

Flax and hemp fibres as raw materials for thermal insulations

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Abstract

Bast fibres of, for example, flax and hemp are used as raw materials of thermal insulations. However, they have only a minor share in the market. The aim of this paper was to evaluate the suitability of bast fibres of flax and hemp for thermal insulations. The functions and requirements of the bast fibrous insulations and their combustion resistance are discussed. Thermal conductivity and the effects of several parameters on thermal performance are reviewed. The potential and costs of the raw material and quality and ecological aspects are also discussed. Finally, needs for future research is proposed.

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1. Introduction

Flax (*Linum usitatissimum* L.) and hemp (*Cannabis Sativa* L.) are annual bast fibre plants, the stems of which consist of surface layers, a bark layer with 20–50 bast fibre bundles, and a woody core with a central lumen. Bast fibres are used as raw materials of thermal insulations. The sawdust-like shive that is produced from the core of the stems has been used as a thermal insulation at least in old buildings. However, this review concentrates mainly on the bast fibres. There is increasing interest in ecological values and renewable materials, and products are increasingly chosen on the basis of their quality merits, including environmental quality [1]. The use of natural fibres in insulation is closely linked to the ecological building sector [2], where selection of materials is based on factors including recyclable, renewable raw materials and low-resource production techniques. Furthermore, cellulosic insulations have a higher moisture regain than inorganic materials, and therefore only cellulosic materials are recommended for old timbered houses [3,4]. Tow of flax and hemp fibres has traditionally been used in insulation tapes between timbers, but during the past decade several

types of mats and loose-fill insulations have been developed into commercial products. Loose-fill insulations and insulation sheets of different thickness are also produced for insulation of modern houses. Despite their historical background, flax and hemp insulations are often considered as new materials in the field of insulations.

In 2001, France and Germany were the biggest producers of hemp insulations in Europe, where approximately 1500 ha of hemp were grown for this purpose. Bast fibre insulations nowadays represent only a very minor part of the insulation market throughout Europe (e.g. <0.5% in Germany) [5]. One reason for the relatively low utilisation is the approximately two-fold higher price of bast fibre insulations compared to, for example, the price of mineral wool. On the other hand, typical positive, although not always approved arguments for these insulations are their ecological properties, e.g. low energy demand in production, potential for recycling and positive effect on indoor air [5,6]. Examples of list prices of thermal insulations are presented in Table 1. However, the prices should be regarded only as tentative, because they vary in different countries and even within one country, and in many cases bulk discounts are given.

Considerable data is available concerning the technical properties of conventional insulations, whereas data for cellulosic insulations has typically been given only for cellulose as a generic material [7,8] or for specific types of

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Table 1
Variation ranges of list prices of a packet (2.95–5.65 m²) of 100 mm thick thermal insulation sheet

Fibre raw material of insulation	Price (eur/m ²)	
	Oct. 2005, in various Finnish shops [99]	Feb. 2007, corrected from [99] with the building cost index (6.4% increase per year)
Flax	9.90–14.20	10.80–15.40
Glass	5.00–8.00	5.40–8.70
Stone	4.50–7.30	4.90–7.90
Cellulose (wood fibre)	8.60–10.80	9.30–11.80

cellulosic materials such as wood or recycled paper [9–11]. However, the thermal performance of bast fibres has been investigated and confirmed generally as competitive with conventional insulations in some studies [2,12–14]. The aim of this paper is to evaluate the suitability of bast fibres of flax and hemp for thermal insulations.

