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The influence of natural reinforcement fibres on insulation values of earth plaster for straw bale buildings

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ABSTRACT

This work aimed to measure the thermal conductivity of some natural plaster materials that could be used for straw bale buildings. Thermal conductivity is very important to determine the insulation value and other thermal parameters for natural plaster materials. Plaster materials consisted of soil, sand and straw. Straw is used as a reinforcement fibre for plaster. Three types of fibres were used such as wheat straw, barley straw and wood shavings. The results indicated that the thermal conductivity of all materials decreased with increasing straw fibre content and decreased with increasing sand content. The straw fibres have greater effect on the change of thermal conductivity than the effect of sand. The results also revealed that plaster reinforced by barley straw fibres has the highest values of thermal insulation.

1. Introduction

There is a growing interest in using earth as a building material which exhibits excellent physical properties with respect to ecological design, and fulfils all strength and serviceability requirements for thermal transmittance. This development is also due to the present concerns for sustainable development that have arisen out of extensive environmental problems (such as climate change and impoverishment of resources) and also rapid pace of technological development within the building sector. Most building regulations have increasingly laid down strict criteria for the thermal performance of buildings rather than the theoretically possible level of performance derived in the past. This has become necessary because the energy efficiency of building depends on the ability of the whole building envelope to retain internal heat, and also considers other factors such as heat loss and moisture movement through the walls. Understandably, the need for energy efficient structures in the built environment is increasing. Residential buildings use the largest proportion of energy, where heating and cooling are the predominant forms, and this is exacerbated by the adoption of air-conditioning, which has increased dramatically in recent years [1].

Studies on the thermal conductivity of building and insulating materials have increased in recent years. New materials are being developed and new uses for existing materials are being found. Today it is often not enough to obtain approximate data from text books, but measurements of real samples are necessary. Rapid technological developments in recent years have resulted in increasing effort to expand our knowledge of the transport properties of construction materials [2].

On the other hand, faced with the worldwide shortage of forest resources, industry is showing increased interest in the production of particle board from agricultural residues [3]. Wheat straw contains a large amount of fibre with the potential to replace wood for particleboard fabrication. Particleboard with a density range from 0.59 to 0.8 g/cm^3 is designated as medium-density particleboard [4]. It has broad applications for both structural and non-structural uses. Also barley straw is a significant raw material used in cellulose production as an energy resource [5–11].

Furthermore, thermal conductivity of wheat and barley straw bales ranged from 0.0414 to 0.0486 and 0.0353 to 0.0539 W/mK for all bale densities at different temperature for wheat and barley straw bales respectively. The average values of thermal conductivity and thermal resistance at both 20.7 and 34.2 °C were much higher than those of at 10.3 °C. The differences in the thermal conductivity and thermal resistance values as temperature changed from 10.3 to 20.7 °C is higher than when temperature changed from 20.7 to 34.2 °C [12]. McCabe [13] measured the thermal conductivity of wheat straw bales was found to be 0.046 W/mK. The

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lightweight straw loam with density of 750 kg/m^3 gave a k-value of 0.20 W/mK whereas a lightweight expanded day loam with a density of 740 kg/m^3 gave a value of 0.18 W/mK. The specific heat for the same material was 1.0 kJ/kg K [14].

Thermal expansion coefficients of plaster made from heavy loam were 0.0043–0.0052 mm/mK. Thermal expansion coefficients for mud brick masonry were up to 0.0062 mm/mK, and for sandy mud mortar has a value of 0.005 mm/mK, and strong cement mortar 0.01 mm/mK, the same as a concrete [15].

In addition the insulation is rated by R-value, the resistance to heat flow. The R-value of wood is 1 per inch (0.15 W/mK), brick is 0.2 (0.734 W/mK), fibre glass bats are 3.0 (0.05 W/mK). Straw bale buildings are thermally efficient and energy conserving, with R-values significantly better than conventional construction, depending on the type of straw and the wall thickness [16]. While Stone [17] estimated the insulation value for the straw bale walls. The R-value for the bale walls was R-44 (0.04 W/mK).

The thermal properties of sustainable earth materials were measured by using a novel thermal probe technique involving an iterative method of data analysis for determining simultaneously the thermal conductivity and diffusivity [18,19].

The viability of using coconut fibre as thermal insulation was explored by conducting thermal conductivity tests on 200 × 400 × 60 mm thick slab-like specimens. The thermal conductivity was 0.058 W/mK occurred at an optimum density of 85 kg/m^3 at 38 °C temperature [20].

The effect of adding wood shavings to sand concretes was studies. Results demonstrate that the inclusion of shavings into sand concretes reduces material density to a considerable extent, whilst the structure remained homogeneous with a strong wood–matrix adherence; furthermore, thermal conductivity has been improved [21].

Gatland et al. [22] described a unique guarded hot box designed for thermal testing of fenestration products incorporates several new design concepts from guarded hot plates, namely wall and edge guards. The wall and edge guarded hot box was built to meet the test methodologies specified in the American Society for Testing and Materials (ASTM) Standard Test Methods C 236-89 [23]. Our article presents an investigation into the thermal conductivity of earth plasters reinforced with different natural fibres such as wheat straw, barley straw and wood shavings under different mix ratios.

2. Materials and methods

2.1. Materials tested

Three different materials are used, i.e. cohesive soil, sand and reinforcement fibres. The composition of the cohesive soil texture is as follows: 31% clay (<2 μm), 22% silt (20–63 μm) and 47% sand (63–2000 μm). Three different fibre types, barley straw, wheat straw and wood shavings are used. The average length of straw particles is about 5 cm, while the length of wood shavings is about 2 cm.

2.2. Sample preparation

At first, the oversized gravels and organic matter (grass root) were removed from the natural cohesive soil. The soil was then oven dried at 105 °C to obtain a constant mass. After the drying process, the hard soil lumps were broken up with a hammer. The natural fibres were also oven dried at 105 °C to constant mass.

