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(REVIEW ARTICLE)

Study on sisal fibres as insulator in building materials: Review

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Abstract

Developing sustainable and environmental-friendly buildings is a common motivation for engineers and researchers towards a green, clean, and resilient world for all. The problem arising from excess waste disposal from non-biodegradable materials have recently raised concerns from governments, researchers and industrial sectors on the usage and disposal of these types of synthetic materials. One of the approaches ventured is the use of renewable materials that are biodegradable when they are no longer required. Such materials are commonly plant based. This is due to their renewability and abundance. However, it cannot be ignored that natural fibres derived from plants are susceptible to moisture, thermal, and microorganism degradation . Therefore, immense efforts are required to sufficiently study the performance of natural fibres as building materials before they can fully replace synthetic fibres. This study is motivated by the need to expand the knowledge on the use of natural fibres in the construction industry. Specifically, this study will focus on the effect of heat conductivity of gypsum panels reinforced with natural fibres. The developed material may contribute to the improvement of thermal insulation properties of building panels.

Keywords: Sisal Fibre; Natural Fibre; Building Materials; Civil; Thermal Conductivity

1. Introduction

In recent years, there is an increase in interest in the development of natural fibres for industrial applications by engineers and researchers. Many efforts are focused on the possibility of replacing natural fibres with the more conventional synthetic fibres, such as glass, carbon, and aramid. Natural fibres possess good properties, suitable to be used as engineering materials. These properties include high strength, low weight, corrosion resistance, low cost, less health hazards, and obtained from renewable resources [1, 2]. A particular interest for the use of natural fibres is in the form of reinforcing fibres in composite materials. This can be observed in the automotive industry, whereby in the last decades, many Western European automotive manufactures, such as Audi, BMW and Volkswagen are using these types of composites within various parts of a vehicle, mainly as interior linings, padding and panelling [3].

The civil engineering industry had witnessed many changes and development in the use of building materials. Most recently is the application of fibres as reinforcement for cement, concrete and polymers. Another possible combination is with gypsum, to provide finishing interior work, panelling and partition walls in buildings. It is estimated that about 95% of total gypsum produced is consumed by the building sector [6]. The main contribution of this material is to provide comfort to people residing in buildings due to its thermal and acoustical properties. Gypsum board is also known as drywall, wallboard, and plasterboard. It has a non-combustible core and paper facers, therefore, making it advantageous from other panel–type building products, such as plywood, hardboard, and fibreboard. In practice, gypsum boards are sometimes faced with various materials, including paper and fibre glass mats [7]. Therefore, in this

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study, the performance of gypsum in combination with natural fibre is evaluated. Its thermal insulation property is primarily observed for any improvement or deterioration with the addition of sisal fibres.

2. Materials in building construction

The construction industry is in constant development whereby traditional materials used as building blocks are continuously replaced as better materials are developed. Traditional materials such as timber, stones, rocks, bricks, straws, mud etc. have made way for more robust materials such as concrete and steel. Most recent is the development of fibre reinforced composites, with matrices including polymer, ferrocement, and gypsum.

2.1. Advantages and disadvantages of fibre reinforced composites

Composite materials have existed even approximately 3500 years ago where brittle building materials such as sun-baked bricks were reinforced with horsehair, straw and other vegetable fibres. In modern times, in about 1900, the concept of fibre reinforcement was developed on brittle cement-based paste reinforced with asbestos fibres. The Hatschek technology was invented for production of plates for roofing, pipes, etc. More recently, glass fibres were proposed for reinforcement of cement paste and mortar by Biryukovichs [9]. Since 1960 onwards, advanced composite materials have found to have expanded especially in areas such as aerospace, marine and automobile industries. This is due to their good engineering properties such as high specific strength and stiffness, lower density, high fatigue endurance, high damping and low thermal coefficient (in fibre direction) [10]. In addition, the structural capacity of FRP can be tailored and maximized by aligning fibres along its optimal orientation [11]. This shows that FRP is a flexible material and can be applied on many types and shapes of surfaces. Furthermore, FRP composites are light weight and highly durable in many environments. The light weight is an attractive characteristic as it makes construction and rehabilitation works much easier as heavy handling equipment is not needed in constricted spaces. From the seismic perspective, the strength and stiffness of a structure can be increased with very little increase in mass and this is highly desirable [12].

Compared to traditional materials such as wood, steel and concrete, composite materials such as fibre reinforced polymers (FRPs) have very good corrosion resistance. This leads to the exploration of new construction technologies focusing on using FRP materials as an alternative to the traditional steel, concrete, and wood materials [13]. FRP composites are also being considered as a replacement to the conventional steel in reinforced concrete structures due to continuing drop in the cost of FRP composite materials. They are available in the form of rods, grids, sheets and winding strands. [10].

The mechanism of composites reinforced with fibres is through the interaction between the fibres and the matrix. The interfacial bonds between the fibre and the matrix can be defined by the shear stress at the interface, which transfers stress between the fibre and the matrix surrounding the fibre [14]. There are many types of fibres used as reinforcement for various matrices in composite materials. These include glass, carbon, aramid and Kevlar. Different fibres give different properties to the fabricated composite as well as its final cost of production. Some of the specific properties of these fibres as described by Hollaway [15] are:

- Carbon fibres and FRP rods have good durability characteristics and are also very expensive.
- Aramid fibre and FRP rods are durable except under conditions such as static fatigue, UV radiation and acidic environment.
- Glass fibres are widely used due to its relatively lower cost but good mechanical properties. However, it is less durable than the other synthetic fibres as far as their alkaline resistance is concerned. Glass fibres are susceptible to the moisture extracting ions from the glass (corrosion of glass) and chemical attack and also degrade when exposed to UV radiation from the sun [16]. They showed satisfactory characteristics in an acidic and freeze thaw environment.

However, there are important challenges that need to be addressed when using fibre reinforced composites. As their application has now been increased in the building industry, even expanding to repairing, strengthening and replacement of old structures, their reliability must be fully understood. One of the disadvantage highlighted by Hollaway [15] is that FRP materials in general showed poor performance at high temperatures and therefore their use are avoided when fire resistance is required. At the service temperature of most structures, the binding resins are stable and perform as intended, but with increasing temperature, the resin breaks down and evaporates. A method used to improve this condition is by spraying fire retardants on the surface of the composite to provide some heat and fire resistance. However, further work is necessary in this field of study. Another drawback of using FRP composites is the susceptibility of the resin to ultraviolet light. The resin slowly becomes brittle when they are exposed to sunlight for long period of time. To overcome this, FRP must be protected from exposure to direct sunlight and this can easily be achieved indoors and with paint. Many studies have focused on the development of new resin formulations that will eliminate this problem [12].

