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Thermal conductivity of unfired earth bricks reinforced by agricultural wastes with cement and gypsum

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ABSTRACT

Energy-efficiency of sustainable constructions and buildings are evaluated based upon the heating and cooling demands, but also according to the primary-energy demand, CO_2 savings potential, and the ecological properties of building materials. To meet increasingly rigorous requirements, the demand for natural building materials is growing rapidly. The research objective of the here presented study is to stabilize soils with natural straw fibres to produce a composite, sustainable, non-toxic and locally sourced building material. The material appropriateness was determined by establishing the thermal conductivity of a selection of unfired earth bricks that were identified as potential new natural building materials. The thermal conductivity is an essential material characteristic to achieve the required insulation level and for market success as a new product. The earth bricks consist of soil, cement, gypsum and straw fibres. Straw was applied as fibre reinforcement for unfired bricks. Two fibre types were used: wheat and barley straw. The results indicated that the thermal conductivity of all investigated variants decreased with increasing fibre content while increasing with higher cement and gypsum contents. They also show that barley straw fibre reinforced bricks exhibited the highest thermal insulation values. The addition of fibre positively improves both, thermal and static properties.

1. Introduction

The promotion of sustainable development has put pressure on all industries, including the construction industry to adopt and implement proper methods to protect the environment. The construction building process requires high energy input and causes a wide range of quantifiable environmental side effects including greenhouse gas emissions, large amounts of water use, as well as solid and liquid waste production.

Due to current global concerns for sustainable development that have arisen from extensive environmental problems such as climate change and the impoverishment of resources coupled with the rapid pace of technological advancement within the building sector, interest in alternative building materials such as earth has developed. Most building regulations have increasingly strict criteria for the thermal performance of buildings, including building ecology and sustainability. Soil as a building material has good physical properties when considering energy-conscious and ecological design, and also fulfils all strength and serviceability requirements for thermal transmittance, i.e. thermal value.

The pressure to build energy efficient buildings is increasing due to the current sustainability alert worldwide. The bulk of energy is consumed in the residential building sector, where heating and cooling are the predominant end uses and the adoption of air-conditioning has increased dramatically in recent years [1].

In addition, recent studies to determine the thermal conductivity of building materials have increased for a wide range of temperatures, from low to moderately high temperature, as new materials are developed and new applications for existing materials are discovered. Today, it is often insufficient to obtain approximate data from textbooks; real sample measurements are necessary and the rapid technology developments during the last decades have generated an increasing effort to expand our knowledge of the transport properties in various materials [2].

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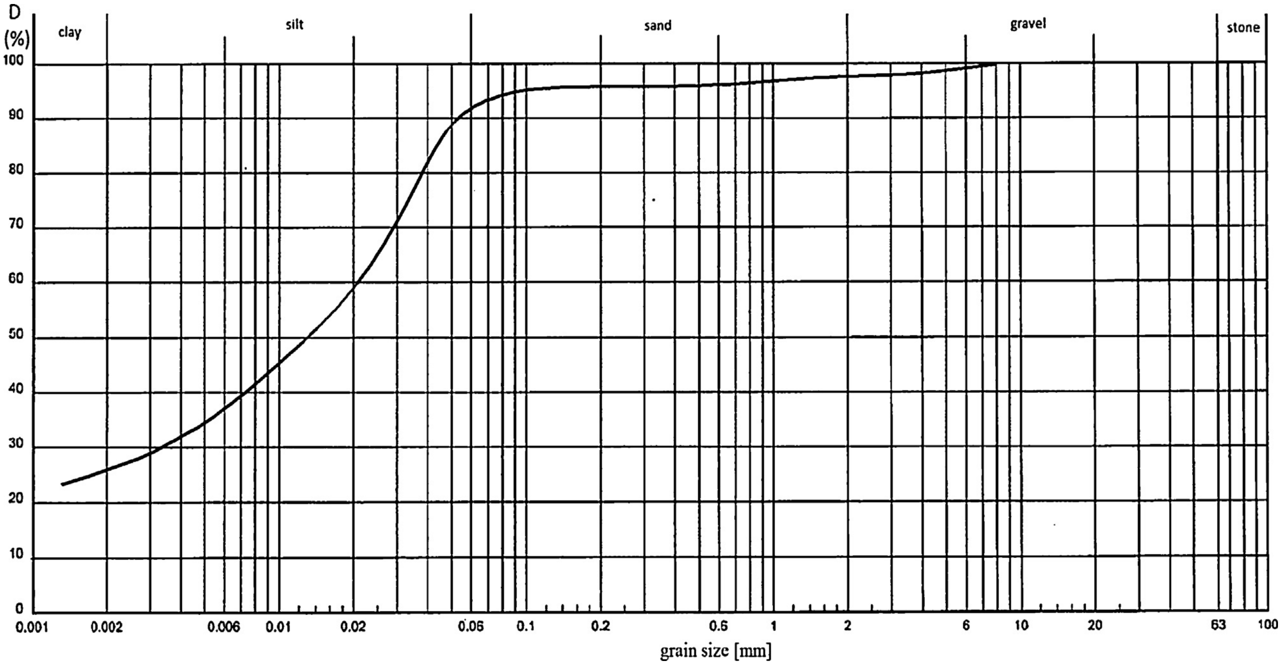

Fig. 1. The grain size distribution of the tested soil.