Different recipes of earth plasters with different compositions of cohesive soil, sand and fibre were used for testing. The dosing of different materials was controlled by volume with given density. This was done by compressing the materials in a mold. The densities of wheat straw, barley straw and wood shavings are 103.6 kg/m^3, 106.9 kg/m^3 and 111.4 kg/m^3 respectively. The densities of soil and sand are 1666.8 kg/m^3 and 1974.4 kg/m^3 respectively. The amount of soil and the fibre of a given recipe were placed in a container and mixed by hand without water until the different materials are homogeneously distributed. Afterwards, 2 L of water was sprayed over the materials and the materials were mixed by hand for about 15 min until a homogeneous mixture was obtained. The soil–fibre mixture was left to rest for about 30 min and then manually mixed for about 15 min. Earth plaster of four different recipes combined with three different natural fibres used in the thermal conductivity tests are given in Table 1. The compositions of the materials in Table 1 are given in volume percentage with the average material densities mentioned above.

The soil–fibre mixture was poured into a steel mold placed on a wood board. The square steel mold has a side length of 30 cm and a depth of 5 cm (see Fig. 1). The surface was leveled and compressed with a loading plate under a force of about 50 kg, which simulates the plaster operation on site. Afterwards, the steel mold was lifted leaving an earth plaster sample on the wood board.

The samples were allowed to dry slowly to avoid any cracks. This was done in a climate chamber under the temperature of 30 °C and the humidity of 40% for 60 days. The temperature and relative humidity inside the climate chamber can be controlled. A

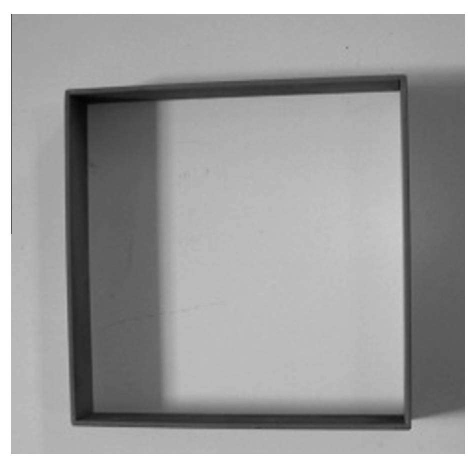


Fig. 1. Steel frame for samples preparation.

Table 1
Four earth plasters with three natural fibres.

Earth plaster recipes	Wood shavings			Wheat straw			Barley straw		
	Soil (%)	Soil (%)	Reinforcement fibres (%)	Soil (%)	Soil (%)	Reinforcement fibres (%)	Soil (%)	Soil (%)	Reinforcement fibres (%)
A	25	0	75	25	0	75	25	0	75
B	25	25	50	25	25	50	25	25	50
C	25	50	25	25	50	25	25	50	25
D	25	75	0	25	75	0	25	75	0

unique facility is that the water moving into or out of the climate chamber. The humidity control unit within the chamber measures how much water it collects or releases. Basically, water is evaporated from or condensed into a weighed water tank whose temperature is controlled by a Peltier heat pump.

2.3. Guarded hot plate apparatus

The guarded hot plate apparatus (GHPA) is widely accepted as a primary apparatus to determine the apparent thermal conductivity of insulating materials. Fig. 2 shows the principal characterizes of a GHPA.

The hot and cold plate maintains the boundary conditions constants (temperature) in the superior and inferior surfaces of the specimen. In the ideal case, the plates are in perfect thermal contact with the specimen and the heat flow through it is one-dimensional and independent of time. The specification for the thermal conductivity equipment λ-Meter EP 500 can be seen in Table 2.

The single-specimen conductivity test tool λ-Meter EP 500 is a guarded hot plate apparatus and measures the thermal conductivity, thermal resistance as well as the *k*-value and *U*-value respectively of an insulating material and other products. Thermal conductivity tests were done in accordance with different standard methods [23–30].

2.4. Test procedure

Forty-eight block samples of different plaster materials were used for the thermal conductivity test. The samples were prepared by using a steel frame of dimensions 30 × 30 × 5 cm for length × width × height respectively (Fig. 2).

For each straw type and each treatment five samples of the same material were used as replicates as shows in Fig. 3.

Table 2
Specifications for thermal conductivity equipment.

Model	λ-Meter EP 500
Measurement temperatures	Random choice of temperature in the range of 10–40 °C
Temperature difference between sensor plates	Range random choice in range of 5–15 °C
Measurement range	R = 0.250–5 m^2 K/W and λ = 4–250 mW/mK
Specimen thickness	10–200 mm
Maximum specimen dimensions	500 × 500 mm
Accuracy	<1.5% for specimen thickness < 90 mm and λ = 10–60 mW/mK (mostly <0.5)
Tool dimension (length × breadth × height)	630 × 630 × 880 cm
Mass	Ca. 85 kg
Voltage	220 V/50 Hz
Maximum power input	450 W

After placing plastering samples in the thermal conductivity device, the borders of samples were insulated with "Polystyrene", which has a thermal conductivity of 0.025 W/mK Fig. 4.

The guarded hot plate apparatus λ-Meter EP 500 can test the thermal conductivity at exactly the desired test temperature. Its heat control does not switch off when thermal conditions within the specimen are almost stationary to allow for adjusting to the test temperature. This is common for heat flow meters and in most cases leads to marginal differences between real and desired test temperatures. For the evaluation of λ_{10} on the guarded hot plate apparatus only a single test is needed.

The guarded hot plate apparatus λ-Meter EP 500 can automatically complete three subsequent tests on one specimen at different temperatures between 10 and 40 °C. The average of measuring temperature was 10, 25, 40 °C. The difference between cool and

