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B. Grohe

Heat conductivities of insulation mats based on water glass bonded non-textile hemp or flax fibres

Abstract Heat insulation mats based on water glass bonded non-textile flax and hemp fibres were fabricated via a pilot plant, and their heat conductivities investigated. Under the influence of various factors like moisture content, water sorption and diffusion processes, fibre characteristics and heat radiation as well as thickness and apparent density, heat conductivities in the range of 0.0392–0.0484 W/mK for flax fibre mats and 0.0441–0.0592 W/mK for hemp fibre mats were obtained. Strong interactions between the fibre characteristics on the one hand and the water sorption and diffusion processes, the heat radiation, the apparent density and the thickness on the other hand were found. Investigations of tensile strengths and dimension stabilities indicate that the isolation mats are easy to handle and a structural alteration of an overall construction will not occur.

Wärmeleitfähigkeiten von Dämmstoffmatten basierend auf wasserglasgebundenen nichttextilen Hanf- oder Flachsfasern

Zusammenfassung Wärme-Dämmstoffmatten, basierend auf wasserglasgebundenen, nichttextilen Flachs- und Hanffasern, wurden über eine Technikumanlage hergestellt und deren Wärmeleitfähigkeiten untersucht. Unter dem Einfluss verschiedener Faktoren wie Feuchtegehalt, Wassersorptions- und Diffusionsprozesse, Fasereigenschaften und Wärmestrahlung sowie Dicke und Rohdichte wurden Wärmeleitfähigkeiten im Bereich von 0.0392–0.0484 W/mK für Flachsfasermatten und 0.0441–0.0592 W/mK für Hanffasermatten erhalten. Es wurden starke Wechselwirkungen zwischen den Fasereigenschaften auf der einen Seite und den Wassersorptions- und Diffusionsprozessen, der Wärmestrahlung, der Rohdichte und der Dicke andererseits gefunden. Untersuchungen der Zugfestigkeit und Formbeständigkeit zeigen, dass die Isolationsmatten einfach zu handhaben sind und eine bauliche Veränderung einer Gesamtkonstruktion nicht auftreten wird.

1 Introduction

For applications in the area of heat insulation materials technical non-textile hemp and flax fibres are particularly suitable. The coarse fibres, which are commonly used only for non-wovens or as filler, provide low bulk densities and high tensile strengths, for slightly stiff mats (Bobeth 1993; Kozlowski 2000). Moreover, the lower costs for their manufacturing compared to natural textile fibres have to be considered as well. The employment of such fibres for heat insulation mats demands an adhesive, which binds the material at possibly all fibre contact points after compacting the material to the open structured end products. This is warranted by using water glass, which is able to wet nearly the complete fibre surfaces (Scheiding 2001).

But the main claim for an efficient isolation in buildings is the application of materials having possible low heat conductivities. The transport of the heat, respective the heat forward resistance, depends on a multitude of parameters. Primarily, the thickness and density of insulation mats (Caps et al. 1990; Scheiding 2000), the fraction of fibres and binder, the fineness and the surface profile of the materials, the fibre orientation in the mats (Hell 1982; Caps et al. 1990; Scheiding 2000), the moisture content of the mats and the tendency of materials to adsorb water (Kisseloff 1969) but also the scattering- and absorption characteristic of the mat materials concerning heat radiation (Caps et al. 1990) affect the properties of the heat forward resistance. After all, the composition and the fabrication process for such insulation mats have to be optimized regarding to the fibre quality, the thickness, the apparent density, the moisture content of the materials and the binder.

B. Grohe (✉)
Fachhochschule Pirmasens,
Carl-Schurz-Straße 1–9, 66953 Pirmasens, Germany
e-mail: bgrohe@web.de

Present address:
B. Grohe, 17 Mohawk Road, London, Ontario N6G 2P6, Canada

Within the scope of a research project first results of measured heat conductivities in dependence on influencing factors like the fibre characteristics, the apparent density etc. are given for different kinds of insulation mats.