There are uncertainties in designing fibre composite structures. Unlike steel which is a homogenous material with constant stiffness in all directions, the FRP composite material has different stiffness in different directions. They are generally anisotropic, brittle, low modulus, and are highly dependent on the properties of its components matrix and fibre. For example, the fibre composite member designed for tension cannot be loaded with torsion forces. Additionally, to design a fibre composite structure, the design process does not only include the shape or geometry design, the material itself should be included whereby the fibre plies should be considered in the design level and the overall geometry level of the structure. To overcome this, optimization methods can be applied as they have the advantages of offering the solution of geometry and materials design at the same stage [13].

The lack of information on the durability performance of FRP materials is recognized as being the primary impediment to expand the utilization of these materials in civil infrastructure applications. The definition of a durable material is "the ability of the material to resist cracking, oxidation, chemical degradation, delamination, wear, and effects of foreign object damage for a specified period of time, under the appropriate load conditions, under specified environmental conditions". Therefore, the performance of FRP composites for their intended use and environmental condition need to be considered before they are being applied. For instance, the combined effects of moisture or humidity and heat, also known as hygrothermal effect, are generally dominant in the degradation processes of FRP materials. Additionally, moisture absorption along with chemicals in solution may aggravate the degradation of FRP composites. Such condition is present when used with concrete due to the presence of salts and the high alkalinity of concrete pore water. Water absorption is also known to affect the bond between FRP and concrete, even more so than it does the FRP properties themselves. Moisture absorbed by the matrix of an FRP system can lead to the degradation of the matrix itself which consequently diminish its protection and stress transfer to the fibres. This phenomenon can be greatly magnified for incompatible fibre and resin [16].

2.2. Fibre reinforced composite for construction application

Fibres have been used to reinforce concrete for construction applications, such as shotcrete, tunnel lining, maritime structures, seismic structures, and slabs on grade. Increased use of this material was observed in recent years as it can significantly increase the ductility of cementitious materials by improving their resistance to rupture and crack propagation. The fibre works by contributing to the increase in the ductility of cementitious composites through dominantly by the energy dispersion mechanism, which is related to pull-out of the fibre from the matrix. By improving the bonding between the fibres and cementitious material, the developed composites will have higher strength and toughness. To study the effectiveness of fibre in this relationship, single-fibre pull-out tests can be performed to elucidate the mechanism of fibre reinforcement and to optimize the characteristics of the matrix and the fibres [14].

Because of their good engineering properties, an increase in the application of FRP composites has been seen in the construction industry over the last decade. Strengthening and rehabilitation of deteriorated infrastructures has recently brought the attention of civil engineers to the potential of composites as strengthening material. Initially, the applications of composites were in the form of rebars and structural shapes. Later, FRP composite laminates were introduced in the strengthening of concrete bridge girders by bonding them to the tension face of girder and also for retrofitting of concrete columns [10].

Columns are fundamental in civil structures and to improve the state of this structural component is important for the safety of the building's occupants. Repair, retrofitting, and strengthening of damaged concrete columns using FRP composite wrapping or jacketing are increasingly becoming essential in civil infrastructures due to the high strength/stiffness to weight ratio, corrosion resistance, and ease of installation of FRPs. One of the parameters considered in designing the retrofits of columns using FRPs is the orientation of the fibre reinforcements. In practice, a column is usually subjected to an eccentric axial load, which can be divided into a co-axial compressive load and a bending moment. This requires an engineer to treat columns as beam-columns. To support co-axial compressive loads, the optimal fibre orientation is in the hoop direction while the optimal direction for fibre orientation to support bending moment is in the axial direction. Therefore, fibre orientation is an important variable in the structural design of FRP wrapped concrete columns [11].

Apart from retrofitting concrete, FRP can also be used to reinforce timber structures. FRPs are bonded using adhesives to repair and strengthen timber and engineered wood products. However, the lack of established standards and guidelines has impeded the use of FRP strengthening although it could make a better alternative than most traditional techniques. The commonly used adhesive for on-site repair jobs is epoxy based. Other types of adhesives are polyurethanes, polyesters, phenolics and amino plastics. For timber and wood applications, this adhesive is found to be unsuitable as they are generally too rigid for bonding timber and there is no chemical bonding or suitable mechanical anchorage in wood. The bonding interface is found to be prone to failure due to the dimensional changes in the wood induced by moisture content variations, even for indoor applications. This has led to the formulations of epoxy developed specifically for use with wood. The selection of the adhesive for bonding of FRP to timber must be undertaken with great care as it must be capable of bonding with both the FRP and timber and should have adequate strength. While many adhesive types have proven to provide satisfactory bonding performance when used in a controlled environment, it was found that two-part cold-cure epoxy adhesives are most suitable for on-site bonding as they demonstrate good gap-filling properties, are thixotropic and have low curing shrinkage. The advantages offered by this adhesive bonding, as well as the high strength and stiffness, light weight and good durability of FRP composite laminates have shown to be an effective and economical method for strengthening and repair of wooden structural members. It is important to note that careful surface preparation is essential in order to achieve good bond strength and durability [17].

FRP bars have been used to replace steel bars in concrete structures. However, the use of FRP bars is still a difficult challenge for engineers because of the massive differences in the physical and mechanical properties between FRP and conventional steel. One of the drawbacks of FRP bars is the lower elastic modulus than that of steel bars and this leads to higher deflection and larger crack width in FRP bar-reinforced concrete beams that have an equivalent reinforcement ratio to steel-reinforced concrete beams. Glass fibre-reinforced polymer (GFRP) bars and aramid fibre-reinforced polymer (AFRP) bars have an elastic modulus that ranges between 35 and 50 GPa, while the elastic modulus of carbon fibre-reinforced polymer (CFRP) bars is between 120 and 150 GPa. Another major difference between steel and FRP bars is their failure behaviour. Steel is ductile up to failure while FRP fails in a brittle manner. In a reinforced concrete beam, brittle failure must be prevented and are avoided for FRP-reinforced concrete design by favouring failure by concrete crushing. This is usually avoided in steel-reinforced concrete design. Yang, Min [18] have suggested the use of fibre reinforced concrete (FRC) as an alternative solution to overcome this problem. Steel fibres in concrete provide increased toughness, durability, and impact resistance, and control the initiation and growth of cracks. This application on steel-reinforced concrete design has been proven by many researchers to increase the ductility of the structural component. The author reported that the ductility indexes of GFRP beams with steel and synthetic fibres were approximately 70% and 80% higher, respectively, than the ductility index of GFRP beam with no fibres. It was summarised that the addition of fibres could be a possible method to overcome the low ductility of FRP bar-reinforced beams.

2.3. Natural fibres in building materials

The insulation of a building is crucial as it protects the inhabitants inside from extremely hot or cold climate. This relates to the efficient use of energy in residential housing and commercial offices in providing certain levels of comfort to the residents. Therefore, the study of thermal conductivity of building materials is important in order to better understand the insulation properties of these materials. In this study, a new approach has been evaluated regarding the fabrication of building materials, in particular wall panels, to reduce the heat transfer from outside temperature into the building while reducing the energy consumption by air conditioners or heaters. Natural fibres based composite materials have shown promising potential as building materials as they have several attractive features such as low cost, less health hazards, are biodegradable and are derived from renewable resources. All these features will help towards environmental sustainability in the global building construction industry.

