NATURAL FIBRE COMPOSITE PANELS FOR THERMAL INSULATION OF BUILDINGS: A REVIEW

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Abstract

In this paper natural fibre composite panels were analysed, regarding their thermal performance. Four categories of vegetal fibres were assessed, namely bast fibres, seed fibres, leaf fibres, and fruit fibres. In total, 13 types of natural fibres were studied. In each category of fibres, the individual types were compared according to the values of the coefficient of thermal conductivity, the most performing fibres being highlighted. It was concluded that among the studied fibres cork, jute, kapok, pineapple leaves, tea leaves, and coconut husk are the most performing organic materials, being suitable to be used as thermal insulation materials.

Key words**:** *natural fibre, composite, thermal conductivity, sustainability*

INTRODUCTION

Sustainable production is one of the most serious issues today's industries are facing. In the area of building materials it is increasingly advisable the use of materials that are not dependent on non-renewable resources. Such materials might be formulated with natural fibres, which have a fast regeneration.

Natural fibres have several advantages, such as they are easily recycled and eliminated, with beneficial effects on health [1], and by using natural fibres the non-renewable natural resources are protected [8], plus, in some cases the agricultural waste materials are being reusedmn[16] Moreover, the fibres can be burned to recover heat [10], have low cost, low density and low energy consumption, are renewable, the fibres are not abrasive and do not cause skin irritation, they present low health risk, are biodegradable [17], highly available [24], do not emit toxic substances, are permeable, non-radioactive and are electrically neutral [5].

Besides these qualities, natural fibres and natural fibre composites have some disadvantages, including low fibre-matrix compatibility, reduced impact resistance, long-term stability of composites installed outdoor is also reduced [13], high risk of attack of microorganisms, the fibre quality should be monitored regularly, and the processes of harvesting, processing, manufacturing and use must be carried out with care [20].

According to [10], vegetal fibres can be divided in several classes, based on the portion of the plant that is used. Thereby, the following categories can be distinguished: seed fibres, leaf fibres, bast fibres, fruit fibres and stalk fibres. Seed fibres form around the seeds, leaf fibres can be obtained from leaves, bast fibres are found in the outer layer of the stem, fruit fibres surround the fruit of the plant or can be harvested from the fruit itself, and stalk fibres are collected from the stalk of the plant.

In this paper, natural fibre composite materials are assessed from the perspective of thermal performance, namely composite panels based on bast fibres, seed fibres, leaf fibres, and fruit fibres, respectively.

MATERIALS AND METHODS

This paper is based on the study of several scientific articles regarding the use and valorisation of natural fibres. The articles were selected according to various criteria, such as year of publication, number of citations, type of fibre that is studied, conducted experiments, and relevance of findings.

Each relevant article was analysed, and the main conclusions were synthesized.

In this paper two parameters of thermal performance are assessed: thermal conductivity (λ [W/m·K]) and thermal resistance (R [m2K/W]). Thermal conductivity is a parameter that measures a material's ability to conduct heat, a low value implies that the material is an excellent thermal insulator, which is to be desired in the field of construction materials.

Thermal resistance is inversely proportional with thermal conductivity and depends on the material's thickness, so in the field of thermal insulations a high value is seeked.

Bast fibre composite panels

Banana

The banana (Musa) is a tropical plant that has the aspect of a tree. The plant is grown in abundance in many countries (India, China, Philippines), and after harvesting its fruit, the plant becomes an agricultural waste.

Banana fibres show high compatibility with polymer matrices, so fibres are used as a reinforcement [17]. The density of banana fibres is 750-950 kg/m3, the water absorption is 60%, the fibre's Young's modulus is 23 GPa and its tensile strength is between 180-430 MPa [10].

Thermal insulating capacity of the bio-composite consisting of banana fibres and epoxy resin was investigated in [24], in accordance with the density of the specimen. The lowest λ-value was measured for the specimen with a density of 0.08 g/cm3, but in general, the value of thermal conductivity of the composite was not satisfactory for a thermal insulating material.

