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Potentials and Challenges of Bio-Composites Materials as Engineering Structures in Ecological Slope Protection: A Review

(Potensi Dan Cabaran Bahan Biokomposit sebagai Struktur Kejuruteraan dalam Perlindungan Cerun Ekologi: Satu Tinjauan)

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ABSTRACT

Ecological slope protection technology has gained popularity as a sustainable and eco-friendly approach for slope restoration and conservation. The integration of ecological considerations into slope protection techniques has resulted in more sustainable and environmentally friendly solutions. In order to advance the development of ecological self-cycling, this study conducts a comprehensive review of the latest advancements in ecological slope protection technology materials. A systematic literature search was conducted using four databases (Web of Science, Scopus, Science Direct, and Google Scholar) and based on the keywords: ecological slope protection; slope protection; bio-composite material; bio-material; eco-material; eco-friendly building material; mycelium based material; natural fiber composite and biochar. This article provides a detailed discussion of the fundamental types of ecological slope conservation and the properties of materials used in ecological slope protection technology. The usage of environmentally friendly innovative materials has overtaken traditional engineered structures as the primary mode of ecological slope protection innovation. In particular, this study focuses on the structural basis of ecological slope protection, conducting a comparative analysis of the properties of existing bio-composites and evaluating whether they could replace the base structure of ecological slope protection. The findings of this study will contribute to the development of more sustainable and effective ecological slope protection techniques, thereby promoting ecological conservation and restoration.

Keywords: Ecological slope protection; bio-composite material; mycelium based material

INTRODUCTION

Slope protection is a prevention and control measure used to tackle environmental stability issues on slopes, the effectiveness of which influences the surrounding ecosystem's balance. Slope protection focuses primarily on fortifying slopes, riverbanks, and earthen embankment environments, reducing the weathering and spalling of rock and soil on the slope, and preventing the slope from being impacted by negative influences such as erosion or rapid decline. Traditional slope protection is more structurally secure, with soil reinforcement in the form of slurry slope protection, concrete slope protection, and wire mesh slope protection (Fu et al. 2020), which can effectively enhance slope stability and prevent soil erosion. However, these methods are expensive, resource-intensive, and unfriendly to the environment. Traditional slope protection is mostly built on non-renewable hard materials such as cement, steel, and concrete, all of which contain additives in variable degrees. The quality of these synthetic materials degrades over time, and the usage of large amounts of synthetic materials can lead to soil consolidation and salt issues on slopes, decreasing the soil quality and directly harming the growth of plants and microorganisms (Achal et al. 2020). Carbon emissions, other hazardous gases (e.g., SO^2, NO^2), and dust are generated in enormous quantities during the manufacturing of cement and wire (Fu et al. 2020). Traditional slope protection has a more straightforward appearance and is less prone to merge with the surrounding terrain. When these structures are broken, they tend to disrupt the environmental balance. This demonstrates that traditional slope works have overlooked soil and water conservation, landscape aesthetics, and ecological protection, and are therefore not consistent with contemporary sustainable development principles. Therefore, researchers must seek for more ecological strategies for slope conservation.

As people's awareness of environmental protection grows and environmental activities expand, slope protection is transitioning progressively from an engineering phase to a more ecologically sustainable phase of development. Increasing interest is being paid to the application of ecological conservation techniques to slope protection. Ecological slope protection mainly includes vegetation slope protection and vegetation engineering composite slope protection technology (Wang et al. 2005); or conventional method to restore the natural ecological environment. It is claimed to be a more practical solution for slope protection and consolidation. Liu et al. (2001) proposed that biological slope protection engineering is mainly to revegetate slopes, so as to achieve the purpose of controlling soil erosion and restoring the ecological environment. Xiao conducted a systematic study on plant slope protection in 2005, pointing out that the mutual anchoring effect between plant roots and slope rock and soil can effectively reinforce the slope. Planted slope protection can effectively restore slope vegetation and rebuild a new slope ecosystem. However, the slope stabilization effect is weak and does not eliminate the problem of soil erosion. It is also restricted in use, and can only be used on some gentler slopes. Therefore, further engineering techniques are required to stabilize and protect the slopes as necessary to achieve stability (Yamadera 1982). Subsequently, Wang et al. (2005) suggested that a true ecological berm should be a complete ecosystem, including the interaction between animals, plants, and microorganisms. After the basic berm structure is built, it can repair itself through its own virtuous circulation system, thus effectively solving the problems of soil erosion and slope landslides and achieving the purpose of ecological environment restoration. It can be seen that the composite slope protection technology of vegetation and traditional slope protection engineering is the mainstream mode of ecological slope protection at present. Preliminary bracing of the slope with civil structures or materials is combined with vegetation to restore the ecological environment on the basis of a more effective reduction of soil erosion on the slope.