Fig. 2. Electrical mixer for different materials.

A straw bale house located in Bavaria, Germany was evaluated by Ashour et al. [3]. An extensive test program was carried out where the evaluation parameters included tests for compression strength, moisture content determination, thermal stability of bales, and pH. In-situ monitoring included temperature and relative humidity measurements inside the straw bale wall. The results revealed that wheat and barley straw could be used as an excellent insulation material. Agoudjil [4] reported that date palm wood is also a good candidate to develop efficient and non-toxic insulation materials when compared to other natural materials.

On the other hand, faced with the worldwide shortage of forest resources, the building industry is showing increasing interest in particleboard production from agricultural waste products [5]. Wheat straw has high fibre content showing good potential to replace wood in particleboard fabrication. Particleboard with a density range from 0.59 to 0.8 g/cm^3 is designated as medium-density particleboard [6]. It has broad applications for both structural and non-structural uses. Barley straw is another significant raw material used in cellulose production as an energy resource [7–12]. The thermal conductivity of straw bales ranged from 0.0414 to 0.0486 and 0.0353 to 0.0539 W/m K for all straw bale densities at various temperatures for wheat and barley straw bales, respectively. The average thermal conductivity values and thermal resistances at both 20.7 °C and 34.2 °C were much higher than those of at 10.3 °C. The thermal conductivity values and the thermal resistance values exhibit greater change as temperature changed from 10.3 to 20.7 °C than those values when temperature changed from 20.7 to 34.2 °C [13]. In [14], the thermal conductivity of wheat straw bales was measured and the thermal resistance was found to be 0.046 W/m K. A lightweight straw loam with a density of 750 kg/m^3 had a λ-value of 0.20 W/m K, whereas a lightweight expanded loam with a density of 740 kg/m^3 had a λ-value of 0.18 W/m K. The specific heat for the same material was 1.0 kJ/kg K [15].

On the other hand, the influence of straw fibres on the thermal conductivity for earth plaster was studied by Ashour et al. [16]. The thermal conductivity of barley straw reinforced plaster was 0.154, 0.241 and 0.297 W/m K for fibre content of 75, 50 and 25%, respectively. The results also showed that by increasing the fibre content of barley straw to 75% resulted in increasing the thermal insulation capacity to 44.4% since both the fibre content and the sand content were changed simultaneously. Zach et al. [17–19] studied the possibility of using jute, flax, and hemp to develop a new insulating material from renewable resources with comparable building physics and mechanical properties to commonly used insulation materials. All input components were varied in the tests. The impact of moisture content changes in relation to the change rate of other properties was the focus of the investigation. The test results show that the correct combination of natural materials is comparable to the physical performance of conventional building materials. Thermal expansion coefficients for heavy loam plaster were 0.0043 to 0.0052 mm/m K; for mud brick masonry, thermal expansion coefficients were up to 0.0062 mm/m K; for sandy mud mortar the thermal expansion coefficient was 0.005 mm/m K; and strong cement mortar exhibited a thermal expansion coefficient of 0.01 mm/m K, the same as a concrete [20]. Insulation is rated by its *R*-value, the resistance to heat flow. The *R*-value of wood is 1.0 per inch (0.15 W/m K), brick is 0.20 per inch (0.734 W/m K), and fibreglass bats are 3.0 per inch (0.05 W/m K). 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 [21]. The insulation value for the straw bale walls was estimated in [22]. The *R*-value for the straw bale walls was R-44 (0.04 W/m K). The thermal properties of sustainable earth materials using a novel thermal probe technique involving an iterative data analysis method for simultaneously determining the thermal conductivity and diffusivity were discussed in [23,24]. The viability of using coconut fibre as a thermal insulation for buildings was explored by conducting thermal conductivity tests on 200 × 400 × 60 mm slab specimens. The thermal conductivity was 0.058 W/m K which occurred at an optimum density of 85 kg/m^3 at 38 °C [25]. Hot wire methods are most commonly used to measure the thermal conductivity of "refractories" such as insulating bricks. Because it is basically a transient radial flow technique, isotropic specimens are required. The technique has been used in a more limited way to measure properties of liquids and plastic materials of relatively low thermal conductivity. The hot wire method was established to meet the test methodologies specified in the American Society for Testing and Materials (ASTM) Standard Test Methods C 1113 [26]. Within the framework of here presented investigations, the earth bricks were stabilized and thermally improved by the addition of natural fibres. The fibre addition positively improves not only thermal but also mechanical properties. The investigations regarding the mechanical properties will be presented in a future paper. This article presents the results of an investigation into the thermal conductivity of earth bricks made from earth, cement, and gypsum reinforced with wheat and barley straw natural fibres with different mixing ratios.