The approach that is being investigated in this study is to use sisal fibres in combination with traditional building materials as insulator in interior walls of building. The standard building materials currently in use have several disadvantages on the environment such as increase of waste disposal from construction sites and the hazardous emissions produced from fabrication works. Additionally, synthetic materials are relatively high cost, non-biodegradable and not recyclable.

Many previous investigations were carried out with the use of natural fibres as building materials and the outcomes show that they are comparable with other conventional building materials. However, it was highlighted that further studies are required to overcome the weakness of natural fibres.

Many searches have been carried out in this promising area. Benmansour, Agoudjil [19] investigated a composite made of natural cement, sand, and date palm fibre (DPF), and to evaluate the possibility of using it as insulating building materials. The authors revealed that the introduction of DPF reduces the thermal conductivity and compressive strength of the composite. If the content of DPF is lower than 15%, the composite satisfies both thermal and mechanical requirements for construction materials. The research concluded that the developed material is able to be used as wall structures.

Another study using DPF was carried out by Chikhi, Agoudjil [20]. The authors developed a new bio-composite made of DPF and gypsum. Biomaterials containing different DPF filler contents and two different sizes of DPF were prepared. The experiment results showed that the thermal conductivity of the gypsum-based materials decreases with the increment of DPF contents. Mechanical properties such as compressive and flexural strength of the bio-composites were also improved by adding adequate fibre contents. It is concluded that this new bio-composites have good thermal and mechanical properties and could be applied as thermal insulation for building materials.

Joseph Khedari, Suttisonk [21] investigated a possible lightweight construction material composed of cement, sand and coconut and durian fibres. Thermal conductivity test results revealed that the addition of coconut and durian fibres reduced the composite's thermal conductivity. Meanwhile, the compressive strength and bulk density results showed that the material satisfied the basic requirements for construction materials and can be used in walls and roofs fabrications.

Agoudjil, Benchabane [22] studied the thermophysical, chemical and dielectric properties of three types of date palm wood (DPW). Their results from Scanning Electron Microscopy (SEM) revealed that the surfaces of the samples are irregular with many filaments, impurities, cells, and pores. Thermal conductivity test results show this material has relatively good insulating properties and is a good candidate for the development of efficient and safe insulating materials.

2.4. Sisal fibre as reinforcement in composites

In this study, sisal fibre is used as natural fibre reinforcement for building materials. This section compiles the findings and conclusions of researchers on the properties of sisal fibres that are relevant for civil engineering applications.

2.4.1. Properties of sisal fibres

Sisal fibre is extracted from the leaves of sisal (Agave sisalana), which is widely grown in Tanzania, Brazil, and other tropical countries with an annual yield of 4.5 million tons [23]. Sisal fibres are composed of three main constituents: cellulose, hemicellulose, and lignin. Cellulose is the highest constituent, but its portion varies in different areas. The physical properties of sisal fibres include a density range of 1400~1450 kg/m3, and fibre diameter range of 100~300 µm. Its tensile strength ranges from 400~700 MPa, with the tensile modulus from 7~22 GPa.

The tensile and fatigue properties of sisal fibres from Algeria, with approximately 250µm of diameter and 0.8-1 m of length were tested by Belaadi, Bezazi [24] tested. Over 15 samples were measured, and it is found that the strength of the fibres are higher (9N~22N) than previous figures in open literature. The S-N curves results received from the fatigue testing can be used to predict the fatigue and structural integrity behaviour of sisal reinforced polymer composites and may assist in the design of this natural fibre. Belaadi, Bezazi [25] investigated over 40 sisal fibres samples on their mechanical properties statistical model versus fibre diameters. Weibull distribution statistics were used to estimate their tensile and modulus properties and was compared with experimental data. At the gauge length of 20 mm, high tensile strength / modulus was obtained from the finest fibre diameters, approximately 140 µm. The authors also used FTIR and DSC results to observe its cellulose, lignin, and hemicellulose structure.

Another test on the tensile properties of sisal fibres were conducted by Silva, Chawla [26]. Four different gauge lengths (10, 20, 30, 40 mm) were used in the study. The results showed that the tensile strength and the tensile modulus (approximately 18 GPa) was not impacted by the gauge length. The fracture mode through SEM images was found to be resulted by delamination between primary and tertiary wall, and between fibre-cells. The authors studied the sisal fibre's fatigue behaviours through tensile experiments. The sisal fibres were tested at stress between 80 ~ 400 MPa. It is found that fibres subjected to a ratio of 0.5 of ultimate tensile strength have survived 10^6 cycles and failed at ratio between 0.6 to 0.8 and fatigue lives between 10^3 and 10^6 cycles. No significant stress-strain hysteresis was found during fatigue.

Martin, Martins [27] analysed raw and defatted sisal fibre's thermal properties through TG and DSC analysis. The DSC curves in inert atmosphere show that the sisal fibres have different peaks for each constituent (cellulose, hemicellulose, and lignin). However, in air atmosphere, there are two exothermic peaks for all constituents. TGA results showed that cellulose and hemicellulose degraded at lower temperatures for treated sisal fibres due to removal of lignin. The thermal degradation of sisal fibre and its constituents is like other natural fibres such as jute and hemp.

2.4.2. Various fibre treatments on sisal fibres

To use sisal fibre to reinforce polymers, some fibre modification is necessary. The commonly used methods include treatment using benzol/alcohol, alkali, acetylate, silane, thermal and combination of two or more methods. The treatment of sisal fibres will improve its interfacial bond with polymers and therefore, resulting in good reinforcing effect on the polymer matrices.

Zhou, Cheng [28] used silane coupling agents to modify sisal fibre and investigated the chemical reaction between sisal fibre and silane. Through SEM, FTIR, TG, DSC, TG/MS, it is found there is a layer composed of siloxane and polydioxanone on the sisal fibre surface. Chemical bonds were formed between sisal fibre and silane agent. These results indicate that silane changes the surface topography and chemical structure of sisal fibre. This leads to better cohesion with the polymer matrix to produce sisal-fibre reinforced polymer composites.

Another treatment widely used to modify natural fibres is by soaking them in alkali, known as alkalization. Barreto, Rosa [29] modified sisal fibres using alkali solution NaOH at 5% and 10% concentration and bleached them with sodium hypochlorite NaClO /H2O (1:1) at 60-75 degrees, and then combined with phenolic matrix derived from cashew nut shell liquid (CNSL) to make a biocomposites. It is found that the alkali chemical treatment increased the crystalline fraction and improved the thermal stability of sisal fibres. Additionally, from the morphological study through SEM, it was found that this chemical treatment exposed the cellulose component of the fibre and increased its superficial area. This provided better cohesion between the sisal fibres and the phenolic matrix material.