A bibliometric analysis of the literature on the topic of ecological slope conservation over the past three decades shows that the number of articles published on the topic has been increasing. Compared to the number of articles published between 2002 and 2011, the number of articles published in the last decade has increased by 56.25%, accounting for 15% of the total number of articles on slope protection. In this context, the forms and materials used in ecological slope conservation are more diverse and updated. As can be seen from the above, in addition to the choice of support structures and plantings, the choice of materials for protective structures also plays a crucial role in influencing the effectiveness of ecological slope protection (Fu et al. 2020). In this paper, the authors summarise the research on the characteristics of ecological slope conservation projects and iterations in material selection and explore more possibilities in material selection.

ECOLOGICAL SLOPE PROTECTION

The trend of ecological slope protection has gradually shifted from engineering structures to the application of new environmentally friendly materials. More widely used techniques now include eco-concrete protection, geotextile mat protection, eco-bag protection, and concrete frame protection, all of which is new material technology attempts at eco-slope protection (Fu et al. 2020).

ECOLOGICAL CONCRETE PROTECTION TECHNOLOGY

Eco-concrete is an ecological slope restoration technique consisting of a mixture of cement, water, coarse aggregates, and plant seeds laid as a slope stabilization base with sufficient strength to enable it to ensure slope stability and be environmentally friendly (Tang et al. 2018). Several studies have evaluated the mechanical properties of eco-concrete, including compressive strength, flexural strength, and splitting tensile strength (Wang et al. 2019). The results show that the compressive strength of eco-concrete typically ranges from 1.67 - 25.2 MPa, which is lower than the compressive strength of conventional concrete of 24 MPa - 34 MPa (Bao et al. 2017). Therefore, this technique is only applicable for slopes less than 75 percent. Some reports suggest that the compressive strength of ecological concrete can be effectively increased by changing its composition, depending to a large extent on the maintenance period of the material itself, the soil texture, and the cement ratio (Faiz et al. 2022). Chen et al. (2013) analysed the effect of ecological concrete on the growth of grasses

(*Festuca arundinacea*, *Magnolia multiflora*, and *Medicago sativa*). The results showed that the proportion of concrete in the substrate had a significant effect on seed germination, seedling survival, and growth. 8% concrete content was appropriate for seed germination and seedling growth (Chen et al. 2013). The addition of biochar to eco-concrete can alter the compressive strength of the material and increase soil fertility to promote plant growth rates (Zhao et al. 2019). In summary, eco-concrete has a positive effect on promoting vegetation restoration and biodiversity by combining support structures with plants to improve slope stability. However, it still has shortcomings, and how to balance the stability of the support structure with the plant growth rate by optimising the mix ratio design is a key challenge to be addressed.

GEOTEXTILE MAT PROTECTION TECHNOLOGY

Geotextile mats are a cost-effective, eco-friendly erosion control method with a strong resistance to soil erosion. Geotextiles are permeable geosynthetics composed of natural or synthetic organic fibers (jute, coir fibers, sisal, straw, palm leaves, etc.). Geosynthetics can be tailored to specific functional requirements, allowing for a greater variety of geotextile material combinations. Natural fibers and reinforcements are combined to create synthetic fiber composites with increased stiffness and strength. However, the high initial cost and elevated energy consumption of synthetic fiber materials have steadily diverted them from sustainable development (Santhosh & Hiremath 2020). Geotextiles have a rough surface and are resistant to abrasion and slipping. This also leads to interaction with the soil, which inhibits plant growth. Researchers believe that the usage of geotextiles containing natural fiber blends can mitigate the harmful impacts of synthetic geotextiles on the growth of soil flora and fauna (Álvarez-Mozos et al. 2014). Grass-legume combinations, for instance, are excellent in enhancing soil fertility and fostering better plant germination and root growth (Agbenin & Adeniyi, 2005); coconut fiber has a higher lignin content and a slower breakdown rate than other plant fibers (Sotomayor et al. 2018). However, the high biodegradability of natural fibers still affects slope reinforcement and soil structural qualities, necessitating the use of synthetic materials (e.g. HDPE, polypropylene, etc.) to enhance the longevity of natural fiber-based geotextiles (Yang et al. 2016).

