doi.org/10.62683/SINARG2025.211

Research paper

INVESTIGATING SUSTAINABLE OPTIONS FOR THE TRADITIONAL MATERIALS IN THE CONSTRUCTION INDUSTRY

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Abstract

The current trends in the construction industry show that the use of sustainable materials is increasing instead of traditional construction materials. Since the construction industry is one of the largest consumers of energy and emitters of carbon dioxide, there is a need for more sustainable materials to be applied in construction. With the advanced technology, many building materials are available as sustainable options. In this study, the application of sustainable materials as a replacement for traditional construction materials is investigated. Sustainable options are considered instead of traditional building materials in the construction industry, including their characteristics and how and where sustainable materials can replace conventional building materials. In particular, bamboo, rammed earth, and mycelium are considered sustainable materials. The common characteristics of these materials are good thermal performance, reduced CO_2 emissions, low energy consumption, low waste generation, and low price. The mechanical characteristics are quite different, as well as the density of materials and performance in earthquakes. The bamboo has quite good mechanical characteristics compared to rammed earth and mycelium-based material, making it earthquake-resistant. However, it is not fungi-resistant or fire-resistant. On the other hand, mycelium-based material is pest-resistant and fire-resistant. The potential to use sustainable materials in the construction industry is rapidly increasing due to modern technology and innovations.

Keywords: *Sustainable materials, Bamboo, Rammed earth, Mycelium, Construction industry*

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1. INTRODUCTION

In total, buildings account for around 40% of global energy consumption, which leads the construction industry to be in the first place in the energy consumption market [1, 2]. According to predictions, this trend of energy consumption in the construction industry will continue to rise in the following decades [1]. Such high energy consumption and greenhouse gas emissions contribute to climate change and global warming, representing the significant threats of modern societies. To reduce this harmful environmental impact, it is of essential importance to incorporate sustainability in civil engineering. The meaning of sustainability is similar to sustainable development. Sustainability means the optimal use of natural resources to avoid decay, depletion, and reaching a point of no return and handing down to next generations by developing them. Similar to sustainability, sustainable development is very common in the current literature. There are many studies that address how to incorporate sustainability in the different research fields, industries, our lives, and systems. The concept of sustainable development refers to meeting the needs of the current generations without compromising the ability of future generations to meet their needs [3]. Sustainability includes three different pillars, environmental, social and economic. The social aspect of sustainability in the construction industry is described as encouraging community involvement, establishing suitable institutional structures, evaluating the influence on the current social context, and assessing the effects on health and well-being [4]. The economic sustainability pillar incorporates external costs, explores alternative financing methods, creates suitable economic tools to encourage sustainable consumption, and evaluates the economic impact on local structures [4]. The environmental aspect of sustainable construction is to decrease material intensity through substitution technology, improve the recycling of materials, minimise the usage of harmful materials, decrease the energy for processing goods and delivering services, back international agreements and conventions, optimisation of sustainable utilisation of biological and renewable resources, and consider the effects of planned project on air, soil, water, flora and fauna [4]. Mitigating towards more sustainable practices and green buildings can reduce energy consumption, decrease construction waste, decrease pollution, and optimise the usage of resources [5].

The most common traditional materials in construction are cement, concrete, and steel. Concrete is the key material in buildings and infrastructure development. It is reported that almost 30 billion tons of concrete are used per year worldwide, taking the first place of material consumption in construction and leaving steel and wood behind [6]. Since concrete comprises aggregates, cement and water, cement production is estimated to be over 4 billion tons annually [7]. Such a large amount of cement production generates 8% of the global CO_2 emissions [8]. Further, the amount of CO_2 emission due to cement production is rising since it is reported that 1.57 Gt of process-related CO_2 emission was in 2019 and 2.9 Gt in 2021 [8, 9, 10]. Cement production and concrete manufacturing cause challenges to modern societies and contribute to climate change and other natural hazards.