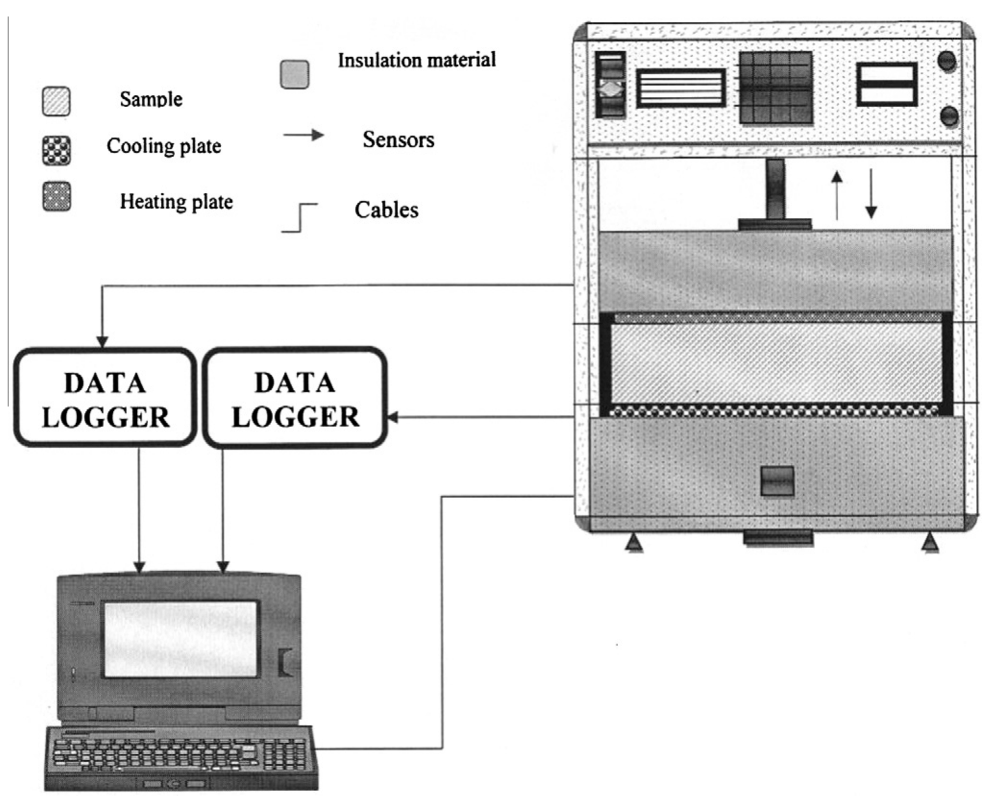


Fig. 2. Experimental setup for the thermal conductivity measurement.

Fig. 3. Thermal conductivity samples after preparation.

Fig. 4. Thermal conductivity instrument.

heat plate was 5 °C for all test sequent. The average temperature was calculated from the cold and heating plates. The software is determining the thermal conductivity for the obtained data from the instrument through data logger. The instrument is change digitally to the second point condition, when the thermal conductivity line is stable. This means that the thermal conductivity at these conditions was evaluated as shows in Fig. 5.

The difference between based on the individual test results the tool can compute moist thermal conductivity at 10 °C (λ_{10}), moist thermal insulation at 10 °C (R_{10}) and temperature coefficient of conductivity (T_K) by applying linear regression. The program draws the regression line and fit the best equation with high coefficient of determination (R^2). The program also calculates dry thermal conductivity at 10 °C ($\lambda_{10\ \mathrm{dry}}$) and dry thermal insulation ($R_{10\ \mathrm{dry}}$) as shows in Fig. 6.

2.5. Mathematical equations

2.5.1. Thermal conductivity

Thermal conductivity determinations are depending on several equations. The data were taken from the data logger and thermal conductivity was calculated through software related to the λ-instrument. Thermal conductivity was calculated using the following equation.

$$\lambda_{10,\mathrm{most}} = \frac{\Phi_c \cdot L}{2A(T_\mathrm{h} - T_\mathrm{C})} \tag{1}$$

where $\lambda_{10,\ \mathrm{moist}}$ is the thermal conductivity at 10 °C (W/mK), Φ_c the heat flow, which flows under stationary conditions perpendicularly to the sample surface through the sample (W), A the heating plate area (m^2), L the thickness of the samples (m), T_h the temperature at the heating plate surface (K), and $\mathrm{T_C}$ is the temperature at the cooling plates surface (K)

In the case of electrical heating with direct current is the heat flow in "Watt", the voltage "U" in volts and the current "I" in ampere is measured at the clips of the heating plate.

$$\Phi_c = U \cdot I \tag{2}$$

The calculated thermal conductivity is referred to the average temperature "T" between the heated and cooled surfaces.

$$T = \frac{1}{2}(T_\mathrm{h} + T_\mathrm{C}) \tag{3}$$

After measuring of the thermal conductivity, the samples were dried to determine the moisture content of the plastering samples. The thermal conductivity values should be modified for dry by using the following equations:

$$\lambda_{10\ \mathrm{dry}} = \lambda_{10\ \mathrm{moist}} - (\mathrm{MC} * \lambda_{10\ \mathrm{moist}}) \tag{4}$$

$$\lambda_{\mathrm{dry}} = \lambda_{10\ \mathrm{dry}} + \lambda_{10\ \mathrm{dry}} * 0.2 \tag{5}$$

where $\lambda_{10\ \mathrm{moist}}$ is the moist thermal conductivity for the samples on wet basis of 10 °C (W/mK), $\lambda_{10\ \mathrm{dry}}$ the thermal conductivity on dry basis at temperature 10 °C (W/mK), λ_{dry} the thermal conductivity on dry basis (W/mK), and MC is the moisture content for dry weight.

2.5.2. Moisture content equation

The materials were dried according to DIN EN ISO [31]. The following equation was used to calculate the moisture content as follows:

$$\mathrm{MC}\ (\%) = \frac{(W_\mathrm{m} - W_\mathrm{d})}{W_\mathrm{d}} * 100 \tag{6}$$

where MC is the moisture content (%), W_m the moist weight (kg), and W_d is the dry weight (kg).

3. Results and discussion

3.1. Plaster material reinforced by wheat straw fibre

3.1.1. Measurements of moisture content and dry density

The average moisture content of plasters reinforced with wheat straw fibres are 2.78%, 1.3%, and 0.61% for reinforcement fibres 75%, 50%, and 25% respectively. These measurements were made after finishing the test. On the other hand, the average of dry densities of plasters reinforced with wheat straw fibres are

