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Chapter 1

Unconventional Insulation Materials

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Additional information is available at the end of the chapter

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Abstract

Materials obtained from petrochemicals (mainly polystyrene) or from natural sources processed with high-energy consumptions such as glass and rock wools are commonly utilized for the insulation of buildings. From the perspective of sustainable development, it is important to choose easily recyclable, renewable, locally available and environmentally friendly raw materials. Thermal performance of unconventional insulation materials such as pine apple leaves, wheat straw, rice straw, rice husk/hull, coconut fibre, bagasse, date palm fibre, cellulose fibre-forestry waste, corn cob and sheep wool were investigated for this study. In addition, an experiment was conducted to compare the thermal performance of different materials being used at the Eco-Center in Turkey. As a result, it can be said that the thermal conductivity of petroleum by-products (XPS, EPS, polyurethane foam) is slightly lower than that of plant/agricultural waste materials; however, preferring the latter over the former has many hidden advantages that have great long-term impacts.

Keywords: thermal insulation, thermal conductivity, conventional materials, ecological materials, waste materials

1. Introduction

From construction to demolition, the reduction of energy consumption on upcoming constructions comes as a great challenge [1]. It is becoming more and more significant to improve the energy efficiency of buildings as a large part of the world's total energy use and greenhouse gas emissions come from such constructions [2]. When comparing more energy-efficient buildings to the standard build, fossil fuels are consumed in much less quantity, therefore reducing the emissions of carbon dioxide and sulphur dioxide into the atmosphere, particularly on a micro- and meso-scale [3].

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There are ways of reducing heating and cooling loads; notable among them is the proper design and selection of building envelope and its components [4]. For the implementation of the thermal protection, currently there are no better measures than the insulation of the shell of a building [5]. In addition to the overall U-value of the corresponding component including insulation, the thermal performance of building envelope is also controlled by the material's thermal properties characterized by its ability to absorb or emit solar heat [4]. A material is usually considered as a thermal insulator if its conductivity is lower than 0.07 W/mK [1].

Thermal conductivity is the primary key property of thermal building insulation material and solution, where the typical system or objective is to accomplish as low warm conductivity as could reasonably be expected [2]. Lower thermal conductivity is a result of better quality insulation properties, which also implies a higher resistance to conduction of heat through the material, creating a barrier between the surrounding environment and the samples [6]. The insulation properties of a material are typically characterized by thermal conductivity, k (N America) or λ (Europe). Thermal conductivity is expressed in units of watts per meter degree Kelvin (W/mK) and may be expressed as thermal resistance (RSI) by dividing the material thickness (m) by the thermal conductivity producing RSI (m^2K/W) [7]. Subsequently, quantitative comparisons are to be conducted between the effectiveness of different thermal insulation materials due to increased knowledge on thermal conductivity values. As a result of countless microscopic dead air-cells, which suppress convective heat transfer by preventing air from moving, thermal insulating materials begin to resist heat flow. It is the air entrapped within the insulation, which provides the thermal resistance [4].

Increased awareness towards the environment and public health is leading to an integrated evaluation of insulation materials [8]. Materials obtained from petrochemicals (mainly polystyrene) or from natural sources processed with high-energy consumptions such as glass and rock wools are commonly utilized for the insulation of buildings. However, such materials cause significant detrimental effects on the environment mainly due to the production stage including the use of non-renewable materials and fossil fuel consumption. The disposal stage also comes with unfavourable outcomes due to end of life product reuse and recycling problems. The 'sustainability' concept introduced into the building design process encouraged researchers to develop thermal and acoustic insulating materials as a result of using natural or recycled materials [1]. The energy efficiency and sustainability of buildings are currently evaluated upon many factors, not only thermal insulation thickness and heating demand, but also according to primary energy demand, CO_2 reductions and ecological properties of the building materials. Meeting these essential properties that is crucial for a holistic assessment is increasing the demand for ecological building materials, especially renewable raw material composed insulating materials. These properties are essential for a holistic assessment [9].

When recollecting on vernacular and indigenous architecture dating back thousands of years, natural insulation materials were frequently used. For example, the thatches on English country cottages or the walls and roofs in central Chile of the indigenous *Mapuche Ruca* were commonly constructed using reeds and grasses. More recent examples are included in the UNESCO Heritage side of Sewell, a mining town in Central Chile in 1905 as well as straw bale houses dating from the twentieth century in Sandhills, Nebraska, USA, where newspapers were used for the insulation of timber walls. Since the first energy crisis of the 1970s and then the pre-occupation with sustainability that has been steadily growing since the 1990s, interest has now been refocused on these materials [10].

