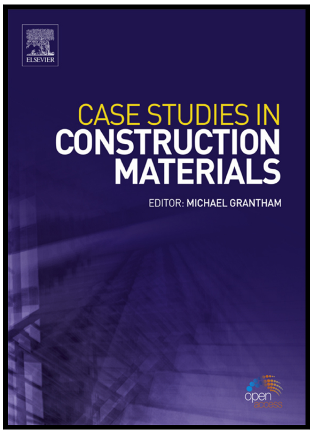

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Thermal conductivity of biochar-clay composites for the internal insulation of buildings

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Abstract

The application of biochar-clay composites as internal insulation of buildings is very promising since the employed materials are ecological and commonly available, corresponding to a forward-looking construction method. To bring this solution to its full potential however, additional data on the thermal performance of such composites are required. In this study new biochar-clay composites are investigated by varying composite's parameters such as biochar and clay type, biochar weight fraction and addition of natural fibres. Measurements of the thermal conductivity are performed by the heat flow meter method at different temperatures and moisture contents. Based on the measured outcomes, an empirical model is developed and calibrated to predict the impact of the composite`s density, temperature and moisture content on the composite thermal conductivity. At an average temperature of 20°C and dry conditions, for composite densities ranging between 222 and 610 Kg/m^3, thermal conductivities between 0.06 and 0.18 W/(m K) are obtained. Combined increases of temperature and moisture content of 10 K and 20 Kg/m^3 lead to an increase of the thermal conductivity of the composite between 10% and 26%, depending on the composite type.

Keywords:
biochar-clay composites; internal insulation; recyclable materials; thermal, conductivity; heat flow meter

1. Introduction

The application of biochar-clay composites in internal insulation systems has rarely been explored so far. It suggests however great potential since the starting materials are commonly available, ecological, recyclable and easy to dispose of with low primary energy requirement

[1][2][3]. Biochar-clay composites can be applied in the form of boards, bricks or plaster directly on the existing wall as internal layer or in combination with other insulation materials as, e.g., blown cellulose. These composites might therefore represent a valid alternative to other light earth materials used as thermal insulation, such as hemp-earth composites recently investigated in [4].

In terms of hygrothermal properties biochar and clay complement each other perfectly. The use of biochar leads to a low effective thermal conductivity of the composite which contributes at significantly reducing the wall´s thermal transmittance [3][5][6]. Clay brings a high moisture buffering capability which is beneficial to passively regulate indoor relative humidity and reduces the risk of mould germination [7][8]. These properties suggest high suitability of such composites in diffusion-open internal insulation systems, especially for energy efficient and conservation compatible refurbishment of listed buildings in which external insulation is not permitted.

Although a lot of promise lays in biochar composites, the current knowledge on their heat transfer behaviour is still fragmented and incomplete. While several studies consider the addition of biochar in cementitious materials [9][10][11][12], data concerning combination of biochar and clay for the application as building insulation are still rare. To the authors best knowledge, composites presenting biochar weight fractions above 12wt% have rarely been considered so far and deserve higher attention. Further research is also required to study the effect of different biochar types and corn size distribution on the thermal performance of the composite.

Table 1 gives an overview on current scientific research relative to heat transfer in composites containing hemp or biochar by reporting available data on their thermal conductivity. Hygrothermal properties of light-earth building materials containing hemp have been recently studied in [4] which reports values of thermal conductivity between 0.1 and 0.06 for biomass fractions ranging between 34 and 67wt%. The so far investigated building materials with biochar addiction, present significantly higher thermal conductivity. Cement pastes containing sugarcane bagasse biochar present, according to [10], thermal conductivities of 0.314 W/(mK) and 0.287 W/(mK) for 2 and 6wt% biochar rates, respectively. The addition of biochar from residual biomass in concrete to obtain composites with thermal conductivities ranging between 0.45 and 0.19 W/(mK) and biochar rates between 1 and 12wt% is addressed in [11]. Another recent paper concerns the use of biochar obtained by pyrolysis from oilseed rape and mixed softwood in mortar composites with biochar rates between 2 and 8wt% [5]. For 8wt% biochar rate, minimum thermal conductivities of 0.666 W/(mK) and 0.723 W/(mK) are observed for mixed softwood biochar composites and oilseed rape biochar composites, respectively. These values are significantly lower than the thermal conductivity of mortar without biochar addiction equal to 1.205 W/(mK) but still much higher than thermal conductivities of conventional insulation materials.

In [13] data are reported on the thermal conductivity of coal char-based bricks (char content 70wt%) ranging between 0.26 and 0.35 W/(mK), with the thermal conductivity of bricks without coal char addiction ranging between 0.39 and 0.63 W/(mK). Natural inorganic clay composites with biochar obtained by pyrolysis from rice husk, coconut shell, and bamboo are investigated in [3]. Values of thermal conductivity between 0.276 W/(mK) (1wt% biochar rate) and 0.101 W/(mK) (10wt% biochar rate) for coconut shell biochar composites, between 0.295 W/(mK) (1wt% biochar rate) and 0.14 W/(mK) (10wt% biochar rate) for rice husk biochar composites and between 0.283 W/(mK) (1wt% biochar rate) and 0.155 W/(mK) (10wt% biochar rate) for bamboo biochar composites are observed, with a thermal conductivity of the clay without biochar of 0.306 W/(mK).