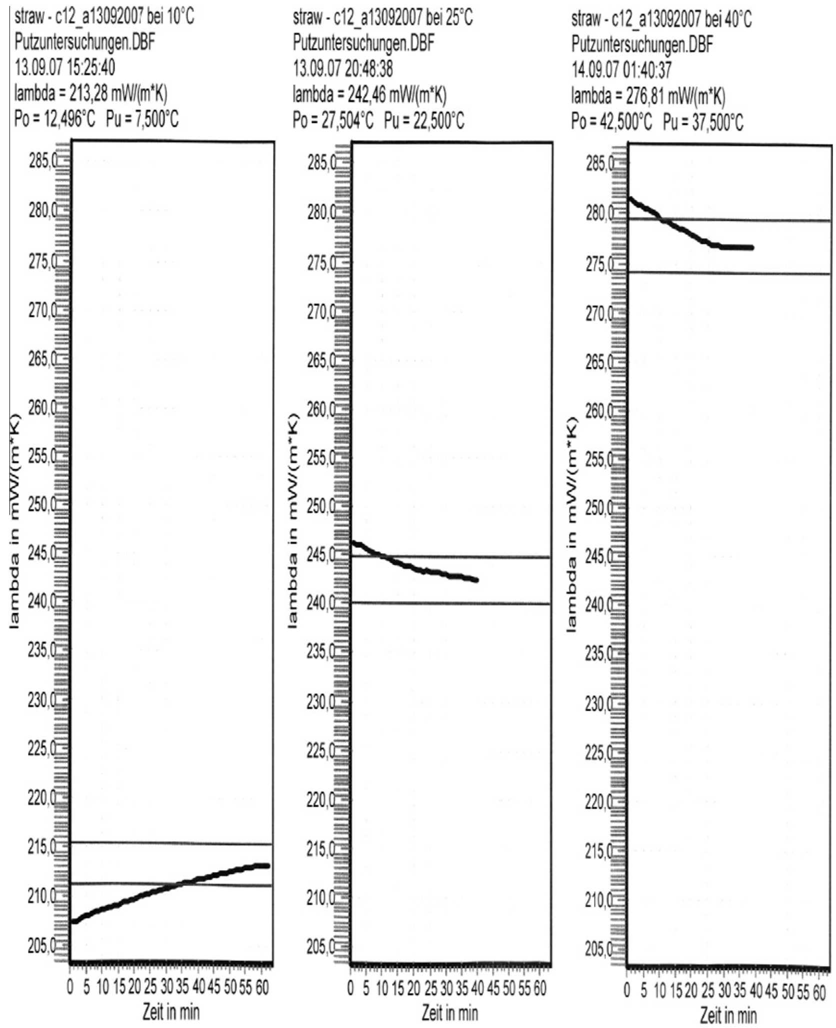


Fig. 5. Summarize the thermal conductivity steps measurements.

1123.89, 1416.31 and 1699.55 kg/m^3 for reinforcement fibres 75%, 50%, and 25% respectively. The results revealed that the moisture content increases with the wheat straw content. As may be expected, the dry density decreases with increasing fibre content.

3.1.2. Thermal conductivity

Fig. 7 shows the relationship between different recipes and the thermal conductivity of plaster reinforced by wheat straw fibres. Plaster materials density ranged from 949 to 1069 kg/m^3 with an average of 1000 ± 49 kg/m^3 for recipe A, while it is 1516–1527 kg/m^3 with an average of 1512 ± 26 kg/m^3 for recipe B. For recipe C, the plaster density is 1702–1759 kg/m^3 with an average of 1725 ± 28 kg/m^3.

The average thermal conductivity of recipe A is 0.1626, 0.1856 and 0.2118 W/mK for the test temperatures of 10, 25 and 40 °C respectively. For recipe B it is 0.22610, 0.24850 and 0.26810 W/mK, while for recipe C it is 0.27763, 0.30750 and 0.32975 W/mK for 10, 25 and 40 °C temperatures respectively.

The results indicated that increasing wheat straw fibres percentages from 0% to 75% caused an increase in thermal insulation to 43.9%, 43.4%, and 39.8% for temperatures of 10, 25 and 40 °C in a comparison with plaster material without reinforcement fibres.

Fig. 7 shows also that an increase of fibre content brings only marginal improvement in thermal insulation for all recipes under different temperature.

Thermal conductivity of dry basis at 10 °C ($\lambda_{10\ \mathrm{dry}}$) is 0.16210, 0.22660 and 0.27890 W/mK for recipes A, B and C respectively. While thermal conductivity at dry basis (λ_{dry}) of plaster reinforced by wheat straw fibre is 0.19448, 0.27189 and 0.33468 W/mK for recipes A, B and C respectively as shown in Fig. 8.

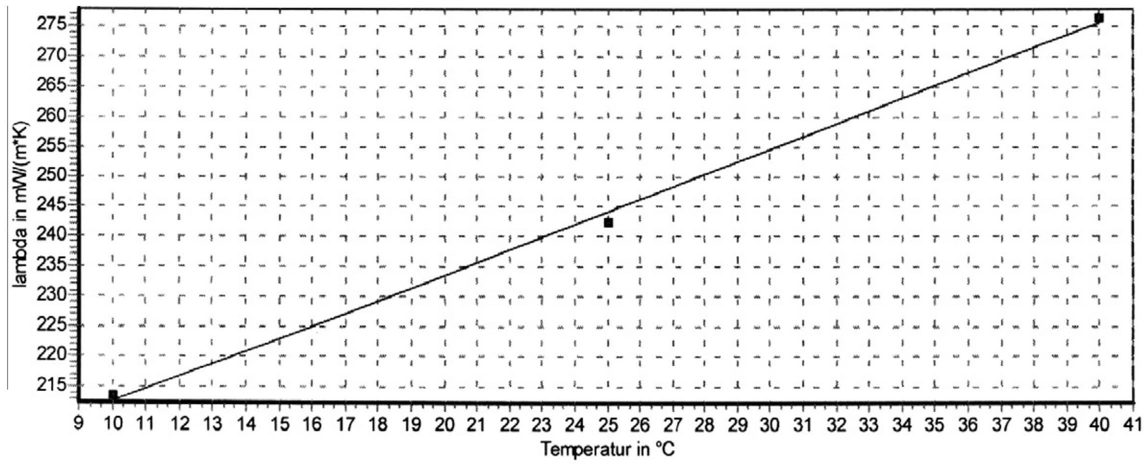
It is clear that the thermal conductivity of the plaster material reinforced with wheat straw fibre decreased with increasing fibre content, but it increased as sand content increased. It seems that the reinforcement fibres have greater effect on the thermal conductivity than the sand content.

The thermal conductivity results at dry basis (λ_{dry}) showed also that increasing wheat straw fibres percentages to 75% lead to thermal insulation increasing to 44.4%. Since both the fibre content and the sand content were changed simultaneously, it is difficult to separate the influence of each of them.

3.2. Plaster material reinforced by barley straw fibre

3.2.1. Measurements of moisture content and dry density

Plaster materials density ranged from 869 to 902 kg/m^3 with the average of 876 ± 17 kg/m^3 for recipe A, while it is 1352–1366 kg/m^3 with the average of 1359 ± 5 kg/m^3 for recipe B. The plaster density for recipe C is 1618–1734 kg/m^3 with the average of 11684 ± 44 kg/m^3.



