum dry density (MDD) and optimum moisture content (OMC) increase with increasing jute fibre content. In addition, the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) also increase with increasing jute fibre content. From the data obtained, it can be concluded that the optimal proportion of the mixture consists of 10% jute fibre.

Amitesh Kumar & Dr. Sandeep Singla (2020) conducted a study on the effect of the addition of cement and jute fibre on the strength parameters of mountainous clayey soil. 6 mm of jute fibre (0.4%, 0.7%, 1.0%, 2.0%, and 4.0%) and cement (1%, 3%, 5%, and 7%) of the soil weight were mixed with a clayey soil sample to determine the optimal proportion of cement and jute fibres. The tests carried out in the laboratory were the specific gravity test, Atterberg limit test, standard Proctor compaction test, modified Proctor compaction test, and California Bearing Ratio (CBR) test in the soaked and unsoaked conditions.
According to Amitesh Kumar & Dr. Sandeep Singla (2020), the results show that the addition of cement reduces the maximum dry density (MDD) of the soil, while the optimum moisture content (OMC) varies with the addition of cement. On the other hand, both the maximum dry density (MDD) and the optimum moisture content increase by up to 0.4% with the addition of jute fibres. However, the mixture of cement and jute fibre further increases the maximum dry density (MDD) of the soil up to 1% cement and 0.4% jute fibre.

Additionally, both soaked and unsoaked California Bearing Ratios (CBR) increase with increasing cement and jute fibre content or a combination of cement and jute fibres as shown in Fig. (11). From the data obtained, it can be concluded that the optimal value of cement and 6 mm jute fibre is 5% and 0.4%, respectively.

Lal et al. (2020) conducted a study on improving soil properties by adding of jute fibre sheet. Jute fibres were placed in three layers: in one layer, the fibre was placed in the middle of the sample; in two layers at a distance of 1/3rd, and 2/3rd sample; and finally, for three layers, the jute fibre was located at a distance of 1/4th, 2/4th, and 3/4th of the sample. Soil samples with a diameter of 38 mm and a height of 76 mm were prepared and tested. The triaxial test and California Bearing Ratio (CBR) test were carried out on unstabilised and stabilised soil.

According to Lal et al. (2020), the results of the California Bearing Ratio (CBR) test and the triaxial test show that the layered arrangement of the jute fibre reinforcement significantly improved the strength and stiffness properties of the soil. In addition, it can be concluded that placing two layers of jute fibre reinforcement is more effective than one or three layers.

Prasanna et al. (2020) conducted a study on the potential for soil stabilisation using jute fibres as a stabiliser when cut into lengths of approximately 30 mm. Different proportions (0.5%, 1%, 1.5% and 2%) of jute fibres were used and mixed with the soil. To observe the change in the engineering properties of soil, laboratory tests such as California Bearing Ratio (CBR) test, Modified Proctor Compaction test and Direct Shear Strength test were carried out. The results show that stabilising the soil with 30 mm pieces of jute fibre improves the strength properties of the soil. In addition, it has been shown that jute fibres can be used as a reinforcing material for construction work where the subsoil is unsuitable or weak.

Table 7. Chemical composition of flax fibre [83].

<table>
<thead>
<tr>
<th>Content</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>60-81</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>14-19</td>
</tr>
<tr>
<td>Lignin</td>
<td>2-3</td>
</tr>
<tr>
<td>Pectin</td>
<td>0.9</td>
</tr>
</tbody>
</table>