2. Flax and hemp fibres as raw material for thermal insulations

2.1. Requirements of the insulations, especially bast fibrous insulations

The criteria or functions and quality properties of insulations are regulated by legislation, for which several internationally applicable standards have been developed [11]. The criteria are also directed by environmental labels and declarations, based mainly on the life-cycle approach [15]. The quality parameters affecting the thermal conductivity of bast fibrous insulations are discussed in the following section. A European quality mark “Natureplus” has been developed for building materials in Germany [16]. The aim of this mark is to guarantee both technical and ecological performance for several building materials, including thermal insulations made from flax and hemp. Numerous criteria and measurements of both the raw materials and the insulation are required for obtaining this quality mark. These criteria include, for example, declaration of input materials, requirements for renewable raw materials, energy consumption of manufacturing and packaging, and information on processing. Furthermore, restrictions of impurities and atypical fibres, pesticide residues, and emissions of VOCs and formaldehyde are given. In principle, the “Natureplus” mark offers a good collection of criteria that well define different features of the insulations.

2.2. Thermal performance

Bast fibres, which are in fact fibre bundles, each contain 10–40 single cells or elementary fibres. A single stem includes 20–50 fibre bundles. The elementary fibres (single cells) of flax and hemp consist of layers and there is a

lumen inside the cell [17,18]. The porous structure of the bast fibres makes them suitable for thermal insulations. The thermal conductivity of insulations made of bast fibres is compatible with that of conventional insulations. However, the variation between the k values of all insulations varies, e.g. in relation to bulk density (Table 2). The relationship between density and k is not linear and it varies between different studies. Bast fibres can fulfil the main function of the insulation because of their porous structure and the low bulk density of the fibre conglomerate, leading to trapping of a large amount of air between the fibres in the insulation.

2.3. Combustion resistance

Fire resistance is an important property of thermal insulations, especially those made of cellulosic fibres. Due to their chemical composition, cellulosic materials themselves are not fire resistant. A mass fraction of approximately 20% of chemicals is added to cellulose to provide flame retardance [19]. In a study by Kokkala [20], smouldering was a risk of cellulose insulation compared to glass wool. In a study by Kauriinvaha et al. [14], the fire resistance of flax insulations was similar to that of insulations made of recycled paper, and a mass fraction of 13% of boric compounds was needed in the flax and paper insulations to prevent smouldering. In insulations made from hemp shives, smouldering occurred even with a mass fraction of 25% of boric compounds, due to presence of large shive ships.

3. Discussion

3.1. Potential and cost of the raw material

Flax and hemp can be grown in temperate climates and they require relatively low input to give high yields [21]. Flax ranges in height from 0.4 to 1.5 m [18] and hemp from 1.2 to 5 m [22]. By breeding, different varieties of flax have been developed for production of fibre and oilseed. As can be seen in Fig. 1, the growing areas of flax and fibre hemp are nowadays small compared to the 19th and early 20th centuries [23,24]. In Europe, approximately 327,000 ha of linseed, 323,000 ha of flax and 29,000 ha of fibre hemp were cultivated in 2004, with an increase in recent years. The worldwide growing area of the oil seed plant linseed is greater than the growing areas of the fibre plants flax and hemp. The main production areas of linseed are the Far East and Canada [25]. The bast fibre plants offer one alternative to agricultural production, where the need to find non-food plants as alternatives for food plants is under discussion. The yield of bast fibres of flax was approximately 600–900 kg/ha and of hemp approximately 1050 kg/ha in a study by Pasila [26]. However, the amount of separated fibre, from many European domestic sources is low compared to the potential needs of production.

Table 2
Variation ranges of thermal conductivity k (or λ) of fibrous thermal insulations at different variation ranges of densities

Type of insulation	Fibre raw material	Bulk density (kg/m ³)	k (or λ) (W/m K)	References
—	Flax	—	0.040–0.046	[12]
Mat	Flax	5–50	0.038–0.075	[13]
—	Flax	20–100	0.035–0.045	[51]
—	Flax and hemp	25–40	0.050	[2]
Mat	Flax and hemp	39	0.033	[14]
Mat	Flax and hemp	19	0.060	[14]
Mat	Hemp, retted	5–50	0.040–0.082	[13]
Mat	Hemp, green	5–50	0.044–0.094	[13]
Loose-fill	Hemp, frost-retted	25–100	0.040–0.049	[14]
—	Hemp	20–45	0.040–0.060	[51]
—	Glass wool	20–50	<0.040	[2]
—	Glass wool	18–50	0.050	[52]
Mat	Stone wool (mineral wool)	5–50	0.035–0.071	[13]
—	Stone wool (mineral wool)	15–300	0.037–0.050	[53]
—	Stone wool	30–60	0.050	[52]
—	Cellulose	30–45	0.041–0.050	[53]
Loose-fill	Cellulose (recycled paper)	30	0.041	[54]
—	Cellulose (wood fibre)	30–60	0.050	[52]

—, not provided.