	1. Messung	2. Messung	3. Messung
Versuchsnummer	c12_a1309200	c12_a1309200	c12_a1309200
Messtemperatur in °C	10	25	40
Temp.-Diff. in K	5	5	5
lambda in mW/m*K	213,31	242,43	276,67
R in m²K/W	0,256	0,225	0,197

Polynom
$y = f(T) = 2{,}1120 * T + 191{,}34$

lambda-10	212,46	mW/(m*K)
R-10	0,210	m²K/W
TK	2,112	mW/(m*K²)

Fig. 6. Software regression analysis and thermal conductivity (λ_{10}) value.

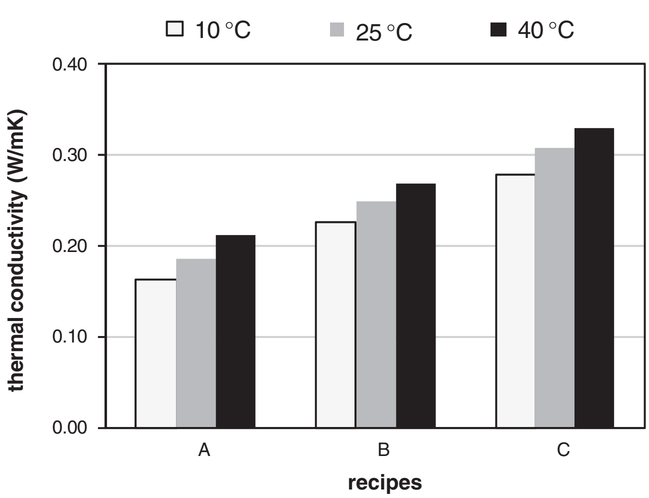


Fig. 7. Thermal conductivity of wheat straw plasters.

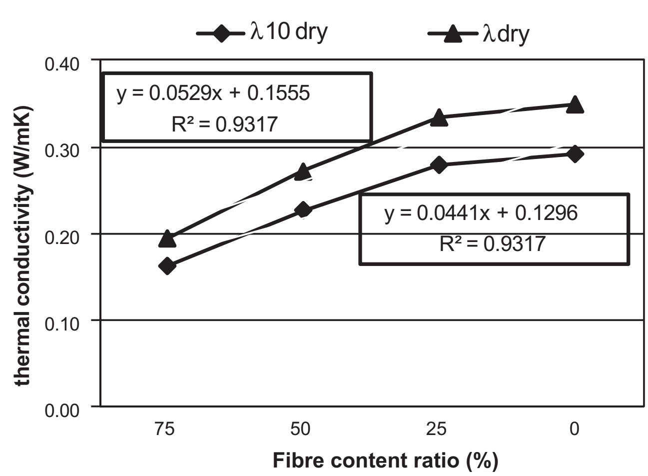


Fig. 8. Thermal conductivity of dry basis for wheat straw plasters.

3.2.2. Thermal conductivity

Fig. 9 shows the thermal conductivity of plaster material reinforced with barley straw fibres. The average thermal conductivity of recipe A is 0.12890, 0.14290 and 0.15920 W/mK for different temperatures of 10, 25 and 40 °C respectively. For recipe B it is 0.20016, 0.21899 and 0.23474 W/mK, and for recipe C it is 0.24678, 0.27469 and 0.29645 W/mK for 10, 25 and 40 °C temperatures respectively.

The results indicated that increasing barley straw fibre percentages from 0% to 75% caused an increase of thermal insulation to 55.5%, 56.1%, and 54.7% for the temperatures of 10, 25 and 40 °C compared with plaster material without reinforcement fibres.

Thermal conductivity of dry basis at 10 °C ($\lambda_{10\ dry}$) was 0.12856, 0.20067 and 0.24780 W/mK for recipes A, B and C respectively. Thermal conductivity at dry basis (λ_{dry}) of plaster reinforced with barley straw fibre is 0.15427, 0.24080 and 0.29736 W/mK for recipes A, B and C respectively as shown in Fig. 10.

The thermal conductivity of the plaster material reinforced by barley straw plaster decreased with increasing fibre but it increased with increasing sand content. It seems that the reinforcement fibres have greater effect on the thermal conductivity.

The results of thermal conductivity at dry basis (λ_{dry}) for plaster reinforced by barley straw fibres revealed also that increasing of barley straw fibre percentages to 75% lead to thermal insulation increasing to 55.9%. Our tests show that the reinforcement fibres have a large effect on the thermal conductivity of plasters, which is of great importance for straw bale buildings. In straw bale buildings, the plasters are usually used as cladding for the straw bale

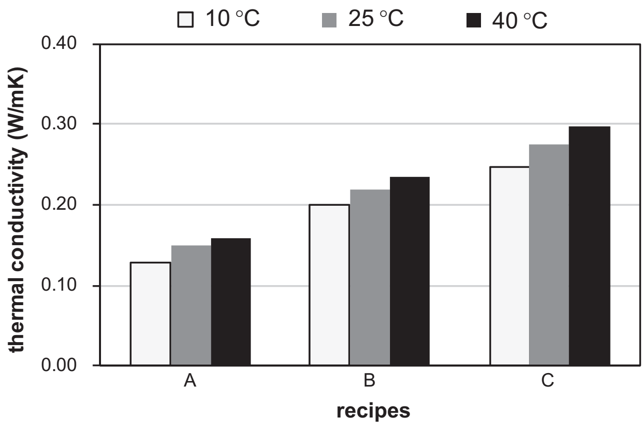


Fig. 9. Thermal conductivity of barley straw plasters.

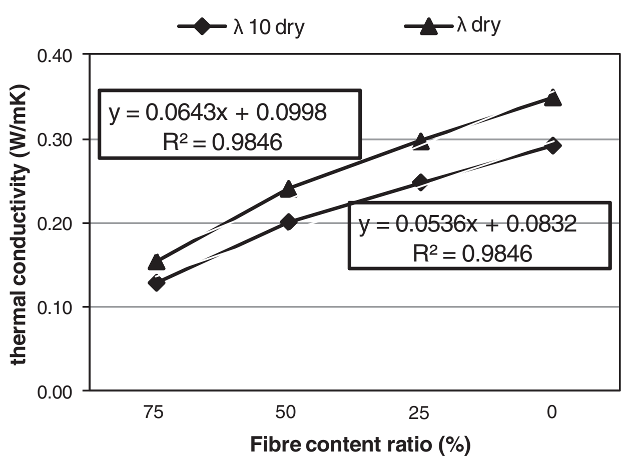


Fig. 10. Thermal conductivity of dry basis for barley straw plasters.

walls (both interior and exterior). The plasters and the straw bales can be regarded as a composite panel.