Table 1: Thermal conductivity of building materials containing hemp or biochar.

Bunding material	**Employed biomass**		**Biomass fraction [wt%]**	**Thermal conductivity [W/(m K)]**	**Ref.**
earth	hemp		34 to 67	0.1 to 0.06	[4]
cement	sugarcane bagasse		2 to 6	0.31 to 0.29	[10]
concrete	residual biomass		1 to 12	0.45 to 0.19	[11]
mortar	oilseed rape	biochar	8	0.72	[5]
mortar	mixed softwood		8	0.67	[5]
cement	coal char		70	0.35 to 0.19	[13]
natural inorganic clay	rice husk		1 to 10	0.29 to 0.14	[3]
natural inorganic clay	coconut shell		1 to 10	0.28 to 0.10	[3]
natural inorganic clay	bamboo		1 to 10	0.28 to 0.15	[3]
clay-loam	residual biomass		19 to 72	0.18 to 0.09	this study
clay-loam	miscanthus		11 to 54	0.11 to 0.06	this study

The literature review reported above demonstrates that the addition of biochar drastically reduces the thermal conductivity of building materials. For the application of such composites as thermal insulation however, further development is required to increase the biochar rate and reduce thermal conductivity. Moreover, to the authors best knowledge, no specific research has been conducted so far on composites of natural clay-loam and biochar, although this solution presents major advantages in relation to the expected low environmental impact and high moisture buffering potential.

This study responds to the addressed research gap by investigating a set of novel biochar-clay-loam composites with biochar fractions between 11 and 72 wt%. The effect of using different biochar and clay types as well as the addition of natural additives (straw fibres) is investigated, by exploring how the material composition affects its thermal conductivity. A thermal conductivity of 0.06 W/(mK) is targeted to compete with well-established capillary active materials used as diffusion-open internal insulation as, e.g., calcium silicate. The composites presenting low thermal conductivity and adequate mechanical strength are suitable to develop insulation plasters and boards for building retrofit.

2. Composite variants

In this section, the employed clay-loam and biochar types and the process to obtain composites and material samples are described.

2.1 Biochar types

The composites investigated in this study are obtained with two different biochar types. The first one, presenting a bulk density of 244 [kg/m^3], is the by-product of a biomass powerplant (BC1, Figure 1 a), the second one, with a bulk density of 56 [kg/m^3], is obtained by pyrolysis from miscanthus biomass (BC2, Figure 1 b).

The BC1-type presents compact grains of diameter ranging between few micrometres up to ca. 1 cm, particularly suitable to develop composites for plastering applications. The original grain size distribution of the biochar can be adjusted by a sieving process, to reduce the fraction of ash and fine particles. This procedure allows achieving final composites with lower density and thermal conductivity. A proper grain size distribution can also increase the bending strength of the composite. By applying different sieving procedures, additional biochar variants with bulk-densities of 162 [kg/m^3] and 192 [kg/m^3] are obtained. In particular, the variant of density equal to 162 [kg/m^3] is produced by removing all biochar particles of diameter smaller than 3mm, while the variant of density equal to 192 [kg/m^3] presents a grain size distribution between the A8 and B8 curves defined in [14].

Biochar type BC2 presents a relevant fraction of elongated cylindrical elements (length 2-5 cm, diameter 5-6 mm) allowing producing significantly lighter composites relative to the ones obtained with the BC1-variants. BC2-composites appear therefore particularly promising to develop light insulation boards.

Figure 1: employed biochar types BC1 (a) and BC2 (b).

2.2 Clay-loam types

The clay-loam serves as binder between the biochar particles. Selecting a proper clay-loam type is therefore important to achieve sufficiently stable and compact composites, with low density and thermal conductivity. Two regional clay-loams from the alpine section of the Rhine River's drainage basin (Vorarlberg, Austria) are considered in this study. The first one (CL1) is a yellow clay-loam with a dry apparent density of 2588 [kg/m^3] and medium clay content. The second one (CL2) is a blue clay loam with a dry apparent density of 2280 [kg/m^3] and high clay content. In Figure 2 (a), 20ml samples of clay-loam-water mixtures are shown while Figure 2 (b) depicts the shrinkage of CL1 and CL2 samples after one week drying. It can be observed that the CL1 sample presents shrinkage cracks, while the CL2 sample remains compact. This indicates a better bonding capability of CL2 relative to CL1-clay.