2 Materials and methods

2.1 Fibre materials and chemicals

Harvested and field retted hemp and flax crop were further processed by cutting and milling (hammer mill) the straw as well as separating (drum separator) the material to technical, non-textile fibres and shiver, by MBR Agrar Service, Montabaur, Germany. The fibre material, which contains residuals of shiver (HSC), was used for the fabrication of the insulation mats or reprocessed again. The reprocessing-line (Stummer Konstruktion GmbH & Co. KG, Wiebelsheim, Germany) consists of a disk opener, rotating sieves and a screen (works by a stream of air) to achieve finer fibres and to lower the fractions of shiver and dust drastically. The reprocessed fibres (LSC) were employed for the manufacturing of insulation mats as well. For control, hemp and flax fibres of the quality HSC respective LSC (5 charges of each grade; each 250 g) were oven-dried for 24 h at 105°C, leading to mass losses by water for hemp fibres between 8.8–11.5 wt.% and for flax fibres in the range of 8–10.8 wt.%. The measured moisture content of the material depends on the given uncontrolled relative humidity (rH%) and the fibre-quality (fraction of the shiver).

As an adhesive a diluted water glass solution was prepared by adding 50 vol. % water to the received viscous water glass (Betol 39T1, 36 wt.% solids in water, pH=11.3, Woellner Silikat GmbH, Ludwigshafen, Germany) leading to 18 wt.% solids in water (pH~11).

2.2 Insulation mat processing

The fabrication of the insulation mats was accomplished via a pilot plant, which was set up and provided by the FH Kaiserslautern, Germany with the collaboration of MBR Agrar Service, Montabaur, Germany and Erlenbach GmbH, Lautert, Germany. Figure 1 shows a draft of the pilot plant and the production of the insulation mats. The fabrication steps of the mats are in the sequence: deposition of a fluffily fleece (thickness: 40–50 mm), spraying the upper fleece-side with water glass, drying (~150°C, hot-air stream) and turn over of the fleece, spraying the reverse fleece-side with water glass, pressing the fleece via a pressure roller, drying the fleece (150°C), calibration of the fleece-thickness by another pressure roller, cutting the fleece lengthwise and in cross direction by rotating cutters having finally single fleeces (1000×625×~12 mm), pile up the single fleeces (4–12 pieces) to mats and spraying them with water glass, pre-pressing of the mats, calibration of the end-thickness via a belt press and, simultaneously, end-drying of the mats by an hot air stream (120°C; containing CO_2). For comparison purposes LSC-flax and hemp were deposited by hand to insulation mats. For some of these mats the water glass-adhesive was used.

2.3 Verifying the heat conductivity and related properties

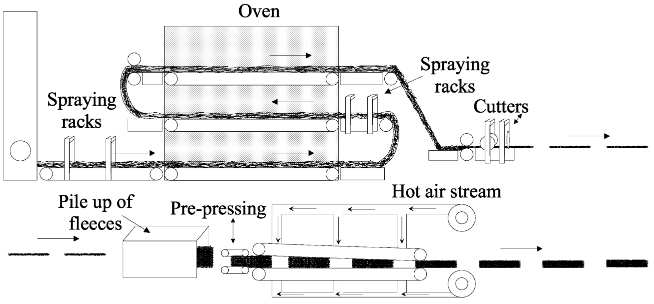

Fig. 1 Draft of the pilot plant for the fabrication of insulation mats based on water glass bonded hemp or flax fibres. The steps of the mat fabrication process are described in Sect. 2.2
Abb. 1 Skizze der Technikumsanlage für die Herstellung von Dämmstoffmatten basierend auf Wasserglas gebundenen Hanf- oder Flachsfasern. Die Schritte des Mattenherstellungsprozesses sind in Kap. 2.2 beschrieben

Heat insulation characteristics of fabricated mats were determined according to DIN 52612 and 68755-1, which demands that the heat conductivity has to be investigated via the so-called two-plate set-up. During the test procedures, which were carried out by a TLP900-H system (Taurus Daten und Messtechnik GmbH, Weimar, Germany) the average heat conductivity—or the heat forward resistance—of two plate-like samples was measured. For each kind of insulation mat three measurements were accomplished for dry samples (dried at 105°C, rH%<10% until mass constancy) and for moist samples (stored at 23°C, rH%=80% until mass constancy), respectively. Finally, a classification in categories of heat conductivity groups were performed via the consideration of the heat conductivities of the samples in the dry and the moist state (DIN 68755-1). In addition, the mass differences between dry and moist insulation mats and their apparent densities were measured according to DIN 52620 and DIN EN 1602, respectively.