2. Materials and methods

2.1. Materials tested

In this investigation four different materials were used, i.e. cohesive soil, cement, gypsum and reinforcement fibres. The composition of the cohesive soil texture is 28.7% clay, 63.3% silt, 3% gravel and 5% sand. Two different fibre types, wheat and barley straw, were applied for reinforcement. The average straw length was approximately 4 cm.

2.2. Sample preparation

At first, oversized gravel and organic matter (grass roots) were removed from the natural cohesive soil. The soil samples were put in an oven to dry at a temperature of 105 °C to obtain the soil dry weight at a constant mass. To analyse the composition of clay minerals in the material an X-ray diffraction clay mineral analysis was performed. Type and amount of these clay minerals have a crucial influence on the binding force and therefore also on the bending tension and compressive strength. The content of clay minerals can be given as follows: 50% smectite (low binding force), 30% illite (high binding force), 10% kaolinite (high binding force) and 10% vermiculite (medium binding force). Fig. 1 illustrates the grain size distribution of the tested soil. The natural fibres were also oven dried at 105 °C to obtain a constant mass.

A variety of earth bricks with different compositions of cohesive soil, cement, gypsum and fibre were used in the tests. The dosing of different materials was controlled by the dry weight. The amount of soil, cement, gypsum and fibre of a given mixture were placed in a mechanical mixer and dry blended for circa 20 min until the different materials were homogeneously combined. Afterwards, water was sprayed over the mixture until 24% moisture content level was achieved. The materials were again blended using an electric mixer for approximately 30 min until a homogenous mixture was obtained (Fig. 2).

Earth bricks from different mixtures combined with different natural fibres that were used in the thermal conductivity tests are given in Table 1. The material compositions in Table 1 are given as a percentage of earth material dry weight.

The soil–fibre mixture was then poured into a steel mould and compacted in a press. The steel mould dimensions have a length of 24 cm, by width of 12 cm, and height of 6 cm (see Fig. 3). The surface

Table 1
Recipes of earth bricks.

Earth bricks recipes	Clay (%)	Barley (%)	Wheat (%)	Cement (%)	Gypsum (%)
Clay	100	–	–	–	–
B_1	99	1	–	–	–
W_1	99	–	1	–	–
B_3	97	3	–	–	–
W_3	97	–	3	–	–
B_1C_5	94	1	–	5	–
W_1C_5	94	–	1	5	–
B_1C_{10}	89	1	–	10	–
W_1C_{10}	89	–	1	10	–
B_3C_5	92	3	–	5	–
W_3C_5	92	–	3	5	–
B_3C_{10}	87	3	–	10	–
W_3C_{10}	87	–	3	10	–
B_1G_5	94	1	–	–	5
W_1G_5	94	–	1	–	5
B_1G_{10}	89	1	–	–	10
W_1G_{10}	89	–	1	–	10
B_3G_5	92	3	–	–	5
W_3G_5	92	–	3	–	5
B_3G_{10}	87	3	–	–	10
W_3G_{10}	87	–	3	–	10

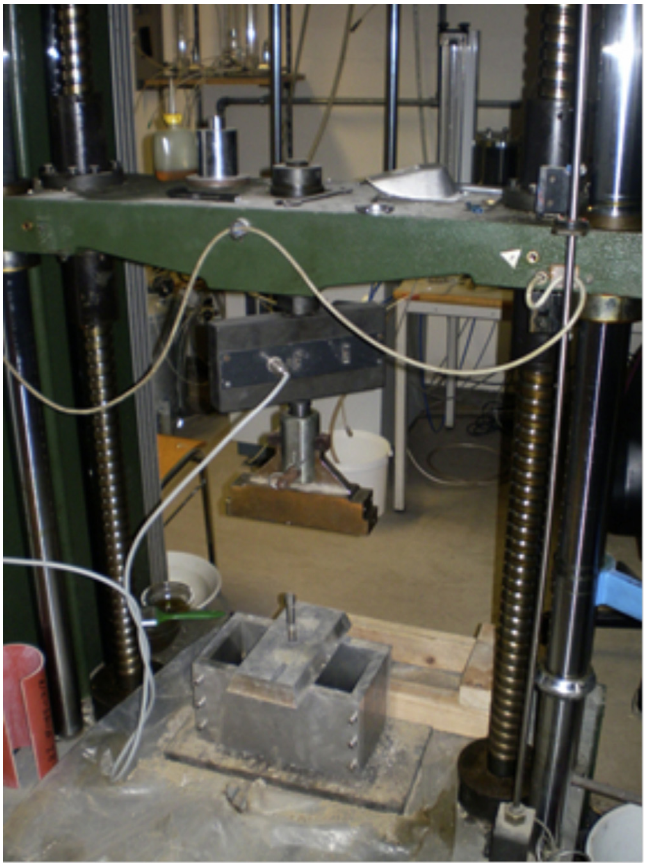

Fig. 3. Earth bricks preparation under compression.