From the perspective of sustainable development, it is important to choose easily recyclable, renewable, locally available and environmentally friendly raw materials [11]. Considering the cost-effective, bio-degradable, durable eco-friendly green building materials, global needs are to be met on thermal rehabilitation due to these interesting properties [12]. The low thermal conductivity and fibrous characteristics from the majority of organic materials have contributed to significant improvements of thermal insulation properties after incorporation in the structure of the exterior building envelope. Natural organic materials contain a higher specific heat capacity and higher moisture sensitivity, which are different physical properties when compared to ordinary silicate materials [5].

In order to find alternative sustainable building materials as well as low technology methods, which result in more affordable and more sustainable constructions, huge efforts have been applied worldwide by the research community to comply with the comfort standards required nowadays [13]. The resulting solutions can be therefore adapted by the industry, leading to a more sustainable society. The building industry is not immune to this reality [14]. Therefore, once the use of these natural materials increases, the production costs will be reduced [15].

This study consists of three steps: First, a literature survey was conducted on thermal conductivity of natural materials. Researched materials are: pine apple leaves, wheat straw, rice straw, rice husk/hull, coconut fibre, bagasse, date palm fibre, corn cob and sheep wool. Then, the thermal data collected from various ecological buildings at the Kerkenes Eco-Center in Turkey were analyzed. Finally, thermal performances of conventional and unconventional insulation materials were compared and the advantages and disadvantages of using such materials were discussed.

2. Unconventional materials

A literature review was conducted on unconventional materials: pine apple leaves, wheat straw, rice straw, rice husk/hull, coconut fibre, bagasse, date palm fibre, corn cob and sheep wool. These materials except for sheep wool are agricultural waste and generally burned after harvesting. Investigations are done on these materials for their use of thermal insulation and infill material. This part of the paper presents information and thermal conductivity values of mentioned materials.

2.1. Pineapple leaves

One of the most cultivated crops from around the world is the familiar tropical fruit, pineapple [16]. The collection and manufacturing of pineapple produces some excess residue including leaves that are currently being treated within energy plants or sometimes simply burned [1]. Burning the pineapple leaves causes environmental problems such as pollution, soil erosion and decreased soil biological activity. Therefore, industrial utilization of this material does not only prevent air pollution, which has adverse effect on air quality, human and environmental health, but is also economically profitable for agriculturists [17]. Fibres are easily extracted from the pineapple leaf as seen in **Figure 1** [18].

Figure 1. Pineapple plant and pineapple leaf fibre [18].

Research was conducted on thermal properties of pineapple leaves. Raw materials used for the study were collected from Uttaradit province located in the Northern part of Thailand. Natural rubber latex (free formaldehyde) was used as binder for the preparation of the particle boards which are 200 × 200 mm in size and 15 mm in thickness. The boards were cut into various test samples and each measurement shows the average of three different samples from three different boards. **Table 1** shows the physical properties of particle boards. Supported by the study, the use of pineapple leaves in the construction of buildings is practicable. With board densities ranging from 178–232 kg/m^3, the pre-treated natural rubber latex can be sprayed onto pineapple fibre for the manufacturing of the particle board. Fairly low readings varying between 0.043 and 0.035 W/mK were observed on the thermal conductivity of the boards. When taking into consideration the thermal conductivity and physical properties of the pineapple leaves particle board, the boards with particle binder ratios of 1:3 with density of 210 kg/m^3 are found to be promising building materials to save energy in thermal insulation applications [17].

Particle:Binder	Moisture contents (%)	Density (kg/m^3)	Water absorption (%)		Thickness swelling (%)	
			2 h	24 h	2 h	24 h
1:2	4.99	178	376	413	19	25
1:3	4.52	210	272	310	21	34
1:4	3.77	232	190	250	20	27

Table 1. The physical properties of particle boards [17].

2.2. Wheat straw

Straw, a by-product of cereal cultivation, available in large quantities at low cost from numerous countries has been one of the main materials used for the construction of green buildings throughout the world. Deriving from the cultivation of wheat, straw is commonly used for application on buildings [1]. Bales of straw are used commonly for building construction (**Figure 2**).

Figure 2. Straw bales production in Turkey [19].

Built environment professionals find straw to be an excellent construction material and recognize that some of its limitations can easily be overcome. Straw bales can be used either as load-bearing structure or as infill wall. There are different techniques used in construction for the infill wall system including post and beam structures, and more commonly practiced, beam structures and frame (truss) with straw infill (**Figure 3**) [20]. Traditionally, straw has been used for animal bedding or burned by farmers because of the storage problems [12].

Figure 3. Straw bales used as infill wall at the Kerkenes Eco-Center [19].