2.4 Properties of tensile strength and dimensional stability

In some cases the tensile strength (DIN EN 1608) and the dimensional stability of insulation mats were verified (stored at 80°C, rH%=80% until mass constancy; DIN 18165-1).

3 Results and discussion

3.1 Heat conductivity

For applications as isolation material, the classification into possibly low heat conductivity classes (HCC) is the most important criterion for the insulation mats. The value of a given HCC depends on the heat conductivity of a dry sample and the difference of the heat conductivities for this sample in the dry and moist state (see Sect. 2.3). The lower the measured value of the heat conductivity for a dry sample is and the smaller the difference is between the heat conductivities of a sample in the dry and moist state the more likely is the classification in a lower level of these HCC. In Table 1 the heat insulation characteristics as well as the composition of the materials, the moisture contents, the thickness and the apparent densities for different insulation mats are given.

3.1.1 The effect of the moisture content

At first, the influence of the moisture content (U_m) of insulation mats on the HCC will be investigated. For specimens without any binder addition, the lowest amount of moisture was measured for the flax fibre-samples MBR042 and MBR043 and for the hemp fibre-sample

Table 1 Composition, moisture content, thickness, apparent density and heat isolation characteristics of different insulation mats based on water glass bonded flax or hemp fibers. The listed data are average values of respective three measured samples

Tabelle 1 Zusammensetzung, Feuchtegehalt, Rohdichte und Wärmeisolationseigenschaften von verschiedenen Dämmstoffmatten basierend auf wasserglasgebundenen Flachs- oder Hanffasern. Die aufgelisteten Daten sind Durchschnittswerte von jeweils drei gemessenen Proben

Sample	Composite of the material			Moisture content [U_m], thickness [T], apparent density [d], and heat conductivity [λ] for dry—moist conditions							HCC[f]
	Specification[a]	Fractions of materials		Moisture content[c]	Dry[d]			Moist[e]			
		Fibres [wt.%]	*WG*[b] [wt.%]	U_m [wt.%]	T [mm]	d [g/cm^3]	λ [W/mK]	T [mm]	d [g/cm^3]	λ [W/mK]	
MBR043	Flax; LSC, DbH	100	–	14.40	56	52.07	0.0397	60	55.60	0.0412	45
MBR042	Flax; LSC, DbH	100	–	14.24	48	40.72	0.0426	50	48.46	0.0444	45
MBR047	Flax; LSC, DbH	75	25	14.63	36	91.11	0.0409	40	94.00	0.0472	50
MBR053	Flax; LSC, DbPL	77–79	21–23	24.58	43	60.78	0.0392	50	65.88	0.0484	50
MBR062	Flax; LSC, DbPL	77–79	21–23	21.71	45	74.93	0.0424	50	82.08	0.0472	50
MBR054	Hemp; LSC, DbH	100	–	14.45	77	44.03	0.0441	86	45.12	0.0515	55
MBR046	Hemp; LSC, DbH	77–79	21–23	18.99	50	72.88	0.0459	51	85.02	0.0556	60
MBR033	Hemp; HSC, DbPL	77–79	21–23	19.54	81	82.88	0.0443	88	91.20	0.0592	60
MBR044	Hemp; HSC, DbPL	77–79	21–23	26.54	75	69.52	0.0464	81	81.46	0.0563	60
MBR045	Hemp; HSC, DbPL	77–79	21–23	24.15	70	69.91	0.0464	70	86.80	0.0540	60
MBR069	Flax; LSC, DbPL	79–81	19–21	22.80	43	80.74	0.0414	47	89.53	0.0451	50