The aim of this study is to consider more sustainable options for traditional construction materials, where these options can replace traditional materials and find their application in civil engineering and the construction industry to contribute to sustainable development. In this study, three different sustainable materials are considered: bamboo, rammed earth and mycelium. The bamboo forests are concentrated in the tropical and subtropical regions. The growth of bamboo is influenced by temperature, rainfall, soil type, and altitude [11]. Around 80% of the bamboo forests that contain more than 1200 species of bamboo are located in

Southeast, South, and East Asia, particularly in India, the south of China, Myanmar, Thailand, and other [12]. Bamboo is a renewable material that is an eco-friendly and the fastest-growing plant. Rammed earth is one of the oldest construction methods for many heritage structures, and it is widely found on all continents. Rammed earth structures are found in different historical periods and cultures, including Neolithic, Roman, Chaldean, Yangshao, and Incan cultures [13]. This construction technique uses soil from the ground as the main component for rammed earth and compacts it with optimal water content inside [14]. Recently, rammed earth has been gaining popularity as a renewable material that is locally available, eco-friendly, and cost-effective. The third significant sustainable material that is becoming popular in civil engineering is mycelium-based materials. This biomaterial is a vegetative part of fungi that can be grown on organic substrates such as agricultural waste through mycotecture [5]. Mycelium is a dense network of thin threads named hyphae that grow and intertwine together into solid material [15]. During the growth, self-assembling bonds of tiny white fibres invade and degrade the organic substrate by gradually colonising the organic matter to bind them into strong 3D structural material [16]. Mycelium-based material is renewable, biodegradable and eco-friendly. At the end of their lifecycle, this material can be disposed of without negatively impacting the environment, causing pollution or generating waste.

2. LITERATURE REVIEW

Bamboo is a sustainable material with high potential in green building projects and the construction industry. Similar to rammed earth, bamboo was used for building houses in olden times, especially by people who lived in Southeast Asia, South Asia, and China, where bamboo grows naturally. More often, it was used in combination with grass, wood, clay, and lime to build houses [17]. The example of the traditional bamboo house in the Philippines and the construction of a novel modern bamboo house in Indonesia are illustrated in Figure 1. The first study of bamboo was carried out in 1839 by Ruprecht [18]. Recently, an increasing number of studies have confirmed that bamboo can be a suitable substitute for wood. The manufacturing process for bamboo products in construction includes splitting, glueing, pressing, and heating to produce glued laminated bamboo [19].

Figure 1. Traditional bamboo house in the Philippines [17] and modern bamboo house in Bali [20]

Besides, it is approached to bamboo as a construction material from the different aspects. Some studies and reports evaluate bamboo's mechanical characteristics, compressive strength, tensile strength, and bending [18, 21, 22], thermal characteristics [23], and other.

Due to its excellent thermal properties, a case study from Harbin, Dalian and Shenyang in China shows that residential buildings in cold regions in China can be constructed from bamboo [23]. Also, there are studies regarding the significance of bamboo from social aspects of sustainability [24] and an environmental perspective [25]. Currently, China is the number one producer of bamboo, followed by India.

Figure 2. Traditional rammed earth structure - Basgo fortress in the Ladakh [26]

Applying the rammed earth as a material and a technique for building dates back centuries. There are many examples of this construction method in architecture. By chronological study, it is concluded that this method was first used in construction in China [13]. Settlements during the Lungshan era in China were built from rammed earth. The key component of the settlements was the walls. The earthen walls are made by heaping soil to form a rhomboid section wall, and the base width increases proportionally to the wall height. Some earthen walls as part of the Great Wall of China are placed at the Jiayuguan fortress, which was built in 1372 during the Ming Dynasty. Further, the historical evidence of rammed earth structures is found in the Himalayas [26, 27], such as the Basgo fortress in the Ladakh region in Tibet. This fortress was constructed in 1357. It is shown in Figure 2. As examples from Europe, a few rammed-earth castles from the 14th and 15th centuries were built near Castile in Spain [28]. Fortresses are constructed with lime-crusted rammed earth where putlog holes are passant. It is noticed that castles are influenced by the Islamic Medieval Spanish style (Figure 3).