Alkalizations using NaOH was also used by Mohan and Kanny [30] in combination with clay to chemically treat sisal fibre to improve the fibre-matrix compatibility and interfacial strength with the matrix. Structure and morphology study through FTIR, EDX and XRD revealed that the treated sisal fibre has a dissolution of amorphous lignin phase and crystalline fraction of 76%, and with 20% clays in the treated sisal fibre in weight. Mechanical properties such as tensile strength, modulus and strain are increased compared to the untreated sisal fibre by 14~18%, and 10% increase in dynamic stiffness. The improvement in glass transition temperature Tg was also observed in treated sisal fibre composites.

Kim and Netravali [31] mercerized sisal fibres under tension and no tension, to improve their tensile properties and interfacial connection with soy protein matrix. The sisal fibres were treated in 2 M NaOH solution under different tensions (from 0g to 100g weight per fibre) for 2h, and then soaked into procured Soy Protein Concentrate (SPC) resin to fabricate the composites. The composite samples were cured at 120°C. The composite's fracture stress and stiffness were found to increase up to 12.2% and 36.2%, compared to mercerized sisal fibre reinforced composites. Morphology study through SEM on the composite's fracture surfaces indicated that there is better adhesion between sisal fibre and soy matrix after the mercerization treatment.

Rong, Zhang [32] investigated the effects of fibre treatments on mechanical properties of unidirectional sisal fibre reinforced epoxy composites. Many treatment methods such as alkalization, acetylation, cyanoethylation, silane coupling agent, and hearting were applied to modify sisal fibre's structures. Through FTIR, XRD, and SEM investigations, it is found that the adhesion between matrix epoxy and sisal fibres was improved. This improved adhesion between matrix and fibre resulted in better mechanical properties, i.e., higher tensile strength and modulus and higher flexural stiffness in treated sisal fibre composites. Among those chemical treatment methods, AT (Alkali- Treated) + HT (Heat-Treated) treatment seemed to have the best effect in improving flexural stiffness.

3. Mechanical properties of natural fibre composites

The mechanical properties of a material are important benchmarks to evaluate its capability to be used in civil structures. The bending, compressive and tensile behaviours are the most studied properties in the research of composite materials.

3.1. Sisal fibre as reinforcement in polymers

Ramesh, Palanikumar [33] fabricated hybrid fibre composites – polyester reinforced by sisal fibre, jute fibre and glass fibre, and evaluated their mechanical properties such as tensile strength, flexural strength, and impact strength. It is found that the sisal and jute fibres can support glass fibres as reinforcement for polyester and improved its flexural and tensile strength. SEM results also revealed that the breakage occurred in the sisal/jute fibres.

Short sisal fibres were used by Antich, Vazquez [34] to reinforce high impact polystyrene (HIPS) mechanical tests such as tensile and fracture tests were carried out on the composite samples. In the uniaxial tensile test, it was found that for

25% sisal volume, the composite showed an increase in young's modulus (from 1.91 GPa to 2.51GPa), but a decrease in the tensile strength (from 21.66 MPa to 11.52 MPa) and elongation break rate (3.96% to 0.76%). On the other hand, the composite's impact strength decreased from 2.97 kJ/m2 (0% sisal) to 1.67 kJ/m2 (25% sisal). Through morphologic study, the decrease in mechanical properties is observed to be caused by poor adhesion between HIPS matrix and sisal fibre, and therefore the restriction of matrix yielding.

Milanese, Cioffi [35] fabricated woven sisal fabrics/phenolic resin composites using compression moulding and tested its tensile and flexural strength. Experimental results showed that with the introduction of sisal fibre, the phenolic resin's tensile strength increased from 4.9 MPa to 25.2 MPa, with the elongation yield from 0.14% to 7.9%. This demonstrates the change that the material experienced, from brittle to ductile. In the flexural experiment, the phenolic resin's flexural strength increased from 8.6 MPa to 10.7 MPa (sisal without heat treatment), and 11.2 MPa (heat treated sisal), with the deflection increased from 3.0 mm to 14.0 mm and 17.5 mm, respectively.

Belaadi, Bezazi [25] studied the fatigue property of sisal fibre reinforced polyester bio-composite. The samples were fabricated to create fibre directions laminates with [0/90] sequence. Three-point bending static and cyclic tests (frequency 1.5 Hz) were carried out in the study. The results revealed that failure occurred after the first few cycles for high loading levels, while for low loading levels, variance fracture is partial even after 1 million cycles.

Towo and Ansell [36] used 0.06 M NaOH to treat sisal fibres which were used to reinforce polyester and epoxy resins in hot press to fabricate two different composite samples. Fatigue tensile tests under loading levels of 75%, 60%, 50% and 35% were performed to evaluate the fatigue behaviours of the thermoset-sisal fibre composites. The results revealed that epoxy matrix composite had a longer fatigue life than polyester matrix composite. DMTA results showed that the composite's glass transition temperature (Tg) was lowered after the NaOH treatment of sisal fibres. Static tensile test results showed an improvement on both polyester and epoxy matrix composites after the NaOH treatment. It was concluded that the sisal fibre-thermosets composite's fatigue strengths are suitably high for many commercial applications.

3.2. Parameters effecting the mechanical properties of natural fibre composites.

There are many factors that need to be considered to fabricate composites meeting specified physical, mechanical, thermal or acoustic properties. Many researchers have attempted to study the effects of these parameters on the outcome of the fabricated composite samples.

The mechanical properties of sisal fibre reinforced high-density polyethylene (HDPE) composite were studied by Zhao, Li [37]. The critical parameters such as fibre content, interfacial compatibilization and manufacturing process were evaluated. The increment of fibre content and maleic anhydride grafted HDPE (MAPE) which has a better interfacial compatibilization was found to improve the composite's mechanical properties. A pre-impregnation process with compatibilizer MAPE is found to be better than the simultaneous blending. Meanwhile, the general Power-Law equation fits the composite's creep curve quite well and can predict the composite's creep behaviour.

Megiatto, Silva [38] studied the optimized process parameters for manufacturing thermoset phenolic composites reinforced with sisal fibres. The criterion is to control the vaporization of water release during the curing reaction of thermosets. The results showed that higher pressure before the phenolic matrix's gel point leads to a composite with higher performance. SEM images revealed there is less void in the matrix with the application of higher melding pressure during curing. Meanwhile a better filling of fibre channels reduced the water molecules diffusion.

Fung, Xing [39] applied a pre-impregnation technique for the injection moulding of sisal fibre reinforced polypropylene composites. Through thermal analysis, it is found that the composite can be processed at a lower barrel temperature after pre-impregnation treatment, and a significant thermal degradation of sisal fibre can be avoided. This process also resulted in lighter colour and no odour.

Sangthong, Pongprayoon [40] modified sisal fibres using poly(methyl methacrylate, MMA) film's admi cellar polymerization on the fibre surface to improve the interfacial connection between sisal fibres and the unsaturated polyester matrix. The composite's mechanical properties such as tensile strength/modulus, flexural strength/modulus, impact strength and stiffness were tested and compared under different MMA portion. It is observed generally that the composite's mechanical property increased alongside the increment of MMA amount, and the best mechanical properties is obtained at 30 vol% sisal fibre and MMA amount of 0.075% v/v. SEM results on the fracture surface also showed that the bonding is stronger after MMA treatment compared to the untreated fibres, and the failure tend to occur due to fibre breakage rather than interfacial debonding.