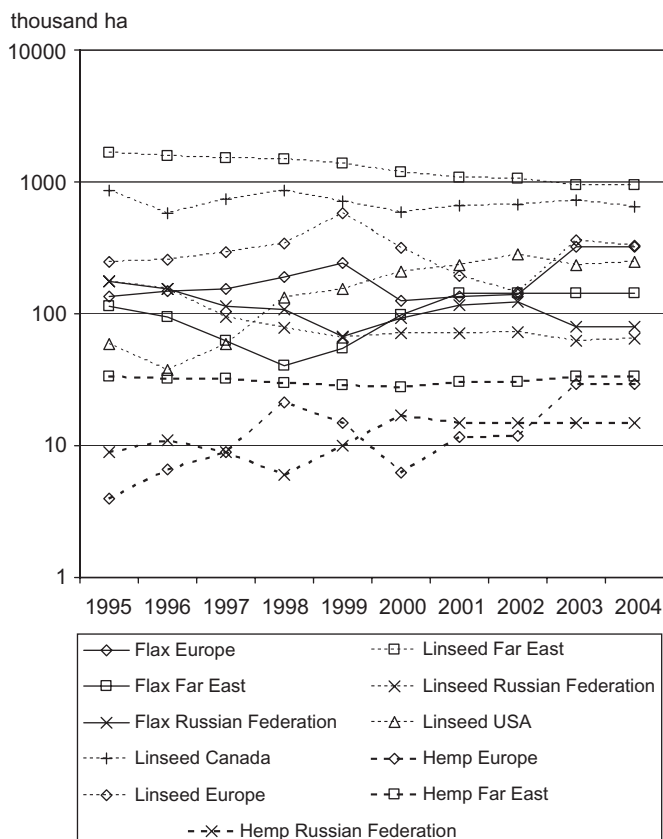


Fig. 1. Harvested areas of flax, linseed and fibre hemp in Europe, the Russian Federation, the Far East, Canada and USA in 1995–2004 (thousand ha). Area data of linseed for Russia and a few minor producing countries relate to crops grown for both seed and fibre. Data of flax and hemp refer generally to scutched and hackled fibre and include tow [25].

In order to obtain the bast fibre, the structure of the plant leads to a need for special separation techniques based on mechanical, biochemical and microbiological

methods. The cost of the fibre used for insulation must be relatively low, which makes the use of many of the retting methods uneconomical [27]. Properties of unretted fibres have been investigated in order to obtain alternatives for retted fibres, the disadvantages of which are, microbiological contamination and costs caused by retting [28–30]. There are clear differences between fibres retted in different harvest times [27]. The agricultural background affects the logistics of the production of insulations. Harvesting takes place once a year, after which the stems are stored and processed. The total yield of fibres should last for the production of the whole year before the next harvesting.

3.2. Quality

The typical quality properties of the bast fibres (Tables 3 and 4) are related to the morphological structure and chemical composition (Table 5) of the plant fractions used as raw materials for insulations. As can be seen in Table 5, the literature concerning these matters is complex and the dimension and composition data have been derived from several sources.