[a] HSC: high shive-content; LSC: low shive-content; DbH: deposited by hand; DbPL: deposited by production line
[b] WG: solid water glass (adhesive)
[c] Apparent moisture: mass difference between the dried and the moist insulation mat, according DIN 52620
[d] Measured after drying at 105°C and a relative humidity <10%, according DIN 52612
[e] Measured after conditioning at 23°C and a relative humidity of 80%, according DIN 52612
[f] Heat conductivity class, according DIN 52612, DIN 68755

MBR054; all with low amounts of shiver (LSC). Whereas the moisture content of these samples is all about the same (~14.36 wt.%) there is a big difference for the determined HCC. For the flax fibre samples a HCC-level of 45 and for the hemp fibre-sample mats a HCC of 55 was found. On the other hand, considering the water glass bonded flax-samples MBR047/053/062/069, which are all classified into the HCC 50, the U_m varies between 14.63 wt.% for MBR0047 and in the range of 21.71–24.58 wt.% for the samples MBR053/062/069. Also the analysis of the water glass bonded hemp-samples MBR033/044/045/046 (all grouped into the HCC 60) results in a wide range of moisture contents between 19–26.5 wt.%. As there are samples either featured by nearly the same U_m but different HCC or samples indicated with the same HCC but having different U_m the moisture content cannot be a decisive factor in affecting the HCC. These results are consistent with those of Scheiding (2000) who measured the heat conduction of different heat insulation materials by keeping the moisture content of the samples constant. Although the moisture content U_m is not a crucial factor it is assured, however, that the heat conductivity depends on the moisture if one compares the properties of heat conductivities for dry and moist samples. One explanation for this behavior is possible via the consideration of the respectively used materials, their tendency to adsorb water and, in particular, how the transport of heat through fleece-like compounds is affected, by more or less moist materials.

3.1.2 The consequences of changing fibre characteristics

Comparing the samples MBR062 and MBR046 differences are only present regarding the used fibre-materials and the measured heat conductivities, if one neglects U_m. Neither the amount of binder nor the apparent densities and thickness of the samples show any big differences for dry and moist states. But, using flax instead of hemp leads to a decreased HCC by a factor of 10. For this reason, specific characteristics of fibres like the surface- and internal profile as well as the number density of fibre contact points are assumed to be influencing factors in contributing to the heat conduction of the materials. Fibre-specific different water sorption and diffusion processes lead to locally different properties of the heat conduction along and through the material (closed pores, tubes etc.). Here, the heat transfer by water molecules results in a heat conduction, which is accelerated if high number densities of water molecules are present and a pronounced forward motion (diffusion) of the molecules from warm to cold regions is given (Kisseloff 1969). Figure 2 shows scanning electron micrographs of (a) hemp and (b) flax fibres. It is obvious that flax materials are provided with smoother surfaces and lower amounts of open pores compared to hemp fibres. In addition, investigations of the water sorption behavior of both fibre types resulted in lower amounts of adsorbed water for flax fibres (Koch 1955; Bobeth 1993). It was found that, besides the surface profile, a lower number of cavities, closed pores and internal tubes are responsible for this behavior (Kymäläinen et al. 2001). After all, in the presence of hemp fibres the contribution to heat transport by watersorption- and diffusion