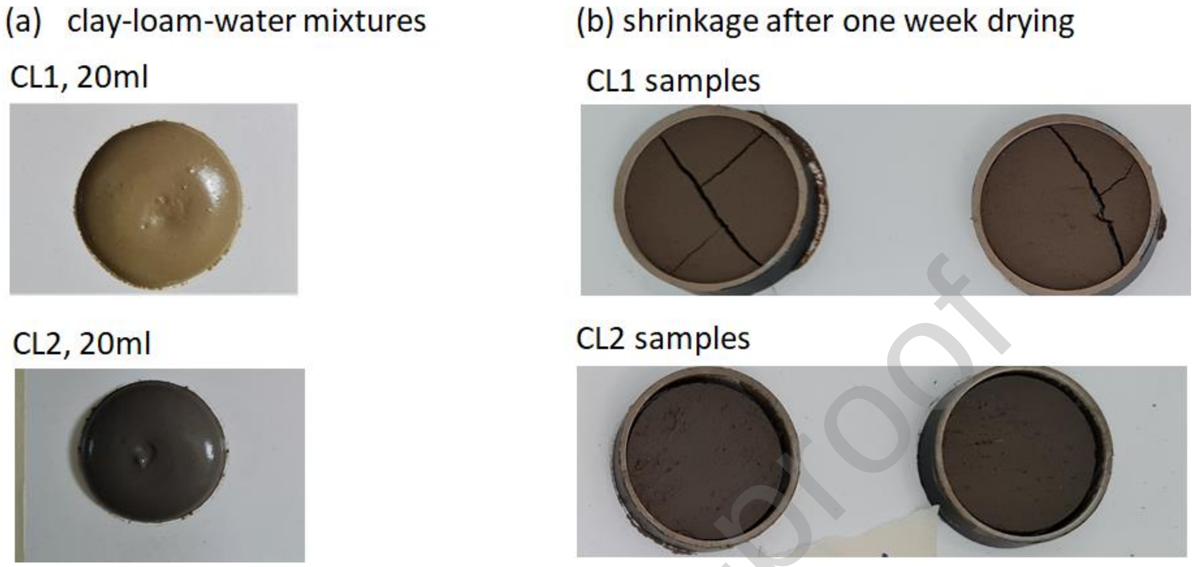

Figure 2: clay loam types CL1 and CL2.

2.3 Composite variants and sample preparation

The investigated biochar-clay composites are shown in Figure 3 and specified in Table 2 by reporting the employed biochar and clay type, the biochar weight fraction, the composite density and the breaking load of the bending test. Composites 01-06 are made using CL1-clay and present dry densities ranging between 610 and 332 [kg/m^3]. Composites 07-15 are made by CL2-clay, presenting densities between 502 and 222 [kg/m^3]. In the latter ones, straw fibres of 0.2 to 5 cm length are used as additives to further increase the bending strength.

For the measurement of the thermal conductivity by the heat flow meter method, square shaped material samples are produced in moulding frames (25x25x5 cm). The sample surface has been smoothed with sandpaper to reduce roughness and improve contact with the metering plates of the heat flow meter. The samples are subsequently oven dried at 105°C for a period of 6 hours. After this time, no further mass loss is observed therefore the drying process can be considered completed and the dry density of the composites is determined. No relevant shrinkage of the samples is observed after drying.

A certain bending strength of the material is necessary to produce boards in large formats and process them easily on the construction site. The bending strength limit of the different composites is therefore examined using additional test specimens of dimensions 12x25x5cm.

Each test specimen is placed on two supports with a span of 150mm while the bending force is introduced evenly in the middle of the sample via a threaded rod. The load is gradually increased until the specimen breaks.

The bending breaking loads of the investigated composites, ranging between 43 and 286 N, are reported in Table 2. It can be observed that the composites obtained by CL2-clay with addition of straw fibres present significantly higher breaking loads relative to the CL1-clay-composites. In BC1-composites a further increase of the bending stress resistance is obtained by applying proper sieving to modify the grain size distribution and bulk density of the biochar. Best results are obtained with biochar bulk density of 192 kg/m^3. The combined effect of these measures is evident by comparing variant M4 with Mi3, which present similar composite densities but quite different maximum bending loads (66 and 217 N, respectively). BC2-composites present, by similar composite density, higher bending stress resistance relative to unsieved BC1-composites (compare variants K6 and Mi1, presenting max. bending stress of 190 and 165 N, respectively). However, composites obtained with sieved BC1-biochar of 192 kg/m^3 bulk density can reach a higher bending load limit than BC2-compodsites (compare variants Mi3 and K6, presenting max. bending stress of 217 and 190 N, respectively).

Table 2: Investigated biochar-clay composites.