The upgrading and reform of ecological slope protection technology has been iterated not only in terms of structure, but also in terms of the selection of materials. The environmental performance of materials and the use of ecological materials are given greater consideration. The primary objective of ecological slope protection is to stabilise the slope environment while regenerating the soil, a lengthy process. In this process, plant roots are primarily responsible for increasing soil shear strength (Mohamed et al. 2022). Plants, soil, and microorganisms are gradually forming an ecosphere of self-restoration through re-cycling. The now-common ecological berm materials do not interconvert with the soil and cannot be degraded or spontaneously differentiated quickly. This indicates that steep slopes are likely to increase the ecological restoration process's load on the soil and vegetation.

To support ecological self-cycling more effectively, it is vital to address not only how to modify nature and provide for development, but also some of the far-reaching repercussions that the process of transforming nature may have. Consequently, a material with the required strength to maintain soil stability, which is also green, low-carbon, renewable, and has a major economic impact, has become necessary. Based on the fundamental structure of ecological berms, this research will investigate new eco-friendly materials and analyze them in a list to determine their potential substitutability for ecological berms.

MATERIALS AND METHODS

Literature searches were conducted using four databases (Web of Science, Scopus, Science Direct and Google Scholar). The keywords: ecological slope protection; slope protection; bio-composite material; bio-material; eco-material; eco-friendly building material; mycelium based material; natural fiber composite; and biochar. The inclusion criterion was the year of publication, where articles published between 2000 and 2022 were considered. Articles that were not within the scope of engineering or construction building technology or architecture research were excluded. The selection was completed by reading the titles, abstracts and methods and materials sections of the articles.

BIO-COMPOSITES MATERIALS

Concerns about the environment have considerably boosted the number of scientists who are interested in biomaterials. The introduction of new materials and products is contingent upon their recyclability and environmental safety (Atiqah et al. 2020). Numerous environmentally sustainable anticipatory technologies have resulted from the creation and use of bio-composites. For instance, low energy consumption, low cost, recyclability, and site-specific application as waste and byproducts (Alemu et al. 2022).

Bio-composites consist of a reinforcement and a matrix, and both the reinforcement and matrix materials are biodegradable (Shaker et al. 2020). The majority of these biodegradable elements are derived from nature, either directly or indirectly. Some of them have carbon sequestration benefits and emit negligible amounts of carbon (Shahinur & Hasan 2020). Bio-composites can be completely degraded under specific conditions, which has a substantial impact on the life cycle. Depending on the end-use situation, bio-composites can be fortified with various reinforcements, altering the type and percentage of reinforcements and, consequently, the material's qualities. These composites have a variety of applications, including domestic and engineering applications, the construction industry, structural components, medicinal equipment, etc.

MYCELIUM ECO-COMPOSITES MATERIAL

Mycelium composites are biodegradable, porous materials created by combining fungal mycelium as a binder with agricultural residues (such as wood, straw, husks, maize, and bagasse) as substrates. Mycelium is the root of the fungus and has a filamentous, deep, branching form. When it comes into touch with an organic substrate, the mycelium will progressively decompose the plant matter while filling the volume with a thick network of colonization and functioning as a binder (Attias et al. 2020).

Mycelium composites provide the advantages of low cost, low density, low energy consumption, and minimal carbon emissions when compared to conventional synthetic materials (Arifin & Yusuf 2013). Mycelium composites can meet certain structural and functional criteria, such as mechanical properties, acoustic qualities, and fire resistance, by manipulating the growth process factors and material composition (Javadian et al. 2020). These characteristics offer renewable and biodegradable options for a number of design and production processes, including the construction industry. Figure 1 illustrates the mycelium brick tower Hy-Fi on the grounds of MoMA, which created by the architectural team "The Living" in 2014. Mycelium composites also have been used to create semi-structural materials (e.g. decorative panels, furniture) and structural mycelium composite bricks. Figure 2 illustrates the mycelium decorative panels from mogo bio. However, extremely limited study has been conducted on the practicality and usability of mycelium composites for large support or reinforcing systems (Jiang et al. 2017). Mycelium composites' lack of tensile and flexural strength is one of the primary reasons for their limited applicability in braced structures. This is due to the fact that its compressive strength is significantly lower than that of concrete.