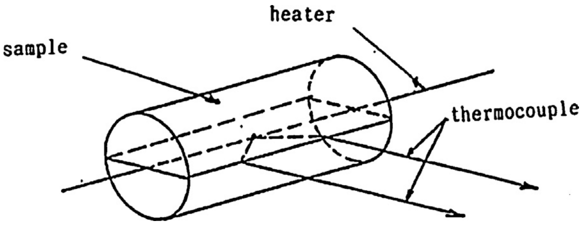

Fig. 4. Hot wire apparatus.

Table 2
Specifications of thermal conductivity equipment.

Items	Specifications
Model	QTM-500 quick thermal conductivity meter
Measurement method	Hot wire method
Reading range	0–150 W/m K
Ambient condition	5 to 35 °C, below 85% RH
Record output	−3.55 mV to 41.3 mV (CA-thermocouple −100 to 1000 °C)
Warming-up time	Approximately 30 min
Repeat mode	Maximum 100 times
Memory of data	Maximum 100 measurement results stored
Power consumption	70 W
Power source	AC100 to 240 V 50/60 Hz
Weight	8.5 kg

was levelled and compressed using a loading plate connected to a mechanical press under a force of circa 100 kN. The instrument press rate on the bricks was 0.2 mm/min. After pressing, the steel mould was lifted, leaving the brick sample on the wood board. The samples were allowed to dry slowly to avoid cracking. This bricks were dried under controlled lab room conditions for 60 days. The average temperature and relative humidity inside the laboratory room throughout drying process were 21.7 °C and 56.1%.

2.3. *Hot wire apparatus*

The hot wire apparatus is widely accepted as the primary apparatus to determine the apparent thermal conductivity of insulating materials. The QTM-500 quick thermal conductivity meter has been used for the experiments. When a heated wire is extended through the centre of a homogenous endless cylindrical sample and given constant power (heat), the temperature of the wire will rise at an exponential rate per unit time (Fig. 4).

The hot and cold plates maintain the boundary condition constants (temperature) in the external and internal specimen surfaces. In the ideal case, the plates are in perfect thermal contact with the specimen and one-dimensional heat flow through the material occurs independent of time. The specifications of the QTM-500 thermal conductivity λ-meter can be seen in Table 2.

2.4. *Test procedure*

Sixty three brick samples of different compositions and materials were used for the thermal conductivity tests. The samples were prepared using the steel frame presented in Fig. 3.

For each straw type and each treatment, three identical material samples were used. A thirty samples of each fibre type were used as shown in Fig. 5. After drying, the samples were stored under lab room conditions, 21.7 °C and 56.1% for 60 days. The samples were then placed in the oven to dry at 70 °C until constant weight was achieved. This means that thermal conductivity values were measured for drying samples (dry λ-value).

Fig. 5. Samples after preparation.

Fig. 6. Thermal conductivity instrument.

The QTM-500 λ-Meter from the brand 'Kyoto Electronics' was used to measure thermal conductivity as showed in Fig. 6 and Table 2. A constant electrical current is applied to a pure platinum wire placed between two brick. The rate at which the wire heats is dependent upon how rapidly heat flows from the wire into the constant temperature mass of the refractory brick. The rate of temperature increase of the platinum wire is accurately determined by measuring its increase in resistance in the same way a platinum resistance thermometer is used. A Fourier equation is used to calculate the *k*-value based on the rate of temperature increase of the wire and power input. The samples were measured from four sides of the sample surface. The thermal conductivity for each sample was obtained by calculating the average thermal conductivity measured on the four sides and from several test points on the sample. The average for the three brick samples of each composition was then calculated.

2.5. *Mathematical equation*

2.5.1. *Thermal conductivity*

The thermal conductivity was determined according to ASTM C 1113-99 [26].This test method covers the determination of thermal conductivity of non-carbonacious, dielectric refractories. Applicable refractories include refractory brick, refractory castables, plastic refractories, ramming mixes, powdered materials, granular materials, and refractory fibres.