Nr.	Variant	Biochar type	Biochar bulk density [Kg/m^3]	Natural fibre	Clay type	Biochar sieving	Biochar weight fraction [wt%]	Dry composite density [Kg/m^3]	Bending test breaking load [N]
01	**K1**	BC1	162	None	CL1	Yes	27	468	NA
02	**K3**	BC1	244	None	CL1	No	36	610	NA
03	**K5**	BC2	56	None	CL1	No	11	490	NA
04	**M1**	BC1	162	None	CL1	Yes	16	522	66
05	**M3**	BC1	162	None	CL1	Yes	36	378	43
06	**M4**	BC1	162	None	CL1	Yes	42	332	66
07	**K6**	BC2	56	Straw	CL2	No	37	386	190
08	**K9**	BC1	163	Straw	CL2	Yes	63	268	77
09	**MM1**	BC2	56	Straw	CL2	No	47	302	196
10	**MM2a**	BC2	56	Straw	CL2	No	54	258	149
11	**MM2b**	BC2	56	Straw	CL2	No	54	222	149
12	**Mi1**	BC1	244	Straw	CL2	No	72	386	166
13	**Mi2**	BC1	244	Straw	CL2	No	46	502	206
14	**Mi3**	BC1	192	Straw	CL2	Yes	67	331	217
15	**Mi4**	BC1	192	Straw	CL2	Yes	40	462	286

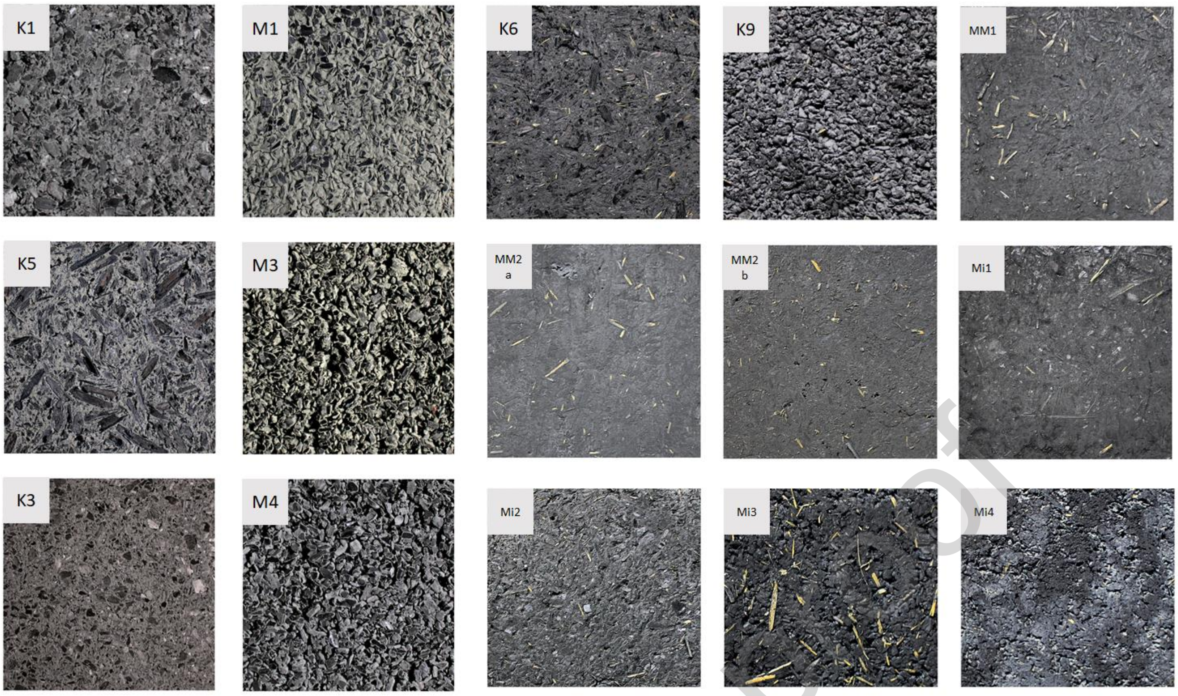

Figure 3: Investigated biochar-clay composites (each square represents a 17x17cm surface).

3. Experimental setup for the thermal conductivity measurement

Measurements of the thermal conductivity are performed according to [15] by means of a heat flow meter previously calibrated with a material sample of known thermal conductivity. A schematic representation of the experimental set up is shown in Figure 4. The heat flux is measured at both hot and cold side by metering surfaces (15x15 cm) located in the centre of guard rings with outer size of 30x30 cm. During the experiment, the sample is subject to a compression force of 200 N by hydraulic press to reduce discontinuities between the sample and metering surfaces. Note that for accurate measurements the samples have to be larger than the metering surface but not necessarily as large as the guard ring. It was verified that samples of 25x25 cm are large enough to perform accurate measurements. Therefore, this size has been chosen, to facilitate sample production and transport.

The measurement is performed for each sample by applying a constant temperature difference of 10K for 6 hours. According to the instrumentation data sheets, the measured thermal conductivity presents an uncertainty of max. ±3%. The sample is weighted before and after each measurement to determine variation of the moisture content during the test. The accuracy of mass-measurements has been estimated as ±1 [g] while the uncertainty regarding the volume of the specimens can be considered as max. ±1%.