Reference [21] calculated thermal conductivity of straw bale samples which were 360 mm by 615 mm with a density of 60 kg/m^3 and supplied by a local farmer in the United Kingdom. Hevacomp Ltd. software MAT version 16.00 were used for the calculations. Results show that the straw bales offer good insulation values of 0.067 W/mK.

A further study was conducted with the aim to research the thermal conductivity of wheat straw by reference [22]. Investigated was the barley straw grown in Southern Germany. For approximately one year, straw was packed tightly into rectangular bales measuring 50 × 40 × 80 cm^3 which were stored in a barn. The density of the bales was around 70 kg/m^3 and the typical straw stalk diameters were 2–4 mm. The walls of the hollow stalks had a density of approximately 300 kg/m^3. Two cylindrical samples with a diameter of 28 cm were prepared from the bale in order to measure thermal conductivity in the guarded hot plate device. The samples were pressed in the measuring device (straw stalks oriented perpendicular to heat flux) until a density of around 80 kg/m^3 was obtained, which is comparable with the density of the bales. The sample's final thickness was 22 mm subsequent to pressing. With the purpose to investigate heat transfer, measurements between −200 and 800°C were used on the evacuable guarded hot plate for thermal. Temperature-dependent thermal conductivity measured in the evacuated state (λ_{evac}) and the non-evacuated state (λ) can be seen in **Table 2**.

T_m (°C)	λ ($Wm^{-1} K^{-1}$)	λ_{evac} ($Wm^{-1} K^{-1}$)
20	0.0408	0.00598
50	0.0444	0.00715
75	0.0476	0.00829

Table 2. Temperature-dependent thermal conductivity measured in the evacuated state (λ_{evac}) and the non-evacuated state (λ) [22].

Measurements for straw insulation (0.041 $Wm^{-1} K^{-1}$ at 20°C) are similar to those of conventional insulation materials used in buildings when evaluating the thermal conductivities. Straw has appealing characteristics including its interesting renewable property for insulation of buildings. For the mass market, boards are required to be available in a variety of dimensions, meaning they must be developed. As thermal coupling of the fibres via gaseous conduction is already well developed at atmospheric pressures, an additional application of binders might not increase the total thermal conductivity significantly. For conventional insulation board sizes ($5 \times 50 \times 100$ cm^3 or $5 \times 62.5 \times 100$ cm^3), thin boards or elements could therefore be produced for building applications with thermal conductivities of less than 0.045 $Wm^{-1} K^{-1}$ [22]. Due to the rigidness, strength and low cost of the straw particleboards, the applications are broad [23].

2.3. Rice straw

Rice, being the world's one of the most important food grains, is produced in at least 95 countries [24]. It is the main staple food in most of the Asian countries [25], and in rice-harvesting countries large amounts of rice residues are produced annually [26] (**Figure 4**). Unsustainable use of rice straw and open burning of it in the field produces threat to environment by producing large amount of greenhouse gas emission [25]. The potential of recycling these rice residues is significant for crop production systems [26].

Figure 4. Rice straw [27].

In reference [28], a new thermal insulation material from rice straw was investigated. Material used for the study was harvested in the agricultural field of Nanjing, Jiangsu Province in China. Rice straw boards with dimension of 300 × 300 × 40 mm were prepared and thermal conductivity measurements of the test specimens were made using the Lambda 2000 measuring device. Methylene diphenyl diisocyanate (MDI) resin and acetone were used to make the boards uniform. A new thermal insulation material from rice straws with a density of 200–350 kg/m^3 and thermal conductivity of 0.051–0.053 W/mK was developed using high-frequency hot-pressing. These residues could be a great component of construction for wall or ceiling insulation to conserve energy. The thermal conductivity, boards' density and ambient temperature were found to have great correlation. Additionally, the thermal conductivity increased as the particle size decreases, and the particle moisture content did not significantly affect the thermal conductivity of the boards observed in the results. The boards with higher density had the best physical and mechanical properties. Furthermore, by decreasing the particle size in a specific range, the properties of the boards are likely to improve, although the insulation properties of the boards would be reduced.

2.4. Rice husk/hull

Rice husk/hull, which is the outer covering of a rice kernel, protects the inner ingredients from external attack by insects and bacteria [29]. Rice husk removal during rice refining creates disposal problem because this organic waste is generally burned after harvest, which causes environmental problems [30]. Thermal conductivity of rice hulls, received from a processing plant, was measured in two laboratories. Materials tested by R&D Services, Inc. (RDS) were parboiled, whereas the rice hulls tested at the Oak Ridge National Laboratory (ORNL) were not parboiled. Equipment built and in accordance with ASTM C 518 and 305 × 305 × 51 mm test frames were used for measurement of the material [31] (**Figure 5**).