3.3. Plaster material reinforced by wood shavings fibre

3.3.1. Measurements of moisture content and dry density

Plaster materials density ranged from 1273 to 1336 kg/m^3 with the average of 1311 ± 33 kg/m^3 for recipe A, while it was 1397–1436 kg/m^3 with the average of 1419 ± 20 kg/m^3 for recipe B. The plaster density for recipe C is 1605–1729 kg/m^3 with the average of 1672 ± 62 kg/m^3.

3.3.2. Thermal Conductivity

Fig. 11 shows the thermal conductivity of plaster material reinforced with wood shavings fibres. The average thermal conductivity of recipe A is 0.19440, 0.21078 and 0.22563 W/mK for 10, 25 and 40 °C respectively. While for recipe B thermal conductivity is 0.20737, 0.22587 and 0.24296 W/mK, while for recipe C it is 0.23343, 0.25966 and 0.28033 W/mK for the temperatures of 10, 25 and 40 °C respectively.

The results indicated that increasing wood shavings fibre percentages from 0% to 75% caused an increase in thermal insulation to 33.0%, 35.2%, and 35.8% for temperature 10, 25 and 40 °C compared with plaster material without reinforcement fibres.

Thermal conductivity of dry basis at 10 °C ($\lambda_{10\ \mathrm{dry}}$) for plaster reinforced with wood shavings fibre is 0.19465, 0.20759 and 0.23435 W/mK for recipes A, B and C respectively. Furthermore, thermal conductivity at dry basis (λ_{dry}) of plaster reinforced with

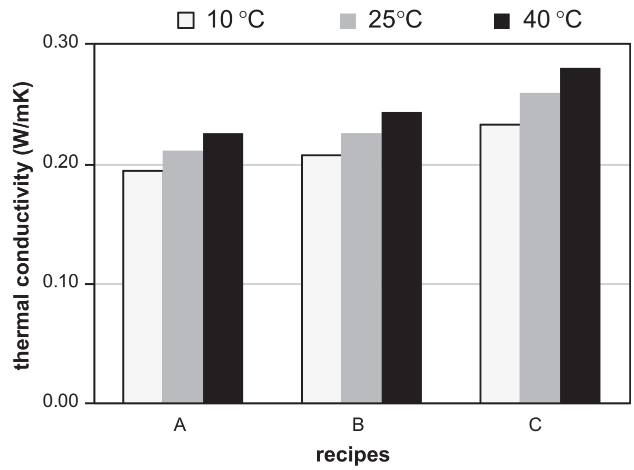


Fig. 11. Thermal conductivity of wood shavings plasters.

wood shavings fibre is 0.23358, 0.24911 and 0.28122 W/mK for recipes A, B and C respectively as shown in Fig. 12.

It can be seen that the thermal conductivity of the plaster material reinforced by wood shavings plaster decreased with increasing the fibres but it increased with increasing sand content.

The results of thermal conductivity of dry basis (λ_{dry}) showed also that increasing wood shavings fibres percentages to 75% lead to a 33.2% increase in thermal insulation.

The thermal conductivity of plasters with wood shaving is slightly higher than those with wheat straw, although the wood shaving fibre is substantially shorter than the wheat straw fibres. Also, the density of wood shavings is higher than that of wheat or barley straw. We believe that the high density of wood shaving fibres is responsible for its higher thermal conductivity or lower insulation than other materials.

A comparison among Figs. 8, 10 and 12 shows that thermal conductivity of dry basis (λ_{dry}) increases almost with fibre content. The best regression equation is a linear equation. The coefficient of determination of all regression equations are high values. The best correlation coefficient 98.46 is obtained for plaster reinforced by barley straw fibres.

3.4. Without reinforcement fibre

Plaster material density ranged from 1743 to 1801 kg/m^3 with the average of 1790 ± 30 kg/m^3 for recipe D. The average of thermal conductivity is 0.25942, 0.29875 and 0.31946 W/mK for 10, 25 and 40 °C respectively. The thermal conductivity of dry basis at 10 °C ($\lambda_{10\ \mathrm{dry}}$) for plaster without reinforcement fibre is 0.29149 W/mK, while it is 0.34979 W/mK for dry basis (λ_{dry}).

3.5. Comparison between the different plaster materials under study

3.5.1. Sample density

The average of dry densities of plaster with 75% fibre content were 1123.9, 1100, and 1273 kg/m^3 for plaster reinforced with wheat, barley and wood shavings respectively. For plasters with 50% fibre content, the average of dry densities were 1416.3, 1402, and 1397.5 kg/m^3 for plaster reinforced with wheat, barley and wood shavings fibre respectively. For plasters with 25% fibre content the average of dry densities are 1699.6, 1617.7 and 1605.1 kg/m^3 for plaster reinforced with wheat, barley and wood shavings fibres respectively.

The average density of plaster without reinforcement fibres is 1804 kg/m^3. The results indicate that the plaster density decreases with increasing fibre content. The dry density of plaster reinforced

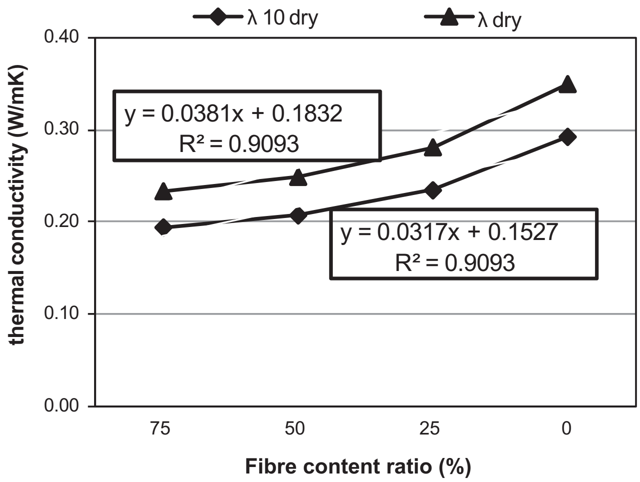


Fig. 12. Thermal conductivity of dry basis for wood shavings plasters.