Theoretically, variation of these plant features during the growing season or as a consequence of retting, fractionation or alternation of atmospheric conditions affects the functions of the insulation (Table 6). However, only a few studies are available (Table 7) concerning the relationship between the quality variation of bast fibres and properties of insulations. Furthermore, as can be seen in Table 6, the typical quality measures (Tables 4 and 5) are insufficient to define the quality of those fibres used for thermal insulations: for example, the effect of moisture on microbiological quality must be taken into consideration. In regions where there is marked variation in outdoor temperature and relative humidity of air during the year,

Table 3
Examples of quality properties of bast fibre of *Linum* (referring to long or short fibres and fibre bundles or elementary fibre cells)

Quality property	References
Chemical composition, caustic loss, DP, fluidity	[55–62]
Ash	[56]
Moisture absorption	[61,63]
Strength, tenacity, elongation	[55,56,58–69]
Fineness	[55,56,58,59,61,64–67,69,70]
Bulk density	[61,64]
Dimensions (i.e. length, diameter), amount and morphology of fibre bundles and individual fibrils	[14,55,56,59,60,62,64–66,69,71]
Microbiological resistance	[61]
Freedom from impurities (other parts of stem than fibre), fibre freeness, shive content	[14,29,58,59,62,65,72,73]
Homogeneity	[70]
Colour, lustre	[66,67]

Table 4
Examples of quality properties of bast fibre of hemp (may refer to fibre bundles or elementary fibre cells)

Quality property	References
Chemical composition, DP	[60,74]
Strength, tenacity, elongation	[29,60,75]
Fineness	[29]
Dimensions (i.e. length, diameter), amount and morphology of fibre bundles and individual fibrils	[29,60,75]
Freedom from impurities	[29]
Evenness, quality of retting	[76]

the moisture content of the stems or of the raw material produced from the plants is one of the most critical factors for achieving materials of acceptable quality [27]. Unless the stems are collected dry enough to prevent microbial action, further deterioration may occur during storage [76]. Moisture reduces the thermal performance of any thermal insulation, causing altered dimensions and chemical composition by removing constituents [31] and possibly moulding in humid conditions [32–34]. Moulding may lead to emissions to air [35], which is further promoted by drying of the moist, moulded insulation.

The variation of length, shown in the present study, may allow the fibres to settle evenly in the insulation [27], thus decreasing air permeability. The thermal conductivity of inorganic insulators increases when their moisture content increases [36] and we can argue the same for cellulosic insulations, leading to reduced thermal performance. In a study by Hansen and Bunch-Nielsen [37], the capillarity of glass and rock wool insulations was relatively low. Correspondingly, in a study by Kauriinvaha et al. [14], the capillarity of bast fibrous insulations was two- to nine-fold that of mineral wool, measured with a similar method as in the present study. Synthetic binders may not be biodegradable, and they will probably be prohibited in the

“Natureplus” quality mark [38]. Resistance to microbes is also required in the “Natureplus” quality mark [39,40]. This will evidently lead to the need to use a great amount of additives in the insulation, because there is a natural microbial flora in bast fibres [41], bast fibres themselves are not resistant to microbes [32,34,35] and the use of organic binders, e.g. starch, increases the nutrient level of the insulation and thus promotes moulding.

In addition to microbes, flax has been found to contain other contaminants, e.g. endotoxins [42]. These are lipopolysaccharides that have strong biological effects in humans [43]. However, in a study by Breum et al. [44] endotoxin exposure varied greatly between two commercial flax insulations, in one case being similar to other fibrous materials and in the other significantly higher. The VOC emissions of thermal insulations made of flax and hemp fibres were rather similar to those of inorganic insulations in a study by Koivula et al. [35].