7.4. Flax Fibre

Flax fibres, also known as linen fibres, are natural plant fibres that are obtained from the stems of the flax plant (Linum usitatissimum). Flax fibres are known for their strength, durability, and smooth texture. The fibres are extracted from the stems of the flax plant through a process called retting, in which the stems are soaked to break down the plant material and separate the fibres. While flax fibres are best known for their diverse applications, they can also be used to reinforce and strengthen soils [97-103]. The chemical composition of flax fibres is shown in Table 7.
Srinivasan et al. (2021) conducted a study on the effectiveness of bamboo strips and flax fibres in soil stabilisation to improve soil conditions. Flax fibres were cut to an average length of 20 and 30 mm, with diameters of approximately 1 mm to 2 mm. Mixtures of bamboo and flax fibres at 1%, 2%, 3%, 4%, and 5% of soil weight were mixed with soil samples. Direct shear tests were then carried out on unstabilised and stabilised soil samples. According to Srinivasan et al. (2021), the results show that the direct shear value increases at doses of 1%, 2%, 3% and 4% and decreases by 5% by weight of soil for mixtures of bamboo strips and flax fibre. Therefore, 4% is the optimal proportion of bamboo strips and flax fibres for soil stabilisation. All results are reported in terms of cohesion and internal friction angle, as shown in Figs. (12 and 13).

Gbenga Matthew Ayininuola & Edidiong Godwin Udoh (2018) conducted a study on the effect of flax fibre on soil geotechnical properties. Flax fibres were added to the soil sample in amounts of 0.3%, 0.6%, 0.9%, 1.2%, and 1.5% of the soil weight. The geotechnical properties of the stabilised and unstabilised soil, including California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS), were then determined in accordance with BS 1377.

According to Ayininuola & Udoh (2018), the results show that the addition of flax fibre resulted in an increase in the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) of the soil. Based on the data obtained, it can be concluded that the maximum California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) of the soil were achieved at an optimum flax fibre content of 1.2%.
7.5. Bamboo Fibre

Bamboo fibre, one of several types of natural fibre, is made from the cellulose of the bamboo plant. Soil stabilisation with bamboo fibres represents an innovative approach to improving soil resilience. This technique utilises the strength and environmental friendliness of bamboo fibres and aims to strengthen the soil, prevent erosion, and improve bearing capacity. As a renewable raw material with biodegradable properties, bamboo offers a sustainable solution that takes environmental concerns into account [103-105]. The chemical composition of bamboo fibre is shown in Table 8.

Sawarkar (2023) conducted a study to determine the optimum percentage of lime mixed with bamboo fibre to add to black cotton soil. 6% lime, and different proportions of bamboo fibres (2%, 4%, 6%, and 8%) were mixed with black cotton soil. The California Bearing Ratio (CBR) test, Modified Proctor Compaction test, and Unconfined Compressive Strength (UCS) test are carried out on the unstabilised and stabilised soil.

According to Sawarkar (2023), the results show that the maximum dry density (MDD) increases while the optimum moisture content (OMC) decreases with increasing bamboo fibre content. Furthermore, as the bamboo fibre increases, the unconfined compressive strength (UCS), and soaked California bearing ratio (CBR) also increase. From the data obtained, it can be concluded that the optimal proportion of the mixture consists of 6% lime and 8% bamboo fibres.

8. SYNTHETIC FIBRE SOIL STABILISATION

Synthetic fibres, including polyester, nylon, and polypropylene, have gained importance due to their exceptional mechanical properties and environmental resistance. Their consistent quality and versatility in changing soil behaviour make them valuable stabilising agents [37, 105-107]. The review evaluates the effects of synthetic fibres on subgrade soil strength, deformation control and moisture regulation.

Table 8. Chemical composition of bamboo fibre [83]

<table>
<thead>
<tr>
<th>Content</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>26-43</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>15-26</td>
</tr>
<tr>
<td>Lignin</td>
<td>21-31</td>
</tr>
<tr>
<td>Pectin</td>
<td></td>
</tr>
</tbody>
</table>

8.1. Polypropylene (PP) Fibre

Polypropylene fibres are synthetic fibres made from the polymer polypropylene. It is a thermoplastic polymer that is widely used in various applications, such as soil stabilisation, due to its versatility, durability, and relatively low cost. Polypropylene fibres are formed when polymer polypropylene is processed into fibres [76, 108].

The chemical and physical characteristics of polypropylene fibres are shown in Table 9:

Table 9. Chemical and Physical Characteristics of polypropylene fibres [109].