Thermal insulating foam from glass waste and banana leaves has acceptable thermal insulating properties [2].

These composites have a porosity between 58.5-87.5%, compressive strength between 1.17-3.50 MPa and thermal conductivity between 0.06-0.15 W/m·K.

Cork

The bark of the cork oak (*Quercus suber*), a tree characteristic of the Mediterranean area, is the source of cork grains. Cork has interesting properties, such as impermeability to gases or liquids, low weight, low burning rate, durability or thermal and sound insulation [33]. Because of these properties, cork is being used in many applications, such as in the composition of composite materials based on polyester [34], gypsum [11], or cement, and in the manufacture of insulating panels (Fig.1.) [14].

Fig.1. Insulation boards made of cork
Source: [14].

The λ-value of cork is approximately 0.045 W/m·K. The density of insulation boards ranges between 110-170 kg/m3 [31], [12]. The influence of cork powder on the insulating properties of phenolic foam-based composites was studied by [22]. The best λ-value was obtained for the sample with 1% cork, the value being 0.0294 W/m·K.

Flax

Flax (*Linum usitatissimum*) is a plant cultivated in colder regions of the Earth and it is valorised in the food and textile industries. Due to the high mechanical strength of flax fibres, these are being used more often in the field of constructions. The fibres are characterized by porosity and elasticity, being suitable to be used as thermal insulation and impact sound insulation [29]. Among several natural fibres, for example hemp and jute, flax fibres could successfully be used to replace glass fibres in various composites, when considering the cost, mechanical performance and yield of the fibres [37]. The density of flax fibres is 1.4-1.5 g/cm^3, their modulus of elasticity is 27.6 GPa, and the tensile strength is around 850-1,500 MPa [35].

The porous structure of flax fibres consists an advantage if they are being used as thermal insulation. In respect of the thermal conductivity values of the fibres, it varies between 0.035-0.046 W/m·K, depending on the material's density, which can have values of 20-100 kg/m^3 [20]. These values are comparable with those of conventional thermal insulating materials.

Hemp

Industrial hemp (*Cannabis sativa*) is a plant whith a reduced content of psychoactive substances, and it can be cultivated efficiently due to its tolerance towards drought. Different parts of the plant can be harnessed, the exterior bast fibres, the interior wooden part, or its seeds. In the field of construction materials, both hemp fibres and particles can be mixed with different binders, such as lime, clay, starch or sapropel, in order to obtain insulating materials or masonry elements. The density of hemp fibre is 1.48 g/cm^3, its modulus of elasticity is 70 GPa, and its tensile strength is 52 MPa, respectively [35].

Long term studies, carried out by [25], concerning a building with walls made of hemp-lime composite, show that this material has an excellent capacity to regulate indoor temperature and humidity. In a similar way, hemp particles bonded with wheat starch, studied by [9], contribute to the regulation of indoor humidity. Moreover, this composite has a λ-value between 0.06-0.07 W/m·K, for densities ranging between 126-143 kg/m3. The value of the thermal conductivity coefficient of lime-hemp samples varies between 0.0899-0.1408 W/m·K, this value being dependent on particle size, particle concentration, and sample density [5]. For a different type of composite material, consisting of sapropel and hemp [4], thermal conductivity has values between 0.059-0.073 W/m·K.

Thermal properties of hemp-based composites are influenced by a series of external parameters. The value of thermal conductivity is negatively influenced by the aging of the composite [6]. An almost linear increase of thermal conductivity is registered for an increase of humidity content of the material [15].

Jute

Jute (*Corchorus*) is cultivated especially in Asia, it can reach a height of 1-4 m and it is produced in large quantities. The fibres are collected from the outer layer of the plant, having a wide range of utilization. The density of jute fibre is 1.3-1.45 g/cm3, their modulus of elasticity is between 13-26.5 GPa, and the tensile strength has a value of 51 MPa [35]. Due to the high availability of fibres, studies were performed regarding the capacity of fibres to form composite materials, applicable in the field of insulating materials.