3.3. Ecological aspects

Ecological information during the life-cycle of the insulation includes ecological indicators, i.e., renewable or non-renewable energy sources and resources, and emissions to water, air and soil [45]. In addition, operative tasks affecting the ecological performance include packaging, installation, recycling and disposal of the product [19,38,46]. Thermal insulations based on agro-based fibres are often considered implicitly as ecological, which has been evaluated to be their most important competitive advantage [47]. The ecological image is also seen in the nomenclature used for organic insulations, i.e., biological [48,49], biogenic [13], alternative [5,24] and eco-insulations [24]. However, only a few studies have focused on the ecological performance of insulations, and their results are not unambiguous. In a study by Behring and Murphy [50] using life-cycle assessment, an insulation based on flax fibre was ranked more ecological compared to glass wool when energy demands and environmental emissions were included in the calculations. In their study, the primary energy consumption was calculated to be 1077 MJ/m³ for glass wool and 511 MJ/m³ for flax insulation. As an example of emissions, the CO₂ emissions were calculated to be 68 g/m³ for glass wool and 43 g/m³ for flax in their study. On the other hand, in a study by Schmidt et al. [49] paper wool had the lowest and flax the highest global and regional environmental impacts, with stone wool in between. In their study, these impacts were also derived from life-cycle assessment and included, for example, global warming, acidification, eutrophication, photooxidation creation potential, toxicological impacts in the working environment and impacts on local ecosystems. The total energy consumption was 18 MJ/kg stone wool, 21 MJ/kg paper wool and 40 MJ/kg flax insulation. The CO₂ emissions were 1200 g/kg stone wool, 629 g/kg paper wool and 1700 g/kg flax insulation. The life-cycle studies give tentative results, but due to several different

Table 5
The main chemical components of the stem, fibre and shive of *Linum* and fibre hemp (%) (% refers to mass fractions)

Component	<i>Linum</i>				Fibre hemp			References
	Stem, mature	Fibre, unretted	Fibre, retted	Shive	Stem*	Fibre**	Shive	
Cellulose	—	63	71	—	—	—	—	[77]
	—	—	65	—	—	—	—	[18]
	—	57	64	—	—	67	—	[78]
	60	—	—	—	—	—	—	[23]
	—	—	—	40–46	—	—	—	[79]
	—	—	—	36–47	—	60–67	40–52	[80]
	—	—	—	—	Approx. 59–67	—	—	[81]
Lignin	—	3	2	—	—	—	—	[77]
	—	3	3	—	—	4	—	[18]
	—	3	2	—	—	3	—	[78]
	—	2–5***	—	—	—	—	—	[57]
	27	—	—	—	—	—	—	[23]
	—	—	—	23–28	—	—	—	[79]
	—	—	—	24–30	—	3–14	22–30	[82]
—	—	—	—	Approx. 54–62	—	—	[81]	
Hemi-cellulose	—	17	19	—	—	—	—	[77]
	—	—	16	—	—	—	—	[18]
	—	15	17	—	—	16	—	[78]
	—	—	—	25–26	—	—	—	[79]
Pectin	7	—	—	—	—	—	—	[23]
	—	4.2	2.0	—	—	—	—	[77]
	—	—	3.0	—	—	—	—	[18]
	—	3.8	1.8	—	—	1.0	—	[78]
Fat and wax	3.0	—	—	—	—	—	—	[23]
	—	1.4	1.7	—	—	—	—	[77]
	—	—	1.5	—	—	—	—	[18]
	—	1.3	1.5	—	—	0.7	—	[78]
	—	—	—	1.2–1.3	—	—	—	[79]
	—	—	—	0.5–1.6 ****	—	—	0.5–1.0****	[26]
—	—	—	0.5–0.8 *****	—	—	0.3–1.4*****	[26]	

—, not provided.

*The variation interval refers to the change of chemical composition due to changes in the maturity of the stem.

**For hemp, there is no available separate data for unretted and retted fibre.

***Depends on the retting degree.

****Spring harvested.

*****Autumn harvested.

assumptions in the models (e.g. exclusions of the model, energy sources, cultivation methods, etc.) there is no simple way to interpret their results. Concerning the environmental impacts of thermal insulations, on the other hand, it has been argued that the use of thermal insulations implicitly yields environmental benefits because of the saving of heating energy in buildings [9]. According to Schmidt et al. [49], insulations will save over one hundred times the impacts from production and disposal, irrespectively of the material used.