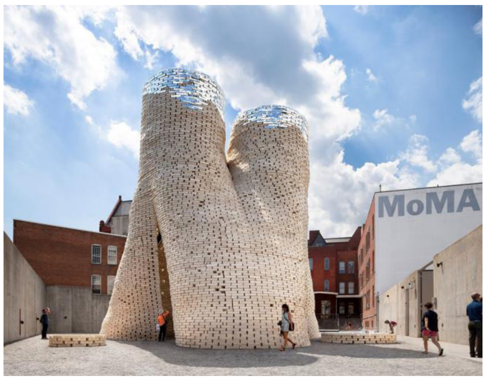

FIGURE 1. Mycelium Brick Tower Hy-Fi On MoMA, By The Architectural Team The Living 2014

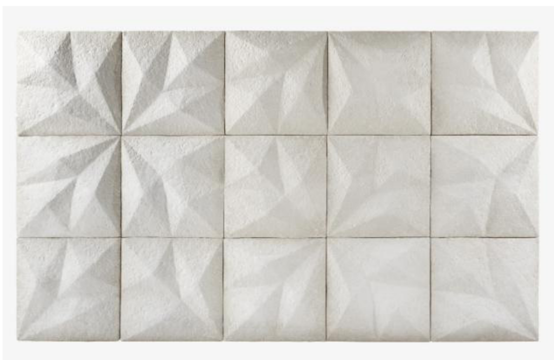

FIGURE 2. Mycelium Decorative Panels, By Mogo Bio 2022

The average compressive strength of *Pleurotus ostreatus* mycelium composites grown on bagassee, sawdust, and wheat bran substrates was 6.5 MPa (Joshi et al. 2020). *Trametes versicolor* veneers combined with yellow birch veneers had the highest composite compressive strength of 1.74 MPa (Sun et al. 2020). The mean global compressive strength varied between 0.36 MPa 0.05 and 0.52 MPa 0.08 (Zimele et al. 2020). Existing research revealed mycelial species and raw materials are not performed in a standardised procedure and a comparable manner. Apple et al. (2019); Haneef et al. (2017); Ziegler et al. (2016); Elsacker et al. (2019) do not completely disclose the preparation of mycelium composites, hindering the formation of a common set of production processes for the time being. These constraints require additional research and development of mycelium composites (Jones et al. 2020). Mycelium composites' mechanical characteristics are continuously being investigated by researchers. Experiments have proven that modifying the development parameters of mycelium materials alters the material's mechanical properties. This consists of substrate type, strain type, growth circumstances, growth duration, and manufacturing technique (Joshi et al. 2020; Haneef et al. 2017; Javadian et al. 2020; Appels 2020; Alemu et al. 2022). Attias (2020) examined 18 sets of mycelium substrates mechanically by controlling for three fungal species and two substrates. The final composites constructed from Gandoerma sessile and sawdust substrates have good compressive strength but limited water absorption. When heat is applied throughout the manufacturing process, mycelium products with a sugarcane bagasse substrate will have a density and compressive strength that are two to three times greater (Apple et al. 2019).

Although the construction industry utilization of mycelium materials is currently in the experimental research phase. Mycelium composites' development potential and environmental qualities cannot be ignored. Mycelium-based materials offer the lightest carbon footprint compared to conventional building materials. This helps to progressively achieve a carbon-neutral building process by gradually replacing traditional non-biodegradable, high-emitting, and costly non-environmentally friendly building materials.

NATURAL FIBER-REINFORCED COMPOSITES

Numerous research has demonstrated the improved characteristics of fibers in bio-composites. The tensile, thermal, and other qualities of both natural and manufactured fibers are fairly diverse (Shahinur & Hasan, 2020). Synthetic fiber materials typically have superior qualities. However, natural fiber materials are numerous, renewable, recyclable, and biodegradable, and their lower density results in a superior environmental impact. Moreover, natural fibers are significantly less expensive to create than synthetic fibers. Natural fibers, such as red hemp, sisal, hemp, palm, coconut, bamboo, and banana, provide more economic and ecological benefits than synthetic fibers. With the exception of standard deviations, these natural fibers offer qualities comparable to synthetic fibers and can substitute synthetic fibers in a range of applications (Gupta et al. 2021). However, natural fibers' low mechanical and thermal qualities limit their applicability. The qualities of some of the most regularly used natural fibers are listed in Table 1. To increase the use of natural fibers in a variety of industries, they are blended with synthetic fibers to improve the qualities of composites.