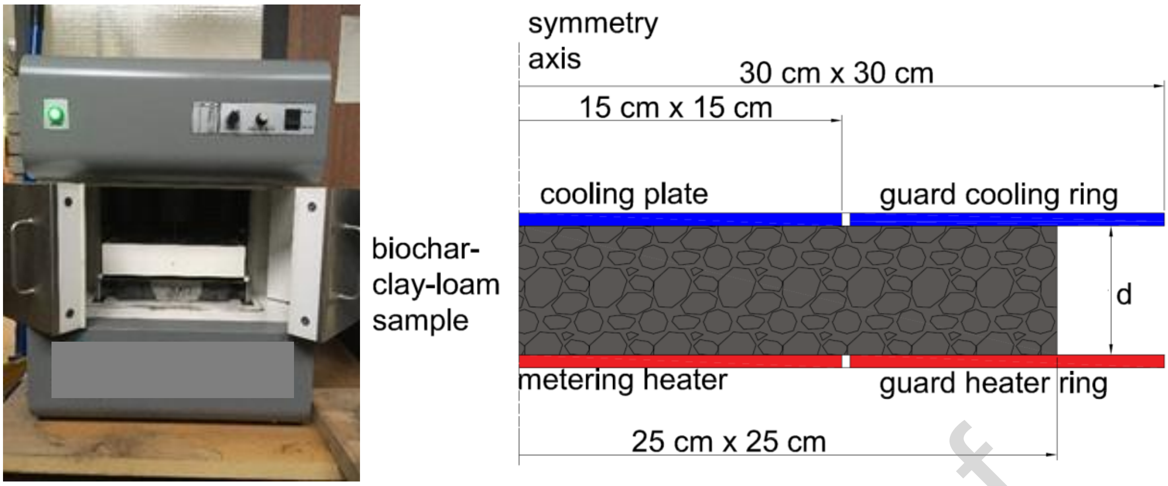

Figure 4: picture and schematic representation of the heat flow meter employed for the measurements (the thickness d varies between 41 and 51 mm, depending on the sample).

4. Results and discussion

The experimental results are reported in Table 3. All measurements are performed at average sample temperatures of 10, 20 and 30 °C to evaluate the impact of temperature on the thermal conductivity. In a first stage, nearly dry samples are employed (experiment Nr. 01 to 15) presenting moisture content between 1.7 and 5.1 [kg/m^3] (in average 3.3 [kg/m^3]). This moisture content is due to vapour absorption from the atmosphere during the samples' transfer from the drying oven to the heat flow meter and during the measurement itself. It was verified that moisture content variations within this range have just a minor impact on the thermal conductivity. At an average temperature of 20°C and nearly dry conditions, for composite densities ranging between 222 and 610 Kg/m^3, thermal conductivities between 0.06 and 0.18 W/(m K) are observed.

In the second stage, additional experiments are performed on composites Mi4, K6 and MM2a, to investigate the impact of the moisture content on the thermal conductivity of the composite (experiment Nr. 16 to 21, Table 3). To this aim, the material samples are first moistened in humid air at RH=90% and T=20°C and subsequently partially dried until an intermediate moisture content is obtained. Overall, the thermal conductivity is thus assessed at three distinguished moisture levels. The investigated temperature and relative humidity range (10°C<T<30°C; RH<90%) is most relevant for the application of the material as internal insulation, while values out of this range are unusual in the praxis and are thus out of scope in this study.

Table 3: Measured thermal conductivities of the investigated composites at different temperatures and moisture contents.

Nr.	Composite	Moisture content [kg/m^3]		Thermal conductivity [W/(m K)]		
				T=10°C	T=20°C	T=30°C
01	**K1**	Nearly dry conditions (average water content 3.3 [kg/m^3])	2,6	0.136	0.139	0.141
02	**K3**		3,1	0.177	0.180	0.183
03	**K5**		4,0	0.106	0.107	0.109
04	**M1**		3,0	0.151	0.152	0.155
05	**M3**		2,3	0.109	0.112	0.115
06	**M4**		5,1	0.112	0.115	0.119
07	**K6**		2,5	0.089	0.090	0.092
08	**K9**		4,7	0.091	0.094	0.097
09	**MM1**		4,0	0.079	0.081	0.083
10	**MM2a**		3,3	0.070	0.071	0.073
11	**MM2b**		4,2	0.062	0.064	0.067
12	**Mi1**		3,1	0.127	0.130	0.133
13	**Mi2**		3,1	0.145	0.148	0.151
14	**Mi3**		3,5	0.114	0.116	0.120
15	**Mi4**		1,7	0.137	0.140	0.143
16	**Mi4**	After moistening in humid air (20°C; 90% RH)	44.2	0.161	0.167	0.173
17	**K6**		31.4	0.108	0.112	0.115
18	**MM2a**		21.9	0.084	0.088	0.090
19	**Mi4**	After partial drying	23.8	0.149	0.153	0.158
20	**K6**		16.0	0.095	0.097	0.099
21	**MM2a**		11.4	0.074	0.076	0.078