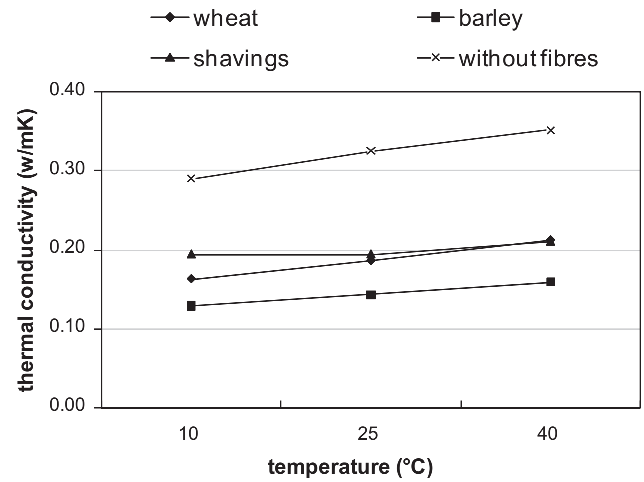


Fig. 13. Thermal conductivity of different plaster materials for treatment A.

with wood shavings is slightly higher than those with wheat and barley straw. This may be due to the fact that the shavings are finer than wheat or barley straw fibres. Also wood shavings have a more lignin and a greater solid composition than wheat and barley straw fibres.

3.5.2. Moisture content

The average moisture content of plaster with 75% fibre contents are 2.78%, 2.68% and 1.11% for plaster reinforced with wheat, barley and wood shavings respectively. For plasters with 50% fibre content, the average moisture contents are 1.3%, 1.04%, and 0.87% for plaster reinforced with wheat, barley and wood shavings fibres respectively. For plasters with 25% fibre content, the average moisture contents are 0.61%, 0.8%, and 0.51% for plaster reinforced by wheat, barley and wood shavings respectively. This compares with the average moisture content of plaster without fibre being about 1.11%. The results confirm that the moisture content increases with increasing fibre content. We believe that the fibres absorb more water than soil. The moisture content for plaster reinforced by wheat and barley straw fibre are slightly higher than plaster reinforced by wood shavings.

3.5.3. Thermal conductivity

Fig. 13 shows the relationship between the thermal conductivity of different plaster materials and different temperatures 10, 25, 40 °C. It can be seen that the thermal conductivity increased gradually with increasing temperature.

For recipe A, thermal conductivity is 0.16260, 0.12894, 0.19440 and 0.289965 W/mK at 10 °C for plaster reinforced by wheat, barley wood shavings and without fibres respectively. While at 25 °C, thermal conductivity is 0.18560, 0.14293, 0.21078 and 0.32532 W/mK for wheat, barley, wood shavings sand plaster respectively. On the other hand, thermal conductivity at 40 °C is 0.21180, 0.15922, 0.22563 and 0.35155 W/mK of plaster reinforced with wheat, barley, wood shavings and without fibres respectively (Fig. 13).

For recipe B, the values of thermal conductivity is 0.22610, 0.20016, 0.20737 and 0.289965 W/mK at 10 °C for plaster reinforced with wheat, barley, wood shavings and without fibres respectively. While at 25 °C, thermal conductivity is 0.24850, 0.21899, 0.22587 and 0.32532 W/mK for wheat, barley, wood shavings and plasters without fibres respectively. Thermal conductivity at 40 °C is 0.26810, 0.23474, 0.24296 and 0.35155 W/mK of plaster reinforced with wheat, barley, wood shavings and sand respectively (Fig. 14).

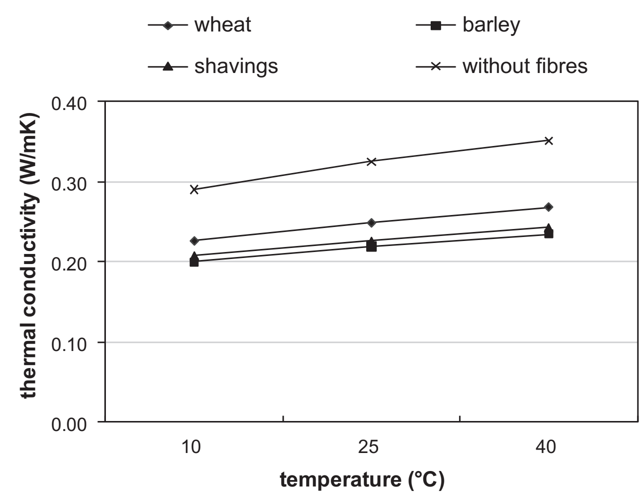


Fig. 14. Thermal conductivity of different plaster materials for treatment B.

For recipe C thermal conductivity is 0.27763, 0.24678, 0.23343 and 0.28997 W/mK at 10 °C temperature for plaster reinforced with wheat, barley, wood shavings and without fibres respectively. Whilst at 25 °C, thermal conductivity is 0.30750, 0.27469, 0.25966 and 0.32532 W/mK for wheat, barley, wood shavings and plaster without fibres respectively. Thermal conductivity at 40 °C is 0.32975, 0.29645, 0.28033 and 0.35155 W/mK of plaster reinforced with wheat, barley, wood shavings and without fibres respectively (Fig. 15).

It is interesting to observe that the lowest thermal conductivity was obtained by plaster reinforced by barley straw fibre. This may be because the barley bales contain finer particles than wheat bales which were more resistant to the heat transfer.

Fig. 16 shows the relationship between dry bases at 10 °C for plasters with different reinforcement fibres. Thermal conductivity of dry basis at 10 °C ($\lambda_{10\ dry}$) for recipe A is 0.16207, 0.12856, 0.19465 and 0.29149 W/mK of wheat, barley, wood shavings and without fibres plaster respectively. While for recipe B, it is 0.22660, 0.20067, 0.20759 and 0.29149 W/mK for wheat, barley, wood shavings and without fibres plaster respectively. $\lambda_{10\ dry}$ for recipe C is 0.27890, 0.24780, 0.23435 and 0.29149 W/mK for plaster reinforced with wheat, barley, wood shavings and without fibres respectively.