Natural fiber reinforced composites are primarily a mixture of diverse fibers and bio-polymers (polylactic acid (PLA), poly hydroxybutyrate, polyamide, starch, cellulose, etc.) that are utilized to improve the functional qualities of the composite material for specific purposes. Figure 3 shows untreated flax and flax in polyamide as well as flax with coating and the corresponding test specimen. Natural fiber reinforced composites effectively increase the stiffness, strength and moisture resistance of the material. It also possesses low density, low energy consumption, low cost, low thermal conductivity, elevated water absorption, and environmental certification (non-toxic, renewable, biodegradable), making it a possible replacement for synthetic fiber.

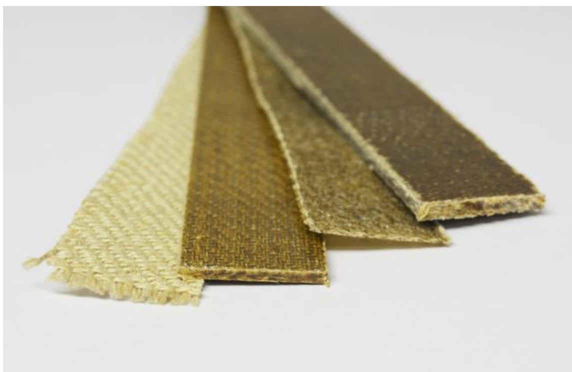

FIGURE 3. Untreated Flax and Flax In Polyamide (left) Coating And The Corresponding Test Specimen (right) Photo By Fraunhofer WKI and Natalie Vellguth 2020

TABLE 1. Summary of fiber properties

Fiber type	**Density (g/cm^3)**	Young's modulus (GPa)	Tensile strength (MPa)	Tensile modulus (GPa)	**Elongation (%)**	**Authors, Year**
Bagasse	1.25	——	222-290	17-27.1	1.1	(Dittenber & GangaRao 2012; Li et al. 2007; Majeed et al. 2012; Saba et al. 2014; Sanjay et al. 2018; Akil et al. 2011; El-Tayeb, 2008)
Bamboo	0.6-1.1	11-32	140-800	11-32	2.5-3.7	
Banana	1.35	——	500	12	1.5-9	
Coconut	——	——	131-175	4-13	——	
Coir	1.15-1.46	——	95-230	2.8-6	15-51.4	
Cotton	1.5-1.6	——	287-800	5.5-12.6	3-10	
Flax	1.42-1.52	75-90	343-2000	27.6-103	1.2-3.3	
Hemp	1.47-1.52	55-70	270-920	23.5-90	1-3.5	
Jute	1.3-1.52	35-60	320-860	8-78	1-2	
Kenaf	1.4-1.5	60-66	195-930	14.5-53	1.3-5.5	
Oil palm EFB	——	——	——	——	——	
Ramie	1.0-1.55	38-44	400-1000	24.5-128	1.2-4.0	
Rice husk	——	——	——	——	——	
Rick straw	——	——	——	——	——	
Sisal	1.33-1.5	10-25	360-790	9.0-38	2.0-7.0	
wheat straw	——	——	——	——	——	
Eucalyptus wood	——	——	——	——	——	
Sugarcane bagasse	——	——	170-290	15-19	——	

composites (Rohit & Dixit, 2016). Yusoff et al. (2016) utilized PLA as a matrix with red hemp, bamboo, and coconut pulp fibers to create composites reinforced with natural fibers. The tensile strength and modulus of the kenaf-bamboo-coir/PLA hybrid composite were the greatest at 187 MPa and 7.5 GPa, respectively. Various combinations of fibers could also compensate for the absence of additional qualities, resulting in improved but variable mechanical properties. For instance, coir fibers boost the material's tensile strength. However, bamboo and kenaf can compensate for their lower strength by bearing tensile loads (Yusoff et al. 2016). Natural fiber composites offer a wide range of uses in manufacturing industries such as the automotive, textile, and fibreboard, and a major field of research in ecologically friendly materials.