3.3. Compressive strength of walls with natural fibres

Many innovations on building materials using some form of natural fibres or recyclable materials have been widely experimented. This includes the incorporation of natural fibres as reinforcements or fillers in panels and walls as part of an effort to promote sustainability in the construction industry. The compressive strength of these structures needs to be thoroughly evaluated before they can be promoted for commercial use. These types of study have been undertaken by a few researchers.

First and foremost, it can be highlighted that the construction industry continuously seeks for improved building materials that are superior in performance but are cost optimized. La Rosa, Recca [41] have studied the environmental impacts of composite materials for building applications. Their aim was to manufacture materials with good structural properties, low environmental impacts and low thermal conductivity. The study suggests that materials with low thermal transmittance uses less material for wall construction, but the environmental impacts evaluated in the manufacture phase is highly influenced by the type of material used than on their weight. Less material means lighter walls and roofs which are easy to install and can reduce construction cycle time by one to four weeks. However, the environmental impacts are very high due to the epoxy resin used but minor energy is required both for material transportation and installation. Therefore, one of the ways to produce lighter materials is by incorporating natural fibres or agricultural waste into the fabrication of building materials. Natural fibres are known to have good strength-to-weight ratio and this may produce lighter materials with satisfactory mechanical properties.

Wu, Bai [42] have introduced a new type of building block using shale and waste as raw materials. These fired hollow blocks were tested for their mechanical and insulating properties. It was found that the strength grade of the block and special mortar meet the strength requirement of materials used in the construction of bearing wall. It was also observed that the failure mechanism of the walls showed ductile behaviour, satisfying the deformation condition and seismic capacity of building requirements. The authors concluded that the blocks from green materials are possible substitutes to the traditional ones currently in use today.

The hazardous use of asbestos has pushed researchers and engineers to find safer alternatives for this material in the building industry. Lertwattanaruk and Suntijitto [43] have suggested the use of natural fiber cement sheets as an alternative, offering the increase in value of reused materials from agricultural manufacturing. The study was performed using cement mortar containing coconut coir fiber and oil palm fiber, fabricated into cement sheets. From the experiments, the results yielded comparable effects in the physical and thermal properties. The natural fibre cement sheets was found to have increase in apparent porosity and a decrease in bulk density. With the addition of fibres soil-the mix proportions, the composite showed lower compressive and flexural strength. However, the values obtained was still acceptable by ASTM standards for fiber cement sheet and roofing.

Another study was performed by Khedari, Watsanasathaporn [44] on soil-cement block, whereby coconut fibres were introduced into the mixture. The special requirement was to maintain the block's natural colour; therefore, a preliminary study was conducted to determine the maximum percentage of cement that could be used without leading to a significant colour change. However, it was found that the compressive strength of the composite was only 3.88 MPa. This is considered low, and it was suggested that the blocks could only be used to build non-load bearing concrete masonry units (2.45 MPa) as they could not support loads from floors and roof.

Benmansour, Agoudjil [19] have studied the possibility of using natural mortar reinforced with date palm fibres as insulating materials in buildings. The same outcome was observed as previous literatures, whereby the increase in fiber content reduces the mechanical strength of the mortar. However, at low concentration of wood (5%, 10%, and 15%), the mechanical and thermal performance of the composites are found to be satisfactory as structural and bearing insulators.

4. Thermal conductivity

Thermal conductivity is the ability of a material to transfer heat. Its testing method is according to ASTM C518. Many research papers have highlighted that natural fibres can decrease a composite's thermal conductivity and therefore, they are a viable material to be used as an insulator in a building.

4.1. Thermal conductivity of natural fibre composites

There are a few methods that can be used to evaluate the thermal conductivity of a material. The common evaluation is by expressing the coefficient of thermal conductivity which is expressed as W/mK. Thermal conductivity is defined as the quantity of heat transmitted through a unit thickness of a material, in a direction normal to a surface of unit area, due to a unit temperature gradient under steady state conditions. This is mainly used to evaluate and compare how easily a material transfer heat; therefore, a higher thermal conductivity shows poor heat insulating property and vice versa. The K values for some materials are tabulated in Table .

Table 1 Coefficient of thermal conductivity of different materials

Material	Coefficient of Thermal Conductivity, K (W/mK)	Reference
Air	0.026	[45]
Sisal fibres	0.042	[46]
Glass fibres	0.038	[46]
Typha angustifolia fibre	0.137	[47]
Cured polyester resin	0.432	[47]
Typha angustifolia fibre-polyester composites	0.32 to 0.39	[47]
Bamboo fibre-polyester composites	0.185 to 0.211	[48]
Glass fibre-polyester composite	0.223	[48]
Borassus seed shoot fibre-polyester composite	0. 176 to 0.193	[49]
Coconut husk and bagasse insulation board	0.046 to 0.068	[50]
Coir based soil–cement block	0.651	[44]
Clay bricks	0.77	[51]
Glasswool	0.04	[51]
Concrete blocks	1.13	[51]
Plaster	0.50	[51]

To achieve the objective of this study, a low thermal conductivity of the developed materials is desirable. Many researchers have studied the thermal conductivity of a variety of materials and composites in order to obtain optimum energy saving from the use of proper materials to serve their intended use.

Liu, Takagi [45] had studied the effect of lumen (the hollow part of fibre bundle) size on the effective transverse thermal conductivity of unidirectional natural fibre composites. Through computer modelling, the unidirectional natural fibre composites are modeled as a two-dimensional square arrayed pipe filament (SAPF). Thermal-electrical analogy technique is used to evaluate the effective transverse thermal conductivity of this model composite. It was concluded that, amongst others, the dimensionless effective transverse thermal conductivity, K_t^+ of natural fibre composites are dependent on the geometrical ratio α, which is the ratio of lumen radius and fibre radius; the thermal conductivity ratio $\beta = K_f/K_m$ (where f and m represents fibre and matrix, respectively); and fibre volume fraction. Also, the lumen size ratio α affects the effective transverse thermal conductivity of natural fibres composites more greatly as compared to conventional fibre composites.

Further testing was performed by Liu, Takagi [52] on the effect of the microstructure of natural fibre on the transverse thermal conductivity of unidirectional epoxy composite reinforced with abaca and bamboo fibres using resin transfer molding (RTM) technique. The results indicated that the transverse thermal conductivity increased with increasing bamboo fibre but decreased with abaca fibres. In comparison to bamboo fibre, abaca fibre presents higher crystallinity in the directions of along and cross fibre. From the microstructure and theoretical analysis, it was found that the lumen structure plays a greater role rather than the crystal structures and chemical compounds on the transverse thermal conductivity of unidirectional composites. This information is useful for further development and design of natural fibre reinforced composites with better thermal insulation property.