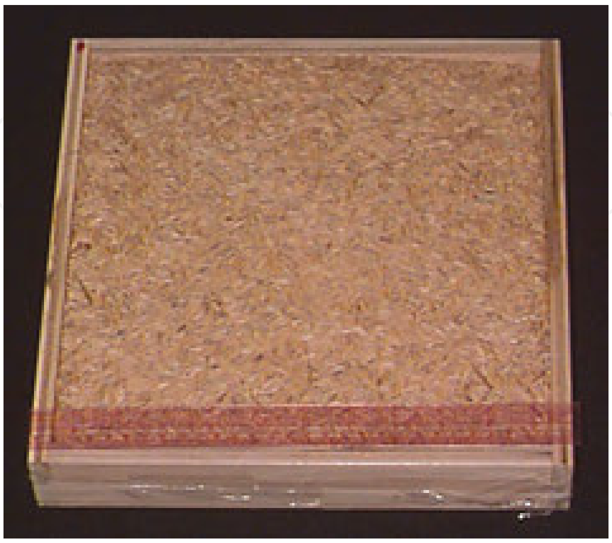

Figure 5. Rice husk in test frame [31].

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The densities of the specimens were 144.3, 139.4, 155.4 and 147.5 kg/m^3. Experimental research conducted in two laboratories shows that thermal conductivity of rice husk ranges from 0.046 to 0.057 W/mK [31]. **Table 3** shows apparent thermal conductivity data for the material. According to reference [32] without the use of chemical binders, rice husk can be made into hard, high-density boards.

Temperature (°C)	Density (kg/m^3)	ka (W/mK)	Laboratory
7.4	153.8	0.0441	ORNL
15.5	153.8	0.0452	ORNL
23.9	153.8	0.0464	ORNL
32.2	153.8	0.0476	ORNL
40.6	153.8	0.0484	ORNL
23.9	153.8	0.0462	ORNL
7.3	168.2	0.0488	ORNL
15.6	168.2	0.0510	ORNL
23.9	168.2	0.0532	ORNL
32.2	168.2	0.0552	ORNL
40.6	168.2	0.0561	ORNL
23.9	168.2	0.0496	ORNL
23.9	144.3	0.0566	RDS
23.9	139.4	0.0477	RDS
23.9	155.4	0.0493	RDS
23.9	147.5	0.0490	RDS

Table 3. Apparent thermal conductivity data for rice husk from two laboratories [31].

2.5. Coconut fibre

Coconuts are growing abundantly in coastal areas of tropical countries [33]. From the outer shell of a coconut, coconut fibre is extracted. There are just two types of coconut fibres which are brown fibres extracted from matured coconuts and from immature coconuts white fibres are extracted. While brown fibres are strong, thick and have high abrasion resistance, white fibres are not only smoother and finer but also weaker. Coconut fibres are commercially accessible in three forms, namely bristle (long fibres), mattress (relatively short) and decorticated (mixed fibres). Depending on the requirement, these different types of fibres have different uses. Taking engineering into consideration, the brown fibres are more commonly applied [34]. Coconut tree, coconut and coconut fibres are seen in **Figure 6**.

Figure 6. Coconut tree, coconut and coconut fibres [35].

The major composition of coconut fibres contains cellulose, hemi-cellulose and lignin, affecting the different properties of the coconut fibres. The composition ultimately changes not only its properties but also the properties of composites when the fibres are pre-treated. From time to time, the fibres' behaviour improves although sometimes the effect is not favourable. The most ductile material amongst all natural fibres is the coconut fibre [35]. Since coconut fibre is a natural material, it decomposes faster and more easily. Therefore, it pertains a clean built environment. This material can be recycled and introduced as an insulation material [36].

In reference [37], the thermal conductivity of coconut fibre was investigated and a minimum material thermal conductivity of about 0.05 W/mK was found. Coconuts used for the study were obtained from coastal areas in Mexico. Horizontal fibre and vertical fibre cylindrical specimens 6 mm in thickness and 15 mm in diameter with 174 kg/m^3 density were prepared (**Figure 7**). Fibres were glued together only by compression; artificial binders were not used. A locally designed constant-temperature, one-piece specimen apparatus was used and recommendation of the ASTM norm C518 was followed for the thermal conductivity tests of the research. According to reference [32] without the use of binders, coconut husk can be made into thermal insulations.