However, they still confront obstacles in terms of their development and full utilization. Low mechanical qualities, poor moisture resistance, low fire resistance, variable fiber quality, and manufacturing difficulties are the primary obstacles for composites made from natural fibers. During processing, the adhesion between the fibers and the matrix is susceptible to flaws such as delamination, fiber pull-out, and spalling (Satyanarayana et al. 2009; Gupta et al. 2021). In addition, the extraction process for bio polymers and biodegradable resins is difficult and costly. In order to establish a balance between performance and cost, researchers need to make better use of natural fibers by designing materials properly.

BIOCHAR COMPOSITES

Biochar is a solid charcoal product of biomass pyrolysis. Biochar can be used as a soil conditioner to lower soil capacity, improve soil remediation, and stimulate plant growth due to its elevated water retention. Its primary raw material sources include low-cost waste goods such as agroforestry residues (straw, hulls, bark, and wood chips), marine products (micro/macro algae), and industrial by-products (coffee grounds, nut shells, grape/apple pomace, etc). (Vivekanandhan 2020). Biochar's structural and functional qualities make it a promising material for a variety of uses, including agriculture, animal husbandry, soil/water remediation, construction, and energy storage (Osman et al. 2022).

In recent years, biochar has been studied as a reinforcement for numerous bio-composites in order to suit the needs of certain composites, such as insulation, moisture regulation, and electromagnetic radiation protection (Osman et al. 2022). Jeon et al. (2021) examined the production of wood-based bio-composites from biochar to compensate for the shortcomings of wood in terms of moisture stability by utilizing the high porosity and microstructure of biochar. Despite the fact that the flexural strength of biochar wood-based bio-composites decreases with increasing biochar concentration, the results of the study indicate that their high insulating properties, ability to control moisture, and climate change resistance make them suitable for use as environmentally friendly building materials to address problematic soil amendments. In addition, the size of biochar particles influences the performance of biochar composites. Biochar-clay composites may be employed as supplemental building materials or to improve the engineering features of problematic soils, according to Williams et al. (2018) study. By comparing two sizes of biochar, it was determined that fine biochar was more effective than coarse biochar at increasing the compressive strength of Buckshot clay while decreasing its density. Numerous advantages and benefits are associated with the manufacture and deployment of biochar, but the potential usage of biochar must be optimized and enhanced to maximize its worth to the building sector.

RESULTS AND DISCUSSION

Through the interaction of slope protection technologies, plant systems, and soil systems, the primary aim of ecological slope protection is to establish a self-regenerating ecosystem. Long-term stabilization of the slope environment is achieved through a combination of preparatory bracing, which increases the slope's slip resistance, and plant root growth, which increases the slope's shear strength. Therefore, mechanical qualities are a crucial metric for evaluating the properties of ecological slope protection materials. As a point of reference, the technical specification for vegetated eco-concrete slope protection is utilized. Vegetated eco-concrete refers to eco-concrete and its products with a porous structure, the ability to accommodate the growth of green plants, and a certain protective function. Plant ecological concrete slope protection is suitable for three categories of slope: road and railway slopes (0 - 45 degrees), mountain slopes (0 - 70 degrees), and water conservation projects (subsidence zones) (0 - 70 degrees). Vegetated ecological concrete slopes should consider the slope's engineering features (compressive strength and flexural strength) and ecological properties (void rate, continuous void rate, greening coverage, and permeability coefficient) in order to provide basic slope protection. increasing vegetation covering and permeability coefficient). Table 2 shows the specifications of technical requirements for vegetated ecological concrete slope protection. The compressive strength standard of vegetated concrete is greater than or equal to 15Mpa, which is the most basic grade standard of concrete strength in GB/T standard (C15), and the flexural strength is consistent with the flexural strength standard of polyethylene closed-cell foam board (GB/T1080.1) as greater than or equal to 2.5 Mpa. Thus, it can be seen that the main role of the vegetated ecological concrete slope protection technique is to promote plant growth and ecological environment restoration. Moreover, the performance of the engineered structure is only required to satisfy the basic slope stability function.

TABLE 3 compares the performance of mycelium composites, natural fiber composites, biochar composites, eco-cement and cementitious materials. As the information presented in these graphs is typically restricted, it is necessary to account for certain mistakes when analyzing them, but they are acceptable for the required comparisons.