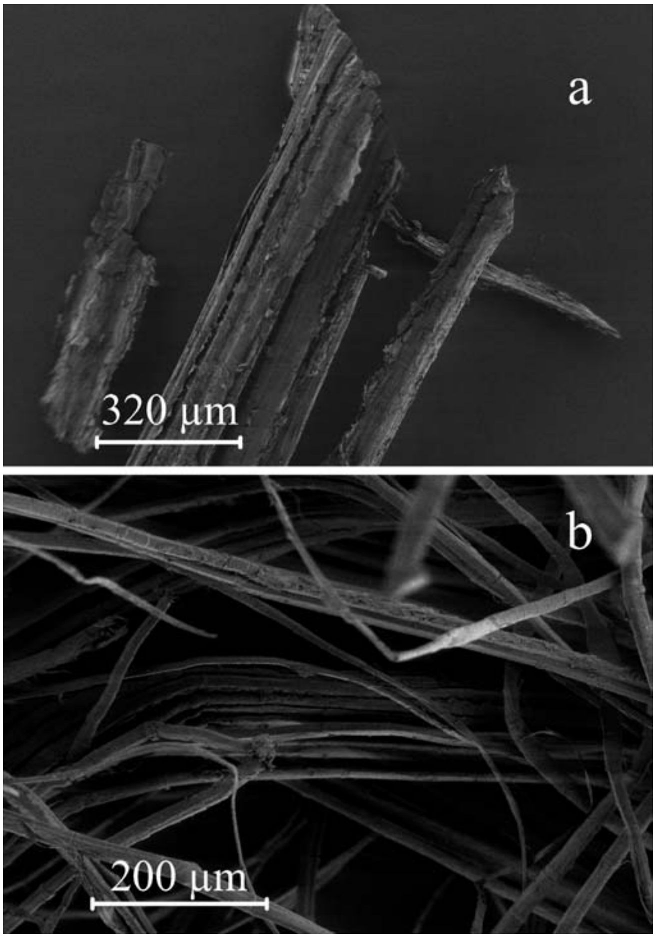

Fig. 2a,b Scanning electron micrographs of non-textile **a** hemp and **b** flax fibres used for the fabrication of insulation mats
Abb. 2a,b Rasterelektronenmikroskopie Aufnahmen von nichttextilen **a** Hanf- und **b** Flachsfasern, die für die Herstellung der Dämmstoffmatten verwendet wurden

processes should exceed the contribution to heat transport by these processes if flax fibers are present.

But, for this consideration, neither the heat conduction through fibre-materials in dry states nor the heat radiation has to be disregarded. Concerning the heat transport through dry fibres, however, relatively small values are expected. According to Martin et al. 1987 and Schardt et al. 1993 appropriate values for the heat conduction through flax and hemp fibres should be approximately 0.5% of the overall heat conduction. In contrast, the contribution of the heat radiation to the overall heat conduction is primarily influenced by the fibre content per volume unit. During the transport of the heat from the warm to the cold side of the isolation material the heat radiation is permanently scattered, absorbed and emitted at the more or less moist fibre-binder-structure. Therefore, the flow rate of the heat radiation is affected by the mean-free-path of the radiation between successive scattering-, absorption- and emission events. The larger the mean-free-path is—or more descriptive the more open-pored the fleece material is—the higher is the rate of the heat radiation (Hell 1982; Caps et al. 1990). As the flax fibres have smaller cross-sections and a higher specific surface and, as they are more flexible then hemp fibres, more fibre material is present per volume unit (see Fig. 2). Therefore, the flux of the heat radiation is more limited by using flax instead of hemp, which in turn leads to a lower contribution to heat conductivities and HCC by using flax fibres. The discussion shows that the present data do not allow a separate consideration of the heat conductivities. But for these superimposed processes an estimate of the total contribution to heat conduction can occur via the differences of the heat conductivities for the dry and moist states. Here, for the samples MBR062 (flax) and MBR046 (hemp) overall contributions were determined, corresponding each with an increase of the heat conductivities of ~10 and ~19% for moist samples. Finally, defined experiments have to be carried out in order to achieve more insight into the respective contributions to the heat conduction.