From the perspective of a thermal insulation, jute felts in different combinations with polyester fibres have a good behaviour. The λ-value ranges between 0.019-0.025 W/m·K, for a density of 461-592 kg/m3 [38]. Concerning the values of thermal conductivity of commercially available materials, their value ranges between 0.038-0.055 W/m·K, and their density is of 35-100 kg/m3 [29].

Kenaf

Kenaf plant (*Hibiscus cannabinus L.*, Fig.2.) is cultivated mainly for its fibres. The fibres are obtained from the exterior layers of the plant. They have properties comparable to those of other fibres (namely jute fibers) and are mainly used to manufacture different products. Tensile strength and flexural strength of jute fibers have high values [28]. The density of kenaf fibres is 1.4 g/cm^3, their modulus of elasticity is 30.8 GPa, and the tensile strength has a value of 1019 MPa, respectively [35].

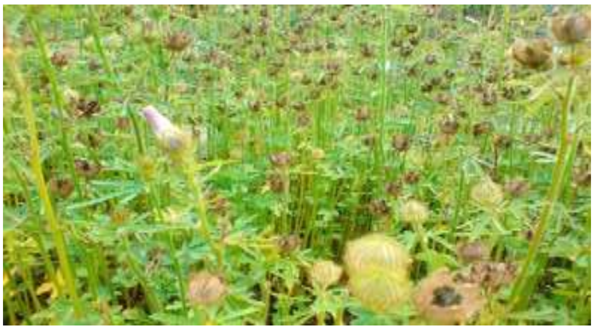

Fig.2. Kenaf plant
Source: [23].

Thermal conductivity of kenaf fibres is between 0.034-0.069 W/m·K, depending on the humidity content of the fibre, and their density has a value of 21.2 kg/m3 [12]. The incorporation of kenaf fibres in the formation of a cement-based composite could improve the thermal resistance of the material [40]. The incorporation of fibres in a clayey matrix influences in a positive way the mechanical performance and λ-value of specimens, an increased fibre length determining a more reduced λ-value [21]. The properties of a particleboard made from the core of the plant were studied by [36]. These boards had good mechanical strength and dimensional stability in contrast with their reduced density (0.15-0.20 g/cm^3), and the value of their thermal conductivity was similar with that of mineral wool (0.051-0.058 W/m·K).

Seed fibre composite panels

Cotton

The cotton plant (*Gossypium*) has the appearance of a shrub and it is typically found in tropical and subtropical climates. The cotton fibre, which is composed almost entirely of cellulose, grows surrounding the seeds of the shrub and it is put to use mainly in the field of textile manufacturing. The density of the fibres is 1.5-1.6 g/cm^3 and their Young's modulus is between 5.5-12.6 GPa [35]. In the field of construction materials studies were performed regarding the valorisation of cotton wastes, namely the fibres and the plant itself.

Fig.3. Cotton waste fibers
Source: [8].

The influence of cotton fibre wastes (Fig.3.) in the composition of multi-layered particleboards was investigated in [8]. It was found that using cotton wastes has a positive influence on the performance of the particleboard, obtaining a construction material with reduced weight and thermal conductivity of 2.2 W/m·K. In a cement matrix, cotton wastes contribute to decrease of thermal conductivity, without significantly reducing mechanical strength, the resulting blocks being suitable for masonry units [7].

The valorisation of cotton stalk as a thermal insulation material was studied by [41]. The particleboards were produced without binder by hot pressing. The density of the boards ranges between 150-450 kg/m^3. The λ-value of boards varies between 0.0585-0.0815 W/m·K, a comparable value with that of other thermal insulating materials, such as perlite. These board could be applied on walls or ceilings in sight of energy saving.

Kapok

The kapok tree (*Ceiba pentandra*) is characteristic of tropical areas. The tree seeds are wrapped in silky, cotton like fibres. Kapok fibres with a hollow structure, are characterized by high buoyancy and can be used in the composition of various composite materials, with thermal insulation and sound absorbing purposes [39].