As noted above, results reported in Table 3 are obtained after 6h measuring time at each temperature level. This time was long enough to reach equilibrium in case of dry samples, while in humid samples the steady state was not always fully reached. The results are however considered still useful for the purpose of this study, since the variation of thermal conductivity is in very low after 6h. To estimate the impact of the measuring time on the thermal conductivity, additional measurements are performed on humid samples with 24h measuring time. The samples are previously wrapped with vapor-tight membrane of negligible thermal resistance to avoid moisture exchange with the environment during the measurement. By comparing the thermal conductivity measured after 6h and 24h, minor differences (<1%) are observed in case of dense BC1 samples, while in case of light BC2 samples larger deviations occur, with a decrease of thermal conductivity up to 7%. In case of dense BC1 samples no condensation is observed, while in light BC2 samples condensation occurs in form of liquid water droplets at the internal side of the membrane in contact with the cooling plate. This fact indicates that in light BC2 samples moisture concentrates in a thin material layer, nearby the cooling plate, while the material layer neighbouring the heater plate progressively dries out during the experiment by decreasing its thermal conductivity. This process requires long time to reach equilibrium, as observed in [16]. On the other hand, in dense BC2 samples moisture is presumably redistributed inside the material due to capillary action or surface diffusion, which produce transport of liquid water from the moist cold side towards the warm side, hence balancing vapour diffusion occurring in the opposite direction, as noted for calcium silicate samples in [17].

The impact of the composite density, biochar type, average temperature and moisture content on the composite's thermal conductivity are discussed in the next sections.

4.1 Effect of the biochar type and composite density on the thermal conductivity

It is found that the employed biochar type and composite density have a major influence on heat transfer through the composite. The effective thermal conductivity measured at 20°C and nearly dry conditions are reported in Figure 5 (a) as a function of the material density. It can be observed that the effective thermal conductivity increases linearly with the composite's density, independently of the employed clay. BC2-composites present by equal density a thermal conductivity nearly 26% lower relative to BC1-composites. This deviation can be explained considering the different pore structure, particle size and shape of the employed biochar types. While BC1-biochar consists of smaller, rather compact-shaped particles, BC2-biochar presents elongated cylindrical particles with a fine porous structure which better hinder heat transfer. Although the employed clay-loam type has just minor impact on the thermal conductivity of the composite, using CL2-clay combined with straw fibres allows obtaining lighter composites due to a better bonding effect. This leads to CL2-composites presenting in average lower thermal conductivity relative to CL1-composites.

The measured data are interpolated with Eq. **(1)**, in which λ [W/(m K)] denotes the composite´s thermal conductivity and ρ [kg/m^3] the dry density.

$$\lambda(\rho) = C_1 + C_2\rho \tag{1}$$

C1 and C2 are fitting parameters obtained by applying the minimization algorithm reported in [18]. We obtain C1=0.0345 [W/(m K)] and C2=2.30e-04 [m^{2}W/(kg K)] for the BC1-composites and C1=0.0306 [W/(m K)] and C2=1.56e-4 [m^{2}W/(kg K)] for the BC2-composites. The model interpolates well the measured outcomes, with a maximum observed deviation of ±7.5%.

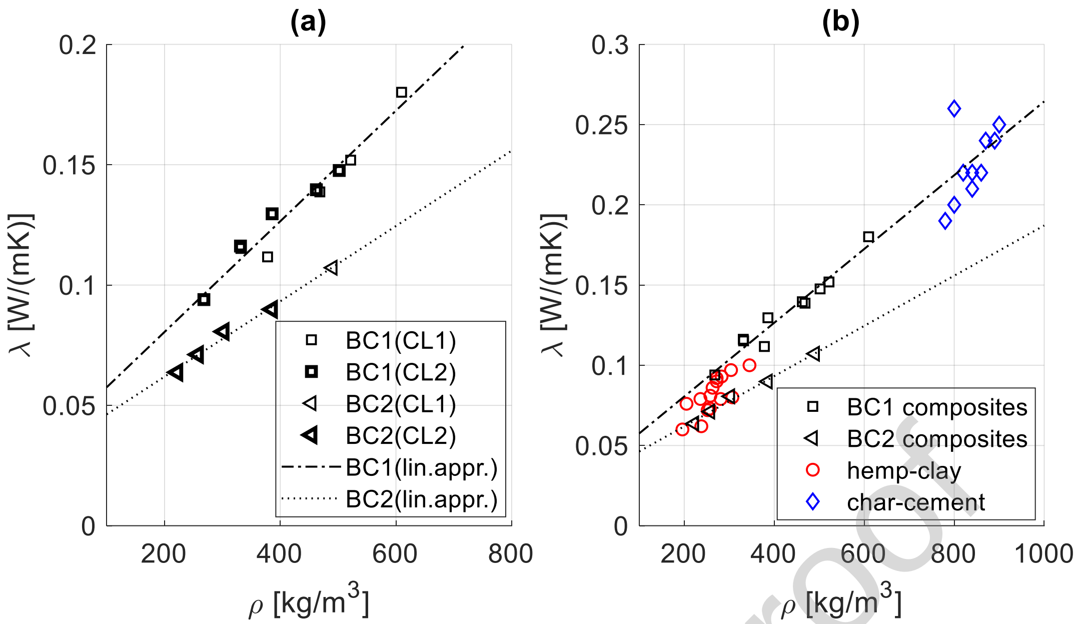

Figure 5: (a) composites' thermal conductivity as a function of the dry density at 20°C temperature and nearly dry conditions (in average 3.3 [kg/m^3] water content). Measured data of composites of biochar type BC1 (by biomass powerplant) and BC2 (by miscanthus pyrolysis) are linearly interpolated, bold marks indicate data obtained with CL2-clay composites; (b) comparison of this study`s results with the thermal conductivity of hemp-clay and char-cement composites according to [4] and [13], respectively.