<table>
<thead>
<tr>
<th>Chemical/Physical Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenacity (g/density)</td>
<td>7</td>
</tr>
<tr>
<td>Elongation at Break (%)</td>
<td>18</td>
</tr>
<tr>
<td>UV Light Resistance</td>
<td>Medium</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>0.91</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>160-175</td>
</tr>
<tr>
<td>Resistance to Alkali</td>
<td>Good</td>
</tr>
<tr>
<td>Resistance to Acids</td>
<td>Good</td>
</tr>
<tr>
<td>Moisture Absorption (%)</td>
<td>0</td>
</tr>
</tbody>
</table>

Choudhary et al. (2021) conducted a study on propylene fibre waste as soil reinforcement. 0.10%, 0.20%, 0.30%, 0.40% and 0.50% randomly distributed propylene fibres were mixed into the soil. The Proctor Compaction Test, Unconfined Compressive Strength (UCS) Test, California Bearing Ratio (CBR) Test and Direct Shear Test were conducted on the unstabilised and stabilised soil. According to Choudhary et al. (2021), the results show that the maximum dry density (MDD) increases while the optimum moisture content decreases with an increase in fibre content up to 0.40%.

In addition, the Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) also increase with an increase in fibre content up to 0.40%. The increase in unconfined compressive strength (UCS) and California Bearing Ratio (CBR) is due to the shear effect created by randomly distributed fibres. The subsequent decrease may be due to increased fibre content leading to slippage between fibres. Based on the data obtained, it can be concluded that reinforcement with waste fibres is very effective in improving various properties and bearing capacity of the soil, thereby contributing to sustainable development. Fig. (14)

Brasse et al. (2020) conducted a study on the effect of adding fibrillated polypropylene fibres to soil-cement composites on their flexural tensile strength and on their behaviour in the post-critical state. Single Fibrillated-tapes Polypropylene Fibres (SFPF) and Bundles of Coiled Fibrillated-tapes Polypropylene Fibres (BCFPF) were used as distributed reinforcement. After 28 days of curing, bending tests were carried out.

9. DISCUSSION

The results show that the use of distributed reinforcement in the form of synthetic fibres increases the flexural tensile strength of the soil-cement properties. Furthermore, according to Brasse et al. in (2020) the effectiveness of the improvement achieved depends primarily on the number and length of the fibres used. The higher values of the mechanical properties determined were achieved by samples with 60 mm long fibres.
Hussein & Ali (2019) conducted a study on the effect of adding polypropylene (PP) fibres on the behaviour of expansive soil to reduce soil swelling. The expansive soil used in this study was artificially prepared by mixing 80% calcium-based bentonite with 20% sandy soil. 0.5%, 1.0%, and 2.0% polypropylene (PP) fibres were added to the expansive soil. Unconfined Compressive Strength (UCS) test, one-dimensional consolidation test, swelling test, sieve analysis, and cycle swell shrink test was carried out on the unstabilised and stabilised expansive soil. The results show that the soils containing 2% polypropylene (PP) fibres have the highest unconfined compressive strength (UCS) and the lowest swelling value.

9.1. Polyester (PET) Fibre

Polyester fibres are synthetic fibres made from a polymer called polyethylene terephthalate (PET). Polyester fibres can be used to stabilise soil in construction and other civil engineering projects. Similar to polypropylene fibres, polyester fibres are added to soil to improve mechanical properties and stability of the soil [67, 74, 110-112]. The chemical and physical properties of polyester fibre is shown in Table 10.

I. Ahmad et al. (2022) conducted a study on the effect of adding polyester fibre on the behaviour of black cotton soil to reduce soil settlement. 0.75%, 1.5%, 2.25%, and 3.0% polyester fibre were added to the black cotton soil. Proctor compaction test and California Bearing Ratio (CBR) test were conducted on the unstabilised and stabilised soil samples, according to I. Ahmad et al. in (2022), the results show that maximum dry density (MDD) decreases while optimum moisture content (OMC) increases with increasing polyester fibre content. In addition, the California Bearing Ratio (CBR) also increases with increasing polyester fibre content.

Table 10. Chemical and physical characteristics of polyester fibre [109].