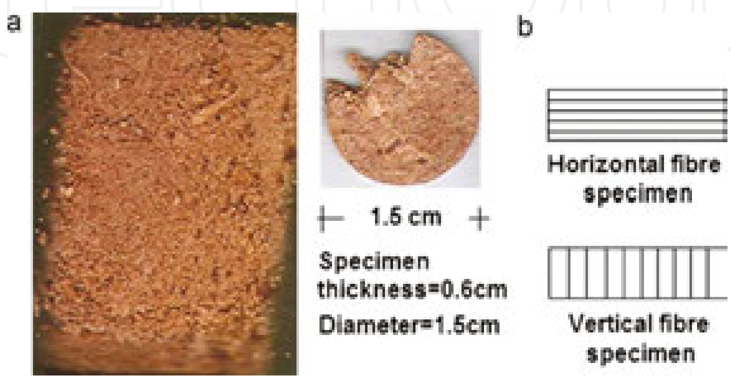

Figure 7. Material and specimen prepared for the study [37].

2.6. Bagasse

Sugarcane bagasse is typically found in tropical countries that process sugarcane such as Brazil, India, Cuba, Iran [38] and Pakistan (**Figure 8**). Traditionally, bagasse is managed as waste; it is burned or used as animal fodder. According to reference [1] besides its great availability, its low cost and cellulose content that helps to reduce the use of synthetic binders fostered several researchers to work towards developing innovative thermal insulation particle boards made from such material [1]. Reference [39] conducted a research on thermal insulation boards made from bagasse. Bagasse was obtained from the waste of the sugar factory in Ratchaburi province of Bangkok, and 25-mm thick test boards were produced at the target board densities of 250, 350 and 450 kg/m^3 in a laboratory at the Royal Department of Forestry, Bangkok, Thailand. Bagasse particles were formed manually using a forming box into a mat of size 450 × 450 mm and 81 binderless insulation boards were made by corresponding to three boards for each of the 27 manufacturing conditions: combinations of board density (three levels: 250, 350 and 450 kg/m^3), hot-pressing temperature (three levels: 160, 180, 200°C) and hot-pressing duration (three levels: 7, 10 and 13 min). All boards were cut and trimmed into various test specimens and thermal conductivity was measured at room temperature using a Heat Flow Meter under steady-state, one-dimensional test condition with upward heat flow. According to the results, the thermal conductivity values of bagasse range from 0.046 to 0.068 W/mK depending on the density of the material. Reference [32] states that hard (high density) boards can be transformed from bagasse without the use of chemical binders.

Figure 8. Sugarcane and sugarcane bagasse [1].

2.7. Date palm fibre

The date palm is cultivated in many regions of the world, especially the arid areas [40]. The residues of the date palm, such as leaves, petioles and bunches, are commonly considered as waste [1]. With four types of fibre, date palms consist of a fibrous structure: leaf fibres in the peduncle, baste fibres in the stem, wood fibres in the trunk and surface fibres located in the trunk [41]. Date palm tree and date palm tree fibres are seen in **Figure 9**. An experimental study was conducted on thermal conductivity of date palm fibre by reference [42]. Natural fibres, which were collected from the region of Errachidia in Morocco, were dried in oven at 60°C after washing. The thermal conductivity of the natural fibres, which were collected, are achieved according to NF ISO 88941 2nd edition 15/05/2010 using the CT meter device. The date palm fibres were separated into single fibres and measurements were done at 25°C. Results of the study show that the lowest thermal conductivity of date palm fibre is 0.041 W/mK.

Figure 9. Date palm tree and date palm fibres [43].

2.8. Corn cob

By processing corn plants the residuals of corn cobs are produced [1]. Corn cob has an advantage when thought in terms of possible application for alternative processed products because it does not collide with the worldwide food stock and it is generally considered as agricultural waste [14]. In terms of shape, texture, density and colour, the corn cob presents three layers which are much different (**Figure 10**). In contrast to common thermal insulation building materials, the corn cob material is heterogeneous which is related to its natural biological origin [44].

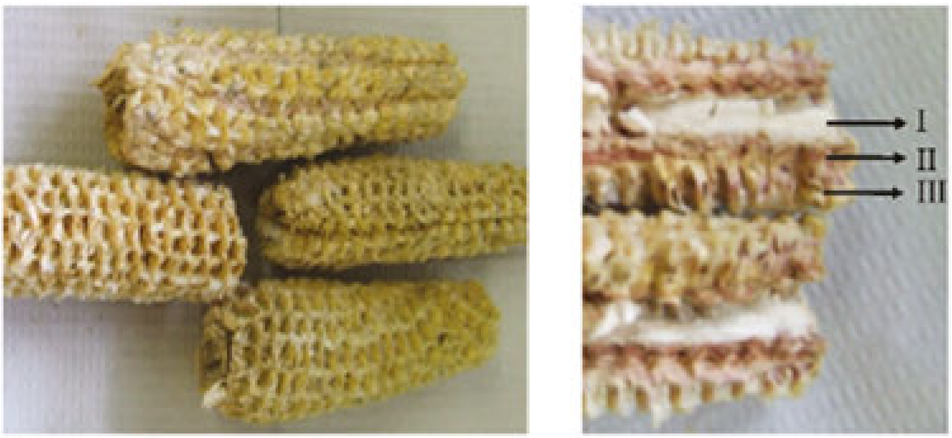

Figure 10. Corn cob and three layers of corn cob [44].