Figure 3. Traditional rammed earth structure – the castle of Palenzuela in Castile [28]

In the modern period, the rammed earth procedure for construction includes the following steps: a proportion of water is added to the soil, the first layer of moist soil is distributed in a formwork, compacted, the subsequent layers are built up in the formwork until it achieves the height of the wall [29]. The soil formwork is removed after one day, and the rammed earth can cure.

Compared to bamboo and rammed-earth, which have a long history in the construction process, mycelium-based materials are relatively new and have started to gain attention in recent years due to their characteristics [15, 30]. The first application of mycelium-based material began in 2007 for high-quality packaging products [15]. In the construction industry, there are two approaches to integrating microbes in material production. By the indirect method, the enzymes from microbes are extracted and added to the production process of materials [31]. As a result, bioblock, biocement, bioconcrete and biopolymer can be produced [15]. Also, enzymes can contribute to soil stabilisation. The direct method is based on the direct application of microbes such as mycelium, cell walls, and spores of microorganisms. One example of a mycelium-based structure is the Hy-Fi organic Mushroom-Brick Tower in New York, as given in Figure 4. The environmental assessment of mycelium-based materials was carried out in the previous studies, and it is concluded that they outperform traditional insulation materials [32].

Figure 4. The Hy-Fi organic Mushroom-Brick Tower [33]

3. THE PROPERTIES OF SUSTAINABLE MATERIALS

In this section, different properties of sustainable materials are considered. Firstly, the mechanical characteristics, as the most essential property of each material, are investigated. Compressive, tensile, and shear strengths are estimated for the mechanical characteristics provided in Table 1.

The bamboo specimens were three to four years old. It has been tested using a Universal testing machine (UTM). Two hollow bamboo specimens of 15 cm length are tested for the compressive strength in a UTM machine [18]. The compressive load is applied to the sections until the specimen breaks. For the tensile strength test, the same bamboo specimen was used in a UTM machine [18]. It is measured that the ultimate load which causes specimens to break is 16.6 kN. Similarly, a UTM machine performed a shear strength test on the identical specimens. Bamboo has four times the tensile strength compared to the compressive strength.

For rammed earth, specimens are made of natural soil with 13% water content. The specimens have a cylinder shape with a diameter of 10.1 cm and a height of 11.5 cm for the uniaxial compression test for rammed earth [34]. UTM is also applied to test specimens. To measure tensile strength, the Brazilian test on cylindrical specimens is applied [35]. Cylindrical specimens are designed with the dimensions of 16 cm in diameter, 32 cm in height, and 11% of the water content in rammed earth. For testing shear strength, a simple method based on compressive strength, tensile strength and Mohr's circle theory is applied [35]. It is tested on the wallets made from soil by compacting each layer to a thickness of 15 cm after compaction. The wall's dimension is 100 cm x 100 cm x 30 cm. From the results, it can be concluded that the tensile strength of the rammed earth is 10 times smaller than the compressive strength.

Mycelium-based material is tested with an MTS servo-hydraulic testing machine for uniaxial compression and tension tests [36]. Different specimens are used for the compressive and tensile tests. This experiment uses cubic specimens of dimensions 20 mm x 20 mm x 16mm for the compression strength and dog bone specimens of dimensions 200 mm x 6 mm x 3.5 mm for the tension tests.

Table 1. The mechanical characteristics of sustainable materials [18, 34, 35, 36]

Material	Bamboo	Rammed earth	Mycelium
Compressive strength [kN/cm^2]	1.896 – 2.228	0.136 – 0.14	0.004 – 0.008
Tensile strength [kN/cm^2]	4.018 – 8.302	0.01 - 0.035	0.01 – 0.03
Shear strength [kN/cm^2]	0.409 – 0.586	0.015 – 0.085	/

Besides mechanical properties, thermal properties for each sustainable material are considered, as well as some other specifics of the materials, such as acoustic properties and density. The thermal characteristics of each material are provided in Table 2. There are studies from different aspects of sustainability, such as environmental, economic, and social.