ATTRIBUTES OF BIO-COMPOSITES MATERIALS

Bio-composites are made with different combinations of reinforcements, depending on the change in their end-use scenario. The type and proportion of reinforcement materials changes the properties of the material itself. The interaction of these materials improves the mechanical properties of the raw material alone, but also increases the negative effects such as process time and cost. The following section analyses and compares bio-composites in the context of the structural part of ecological slope protection projects.

MECHANICAL PROPERTY

According to TABLE 3, the compressive strength of mycelium composites is strong and satisfies the engineering performance requirements for vegetated ecological concrete. Nevertheless, the mechanical characteristics of mycelium composites might vary significantly based on their strain and matrix (Alemu et al. 2022). The compressive strength cannot exceed 0.02±0.01 to 0.04±0.01 (kPa) when coconut powder is used as the matrix material (Teixeira et al. 2018). In contrast, mycelium composites with a matrix of stiffer natural fibers (e.g.,Bagasse, sawdust) and *Pleurotus ostreatus* exhibited a compressive strength of up to 6,500 kPa (Joshi et al. 2020). Mycelium composites inadequate tensile and flexural resistance is one of the primary reasons for their restricted applicability in support systems.

TABLE 2. Specification of engineering performance and ecological performance technical requirements for vegetated ecological concrete slope protection technology

Properties	Index	Test method
Compression strength (MPa)	≥15	GB/T 50081-2002
Flexural strength (MPa)	≥2.5	GB/T 50081-2002 Chapter10
Freezing resistance (%)	≤5	GB/T 50082-2009---4.2
Greening coverage (%)	≥95	
Continuous void rate (%)	≥25	
Permeability coefficient (cm/s)	≥1.0	GB/T 25993-2010---7.4

TABLE 3. Comparative study of different materials properties

Material property	Density (kg/m^3)	Cost (USD/ kg)	Compressive strength (MPa)	Tensile strength (MPa)	Porosity	Water absorption (%)	Recyclability	Raw materials	Authors, Year
Mycelium-based materials	110±0.01 to 330±0.05	0.07 to 0.17	360±5 to 520±8	0.24 ± 0.03	porous	200	Fully degradable	Mycelium and organic wastes or substrates	(Apple et al. 2019; (Attias, 2020)
Natural fiber composites	0.6 to 1.55	0.22 to 1.10	——	95 to 2000	porous	6.23 to 9.76	Recyclable	Natural fiber	(Peças et al. 2018) Muñoz & García-Manrique, 2015)
Biochar	0.236 ± 0.007 to 0.557 ± 0.009		——		porous	86.1 to 92.7	Fully degradable	charred biomass	(Gray et al. 2014)
Ecological concrete	600 to 800	0.6 to 1.3	1.67 to 5.2	0.67 to 2.22	porous		Not biodegradable but recyclable	concrete Seed	(Liu et al. 2018)
Cement material	1800 to 1950		3450		porous	12	None	cement and sand	(Alemu et al. 2022)

When natural fibers are treated with reinforcement composites, the mechanical strength of the material fibers is considerably increased. In the work conducted by Yusoff et al. (2016), the tensile strength and modulus of the kenaf-bamboo-coir/PLA hybrid composite reached 187 MPa and 7.5 GPa, respectively. However, as a support structure, the mechanical properties of the natural fiber reinforced material are still inadequate. During processing, it is also susceptible to flaws like as delamination, fiber pull-out, and spalling. Consequently, natural fiber reinforced materials still present substantial hurdles as a slope protection structure on their own and are unsuitable for placement in places with heavy precipitation and steep slopes. Biochar materials on their own have weak mechanical qualities, but a significant deal of effort has gone into improving biochar composites. Various construction materials currently include biochar clay composites, biochar-based natural inorganic clay composites, and biochar incorporated into asphalt mixes. The technology of biochar-reinforced composites is still in its infancy, and additional research is necessary, particularly in the area of durability.