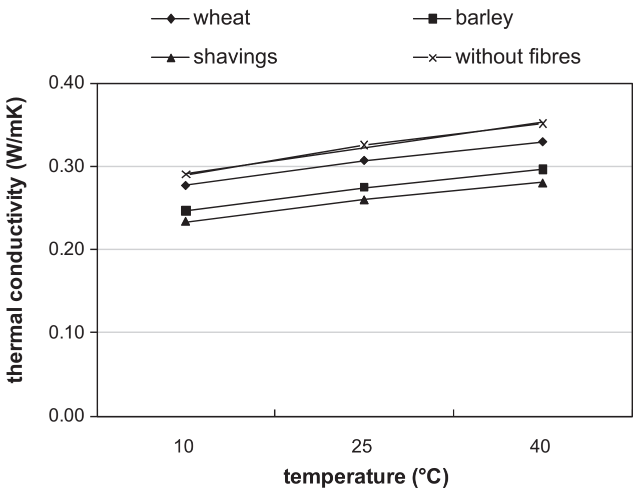


Fig. 15. Thermal conductivity of different plaster materials for treatment C.

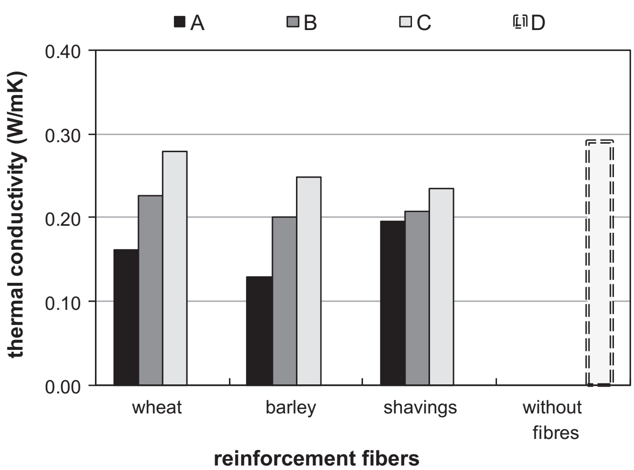


Fig. 16. Thermal conductivity ($\lambda_{10\ dry}$) of different plaster materials.

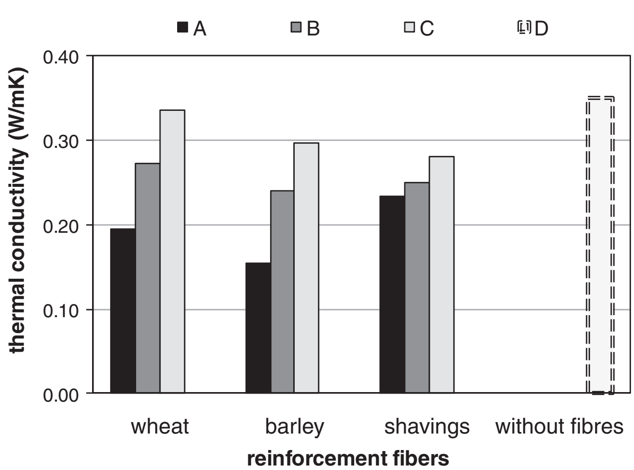


Fig. 17. Thermal conductivity (λ_{dry}) of different plaster materials.

Thermal conductivity of dry basis (λ_{dry}) for recipe A is 0.19448, 0.154272, 0.23358 and 0.34979 W/mK for wheat, barley, and wood shavings and without fibres plaster respectively. λ_{dry} for recipe B is 0.27189, 0.24080, 0.24911 and 0.34979 W/mK for wheat, barley, and wood shavings and without fibres plaster respectively. λ_{dry} for recipe C is 0.33468, 0.29736, 0.28122 and 0.34979 W/mK of plaster reinforced with wheat, barley, wood shavings and without fibres respectively (Fig. 17).

When the straw fibres increased to the percent of 75% and the sand percent decreased to 0% (recipe A), thermal insulation increased to 44.4%, 55.9%, and 33.2% for plaster reinforced with wheat straw, barley straw and wood shavings fibres respectively. For recipe B, thermal insulation increased to 22.3%, 31.2%, and 28.8% for plaster reinforced with wheat straw fibre, barley straw and wood shavings respectively. The results revealed that plaster reinforced by barley straw fibres had the highest values of thermal insulation.

Generally, thermal conductivity for plaster reinforced by wood shavings is higher than plaster reinforced by wheat and barley straw fibres. The highest thermal resistance is obtaining from the plaster reinforced by barley straw fibres.

4. Conclusion and recommendations

Thermal conductivity of dry basis at 10 °C ($\lambda_{10\ dry}$) for recipe A is about 0.16207, 0.12856, 0.19465 and 0.29149 W/mK for wheat, barley, wood shavings and unreinforced fibre plasters respectively. For recipe B, it is about 0.22660, 0.20067, 0.20759 and 0.29149 W/mK for wheat, barley, wood shavings and unreinforced fibre plasters respectively. $\lambda_{10\ dry}$ for recipe C is 0.27890, 0.24780, 0.23435 and 0.29149 W/mK of plaster reinforced with wheat, barley, wood shavings and without fibres respectively.

The thermal conductivity of dry basis (λ_{dry}) for recipe A is 0.19448, 0.154272, 0.23358 and 0.34979 W/mK of wheat, barley, wood shavings and without fibres plaster respectively. On the other hand λ_{dry} for recipe B is 0.27189, 0.24080, 0.24911 and 0.34979 W/mK for the same materials. Furthermore, λ_{dry} for recipe C is 0.33468, 0.29736, 0.28122 and 0.34979 W/mK of the same plaster materials.

By increasing the fibre content to about 75% and removing sand (recipe A), the thermal insulation is increased to about 44.4%, 55.9% and 33.2% for plaster reinforced with wheat straw, barley straw and wood shaving fibres respectively. For recipe B the thermal insulation is increased to about 22.3%, 31.2% and 28.8% for plaster reinforced with wheat straw fibre, barley straw and wood shavings respectively.

The results revealed that the thermal conductivity of the plaster material decreases with increasing fibre content and decreasing sand content. The reinforcement fibres have greater effect on the thermal conductivity than the sand content. Our results show that plaster reinforced by barley straw fibre possesses the highest thermal insulation.

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