The value of thermal conductivity of the individual fibres is 0.035 W/m·K [1]. Investigation of bio-composite materials made from sodium silicate and kapok fibres was carried out in [1]. The thermal conductivity coefficient of the material was 0.022 W/m·K. It has been observed that the λ-value of the fibres decreases with the addition of other types of fibres (sugarcane pulp or coconut husk fibres).

Leaf fibre composite panels

Pineapple leaves

The pineapple plant (*Ananas comosus*) is cultivated in tropical areas mainly for its fruit. One can easily obtain some fibres usable in many fields from the leaves of the plant. The fibres (Fig. 4) are smooth, white, have a medium length and a high tensile strength. On the other hand, fibres are hygroscopic, requiring chemical modification before use [3]. The density of pineapple fibres is 0.8-1.6 g/cm^3, the Young's modulus of the fibre is 1.44 GPa and its tensile strength i
s between 400-627 MPa [13].

Fig.4. Pineapple leaf fibres
Source: [3].

The value of thermal conductivity coefficient of an agglomerated panel prepared from pineapple fibres and natural rubber was determined in [32]. For densities of 178-232 kg/m^3, the conductivity value varies between 0.035-0.043 W/m·K. The best results were obtained for a fibre/binder ratio of 1/3.

Sisal

Sisal (*Agave sisalana*) is a plant cultivated in tropical areas. The fibres extracted from the plant's leaves are resistant, and are mostly used for making strings, clothing or paper. Sisal fibre density is about 700-800 kg/m^3, the water absorption amounts to 56%, the modulus of elasticity of the fibres is 15 GPa, with a tensile strength around 268 MPa [10]. It was also proposed to use these fibres in the field of constructions, with thermal and sound-insulating role.

The possibility of using sisal fibres as a thermal insulating material has been studied by [26].

The value of thermal conductivity of binderless specimens varies according to the nature of the fibres, treated or untreated. So for the untreated fibres the λ-value is 0.042 W/m·K, and for the treated fibres this value is 0.044 W/m·K.

Similar results were obtained by [30], where a composite material based on epoxy resin and sisal fibres was investigated. Untreated fibres had a better insulation capacity than treated ones, the thermal performance increasing with the increase of the fibre percentage, but the use of untreated fibres is not recommended due to mechanical reasons.

Tea leaves

The tea plant (*Camellia sinensis*) is grown for its leaves. The by-product of leaf processing has been the subject of research to exploit this waste.

The value of thermal conductivity of tea leaves was measured by [18]. It has been found that the λ-value is influenced by several factors: moisture content, density and temperature. According to these parameters, the value of thermal conductivity of tea leaves varies between 0.035-0.568 W/m·K for densities of 236-330 kg/m^3.

Fruit fibre composite panels

Beet

Beet (*Beta vulgaris* subsp. *vulgaris* var. *altissima*) is a plant cultivated for the production of sugar.

The remaining pulp after plant processing is valorized in the agricultural, food and cosmetic industries, and as a sorbent for heavy metals [19].

a) b)

Fig.5. Extruded beet pulp granules (a) and the prepared composite (b)
Source: [19].

Bio-composite based on extruded pulp granules and potato starch (Fig.5.) was assessed from the perspective of thermal and acoustic insulation by [19].

The best results were obtained for the sample with the minimum amount of binder, as the porosity positively influences the two properties considered.

The maximum acoustic absorption value was 0.72 for the 4,000 Hz frequency band, and for the medium frequencies, this value was 0.6. The thermal conductivity was between 0.069-0.075 W/m·K, a value which is similar to that of other bio-composites, with the value of density of the extruded granules being 1073.4 kg/m^3.

Coconut

Coconut palm (*Cocos nucifera*) is a tropical coastal tree. The fibres are obtained from the outer bark of the ripe nut, called mesocarp.