Besides changed heat conductivities by water sorption and diffusion processes, different fibre types and heat radiation, the thickness and the apparent density affects the heat transport as well. The overall heat conductivity for a given sample is composed of the different influencing factors and their weighted contributions. These interactions are correlated by the Eq. 1:

$$\lambda = \lambda_L + \lambda_F + \lambda_R \quad (\mathrm{W/mK}) \qquad (1)$$

Here, the overall heat conductivity from the warm to the cold side of a fleece like isolation is given by the superposition of the conductivity by air λ_L (internal air layers), the effective conductivity via the fibre/binder framework λ_F and the conductivity by radiation λ_R. Heat convection can practically be excluded and is only given in the case of draught (Caps et al. 1990). The heat conduction of air is 0.0264 W/mK (at room temperature) and the contribution of the heat conductivity by the fibre material λ_F is given by the Eq. 2:

$$\lambda_F = C_F \cdot d \quad (\mathrm{W/mK}) \qquad (2)$$

Whereas λ_F is proportional to the density d of the fleece and the constant C_F. The constant C_F depends on the kind of the fibre/binder material (Caps et al. 1990) and the more or less moist state of the isolation materials.

3.1.3 The influence of the apparent density and the thickness

Via the data of the samples in Table 1 it is not possible to evaluate any effect of the thickness and apparent densities on the heat conductivities, because samples indicated by the same HCC partially show big differences concerning their thickness and density. In addition, the contribution of e.g. the heat radiation to heat conductivities cannot be excluded. In order to get more information about the influence of the density on the heat transport very different insulation mats of (a) water glass bonded hemp fibres (high amounts of shiver) and (b) hand deposited textile

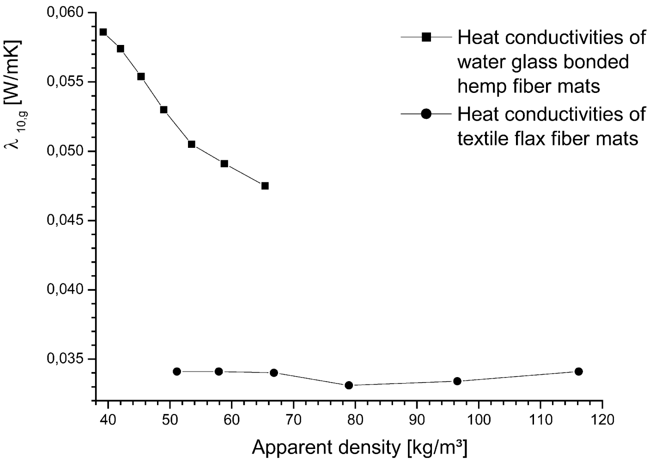

Fig. 3a,b Change of the overall heat conductivity (according to Eq. 1) in dependence of the apparent density, for insulation mats based on **a** water glass bonded hemp fibres with a high amount of shiver and **b** hand deposited textile flax fibres without binder addition

Abb. 3a,b Änderung der Gesamtwärmeleitfähigkeit (nach Gl. 1) in Abhängigkeit von der Rohdichte, für Dämmstoffmatten basierend auf **a** wasserglasgebundenen Hanffasern mit einem hohen Schäbenanteil und **b** handgelegten textilen Flachsfasern ohne Binderzusatz

flax fibres (without binder) were varied with respect to their thickness and the heat conductivities measured; whereas a decreasing thickness leads to an increased density. Before the measurements, the mats were stored in the measuring laboratory and exposed to non-controlled humidity and temperature for five days. Figure 3 reflects the change of the overall heat conduction (Eq. 1) of the samples (a) and (b) in dependence of the apparent density. It is obvious that, in contrast to (b), the relatively coarse fibre-binder-structure of (a) leads to considerably higher heat conductivities. Primarily in the range of densities between 50 and 70 kg/m^3 the wide difference of the heat conductivities can be indicated. This is due to the material specific factors like the fibre characteristics as well as the fibre content per unit of volume and their effect on the heat transfer mentioned in the last section. Regarding (b) the increased densities initially lead to decreased heat conductivities and, after reaching a minimum to an increase of the heat conduction again. This behavior is described by many authors and has to be considered in the context of the fibre content and the available air layers per unit of volume (Martin et al. 1987; Caps et al. 1990; Schardt et al. 1993; Scheiding 2000). If fleece-like materials are compressed the contribution of the heat radiation (λ_R ; see Eq 1) decreases whereas the heat conduction through the material ($\lambda_F = C_F \cdot d$) is increased. Wood, as an extreme example of high density, leads to heat conductivities, which are in considerable order of magnitudes higher, than those for fleeces (Kollmann et al. 1956). With respect to (a) one can assume that a minimum will be reached as well, considering the course of the values for heat conductivities by increasing densities. After all, it should be annotated that an increased thickness at a given apparent density will also reduce the heat transport (Caps et al. 1990; Schardt et al. 1993).