A study by Ramanaiah, Ratna Prasad [47] on the thermal conductivity of typha angustifolia natural fibre reinforced polyester composites have found to decrease with increase in fibre content. The authors justified this behaviour of the composite due to the lower thermal conductivity of the fibre being loaded in the matrix. They confirmed that the values of thermal conductivities obtained from empirical models were in good agreement with the experimentally measured values. It was concluded that the composites under study have good insulating properties, suitable for applications such as electronic packages, insulation boards, automobile parts, building construction, and other uses.

The effect of the stalk particle size and the epoxy/corn stalk particle ratio on the thermal and mechanical properties of the composites prepared were evaluated by Binici, Aksogan [53]. These properties were compared with the commercially available bio-based insulation materials. The study suggested that it was possible to prepare bio-based composite materials with low heat transfer coefficients. The developed composites had thermal conductivity coefficients lower than 0.1 W/mK, meeting the requirement set by TS 805 EN 601 in order to qualify a material as a thermal insulator. The authors were very positive on the impact of this sustainable filler from organic origin, as farmers in rural areas can reuse this waste material for the preparation of commercially feasible and satisfactory insulation material which will finally lead to energy savings.

Wang and Qin [54] had studied the effects of interface or interphase on micro- and macro-thermal behaviours of square-pattern unidirectional fibre-reinforced composites. Interesting findings show that, for both V_f =10% and V_f =30%, the overall thermal property of the composite increases with the increase of interface thickness for carbon and glass fibres but decreases for hemp fibre. It was noted that the increase of interface thickness will increase the volume fraction of the fibre and interface region, significantly affecting the overall thermal property of the composite. For carbon and glass fibres, both interface and fibre materials have greater thermal conductivity than that of the matrix. Therefore, the increase in the volume fraction of the special element resulted in greater thermal conductivity of the composite. In contrast, for the hemp fibre, the increase in the volume fraction of the special element produces lower thermal conductivity of the composite because both interface and fibre materials have lower thermal conductivity than that of the matrix. This provides good explanation on why a higher fibre volume fraction can uncertainly result in either lower or higher effective thermal conductivity of the composite.

Fongang, Pemndje [55] utilized sawdust, a by-product from the wood industries, abundantly available in the tropical areas of the world, to produce low cost, ecological and sustainable lightweight composite for thermal insulation. The thermal conductivity of the sawdust is 0.10 ± 0.02 W/mK and possess lower energy thus inappropriate for the production of good pellets. The sawdust was successfully bound with metakaolin based geopolymer paste. The developed composite had a sponge-like structure with a homogeneously distributed pore network, low density and low thermal conductivity. The properties of the material obtained from the study include a density of approximately 0.79 g/cm^3, bi-axial four-point flexural strength of approximately 4 MPa and thermal conductivity between 0.2 and 0.3 W/mK. This classifies the geopolymer–wood fibre composites as promising clean and lightweight insulating materials. The movement of heat across the matrix indicated a “macro transport” mechanism based on the pores network and the microstructure approximated by a spatial periodic geometry. This mechanism involves the movement of heat through a multicomponent structure including thermo-diffusion and diffusional thermal effects.

It was reported by La Rosa, Recca [41] that it is important to select insulation materials with low thermal conductivity as it enables the application of relatively thin building envelopes with high thermal resistance (m^2 K/W) and low thermal transmittance U (W/m^{2}K). A study performed by Kumar and Suman [56] attempted to observe the behaviour of different insulation materials on conventional walls and roofs used in majority of the buildings. It was highlighted that conventional roof and wall sections have high overall thermal transmittance and by adding insulation in these sections, the U factor reduces. U value is also known as thermal transmittance which represents the rate of transfer of heat through a structure divided by the difference in temperature across that structure. This structure can be a single material or a composite. The U value is higher for a better-insulated structure [51]. Kumar and Suman [56] further explained the effect of the U-value of the materials. The authors found that with lower U-value, the cooling load of building will also be lower and vice-versa. Therefore, the load on mechanical systems will be lower for building sections with low U-value. The study uses guidelines from The Energy Conservation Building Code (ECBC) of India. Walls insulated by various materials with thickness that satisfies the U value as per ECBC was reported. Elastospray, PUF, EPS, Fibre glass and foam concrete required thickness of 50 mm, 60 mm, 70 mm, 80 mm and 150 mm, respectively, to satisfy the ECBC requirements. It was concluded that the results of their study could assist designers, architects, and engineers to design more energy efficient buildings satisfying the ECBC requirements.

4.2. Improvement of thermal properties of natural fibres

In comparison to synthetic fibres, natural fibres have shown less durability in high thermal exposure. Many efforts have been undertaken to improve the performance of natural fibre composites in this type of condition in order to expand its use for various applications.

According to Elenga, Djemia [57], raffia fibres treated with sodium hydroxide (NaOH) had shown higher resistance to thermal degradation. The test was performed using Thermo Gravimetric Analysis (TGA) and t was found that the thermal degradation onsets of the raw, 2.5%, 5%, and 10% NaOH-treated fibres were 256 °C, 272 °C, 278 °C, and 250 °C, respectively. The author explained that the effect of the alkali treatment based on its concentration on the fibre was basically due to the degree of removal of hemicellulose, which is the least stable of the three major constituents of the fibre. At a much higher NaOH concentration, which is at 10%, destabilization of the native cellulose may have decreased the thermal stability of the raffia fibres. Generally, the raw raffia fibre is considered to have a higher onset from the average value reported for plant fibres which is approximately 219 °C.

Apart from fibre treatment, the addition of additives into a composite system during fabrication process is also another method for increasing the thermal stability of natural fibre based composites. Shukor, Hassan [58] have used ammonium polyphosphate (APP) to provide flame retardancy and to increase thermal stability and mechanical properties of alkali treated kenaf fibre filled PLA biocomposites. All three properties were found to be significantly affected by the addition of APP. From the thermo gravimetric analysis (TGA), the increment of APP content demonstrated higher residual char of PLA composites at final temperature. However, this has compromised the mechanical properties of the composite due to the poor compatibility between fibre and PLA matrix. Overall, it was reported that the intumescent flame-retardant system containing treated kenaf and APP showed high efficiency in enhancing flame retardancy of PLA. It was also noted that alkali treatment increased the thermal stability of PLA biocomposites and decreased the residual char at high temperature.

Kabir, Wang [59] had also performed TGA on hemp fibres. The untreated hemp fibre started degrading at 200°C. Its hemicellulose and lignin degradation was reported at 270°C while the 4, 6, 8 and 10% NaOH treated fibres' were at 289, 287, 290 and 288°C, respectively. This indicates that the alkali treatment resulted in higher thermal stability of the fibre. The authors attributed this to the reduction in hemicelluloses and lignin content of the fibre, making it fore thermally stable. Furthermore, the removal of these components may have caused the fibres to become more hydrophobic and enhanced the better possibility to adhere with the matrix. The authors had also treated the same batch of untreated and treated hemp fibres with acetyl. Through this acetylation treatment, the fibres undergo further purification making them more thermally stable than the untreated and alkalized fibres, with higher degradation temperatures of lignin, hemicelluloses and cellulosic constituents for acetylated fibres. The weight loss variations as a function of temperature were also minimized after acetylation treatment.