In Figure 5 (b) the results of this study are compared with data from [4] and [13] concerning hemp-clay and char-cement composites, respectively. The relationship between thermal conductivity and density reported above appears holding well for these composites too. In particular, the thermal conductivity of hemp-clay composites lays between the values reported for BC1 and BC2-composites of similar density, while the char-cement composites present values in line with the trend observed for BC1-composites.

4.2 Effect of temperature and moisture content on the thermal conductivity

To investigate the impact of the temperature and moisture content on the thermal conductivity further measurements on the composite variants Mi4 (BC1), K6 (BC2), and MM2a (BC2) are analysed. The results reported in Figure 6 (a) show that the dependency of composite´s thermal conductivity on average temperature and moisture content can be fairly described in the investigated moisture and temperature range by the following linear relationship:

$$\lambda(\rho, T, u) = C_1 + C_2\rho + C_3(T - T^*) + C_4(u - u^*) + C_5(T - T^*)(u - u^*) \qquad \textbf{\textit{(2)}}$$

In Eq. **(2)**, T [°C] and u [kg/m^3] denote the average temperature and moisture content of the material sample, T^* [°C] and u^* [kg/m^3] are arbitrary reference values of temperature and moisture content, while C_1 to C_5 are empirical parameters which must be inversely determined by interpolation with measured outcomes. By setting $T^*=20$ [°C] and $u^*=3.3$ [kg/m^3], Eq. **(2)** turns into Eq. **(1)**, therefore the parameters C_1 and C_2 are already known from the above section 4.1. The remaining parameters C_3, C_4 and C_5 are determined by fitting the experimental data obtained with moist samples. The values resulting from the calibration of the model are reported in Table 4, while in Figure 6 (b) the experimental data are compared with the results of Eq. (2).

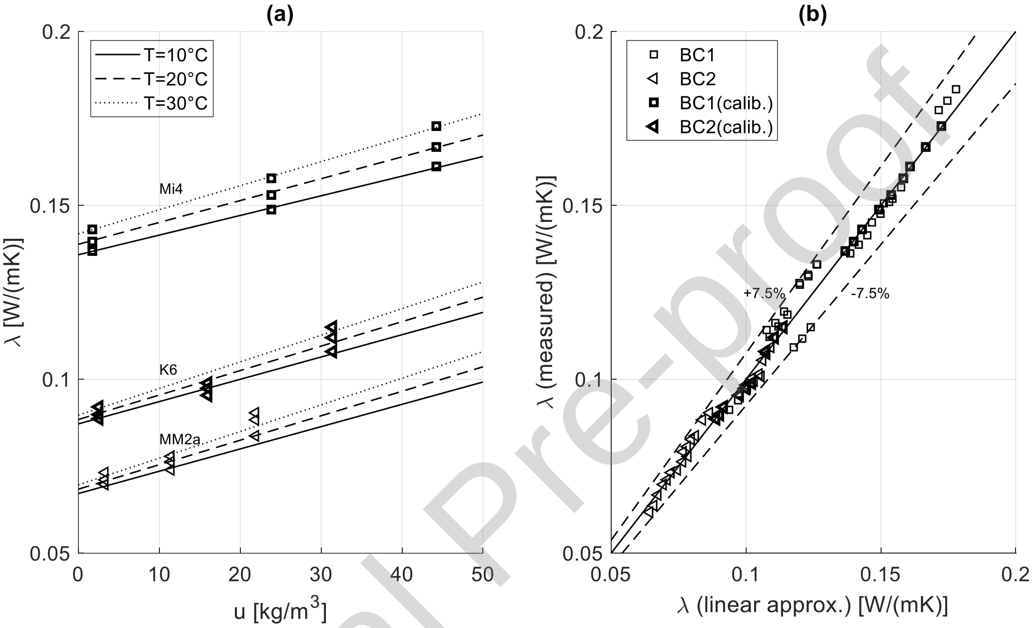

Figure 6: (a) impact of temperature and moisture content on the thermal conductivity of the composite. The data obtained from the variants Mi4 (BC1-biochar) and K6 (BC2-biochar) are used for the model calibration and marked bold in the graph; (b) measured outcomes vs. the linear interpolation according to Eq. (2); the maximum observed deviation is ±7.5% (dashed lines).