<table>
<thead>
<tr>
<th>Chemical/Physical Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenacity (g/density)</td>
<td>9</td>
</tr>
<tr>
<td>Elongation at Break (%)</td>
<td>14</td>
</tr>
<tr>
<td>UV Light Resistance</td>
<td>Medium</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.38</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>250-260</td>
</tr>
<tr>
<td>Resistance to Alkali</td>
<td>Weak</td>
</tr>
<tr>
<td>Resistance to Acids</td>
<td>Good</td>
</tr>
<tr>
<td>Moisture Absorption (%)</td>
<td>0.2-0.5</td>
</tr>
</tbody>
</table>
Table 11. Chemical and physical characteristics of polyethylene fibre [109].

<table>
<thead>
<tr>
<th>Chemical/Physical Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenacity (g/density)</td>
<td>4.7-5.0</td>
</tr>
<tr>
<td>Elongation at Break (%)</td>
<td>25</td>
</tr>
<tr>
<td>UV Light Resistance</td>
<td>Fair</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>0.95</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>115-135</td>
</tr>
<tr>
<td>Resistance to Alkali</td>
<td>Good</td>
</tr>
<tr>
<td>Resistance to Acids</td>
<td>Good</td>
</tr>
<tr>
<td>Moisture Absorption (%)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

9.2. Polyethylene (PE) Fibre

Polyethylene (PE) is made by polymerising ethylene and is a flexible and lightweight synthetic resin. It can be manufactured in various forms, such as low-density polyethylene (LDPE) and, high-density polyethylene (HDPE) [76, 79]. In contrast to fibres such as polypropylene, polyester or steel fibres, polyethylene is typically not used as a direct additive to soil reinforcement in the context of soil stabilisation. The chemical and physical properties of polyethylene fibres are shown in Table 11.

Sathyapriya et al. (2023) conducted a study on the engineering performance of expansive soil treated with guar gum biopolymer and polyethylene terephthalate fibres. The guar gum biopolymer was added to the soil at dosages of 0.5%, 1.0%, 1.5%, and 2%. Extensive geotechnical testing and microstructural investigations were carried out to optimise the guar gum biopolymer to improve the soil properties and understand the interaction mechanism with the soil. Polyethylene terephthalate fibres with an aspect ratio of 28 are used with the soil in increments of 0.4% up to 1.6%. The optimal dosage of guar gum biopolymer was mixed with polyethylene terephthalate fibres, and the effect on soil geotechnical properties was carried out separately.

According to Sathyapriya et al. (2023), it was demonstrated that there is a reduction in plasticity index, swelling, maximum dry density (MDD), and compressibility of soils treated with 0.5% guar gum biopolymer and 1.6% polyethylene terephthalate fibres. On the other hand, the California Bearing Ratio (CBR) of soils treated with 0.5% guar gum biopolymer and 1.6% polyethylene terephthalate fibres increases.

B. Mishra (2016) conducted a study on the effects of addition of recycled polyethylene terephthalate (PET) fibres on soil engineering properties. The engineering properties to be particularly examined are the shear strength, the California Bearing Ratio (CBR) and the Atterberg limit when using clay soil. The recycled polyethylene terephthalate (PET) fibres were added to the clayey soil in an amount of 0% to 0.8% by weight of the soil with an increment of 0.2%. Based on the data obtained, experimental studies show that the shear strength and California Bearing Ratio (CBR) increased, and the plasticity index (PI) decreased. It was found that the optimal amount of recycled polyethylene terephthalate (PET) fibres that exhibited good strength was 0.6%.

9.3. Polyamide (PA) or Nylon Fibre

Nylon fibres are synthetic polymer fibres known for their strength, durability, and versatility. It belongs to a class of polymers known as polyamides. The principle of using nylon fibres for soil stabilisation is similar to other types of fibres: they are added to the soil to improve its mechanical properties and stability [74, 77]. The chemical and physical characteristics of polyester fibres are listed in Table 12.

Tahmid et al. (2022) conducted a study on the effects of coir and nylon fibres on the unconfined compressive strength (UCS) and compaction value of soil. Soil samples were prepared by measuring their maximum dry density (MDD) and optimum moisture content (OMC), as well as different percentages of coir and nylon fibres by the dry weight of the soil. The soil was mixed with 0.5%, 1.0%, and 1.5% by weight of soil of coconut fibre and nylon fibre.