A comparative study was performed by Lu and Oza [60] on hemp-high density polyethylene (HDPE) composites treated with silane and sodium hydroxide (NaOH). It was observed that the thermal stability of the composites improved drastically after fibre chemical modification using both methods. However, amongst the two methods, silane treatment outperforms NaOH treatment at the same fibre volume fractions. The author attributed this to the various type of reactions that occur at the surface of silane treated hemp fibre, such as hydrolysis, condensation, hydrogen bonding and covalent bond formation. The silanol molecules react with the hydroxyl group of hemp, resulting in formation of strong covalent bonds to the cell wall of the fibre. Simultaneously, the vinyl group of the silane molecule also couples with the thermoplastic matrix which resulted in increased physical compatibility and strength of bonding between the silane and the matrix. In short, the silane acts as a bridge, connecting and holding the fibre and matrix together. This in turn increases the thermal stability of the resultant composites.

The use of enzyme to improve the surface and thermal characterization of natural fibres have been undertaken by George, Mussone [61]. These enzymes have reportedly succeeded in removing the hygroscopic pectic and hemicellulose material producing a more homogenous fibre surfaces with improved thermal properties. From the SEM micrographs, the removal of these components resulted in an increase in individual bundle exposure. Also, in terms of the thermal stability of the natural fibres, the enzymetic treatment has selectively removed the least stable pectic and hemicellulosic content. Additionally, the authors found that the ultrastruture of flax fibres results in a more efficient enzymatic treatment compared to the hemp fibres making it a better option for reinforcing polymeric matrices.

Using sulfonic acid derivatives can also be effectively used to enhance the surface and thermal properties of natural fibres for composite applications. Another study by George, Mussone [62] using hemp fibres treated with this acid showed improved thermal properties and reduced surface polarity as a result of grafting of these acid residues that contain bulky benzene rings. These key observations were obtained by the production of a more tightly bonded rigid structure and capping of hydroxyl groups on the surface. One important finding from the study was that the substitution pattern on the benzene ring influences the effectiveness of the chemical during reaction with the surface hydroxyl groups of the fibre. In addition, less sterically hindered aniline-2-sulfonic acid treated fibres displayed better results when compared to 4-aminotoluene-3-sulfonic acid treated hemp fibres.

4.3. Thermal insulation of wall panels in building construction

One of the characteristics that need to be addressed for wall panels in buildings is its ability to provide good heat insulation for the comfort of its occupants. This means that the temperature inside the building can be controlled and maintained at a desired level without heat transfer occurring either from indoors to outdoors or vice versa. Stazi, Bonfigli [63] had studied some parameters involved in providing high thermal insulation in buildings. The study proposed a combination of dynamic strategies which includes daily natural ventilation, inner mass of wall, and vented external wall. It was found that this proposal ensures optimum summer comfort, winter and summer energy saving and a lower global cost despite the higher initial investment. So, in this section, literatures on the contribution of interior walls on the thermal insulation of buildings are reviewed and summarised.

A study on glass fibreboard used for interior building envelope was conducted by Cao, Liu [64]. It was reported that the effective thermal conductivity decreases with the increasing porosity at a near-linear rate. Their results were positive, showing that thermal conductivity of the glass fibre board is lower than normal insulation materials, therefore is suitable for use as interior building envelope insulation. The study was also conducted on internal floor of buildings. The energy consumption simulations of a typical residential building demonstrated that both the interior walls and the floor insulated with glass fibreboards resulted in reduced central heating energy consumptions. As for the effect of locations, in their case, Harbin and Beijing, the energy saving potentials with the interior wall insulation were slightly higher in Harbin than that in Beijing with the same insulation thickness. Conversely, the energy saving potentials with the floor insulation were similar for the two cities. Another important finding was that the potential of energy saving increased with thicker glass fibre insulation. However, the thickness should be reasonably controlled due to economical consideration. The author recommended a maximum insulation thickness of about 20 mm, for the energy savings increased slowly for thickness above 20 mm.

Another type of panels used for thermal insulation in the building construction industry is the Vacuum Insulation Panels, or simply known as VIPs Alam, Singh [65]. This high-performance thermal insulation has a large potential in reducing the CO_2 footprints of buildings (1.56 kg CO_2 m^{-2} a^{-1}) and in conforming to stringent energy standards. VIP is highly attractive due to its ability of using minimal existing space. However, the constraints for the adoption of VIPs are due to their disadvantages which include easily damaged during installation and development, uncertain useful lifetime, thermal bridging, and high cost. Researchers are conducted to improve the use of VIPs. One of the methods is by replacing conventional aluminium and metalized PET with PET multiple sheets coated with silicon. However, this will lead to higher VIP cost due to high market prices of fumed silica core material. To overcome this, the use of fumed silica–perlite composite as the core material for VIP was introduced. This, however, might result into some thermal resistance being sacrificed. Another potential for VIP improvement is my modifying open-celled polystyrene with a suitable filler material to provide low out gassing properties. The author noted that the challenge for using this method is to determine the best type, amount and distribution of filler material in the composite. These optimum conditions are required to achieve and maintain a suitable vacuum level inside the core to result in design thermal conductivity values with intended useful life of 100 years or more.

Other researchers have also tried to explore the possibility of using sustainable materials to provide insulation in buildings. Some have experimented with recycled materials while others have used natural fibres as reinforcement or fillers in composite materials. This was extensively reviewed by Asdrubali, D'Alessandro [66]. The authors shared that the current thermo-acoustic insulators dominating the market includes mineral wool, extruded and expanded polystyrene. Sustainable materials are needed to construct more environmentally friendly buildings. This includes using natural sources such as residues of agricultural production and processing industries as well as recycled products or industrial plants byproducts. The sustainability of these insulation materials are related to the availability of their components since the use of local materials lead to a reduction of economic and environmental impacts. The authors also emphasized that the production of insulators made of natural materials should be focused on using residues and byproducts of the agricultural sector instead of conflicting with the plantation and harvesting of food crops. By using these sustainable materials, it is expected to reduce the use of oil-based and non-renewable sources.

Wu, Bai [42] had introduced a new-type block using shale and waste as raw materials. The authors reported that the heat conductivity coefficient of the fabricated blocks obtained from the thermal test shows remarkable self-insulation characteristics of the wall. Lertwattanaruk and Suntijitto [43] studied the properties of natural fibre cement materials containing coconut coir and oil palm fibres for residential building applications. Based on the authors, these natural fibre cement sheets offer an alternative to products such as asbestos. These sheets could also increase the value of reused materials from agricultural manufacturing. Based on their results, natural fibre cement sheets made of cement mortar containing coconut coir fibre and oil palm fibre yielded comparable effects in terms of their physical and thermal properties. This was achieved by optimizing the heat insulation properties of the material whereby the content of coconut coir fibre or oil palm fibre were added up to 10% weight ratio to the binder. The fibre should also be treated in order to remove some chemical compounds such as inorganic compounds which may affect the quality and durability of cement products in the long term. They observed that the addition of coconut coir fibre and oil palm fibre into the mix proportion lowered the bulk density of the cement sheets and successfully reduced the material's thermal conductivity, which provided effective heat insulation. Furthermore, the heat conductivity was relatively low compared to other fibre cement sheets in the market. They concluded that the natural fibre cement sheets can be applied for both naturally ventilated and air-conditioned residential buildings for better energy efficiency.