The coconut fibre density is between 145-380 kg/m^3, the water absorption is 130-180%, the fibre's elastic modulus is 19-26 GPa, and the tensile strength is between 120-200 MPa [10]. The λ-value of coconut fibre-based materials is satisfactory. Composite panels made of coconut fibres and polyester fibres can achieve a thermal conductivity values between 0.0279-0.0495 W/m·K [16], the panels being made by the felting method. Regarding the coconut fibre panels made by hot-pressing without the addition of fibres or resins, thermal conductivity varies between 0.046-0.068 W/m·K and density between 250-350 kg/m^3 [27].

RESULTS AND DISCUSSIONS

With regard to the thermal properties, a comparison of the presented solutions of bast fibre composites is made in Table 1. The lowest thermal conductivity values (below 0.030 W/m·K) were measured for a cork powder reinforced phenolic foam [22] and for a jute felt [38].

Table 1. Summary of thermal properties of the studied bast fibres

Bast fibre	Density [kg/m^3]	Thermal conductivity [W/m·K]	Thermal resistance [m^{2}K/W]	Ref.
Banana	310-1030	0.06-0.15	-	[2]
Cork	111.7	0.058-0.070	-	[12]
	110-170	0.037-0.050	-	[29]
	100-300	0.045	-	[31]
	34.8-36.0	0.0294-0.0415	-	[22]
Flax	5-50	0.038-0.075	-	[20]
	20-100	0.035-0.045	-	[20]
Hemp	210-410	0.059-0.073	-	[4]
	126-143	0.0738-0.0634	-	[9]
	369-611	0.0899-0.1408	-	[5]
	212-248	0.0775-0.0915	-	[5]
Jute	35-100	0.038-0.055	-	[29]
	461-592	0.019-0.025	0.20-0.35	[38]
Kenaf	21.2	0.034-0.069	-	[12]
	150-200	0.051-0.058	-	[36]

Source: authors' synthesis based on the studied literature mentioned in the table.

In order to analyse the thermal performance of the seed insulation composites an overview was realized in Table 2, where a summary of the thermal properties of the assessed different fibre panels is showed. From the perspective of thermal conductivity, the kapok fibre and sodium silicate composite [1] has the lowest λ-value.

Table 2. Summary of thermal properties of the studied seed fibres

Seed fibre	Density [kg/m^3]	Thermal conductivity [W/m·K]	Ref.
Cotton	-	2.2	[8]
	740-799	0.267-0.302	[7]
	150-450	0.0585-0.0815	[41]
Kapok	1.173-1.415	0.0106-0.0220	[1]
	-	0.035	[1]

Source: authors' synthesis based on the studied literature mentioned in the table.

From the category of leaf fibres three types of composite panels were reviewed. Table 3 aims to provide a schematic presentation of the thermal properties, obtained in the mentioned studies. Regarding the thermal conductivity, the lowest value obtained was 0.035 W/m·K, registered for an agglomerated panel prepared from pineapple fibres and natural rubber [32] and tea leaves [18], respectively.

Table 3. Summary of thermal properties of the studied leaf fibres

Leaf fibre	Density [kg/m^3]	Thermal conductivity [W/m·K]	Ref.
Pineapple leaves	178-232	0.035-0.043	[32]
Sisal	700-800	-	[10]
	-	0.042-0.044	[26]
Tea leaves	236-330	0.035-0.568	[18]

Source: authors' synthesis based on the studied literature mentioned in the table.

Table 4. Summary of thermal properties of the studied fruit fibres

Fruit fibre	Density [kg/m^3]	Thermal conductivity [W/m·K]	Ref.
Beet	≈1222	0.069-0.075	[19]
Coconut	250-350	0.046-0.068	[27]
	-	0.0279-0.0495	[16]

Source: authors' synthesis based on the studied literature mentioned in the table.

The thermal performance of different composite materials based on fruit fibres is presented in Table 4. Coconut fibres are characterized by low thermal conductivity, for a composite panel made of coconut fibres and polyester fibres [16] its value being around 0.030 W/m·K.

CONCLUSIONS

Thus, on the basis of thermal properties it can be concluded, that there are several natural fibre composites that are suitable for use as a thermal insulation material. Among the studied fibres cork, jute, kapok, pineapple leaves, tea leaves, and coconut husk are the most performing organic materials.

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