An experimental research on thermal conductivity of corn cob was conducted by reference [13]. Average density of the randomly picked up corn cob samples was measured as 212.11 kg/m^3. A corn cob particle board with dimensions of 250 × 250 × 50 mm was prepared and wood glue was used as binder. In addition, an XPS panel with dimensions 640 × 760 × 50 mm was used for the study. The panel system of XPS frame and corn cob particle board was replaced by a window of a confined room. The temperature in the room was kept nearly constant at 23°C. Two heat fluxmeters and two temperature sensors were placed on the inner surface of the particle board. Two thermohygrometers were placed inside and outside of the room in order to measure indoor and outdoor temperatures. Two heat fluxmeters were used to measure the heat flow through the corn cob particle board. The measurement was done continuously (10 min timing interval) for 7 days. Results of the study show that the thermal conductivity of the corn cob is 0.139 W/mK.

Reference [44] analyzed samples of corn's cob and XPS by SEM/EDS in order to compare their microstructure and elementary chemical composition. This study was conducted at the Electronic Microscopy Laboratory of the Tras-os-Montes Alto Douro University. Some interesting similarities between the corn's cob and the extruded polystyrene (XPS) materials are indicated in SEM/ED's results. The closed cellular microstructure type explains these similarities, as well as the presence of same chemical elements. The authors suggest using corn cob as a filling material and thermal insulation material.

2.9. Sheep wool

Sheep's wool is a sustainable, natural resource whose inherent characteristics make it attractive as an insulating material [8]. The shearing of sheep grow wool is a pain-free technique commonly carried out at least once a year to relieve the sheep of stress and discomfort, especially in hot and humid conditions. As a result of this non-invasive technique, sheep wool has traditionally been used for the manufacturing of conventional woollen products in the textile industry, such as carpets, garments, curtains, covers and bedding [11]. It is an easily renewable, easily recyclable and environmentally friendly source of raw material (**Figure 11**) [9].

Figure 11. Sheep wool and its application in building construction [9].

Thermal conductivity of sheep wool was found out at steady state using the plate method measured by the Lambda 2300 device, Micromet Inc., Holometrix, USA. The 300 × 300 mm samples with varying thicknesses of 80, 70, 60, 50 and 40 mm were used for the study. The samples were prepared from the manufactured sheep wool-based mats. Thermal conductivity of the samples was measured at mean temperatures +10, +20, +30 and +40°C. Depending on the density of the material, the thermal conductivity of sheep wool is 0.034–0.050 W/mK [9]. **Table 4** shows thermal conductivity and bulk density of the material. Reference [7] states that sheep's wool does have the potential to be developed into a sustainable, natural and renewable insulation material, but one that could perhaps serve local, regional or niche markets.

Sample	Thickness (mm)	Bulk density (kgm^{-3})	Thermal conductivity ($Wm^{-1} K^{-1}$)	Mean temperature (°C)
1	40	40	0.034	
2	50	32	0.035	
3	60	27	0.037	10
4	70	23	0.038	
5	80	20	0.040	
1	40	40	0.036	
2	50	32	0.038	
3	60	27	0.040	20
4	70	23	0.042	
5	80	20	0.044	
1	40	40	0.038	
2	50	32	0.040	
3	60	27	0.042	30
4	70	23	0.045	
5	80	20	0.048	
1	40	40	0.039	
2	50	32	0.041	
3	60	27	0.043	40
4	70	23	0.046	
5	80	20	0.050	

Table 4. Overview of thermal conductivity and bulk density [9].

3. Thermal performance of natural and fabricated materials

Over the span of a few years, nine buildings have been constructed with different materials and configurations at the Kerkenes Eco-Center, which is located in a village in Turkey. The aim of this ongoing applied research was to understand indigenous materials and techniques and compare them with conventional ones to see which performs better, especially from the point of view of thermal comfort. In this regard, an experiment was conducted to compare the thermal performance of different materials being used at the Eco-Center. The data have been plotted in a chart which is presented in **Figure 12**.