A different type of insulated wall system was presented by Alavez-Ramirez, Chiñas-Castillo [67] which uses coconut fibre filled ferrocement on sandwich type wall panels. The coconut fibre is identified as an ecologically friendly and sustainable option to build roofs and panels in hot tropical weather. The study reported that as fibre loading content of coconut filled ferrocement panels is raised, thermal conductivity is reduced down to a certain limit. These panels showed good performance as insulating material for building in southern Mexico and are competitive with other materials such as lightweight concrete brick, hollow concrete block and red clay brick panel walls. Another study using coconut fibre was performed by Khedari, Watsanasathaporn [44]. In this study, the coconut fibre was used as an admixture on soil-cement blocks with the target of reducing the thermal conductivity and weight of the blocks. It was reported that he optimum volume ratio of soil:cement:sand and fibre weight (kg) is 5.75:1.25:2 and 0.8 kg coconut coir. The average properties of the natural fibre blocks show a thermal conductivity of 0.6510 W/m K, compressive strength of 3.88 MPa, mass of 4.85 kg and bulk density of 1586.77 kg/m^3. They compared these values to commercial soil–cement block and found that the samples had significantly lower thermal conductivity and mass, 54% and 750 g, respectively. The weight of coconut coir soil–cement is approximately 13% lower than commercial soil–cement block making them convenient to deliver. Additionally, the low thermal conductivity of the blocks will help to prevent heat transfer into building and consequently contributes to energy saving efforts. Benmansour, Agoudjil [19] have also introduced a more environmental friendly insulating material for building applications. Their study uses date palm fibres to reinforce natural mortar. From their observation, the increase of date palm fibre content has led to lower weight of the mortar composites. This was achieved by decreasing the overall density of the composites which results in higher insulating capacity of mortar. However, by increasing the fibre content of the composites, the mechanical properties were reduced. This requires an optimum fibre volume fraction to achieve a balance between the mechanical and thermal properties of the mortar composites. Based on their analysis, the authors found the optimum ratio of date palm fibres component to be in the range of 5–15%.

Chikhi, Agoudjil [20] developed a new bio-composite material as thermal insulators in buildings. The fibres used are from date palms. From their experimental investigations, the thermal conductivity increases with the introduction of date palm fibres. Additionally, it was found that the composite's compressive and flexural strength was improved by adding the optimum amount of fibre content. According to a research paper by Binici, Aksogan [68], natural fibre reinforced mud bricks had better thermal isolation and mechanical properties which was confirmed to ASTM and Turkish standards. The testing results showed a higher compressive strength and heat conductivity than concrete brick.

Korjenic, Petranek [69] used jute, flax, and hemp to develop a new insulating material for buildings. The thermal conductivity test results of the composite samples revealed that natural fibre composites are likely to become a suitable alternative to commonly used boards. Panyakaew and Fotios [50] made a low-density thermal insulation board from coconut husk and bagasse. It is found that the bagasse insulation board has a low density of 350 Kg/m3 and a thermal conductivity value from 0.046 to 0.068 W/mK and are comparable to cellulose fibres and mineral wool.

4.4. Effect of moisture on the thermal conductivity of materials

There are many factors that need to be considered for an insulating material to be considered feasible and usable for actual wall panels in building constructions. [66] had performed a life-cycle assessment (LCA) for unconventional sustainable building insulation materials. They concluded that there are still issues that need to be solved before a widespread use of these unconventional materials. One of their recommendations is to further investigate some properties such as durability fire resistance, water vapor diffusion, fungal resistance in particular for the best performing materials. These properties are already accounted for commercial insulation materials and in order to compete with them, newer sustainable materials must also confirm to these standards.

The thermal conductivity of composites is highly influenced by moisture absorption. Benmansour, Agoudjil [19] had observed a rapid increase of thermal conductivity with water absorption on their natural mortar reinforced with date palm fibers for building insulation. Alam, Singh [65] who studied the possible improvements of Vacuum Insulation Panels (VIPs) have highlighted the need of identifying newer adhesive materials, with low thermal conductivity and are chemically and physically stable under vacuum conditions and least outgas. The authors mentioned that among various components in the surrounding air, water vapour has the highest transmission rate and it permeates about 30,000 times faster than oxygen and nitrogen. Therefore, moisture is regarded as the major contributor to increasing pressure along with oxygen and nitrogen. Due to this, a better and newer class of super hydrophobic sealants and sealing processes needs to be developed to overcome the problem of permeation of moisture through the seal areas.

A comparative study was performed by Latif, Ciupala [70] on the hygrothermal performance of hemp and stone wool insulations in vapour open timber frame wall panels. Both composite samples showed identical thermal conductivity in identical hygrothermal boundary conditions. The U values for both samples had no significant different. However, both hemp and stone wool insulations were susceptible to mould spore germination, with stone wool facing higher risk of exposure. Similarly, the risk of interstitial condensation for stone wool insulation was also higher than hemp samples as shown by the frequency of the stone wool samples reaching 10% relative humidity. This implies the likelihood of frequent condensation in the Stone Wool-OSB interface. In comparison, the frequency and likelihood of occurrence of condensation seemed to be lower in Hemp-OSB interface. From this study, it can be observed that different filler materials provide different level of moisture exposure on the insulation materials.

5. Conclusion

Based on the results obtained from this study, it can be concluded that:

- The alkalization on the sisal fibres have provided different levels of treatment on the surface topography of the fibres. Rougher surface was observed on fibres treated from 2 to 6 wt.% NaOH. However, at 8 and 10 wt.% NaOH, significant deterioration was detected on the condition of the fibres, indicating that the concentration of alkali is too strong thus weakening the fibres.
- From the compressive test, it was observed that the addition of fibres to the gypsum matrix have improved its compressive strength and resulted in reduced brittleness.
- From the thermal conductivity study, pure gypsum was found to have the highest thermal conductivity. The thermal conductivity of the composites decreases with the increment of fibre volume fraction.
- Sisal fibre-gypsum composites performs slightly better at insulating heat as compared to glass fibre-gypsum composites possibly due to its porous nature, as heat transfer is impeded by the presence of air voids.
- From this literature review, in terms of mechanical and thermal insulating properties, it can be concluded that using sisal fibres as reinforcement on gypsum produces composites suitable for wall panelling in buildings.

Compliance with ethical standards

Disclosure of conflict of interest

All authors declare that they have no conflicts of interest.

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