The results showed that Maximum Dry Density (MDD) decreases while the optimum moisture content increases with the addition of coconut fibre or nylon fibre. In addition, the proportion of coconut fibres significantly increases the Unconfined Compressive Strength (UCS) compared to nylon fibres. Based on the data obtained, it can be concluded that the optimal proportion of adding coconut fibre is 1.5%, while nylon fibre is 1.0%.

Nagu P S et al. (2021) conducted a study to determine the influence of randomly oriented discrete nylon fibre reinforcement (0.15 mm diameter) on the properties of clay soil treated with lime (CaO). The soil was artificially remolded by adding lime and varying percentages of short, discrete nylon fibres with different aspect ratios, as shown in Table 13. Unconfined Compressive Strength (UCS) test, modified direct shear box test, and direct shear test were carried out to investigate the influence of nylon fibre on the strength behaviour of the lime-stabilised clay.

The test results showed a slight improvement in the strength parameters of lime-stabilised clay reinforced with nylon fibres. The addition of fibre caused significant ductility in the soil and changed the failure mode from brittle, caused by lime stabilisation, to ductile.
Table 12. Chemical and physical characteristics of nylon fibre [109].

<table>
<thead>
<tr>
<th>Chemical/Physical Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenacity (g/density)</td>
<td>9</td>
</tr>
<tr>
<td>Elongation at Break (%)</td>
<td>20</td>
</tr>
<tr>
<td>UV Light Resistance</td>
<td>Weak</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.14</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>255-260</td>
</tr>
<tr>
<td>Resistance to Alkali</td>
<td>Good</td>
</tr>
<tr>
<td>Resistance to Acids</td>
<td>Weak</td>
</tr>
<tr>
<td>Moisture Absorption (%)</td>
<td>3.4-4.5</td>
</tr>
</tbody>
</table>

Table 13. Proportion of nylon fibre and percentages of lime used [69].

<table>
<thead>
<tr>
<th>Diameter of Nylon Fibre (mm)</th>
<th>Length of Nylon Fibre (mm)</th>
<th>Aspect Ratios</th>
<th>Percentages of Lime (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>20, 30, 40 &amp; 50</td>
<td>133, 200, 267 &amp; 333</td>
<td>0.2% to 1.0% in increment of 0.1%</td>
</tr>
</tbody>
</table>

Darji & Kajal Vachhani (2018) conducted a study on the effect of the combination of lime and randomly distributed nylon fibres on highly expansive soils in terms of soil strength properties. Lime is used in three different percentages (2%, 4%, and 6%) and nylon fibre in three different percentages (0.2%, 0.4%, and 0.6%) in three length ratios (50, 100, and 150) per diameter (L/D).

The Atterberg Limits Test, Standard Proctor Compaction Test, Unconfined Compressive Strength (UCS) Test, California Bearing Ratio (CBR) Test, and Expansion Ratio Test are performed on unstabilised and stabilised soils. The results showed that the soaked California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and swelling properties were improved beyond satisfactory limits.

Alam et al. (2018) conducted a study on the effect of a nylon fibre-reinforced clay soil on its California Bearing Ratio (CBR). Soil samples were prepared based on their maximum dry density (MDD) and optimum moisture content (OMC) as well as in this study. Different percentages of nylon fibres (0.25%, 0.50%, and 0.75%) of the soil weight are used. The nylon fibre diameter was constant at 1 mm, and the nylon fibre length at 30 mm and 60 mm. The Proctor compaction test and California Bearing Ratio (CBR) test were conducted on unstabilised and stabilised soil samples.

The results show that the California Bearing Ratio (CBR) increased significantly with increasing percentages and lengths of nylon fibres. Furthermore, as the California Bearing Ratio (CBR) ratio increases, the thickness of the pavement decreases. In addition, Alam et al. (2018) suggested that for the California Bearing Ratio (CBR) test, both the soaked and unsoaked conditions must be performed for better analysing and clarification.