3.1.4 The measured heat conductivities in comparison to those of wood fibre insulating material

The physical correlation between heat conduction, heat radiation and convection applies also for other fibre materials. However, the described results characterize only the materials investigated here. The processing, the fibre fineness and internal porosity as well as the thermo-technically favourable density range have to be determined separately for each kind of material. On the other hand, different processed and composed fibre insulating mats could be considered regarding to their heat conductivities, if one takes similar densities into account. For water glass bonded dry wood fibre insulation mats Richter et al. (1995) measured a heat conductivity of λ=0.0351 W/mK (apparent density: d=83 g/cm^3) and Scheiding's (2000) lowest heat conductivity is λ=0.0412 W/mK at an apparent density of d=58 g/cm^3. For comparison (Table 1), the dry flax fibre samples MBR069 (d=80.74 g/cm^3) and MBR047 (d=91.11 g/cm^3) show heat conductivities of λ=0.0414 W/mK and λ=0.0409 W/mK, respectively, a little higher than those measured by Richter et al. (1995). But, in comparison to the measured heat conductivity by Scheiding (2000), for the dry flax fibre mat MBR053 slightly lower values of λ=0.0392 W/mK (d=60.78 g/cm^3) were determined. Regarding to the hemp fibre materials, all the measured heat conductivities are higher than those of Richter et al. (1995) and Scheiding (2000) mentioned above. After all, for low heat conductivities all the criteria mentioned in Sect. 3.1 have to be considered.

3.2 The tensile strength and dimensional stability

Three samples of the production run MBR069 were tested concerning the tensile strength (DIN EN 1608) and the dimensional stability (stored at 80°C, rH%=80% until mass constancy; DIN 18165-1). With respect to the tensile strength an average value of 19 kPa was determined much higher than the required scheduled minimum value of 1.4 kPa. For the dimension stability a relative change of the thickness of +8.9% was achieved, which is well below the maximum of 15%. This means that the investigated insulation mats are also easy to handle and that they will not lead to a structural alteration of an overall construction after their assembly.

4 Conclusions

Heat insulation mats were fabricated via a pilot plant and their heat conductivities investigated with respect to the affecting factors moisture content, water sorption and diffusion processes, fibre characteristics and heat radiation as well as thickness and apparent density. Although the moisture content is not a crucial factor it is assured that the heat conduction depends on water sorption and diffusion processes. If the fibre/binder material promote a local high number density of water molecules and a pronounced forward motion (diffusion) of the molecules from warm to cold regions this will lead to higher values of the heat conduction. Strong interactions between the fibre characteristics on the one hand and the heat radiation, the apparent density and the thickness on the other hand were determined as well. Taking all the criteria into account an optimization of the insulation mats has to occur with respect to the three basic principles. 1. The fibres should be as fine, flexible, smooth and low porous as possible. 2. The apparent densities should be in the range of ~70–95 kg/m^3 and the thickness adequate. 3. For the binder/additive system a possible highly hydrophobic compound should be used or the fibres hydrophobised before the binder will be added. Thus, it should be assured that the flux of the heat conduction is more limited and lower values for the heat conductivity will be measured. But, in contrast to the desired characteristics, there are the higher costs for manufacturing fine natural fibres, the use and development of corresponding binder/additive compounds as well as an optimized process for the fabrication of the insulation mats. With respect to the values for the determined tensile strengths and dimension stabilities results were received, which allow an easy handling and a sufficient guarantee that a structural alteration of an overall construction will not occur.

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