Thermal conductivity *k*-values can be determined from room temperature to 1500 °C, or the maximum service limit of the refractory, or to the temperature at which the refractory is no longer dielectric. The values stated in SI units are to be regarded as standard. The data were taken from the data logger and thermal conductivity was calculated using the software from the λ-instrument. Thermal conductivity was calculated using the following equation.

$$\lambda = q \times \ln\left(\frac{t_2}{t_1}\right)(T_2 - T_1) \qquad (1)$$

where λ is the thermal conductivity of the sample (W/m K), q is the thermal unit of heater per time and length (W), t_1, t_2 is time (s), T_1, T_2 is temperature at t_1, t_2 (K).

2.5.2. *Moisture content equation*

The materials were dried according to [27]. The following equation was used to calculate the moisture content (MC):

$$\text{MC} \quad (\%) = \frac{(W_m - W_d)}{W_d} \times 100 \qquad (2)$$

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

3. Results and discussion

3.1. *Microstructure of earth bricks*

The fibre distribution of the brick surfaces are shown in Fig. 7a and b. The figures represent the typical SEM images taken at the top surface of the block. The figures showed that the fibres are uniformly distributed inside the brick samples. It can be noticed that the straw particle directions are arranged in different directions within the sample.

3.2. *The effect of fibre reinforcement, cement and gypsum on earth brick density*

Fig. 8 shows the relationship between different brick compositions and the dry densities of unfired wheat straw reinforced earth bricks stabilized with cement and gypsum. The effect of the fibre content on density is shown in Fig. 8a. As expected, the dry density decreased when the fibre quantity content increased. It is well demonstrated that the new blocks manufactured with wheat straw fibre have a relatively high density varying between 1575.6 and 1357.7 kg/m^3 for 1% and 3% fibre contents. This corresponds to a

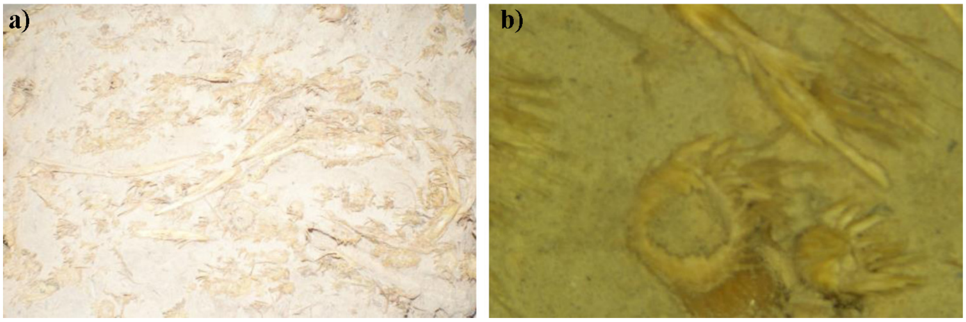

Fig. 7. Fibres distribution inside the bricks, (a) cross section showed fibres distribution, (b) SEM image of fibres reinforcement distribution inside the earth bricks.

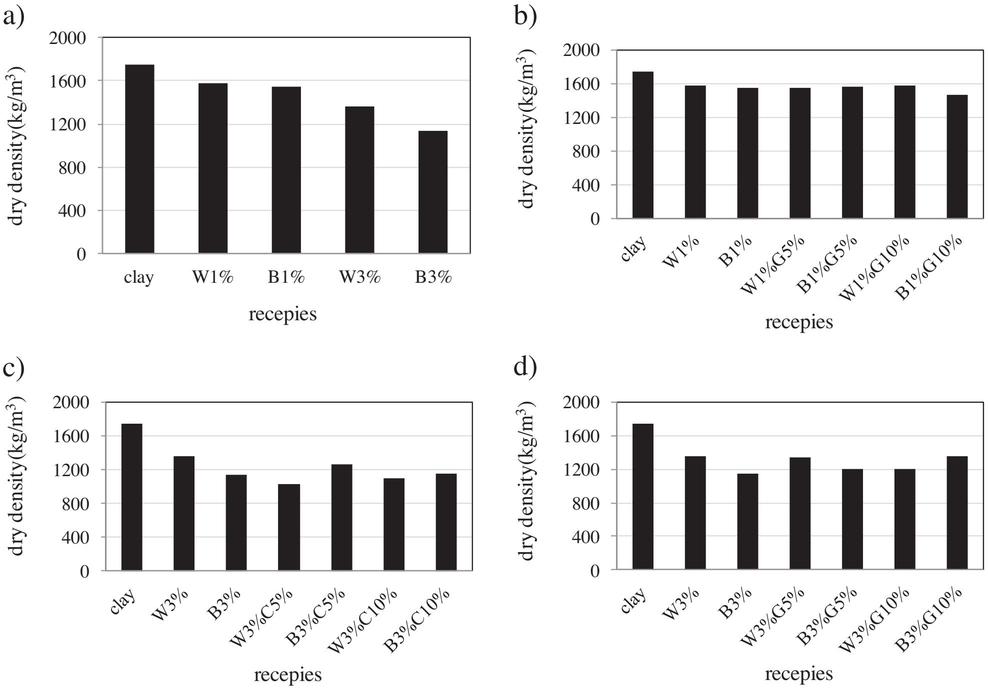

Fig. 8. The effect of fibres, cement and gypsum content on the bricks densities, (a) effect of fibre content, (b) cement content at 1% fibre, (c) cement content at 3% fibre, and (d) gypsum content at 3% fibres.