Table 2. The thermal characteristics of sustainable materials

Material	Bamboo [18]	Rammed earth [37]	Mycelium [32]
Thermal conductivity [W/mK]	0.15 – 0.30	1.13 – 1.82	0.043 – 0.056

The thermal properties of bamboo are high since the thermal conductivity is low [18]. This means that bamboo is a good heat-insulating material. The density of bamboo is between 1000 and 1300 kg/m^3. The modulus of Elasticity for bamboo is 12 GPa [17]. The water absorption is between 12% and 26%. The sustainability performance from the environmental aspect of bamboo is as follows: durability, low pollution, energy saving and renewable resource [17]. The contribution to construction pollution is relatively low, meaning bamboo has a good environmental impact. From an economic aspect, bamboo is a cheap material that is locally available in some places. From a social perspective, it has a positive effect on the people. It reduces greenhouse gas emissions by reducing carbon dioxide. The performance of bamboo buildings under earthquakes shows good resistance since the bamboo material is lighter than wood due to its hollow nature [17]. Since it is lighter, it produces a smaller earthquake force, the product of mass and the acceleration generated by the earthquake. It has poor fire resistance and resistance to fungi and bacteria [38].

Samadianfard and Toufigh conducted an experiment under simulated conditions to measure the thermal performance of rammed earth materials [37]. The experiment included a hygrothermal chamber, which was designed, and Fourier's law was used to determine the thermal conductivity of a few rammed earth samples [37]. The rammed earth sample consists of 88% earth and 12% water. The density of rammed earth material differs depending on the soil type and percentage of moisture content [39]. It is estimated that the average is around 2000 kg/m^3. However, the density of rammed earth materials varies between 1700 kg/m^3 and 2200 kg/m^3. The performance under gravity loads of rammed earth is acceptable [14]. However, the seismic behaviour of rammed earth is deplorable regarding lateral resistance, ductility, and displacement capacity [40]. The main reason for poor seismic performance is the low tensile and shear strength of the earth. The local availability of rammed earth makes this material cost-effective. From the environmental perspective, the rammed earth contributes to the following sustainability factors: recyclability, renewability, energy savings in material production, reducing carbon emissions, and outstanding humidity ventilation [41]. Overall, it is an eco-friendly material. The cost of rammed earth construction is relatively low, which gives this material a good performance from an economic perspective of sustainability. Besides, it creates local job opportunities in the construction industry. During construction, it is necessary to have at least one contractor who is experienced in the rammed earth construction method [29].

The thermal conductivity of mycelium-based material is relatively low, and it is among the lowest values for biodegradable insulation material [32]. Mycelium-based materials are lightweight since the density is between 110 kg/m^3 and 330 kg/m^3. The water absorption can be as high as 200%. This material contributes to the environmental aspect of sustainability by reducing carbon dioxide emissions, energy consumption, and construction waste. The other environmental factors of mycelium-based material are recyclable, compostable and biodegradable [15]. After the building lifecycle, the mycelium-based material is fully degradable and can be returned to nature. The main benefits of mycelium are that it captures and stores CO_2 during its growth, which is absorbed from the environment [30]. It is estimated that biological materials used as substitutes for construction materials can reduce CO_2 emissions by about 800 million tons annually [32]. It is available in nature. From an economic perspective, the benefits are low cost and easy production. The production process of mycelium-based material is simple, including moulding and growing [15]. The optimal conditions for mycelium to grow are the air temperature between 25°C and 30°C and humidity of 65% [42]. Mycelium-based materials have excellent thermal and hydrophobic properties. It is fire-resistant and pest-resistant.