The proposed empirical model appears to adequately predict the experimental values, with again a maximum deviation of ±7.5% (dashed line). According to the model, combined temperature and moisture content increases of 10 K and 20 Kg/m^3 with respect to the reference conditions ($T^*=20$ [°C] and $u^*=3.3$ [kg/m^3]) lead to an increase of the composite thermal conductivity between 10% and 17% for BC1-composites and between 16% and 26% for BC2-composites, within the investigated density range (Figure 7). These results underscore the importance of considering moisture and temperature impact on the thermal conductivity when calculating the thermal transmittance of the building envelope, since applying values determined for the dry material might lead to significant underestimation of heat losses under real conditions.

Table 4: Empirical Parameters of Eq. **(2)** *for composites made with biochar type BC1 and BC2.*

Biochar type	T^* [°C]	u^* [kg/m^3]	C_1 [W/m/K]	C_2 [m^{2}W/kg/K]	C_3 [W/m/K^2]	C_4 [m^{2}W/kg/K]	C_5 [m^{2}W/kg/K^2]
BC1	20	3.3	0.0345	2.30e-04	3.21e-04	6.28e-04	6.35e-06
BC2	20	3.3	0.0306	1.56e-04	1.48e-04	7.03e-04	6.24e-06

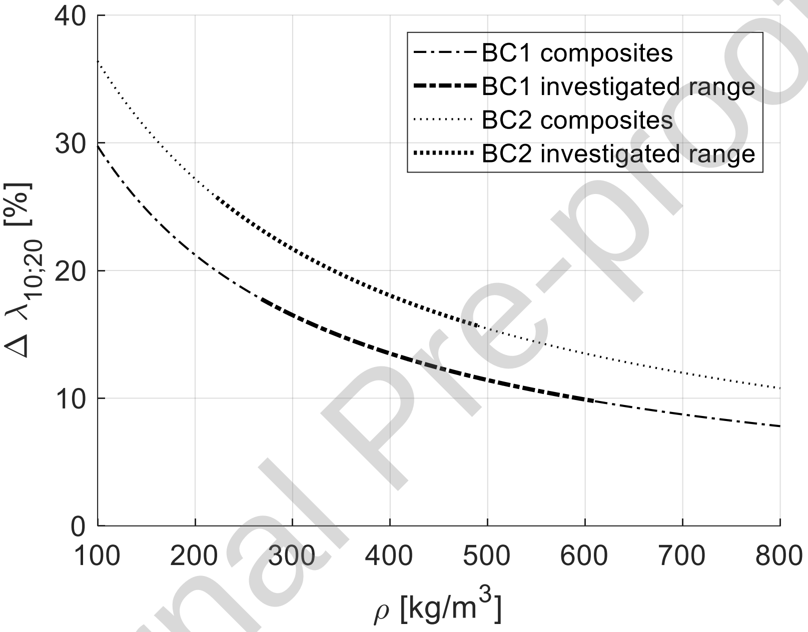

Figure 7: increase of the composite thermal conductivity due to combined temperature and moisture content increases of 10 K and 20 [Kg/m^3] with respect to the reference conditions (T=20 [°C] and u*=3.3 [kg/m^3]).*

5. Conclusion and outlook

In this paper the thermal conductivity of biochar-clay-loam composites is investigated. The impact of applying different biochar weight fractions, composite density, natural additives (straw fibres), biochar and clay type on the thermal conductivity is assessed. It is shown that the thermal conductivity is strongly affected by the density of the composite and employed biochar type. On the other hand, the employed clay type and addiction of straw fibres do not directly impact the thermal conductivity, but are important factors to achieve a composite presenting sufficient compactness and lightness. Other factors which significantly affect the thermal conductivity are the average composite temperature and moisture content. The dependency of the thermal conductivity on the composite density, temperature and moisture content is described by means of an empirical correlation calibrated against measured outcomes.

For nearly dry composites, thermal conductivities between 0.06 and 0.18 W/(m K) are obtained, demonstrating that the material has potential to be applied as (internal) insulation of buildings. It is shown that combined increases of average temperature and moisture content of 10 K and 20 Kg/m^3 lead to an increase of the thermal conductivity of the composite between 10% and 26%, depending on the composite type. Further research is however required to complete the hygrothermal characterization of the material, by determining its moisture transfer and moisture retention properties. The application of the material as internal insulation must be as well investigated in real case studies in the future.

Authors' contributions:

Michele Bianchi Janetti: methodology, writing, funding acquisition; Martina Krusharova: investigation, data curation; Florian Fend: investigation, methodology, funding acquisition; Kai Längle: conceptualization, formal analysis, investigation, funding acquisition; Thomas Mathis: project administration, review & editing, funding acquisition.

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Conflicts of interest/Competing interests:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material:

The data that support the findings of this study are available from the corresponding author (Michele Bianchi Janetti) on reasonable request.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Highlights

- The thermal conductivity of novel biochar-clay composites is measured
- Effects of biochar-type and density on the thermal conductivity are investigated
- Effects of composite´s temperature and moisture content are investigated
- An empirical model of the thermal conductivity is calibrated against measured data
- The application of biochar-clay composites as internal insulation is promising