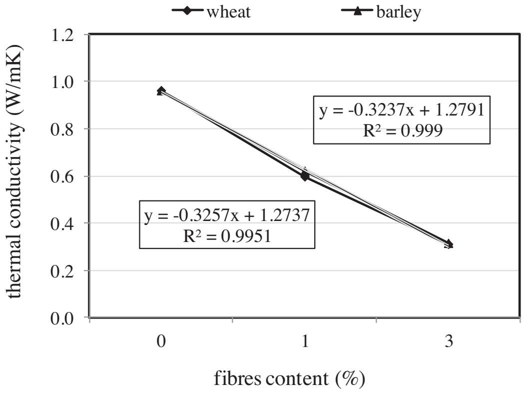

Fig. 9. The influence of different percentages of fibres content on the thermal conductivity of bricks.

decrease of about 9.8% to 22% in comparison with non-fibrous clay bricks.

For bricks reinforced by barley straw fibres, it can be seen that the density ranged between 1542.5 to 1139.9 kg/m^3. This means that the density decreased from 11.6 to 34% when the fibre content increased from 1% to 3%. It could be noticed that the brick densities reinforced with wheat straw are higher than bricks reinforced with barley straw. This may be due to wheat straw containing more solid material and lignin than barley straw. The average brick densities stabilized with cement are 1409 and 1319 kg/m^3 for 5% and 10% cement content at 1% fibre content. Brick densities reinforced by barley straw are 1301.8 and 1211 kg/m^3 at 5% and 10% cement contents as shown in Fig. 8b. The average brick densities stabilized with cement are 1102.9 and 1088.5 kg/m^3 for 5 and 10% cement at 3% fibres while bricks reinforced by barley straw are 1264.7 and 1154.8 kg/m^3 at 5% and 10% cement contents at the same fibre content as shown in Fig. 8c. A similar trend was observed in bricks stabilized by gypsum mixtures as shown in Fig. 8d.

In general, increasing the fibre content in the mixtures decreased the specimen weights. Replacing soil cement or soil gypsum (dense materials) with wheat or barley straw fibres (light materials) resulted in a total volume increase even after compaction at 100 kN. The compacted mix volume increases resulted in a decrease in specimen weights and densities.

3.3. *Thermal conductivity*

3.3.1. *The influence of fibre content*

The average thermal conductivity of unfired earth bricks reinforced with wheat straw are 0.961, 0.596 and 0.310 W/m K for the fibres contents of 0%, 1% and 3%, respectively, while the thermal conductivity for bricks reinforced with barley straw fibres are 0.961, 0.620 and 0.314 W/m K for reinforcement fibres contents of 0%, 1% and 3%, respectively. The mentioned results illustrate that increasing wheat straw fibre percentages from 0% to 3% caused a decreasing of thermal conductivity percentage to 54.4% in comparison to bricks without reinforcement fibres. Also, increasing barley straw fibre percentages from 0% to 3% caused a decreasing of thermal conductivity percentage to 53% in comparison to bricks without reinforcement fibres, results which are extremely satisfying. The change in thermal conductivity by altering the fibre content is shown in Fig. 9. As expected, thermal conductivity decreased with increasing fibre content. Fig. 9 also shows that the decrease in thermal conductivity was gradual with increasing fibre content. The results showed no significance difference between bricks reinforced with wheat and barley straw fibres ($P < 0.05$).

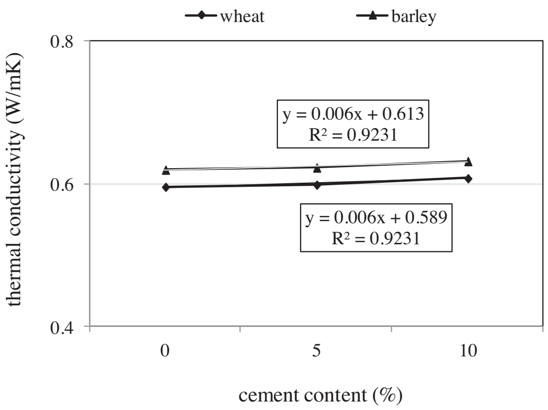

Fig. 10. The effect of cement and 1% fibres content on the thermal conductivity of bricks.