4. THE APPLICATION OF SUSTAINABLE MATERIALS

The potential of sustainable materials in construction is increasing. Similar to wood, the options for bamboo in the construction process are wide. It can be applied to house structural parts, such as roof structures, flooring, foundations, and walls. Since it is lightweight, it can be easily installed as roof trusses. A bamboo roof enables protection towards different forces of nature, such as winds, storms, rain, and animals. Bamboo mats are a good choice for flooring due to their good thermal performance, which prevents the floors from getting heated from the warm weather in the summer and keeps the warmth in the winter. Before using bamboo for foundations, it should be treated with certain chemicals that prevent the decaying property of bamboo when it is in contact with soil. The mass use of bamboo is for constructing walls as an infill in the middle of the framing members. The bamboo scaffoldings for high-rise buildings are gaining popularity in the construction industry in the southern parts of China. As a lightweight material with heavy load-bearing capacity, it is more efficient for scaffoldings than steel scaffoldings. The scaffoldings can be easily assembled, disassembled and transported due to their lightweight. Figure 5 shows the bamboo scaffoldings on one site in Hong Kong. Besides structures, bamboo is used in infrastructure for bridge construction [43] and for reinforcing the embankment in a roadway [44].

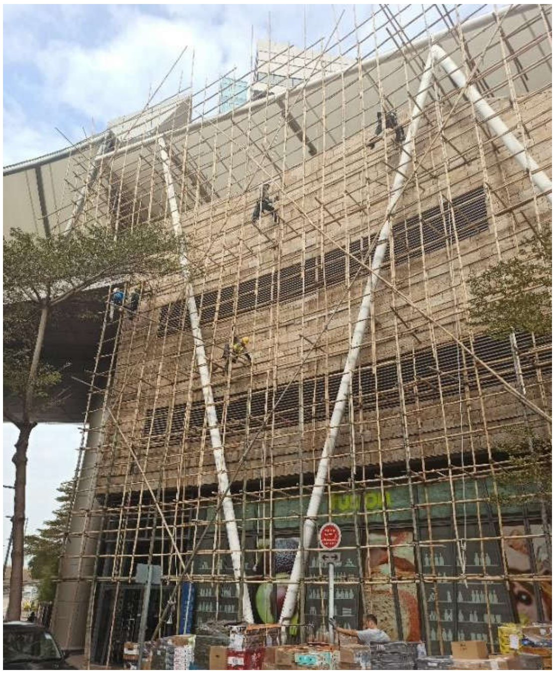

Figure 5. Bamboo scaffolding (photo taken by author)

The rammed-earth presents the optimal solution for building houses and small buildings. The most common structural elements easily built with rammed earth are walls. Building walls in rammed-earth are constructed in layers of continuous rows with a thickness of 46 to 60 cm [45]. The thickness of the layers is about 20 cm. After each layer, the compaction is carried out.

Figure 6. Mycelium bricks [33]

Mycelium-based composites, such as mycelium panels, mycelium boards, mycelium bricks (Figure 6), bio-blocks, and bio-polymers, have been successfully developed and investigated by researchers. The main contribution of the mycelium-based material in the construction industry is to be used as an insulation material due to its excellent thermal and hydrophobic properties.

5. CONCLUSIONS

Bamboo, rammed-earth and mycelium-based materials contribute to sustainability in three aspects: environmental, economic and social. The economic factor is the low price of materials since they can be easily and locally found. From the environmental aspect, sustainable materials are proven to reduce CO_2 emissions and energy consumption during the project lifecycle, increase recyclability, and reduce waste. After the project lifecycle, the material can be returned to nature. The common characteristics of these materials are good thermal performance, reduced CO_2 emissions, low energy consumption, low waste generation, and low price. The mechanical characteristics are quite different, as well as the density of materials and performance in earthquakes. The bamboo has quite good mechanical characteristics compared to rammed earth and mycelium-based material, making it earthquake-resistant. However, it is not fungi-resistant or fire-resistant. On the other hand, mycelium-based material is pest-resistant and fire-resistant. The potential to use sustainable materials in the construction industry is rapidly increasing due to modern technology and innovations.

ACKNOWLEDGMENTS

Research Fund **XJTLU RDF-23-01-003** is well recognised for its support for the research.

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