WATER RETENTION EFFECTIVENESS

Given that ecological slope protection requires plant root growth to improve slope shear strength while maintaining slope stability, ecological slope protection materials should have excellent water retention. Mycelium composites have a steep water absorption rate, and Apple et al. (2019) reported a tendency for mycelium materials to expand during the first two hours of exposure to water and attain saturation after roughly 12 hours. One of the on-cereal-fiber-grown Pleurotus mycelium absorbed up to 278% of water in 24 hours (Apple et al. 2018). The swelling of the fibers caused by water absorption allows the material to delaminate and collapse, resulting in a gradual loss of strength. An environment with a high water content might encourage the growth of fungi and bacteria, leading to the material's decomposition. This phenomenon also happens in natural fiber materials, with strength losses in sisal / polyester composites ranging from 13 to 31 percent, according to studies (Dittenber & GangaRao 2012). Additionally, biopolymers absorb more water than synthetic polymers. Biochar is a lightweight, porous soil supplement that is good at absorbing water and pollutants from the soil and promoting environmental sustainability. Therefore, biochar has a strong water retention capacity. By altering the mix of various biochar raw materials, the soil's capacity to retain water can be successfully increased (Adhikari et al. 2022).

SUSTAINABILITY

Bio-composites' major benefit is their sustainability. Mycelium composites cannot be disregarded due to its low cost, low density, low energy consumption, minimal carbon emission, and biodegradability. Wylick et al. (2022) investigated the changes in mycelium composites when placed in a soil environment for 1 to 16 weeks. The majority of bio-composites are biodegradable through the activity of organisms. All samples of mycelium composites were degraded to varied degrees, according to the results. The mycelium disintegrated initially as a binder; after 4 weeks, the majority of the mycelium had decomposed entirely, and after 16 weeks, the weight of the inert samples generated from the fungal strain *Ganoderma resinaceum* and hemp fibers had decreased by 43%. Mycelium composites following breakdown. Nonetheless, the decomposition of mycelium composites is dependent on the composition of the material, its production method, and a number of characteristics associated with the degradation process; additional tests are required.

Natural fiber-reinforced composites are biodegradable by nature. However, the rate of breakdown might vary considerably based on the polymer. The range is between 0.1 hours and 3.3 years (Gopferich 1996). Stamboulis et al. (2000) discovered that flax fibers began to sprout fungi after three days of contact to moisture, and Nadali et al. (2009) noticed a 30-50% loss in the mechanical characteristics of sugarcane bagasse fiber /polypropylene composites following exposure to Rainbow Fungus (*Coriolus versicolor*).

Biodegradability is the greatest competitive advantage bio-composites have over synthetic materials. Nonetheless, this also means that bio-composites have limited durability. The material degrades quickly when exposed to the proper environment. In order to develop a structural material that does not disintegrate before the plant has completely grown, it is necessary to conduct additional tests on the deterioration rate and plant growth rate.

Therefore, the capacity to precisely anticipate the lifespan of bio-composites is a significant obstacle to their broad use (Satyanarayana et al. 2009).

DISCUSSION

Several research gaps, such as matrix combinations of bio-composites, specific features of bio-composites, and bio-composites' durability, must be filled in order to advance our understanding of the application of bio-composites as engineered structures for ecological slope protection. In addition, research into several additional ecological slope protection technologies is lacking. The use of mycelium as a binder to enhance the mechanical strength of composites with natural fiber reinforcements or biochar might also be thoroughly researched.

On the basis of the results obtained to date, the mechanical properties of bio-composites are typically low and are best suited for use on moderate slopes. Bio-composites require additional research to increase their tensile characteristics, hydrophobicity, etc. Even with the current research development and the closing of the aforementioned study gaps, ecological slope conservation remains impractical. This is because the repair process is much more time-consuming than conventional civil engineering methods. However, the tendency toward incorporating bio-composites into ecological berm engineering constructions is a favourable development.

CONCLUSION

This review presents new information to readers who desire to evaluate the potential of bio-composites as designed structures for ecological slope protection. This review begins with a brief analysis of the potential for frequently utilised ecological slope materials to increase soil and plant burdens during ecological restoration. Therefore, the utilization of bio-composites is required. The features of potential materials (mycelium composites, natural fiber-reinforced composites, and biochar composites) as engineering structures for biological slopes are briefly summarised in this article. Their unique but varying mechanical qualities and their durability are the primary ones (low energy consumption, renewable, biodegradable). Bio-composites have the potential to be utilized in a variety of industries, including construction, manufacturing, and others. Depending on the final application scenario, bio-composites can be increased with various reinforcements, and by adjusting the type and percentage of reinforcements and therefore the material's own qualities, additional research is required to finally improve the sustainability of the material system.

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