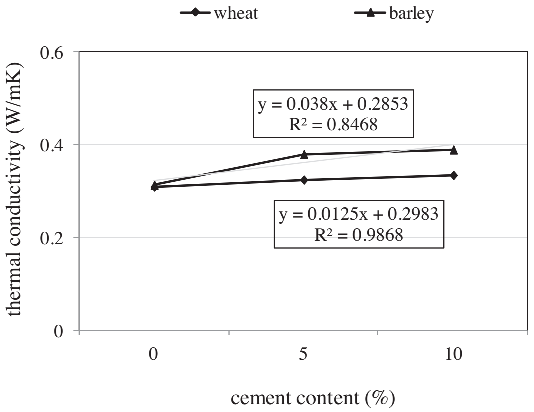

Fig. 11. The influence of cement and 3% fibres content on the thermal conductivity of bricks.

3.3.2. *The effect of cement content*

3.3.2.1. Cement content with 1% fibre. Fig. 10 shows the relationship between cement content and thermal conductivity with 1% fibre content. The figure shows that thermal conductivity increases slightly with increasing cement content. Also, the figure showed that the obtained results for bricks reinforced by wheat and barley straw are in similar trend but slightly differ in values. Statistically, the results showed no significance difference between the performance of wheat and barley straw fibre reinforced bricks ($P < 0.05$). The average thermal conductivities of unfired wheat straw reinforced earth bricks are 0.596, 0.599 and 0.608 W/m K for cement contents of 0%, 5% and 10%, respectively. The thermal conductivity for bricks reinforced with barley straw fibres are 0.620, 0.623 and 0.632 W/m K, for cement contents of 0%, 5% and 10%, respectively.

It could be seen that the results indicated that increasing cement percentages from 0% to 10% caused thermal insulation percentages to decrease from 0% to 2% in comparison to bricks without cement content and with 1% wheat fibre reinforcement. Increasing cement percentages from 0% to 10% caused thermal insulation percentages to increase from 0% to 1.93% with the same fibre content. The figure also showed that the thermal conductivity for barley straw fibre reinforced bricks is higher than wheat straw reinforced bricks.

3.3.2.2. Cement content with 3% fibre. The average thermal conductivity of unfired earth bricks reinforced with wheat straw fibres are 0.310, 0.325 and 0.335 W/m K for the cement contents of 0%, 5% and 10%, respectively. In comparison, the thermal conductivity for barley straw reinforced bricks are 0.314, 0.380 and 0.390 W/m K, for cement contents of 0%, 5% and 10%, respectively. Fig. 11 shows

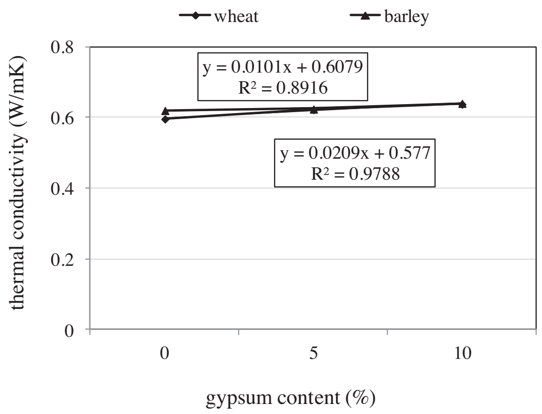

Fig. 12. The consequence of gypsum and fibres at 1% on the thermal conductivity of bricks.

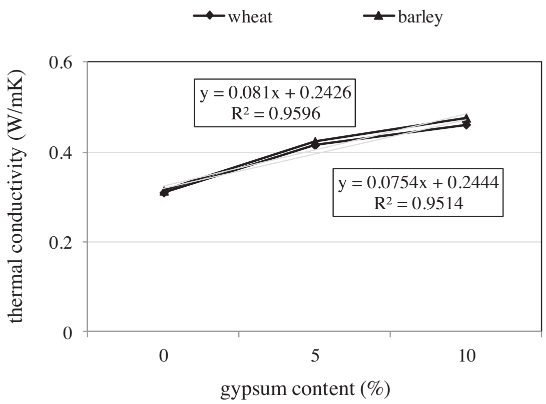

Fig. 13. The influence of gypsum and 3% fibres content on the thermal conductivity of bricks.

Table 3
Summarize the thermal conductivity of earth bricks stabilized with cement and gypsum.

Materials	Mixing ratio	Wheat straw		Barley straw	
	%	1%	3%	1%	3%
Cement	0	0.596	0.300	0.620	0.314
	5	0.599	0.325	0.623	0.380
	10	0.608	0.335	0.632	0.390
Gypsum	0	0.596	0.31	0.621	0.314
	5	0.622	0.415	0.624	0.424
	10	0.638	0.461	0.6402	0.476

the relationship between cement content and thermal conductivity with 3% fibre content. The figure showed that thermal conductivity slightly increased with increasing cement content. The figure illustrated that the obtained results for different materials as in similar trend but slightly differ in values. Statistically, the results showed no significance difference between wheat and barley reinforced bricks ($P < 0.05$).