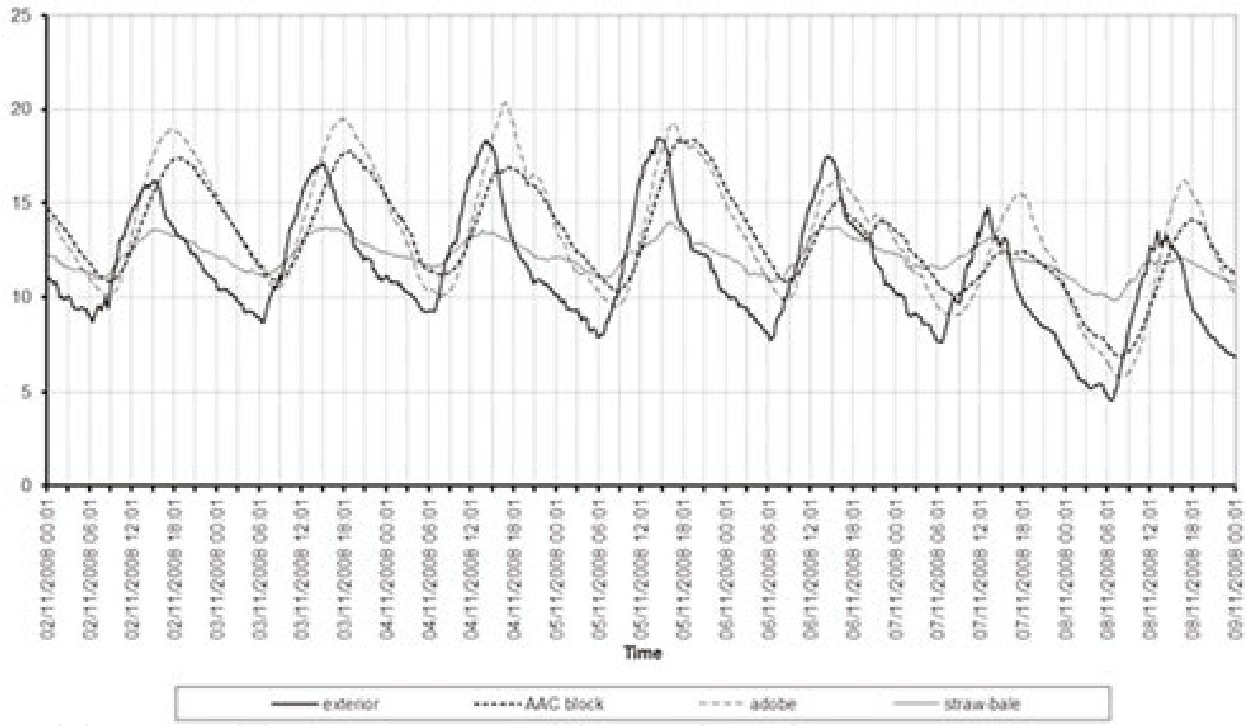

Figure 12. Comparison of materials used in Kerkenes Eco-Center in Turkey.

This study was followed by comparing the thermal behaviour of buildings located at the Eco-Center, constructed with the very same materials. Again data loggers were used to gather temperature and humidity data from these buildings at 15 min intervals and then plotted on a chart for comparison.

The chart (**Figure 13**) is a good example of the behaviour of these materials. Even with a difference in external temperature superior to 10°C between day and night, all of these buildings stayed more or less stable; the diurnal temperature fluctuations were within 2°C. From these results, we can see that buildings made of locally produced indigenous blocks or straw bales are just as thermally comfortable as those produced using AAC blocks, which is a popular construction material in Turkey.