Information concerning materials is sometimes presented as an ecological parameter, i.e., the material content of recovered (recycled) [19] or renewable material [38]. Use of some input materials may be limited or not permitted and records to provide proof of origin of the flax and hemp raw material must be kept, in the “Natureplus” mark [38]. For example, a typical hemp insulation mat contains

approximately 15% synthetic fibres [5]. In the “Natur-eplus” mark, the proportion of renewable raw materials must be at least 85%, and the use of synthetic support fibre up to a maximum of 15% until the end of 2005, after which the use of synthetic fibre may be prohibited. After 2005, a declaration of use of pesticides must be provided [38].

3.4. Development potential and needs for research in the future

The present paper focuses on technical properties of fibres. However, when focusing on the choice of insulations for buildings, the attractiveness of different types of insulations for purchasers is a key issue for the success of insulations on the market. In addition to technical performance of the insulations, several quality properties

Table 6
Functions of fibrous insulations

Type of function*	Meaning of function	Examples of typical functions of insulations	Examples of quality parameters affecting the function
Main function	Purpose for which the product is primarily suited	Thermal performance (minimization of heat transfer)	Material of fibre, dimensions, amount of shive, density or fineness, EMC, capillarity, temperature cycling
Secondary functions	Secondary purpose of the insulation	Fire performance Strength of insulation sheets Suitability of fibre for technological production	Material of fibre, flame retardants, density, amount of shive Material of fibre, dimensions, density Material of fibre, impurities, dimensions, EMC, capillarity
Supportive functions	Increases the value of the insulation but not essential for the main function	Ecological performance (e.g. biodegradability, energy savings) Ability to promote good indoor air Attractiveness for purchasers and customer satisfaction	Material of fibre, binders, additives, energy consumption during production, emissions of production, long term stability of the insulation Material of fibre, additives, dimensions, hygienic quality, EMC, capillarity, endotoxins, construction of the building Material (appearance, ecological image) of fibre, retting degree, hygienic quality, shive content
Stability of main, secondary and supportive functions	Resistance to atmospheric and environmental stress	Maintenance of any quality feature of the insulation	Material of fibre, retting degree, MC, temperature, microbes

*Modified from the ideas of Berglund [83,84] and Lucie-Smith [85].

Table 7
Studies concerning the effects of various parameters on thermal properties of some fibrous insulations

Parameters affecting thermal performance	Studied insulation material	References
Type of material (e.g. constituents, retting time)	Flax, hemp Various plants, wood Recycled paper	[12,14] [86] [14]
Thickness, density*	Flax, hemp Cellulose Various plants and wood Glass and stone wool	[2,14] [87] [86] [2,87,88]
Settling (loose-fill insulations)*	Wood Glass and stone wool	[31] [89,90]
RH and/or temperature of air, free water, wetting, drying	Flax, hemp Cellulose Straw Glass and stone wool	[13,14] [91,92] [92] [13,36,91,93–96]
Air flow (i.e. infiltration, wind, convection**)	Cellulose Glass wool	[97] [95,96–98]

*Settling of loose-fill insulation and thickness of insulation are different views of the same phenomenon, i.e. amount and density of insulation.

**Convection is caused by temperature differences, and there may be connections with the previous row “RH and/or temperature of air ...”.

affecting its practical functions also affect its success on the market via, ecological image and appearance (Table 6).

To avoid the possible negative effects of moulding, increase of additives, reduction of the nutrition level of the bast fibres or restriction of RH below 80% is needed [27]. In order to develop realistic practical applications, more research concerning practical technological solutions to these aspects is needed. To overcome the risk factors, quality control must be adopted for the whole production chain of bast fibres.

4. Conclusions

The bast fibres of flax and hemp are suitable for insulations due to their thermal properties and some ecological features, i.e., biodegradability. However, bast fibres as a natural resource have a risk for microbial and other contaminants, and their quality should be monitored regularly. Careful procedures during harvesting, processing, manufacturing, building and maintenance of buildings are required in order to avoid the risk of negative effects (i.e. moulding) caused by moisture and free water. Furthermore, product development of bast-fibrous thermal insulations and the use of additives are evidently needed in order to avoid negative effects on indoor air quality.

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