9.4. Steel Fibre

Steel fibres, also called steel reinforcing fibres, are a type of reinforcing material used to improve the mechanical properties of concrete and other construction materials or for processes such as soil stabilisation of subgrades. Subgrade soil stabilisation using steel fibre is a construction technique in which steel fibres are incorporated into subgrade soils to improve their strength, durability and load-bearing capacity. Steel fibres are typically small, discontinuous strands or particles made from various types of steel, including carbon steel and stainless steel [74, 110-118].

Pedroso et al. (2023) conducted a study to evaluate the influence of different curing times on the flexural performance of soil cement for pavements reinforced with polypropylene fibres and steel fibres. Polypropylene fibres and steel fibres were used individually in volume proportions of 0.5%, 1.0%, and 1.5% of weight of soil for three different curing times (3, 7, and 28) days. The material was evaluated using the 4-point flexural test.

According to Pedroso et al. (2023), the results show that 1.0% of steel fibres improved the initial strength and peak strength at low deflection. However, the polypropylene fibre mixtures showed better performance achieving ductility index reaching, residual strength, and improved crack control at large deflections. The study shows that fibres significantly influence the mechanical performance of soil cement for pavements reinforced with polypropylene fibre and steel fibres. Therefore, the overall performance presented in this study is useful for selecting the most suitable fibre type according to the different mechanisms as a function of curing time.

CONCLUSION

In conclusion, the article presents a comprehensive overview of subgrade soil stabilisation techniques using both natural and synthetic fibres. The study highlights the importance of improving the mechanical properties of subgrade soils to improve the performance and durability of pavements.

Natural fibres, such as jute, coconut fibre, and sisal, offer environmentally friendly and cost-effective solutions for soil stabilisation. They contribute effectively to soil reinforcement, prevent cracking, and improve load-bearing capacity. However, their effectiveness can be affected by factors such as degradation over time and variability in fibre properties.

On the other hand, synthetic fibres such as polypropylene and polyester have consistent mechanical properties and durability. They effectively control cracks, provide tensile
strength, and resist environmental influences. Nevertheless, their higher costs and possible environmental concerns associated with production and disposal should be considered.

Both natural and synthetic fibres have shown the potential to improve subgrade soil properties, contributing to better pavement performance. The choice between these two fibre types depends on the specific project requirements, including budget constraints, environmental considerations, and desired performance results.

Future research in this area could focus on comparing the long-term effectiveness and sustainability of stabilisation techniques for natural and synthetic fibres. Furthermore, research into hybrid solutions that combine the advantages of both types of fibres could lead to innovative and optimal approaches to subgrade soil stabilisation.

Essentially, the reviewed article highlights the importance of considering the unique properties of natural and synthetic fibres when selecting a soil stabilisation method. Engineers, researchers, and practitioners can use this knowledge to make informed decisions and develop effective strategies to improve subgrade soil and, therefore, pavement performance.

HIGHLIGHTS
- Natural fibre and synthetic fibre increased the California Bearing Ratio (CBR) of the subgrade soil.
- Natural fibre and synthetic fibre increased the Unconfined Compressive Strength (UCS) of the subgrade soil.

LIST OF ABBREVIATIONS
- FRS = Fibre-Reinforced Soil
- ODFRS = Oriented Distributed Fibre Reinforced Soil
- RDFRS = Randomly Distributed Fibre Reinforced Soil
- CBR = California Bearing Ratio
- UCS = Unconfined Compressive Strength
- MDD = Maximum Dry Density

CONSENT FOR PUBLICATION
Not applicable.

STANDARDS OF REPORTING
PRISMA guidelines and methodology were followed. PRISMA checklist is available on the publisher’s website

AVAILABILITY OF DATA AND MATERIALS
The data and supportive information is available within the article.

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CONFLICT OF INTEREST
The authors declare no conflict of interest financial or otherwise.

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SUPPLEMENTARY MATERIAL
PRISMA checklist is available as supplementary material on the publisher’s website along with the published article.

Supplementary material is available on the publisher’s website along with the published article.

REFERENCES


Subgrade Soil Stabilised with Natural and Synthetic Fibres


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