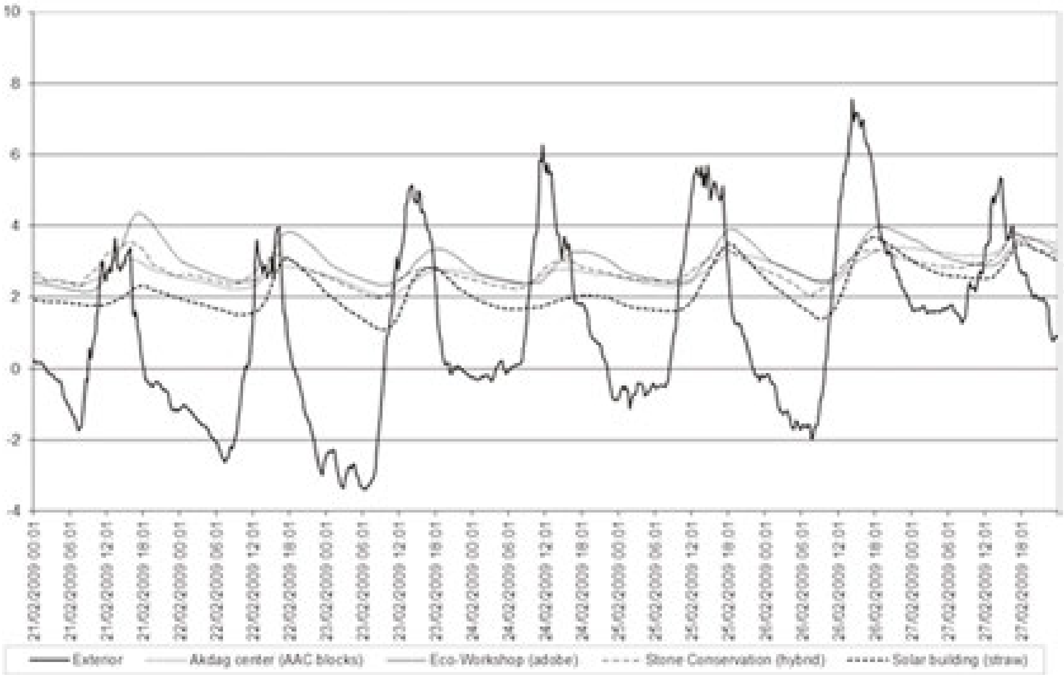

Figure 13. Comparison of thermal performance of the buildings in Kerkenes Eco-Center.

4. Conclusions

The environmentally friendly natural materials presented in this chapter are mostly considered as waste, with the exception of sheep's wool, and are usually burnt on the fields or as fuel in stoves. This method of disposal leads to an increase of CO_2 and ashes in the environment. On the other hand, the thermal conductivity value of each of these materials can be considered as comparable to that of conventional and popular insulation materials being used by the construction industry worldwide. **Table 5** shows the data collected through the survey. The table includes thermal conductivity of natural materials as well as of conventional insulation materials.

From **Table 5**, one can argue that the thermal conductivity of petroleum by-products (XPS, EPS, polyurethane foam) is slightly lower than that of plant/agricultural waste materials; however, preferring the latter over the former has many hidden advantages that have great long-term impacts. Firstly, producing natural materials does not harm the environment in the way toxic materials that are used to produce insulation boards do. Secondly, when these materials are put back into the production cycle as raw material, instead of treating them as waste to be disposed of by burning, the embodied carbon and nitrogen are prevented from being released into the environment as harmful gases and ashes. Thirdly, using these natural materials does not pose any threats to human or environmental health; and finally, the embodied energy and life-cycle costs of natural materials are considerably lower than those of toxic and environmentally harmful conventional insulation materials.

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Material	Regions where these materials are mostly produced	Characteristics	Uses	Information related to the experimental studies reviewed			
				Test specimen	Binder	Density	Thermal Conductivity
Non-conventional insulation materials (thermal conductivity range = 0.034–0.067 W/mK)							
Pineapple leaves	Tropical regions	Plant waste	Particle board	Particle board	Natural rubber latex	178–232 kg/m^3	0.035–0.043 to W/mK
Wheat straw	All over the world	Agricultural waste	Straw bale/ animal fodder/ particleboard/ fibre fill	Straw bale	No binder	60 kg/m^3	0.067 W/mK
				Cylindrical samples	No binder	80 kg/m^3	0.041 W/mK
Rice straw	All over the world	Agricultural waste	Straw bale/ board/fibre fill	Board	Methylene diphenyl diisocyanate and acetone	200–350 kg/m^3	0.051–0.053 W/mK
Rice husk/ hull	All over the world	Plant waste	Board/particle board/fibre fill	Board	No binder	144.3–147.5 kg/m^3	0.046–0.057 W/mK
Coconut fibre	Coastal areas of tropical countries	Plant waste	Particle board/ fibre fill	Particle board	No binder	174 kg/m^3	0.05 W/mK
Bagasse	Tropical regions	Plant waste	Particle board/ fibre fill	Particle board	No binder	250, 350, 450 kg/m^3	0.046–0.068 W/mK
Date palm fibre	Arid areas	Plant waste	Fibre board/fibre fill	Fibre board	No binder	Not mentioned	0.041 W/mK
Corn cob	All over the world	Agricultural waste	Particle board/ fibre fill	Particle board	Wood glue	212.11 kg/m^3 (average)	0.139 W/mK
Sheep wool	All over the world	Animal fibre	Textile and clothing/mat/ fibre fill	Mat	No binder	20–40 kg/m^3	0.034–0.050 W/mK
Conventional insulation materials (thermal conductivity range = 0.029–0.045 W/mK)							
EPS			Insulation boards				0.03–0.033 W/mK
XPS			Insulation boards				0.029–0.039 W/mK
Foam plastic			In-situ insulation				0.03 W/mK
Glass-wool			Insulation boards				0.04 W/mK
Rock-wool			Insulation boards				0.045 W/mK

Table 5. Data collected through the survey including thermal conductivity of natural materials as well as of conventional insulation materials.

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