The results showed that increasing cement percentages from 0% to 10% caused increasing of thermal conductivity percentages from 0% to 8% in comparison with brick materials without cement and with 3% wheat reinforcement fibre content. For barley straw fibres, increasing cement percentages from 0% to 10% caused thermal conductivity to increase from 0% to 24% with the same fibre content. This trend is due to the physical properties of cement and its formation. Thus at 3% fibre content, high porosity and a large number of spaces exist between fibres and soil particles. Cement also fills these gaps. The figure also shows that the thermal conductivity for barley straw reinforced bricks is higher than wheat straw reinforced bricks.

3.3.3. *The influence of gypsum content*

3.3.3.1. Gypsum content at 1%. Fig. 12 shows the relationship between gypsum content and thermal conductivity at 1% fibre content. The figure shows that thermal conductivity slightly increased with increasing gypsum content. The results showed no significance difference ($P < 0.05$) between bricks reinforced with wheat and barley straw fibres. The average thermal conductivity of unfired wheat straw reinforced earth bricks are 0.596, 0.622 and 0.638 W/m K for the gypsum contents of 0%, 5% and 10%, respectively. The thermal conductivity for barley straw reinforced bricks are 0.620, 0.624 and 0.640 W/m K, for cement contents of 0%, 5% and 10%, respectively.

The results proved that increasing gypsum percentages from 0% to 10% caused the thermal conductivity percentage to increase from 0% to 7% in comparison to brick materials without gypsum with 1% wheat reinforcement fibres. Thus, increasing gypsum percentages from 0% to 10% caused thermal conductivity percentages to increase from 0% to 3.3% with the same fibre content. The figure also showed that the thermal conductivity for barley straw reinforced bricks is higher than wheat straw reinforced bricks.

3.3.3.2. Gypsum content at 3% fibre. The average thermal conductivities of earth bricks reinforced with wheat straw are 0.310, 0.415 and 0.461 W/m K for gypsum contents of 0%, 5% and 10%, respectively; while the thermal conductivity for barley straw reinforced bricks are 0.314, 0.424 and 0.476 W/m K for gypsum contents of 0%, 5% and 10%, respectively. Fig. 13 shows the relationship between gypsum content and thermal conductivity with 3% fibre content. The figure showed that the thermal conductivity increased slightly with increasing gypsum content. The results showed no significance difference between bricks reinforced with wheat and barley straw fibres ($P < 0.05$). The results revealed that increasing gypsum percentages from 0% to 10% caused thermal conductivity to increase from 0% to 48.7% in comparison to brick materials without gypsum and with 3% wheat reinforcement fibres. For barley straw fibres, increasing gypsum percentages from 0% to 10% caused thermal conductivity percentages to increase from 0% to 51.6% with the same fibre content. This trend is due to gypsum and its formation. Thus at 3% fibre content, high porosity and many gaps exist between fibres and soil particles. Cement fills these gaps. The figure also showed that the thermal conductivity for barley straw reinforced bricks is higher than wheat straw reinforced bricks.

A perusal comparison among Figs. 9–13 shows that the thermal conductivity of bricks decreases with fibre content and increases with cement and gypsum contents. Table 3 summarizes the thermal conductivity of earth bricks stabilized with cement and gypsum.

The best regression equation is a linear equation with different gradient and intercept values. The determination coefficients of all regression equations are high values.

4. Conclusion and recommendations

The results revealed that the new blocks manufactured with wheat straw fibre have a relatively high density varying between 1575.6 and 1357.7 kg/m^3 for 1% and 3% fibre contents. This corresponds to a decrease of about 9.8% to 22% at 1% to 3% fibre content in comparison to clay bricks without fibres. For barley straw reinforced bricks, it can be seen that the density ranged between 1542.5 and 1139.9 kg/m^3. This means that the density decreased from 11.6% to 34% when the fibres content increased from 1% to 3%. The results illustrate that increasing of wheat straw fibre percentages from 0% to 3% caused thermal conductivity percentages to decrease from 0% to 54.4% in comparison to bricks without reinforcement fibres. Also, increasing barley straw fibre percentages from 0% to 3% caused thermal conductivity percentages to decrease from 0% to 53% of the reference specimen, results which are extremely satisfying. Finally, the increasing of gypsum percentages from 0% to 10% caused thermal conductivity to increase from 0% to 48.7% in comparison to brick materials without gypsum and with 3% wheat reinforcement fibres. For barley straw fibres, increasing gypsum percentages from 0% to 10% caused thermal conductivity percentages to increase from 0% to 51.6% with the same fibre content.

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