Natural thermo-insulation panels made from local renewable resources: esparto grass (alfa) and kenaf fibres

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ABSTRACT – REZUMAT

Natural thermo-insulation panels made from local renewable resources: esparto grass (alfa) and kenaf fibres

This study aims to develop efficient, eco-friendly insulation panels made from abundant local resources from Tunisia. Nonwoven panels were manufactured from kenaf and alfa fibres at different densities, and their air permeability and thermal conductivity were evaluated. A fire-retardant treatment based on natural salt was applied to the fibres, and its influence on the flammability of the resulting nonwoven was assessed. These properties are essential for the use of panels in building thermo-insulation. The thermal conductivity of these panels varies from 0.034 to 0.41 $W \cdot m^{-1} \cdot K^{-1}$, and kenaf panels present lower thermo-conductivity than alfa panels. These values are comparable to those of polystyrene and rock wool fibre panels. The fire-retardant treatment, based on the use of natural salt, showed its efficiency by improving the behaviour of panels exposed to flame.

Keywords: *natural fibres, thermal insulation, kenaf, alfa, thermal conductivity, fire retardancy*

Panouri termoizolante naturale realizate din resurse regenerabile locale: fibre de iarbă esparto (alfa) și fibre de kenaf

Acest studiu își propune să dezvolte panouri de izolație eficiente și ecologice, realizate din resurse locale abundente din Tunisia. Au fost fabricate panouri nețesute din fibre de kenaf și alfa, la diferite densități, iar permeabilitatea lor la aer și conductivitatea termică au fost evaluate. Fibrelor li s-a aplicat un tratament ignifug pe bază de sare naturală, iar influența acestuia asupra inflamabilității materialelor nețesute rezultate a fost analizată. Aceste proprietăți sunt esențiale pentru utilizarea panourilor în termoizolația clădirilor. Conductivitatea termică a acestor panouri variază între 0,034 și 0,41 $W \cdot m^{-1} \cdot K^{-1}$, iar panourile din kenaf prezintă o conductivitate termică mai redusă decât cele din fibre alfa. Aceste valori sunt comparabile cu cele ale panourilor din polistiren și din fibre de vată minerală. Tratamentul ignifug, bazat pe utilizarea sării naturale, și-a demonstrat eficiența prin îmbunătățirea comportamentului panourilor expuse la flacără.

Cuvinte-cheie: *fibre naturale, izolație termică, kenaf, alfa, conductivitate termică, rezistență la foc (ignifugare)*

INTRODUCTION

Thermo-insulation panels are used in buildings to improve their energetic efficiency by reducing heat transfer. We find these materials in walls, roofs, and floors to minimise heat exchange with exterior volumes. They are thermal barriers that guarantee a comfortable indoor temperature by reducing heat gain in summer and heat loss in winter, in a way that reduces energy consumption. These panels are not only a thermal barrier but also present other general properties, such as moisture resistance, sound insulation, and fire resistance. These properties depend on the materials used and the manufacturing process [1].

Several materials and products are thermal insulators for building applications provided they are light in weight, easy to handle, durable, and resistant to moisture and environmental factors. The most common products are made from polystyrene, which is commercialised as a rigid board providing high thermo-insulation properties and good moisture resistance and used especially as basement walls, foundation slabs, and also in roofs and floors [1, 2].

Rigid foam boards from polyurethane have low thermal conductivity, and they are used as a thin panel in walls and roofs for thermo-insulation.

Glass fibres and mineral wool insulators are chosen for their excellent thermo-insulation, sound resistance, and fire resistance properties.

The choice of insulating products used in the building is determined by several factors such as thermal and sound insulation performance, fire resistance properties, the application area, and, in some cases, environmental considerations [3].

Nowadays, eco-friendly and sustainable materials such as natural fibres or recycled content insulation panels are used [4]. These materials reduce environmental impact and contribute to green building practices.

The development of insulation panels made from natural resources was a topic of interest for multiple researchers [5, 6]. These natural resources may be

either raw materials, waste or recycled materials [7–9].
Ali et al. [10] suggest that Boards made of Agave and wheat straw fibres using corn starch as a binder have excellent thermal insulation properties (thermal conductivity equal to 0.043 $W \cdot m^{-1} \cdot K^{-1}$). However, they reported that the major problem faced is the moisture sensitivity of natural fibre. So other studies were focused on the impact of moisture content on the mechanical and physical properties of the insulation panel, and in this context, Korjenic et al. [11], who developed insulation products made of jute, flax, and hemp, have demonstrated that when using the correct combination of natural materials, properties will be comparable with those of conventional materials.
Our research work focused on the development of eco-friendly insulation panels made of local resources, alfa, and kenaf fibres, by evaluating their thermal conductivity in terms of the panel density, and then by improving their flame behaviour by biological treatment of the fibres based on natural salt.

MATERIALS AND METHODS

Natural fibres used in this study are local alfa and kenaf cultivated in an experimental field in Tunisia.
Stippa tenacissima, or esparto grass plant, also known as alfa, is a plant with a graceful tuft of green, linear leaves that are composed of several circular bundles. It is abundant in dry regions of North Africa, especially in Tunisia, Algeria, and Morocco. Alfa fibres are mostly used to produce paper, but recently they have been explored as reinforcement of green composites and other technical applications.
The kenaf or *Hemp Deccan,* belonging to the Malvaceae family, is an annual plant having a long stem that can reach 2 m to 4 m in length in five months. Kenaf fibres are extracted from the stem, and nowadays they attract the attention of researchers and industry thanks to their properties and performance, which compete with synthetic fibres in many technical applications such as automobile interior panels and eco-friendly products.
A combined process was used to extract kenaf and alfa fibres. For kenaf fibre, first fibres were separated from the stem mechanically using a horizontal opener, a Shirley, and then chemically treated to improve fibre separation.
For alfa fibre, chemical extraction was used to move noncellulosic materials, and then the Shirley was used to improve fibre individualisation.

Fibre treatment for fire retardancy

The flammability of cellulose fibres is the major disadvantage that prevents them from being exploited in building thermo-insulation products. In our study, Salt (NaCl) was used to treat kenaf and alfa fibres to improve their fire retardancy performance. It's a non-permanent treatment used with materials that will not be exposed to water during their life cycle.

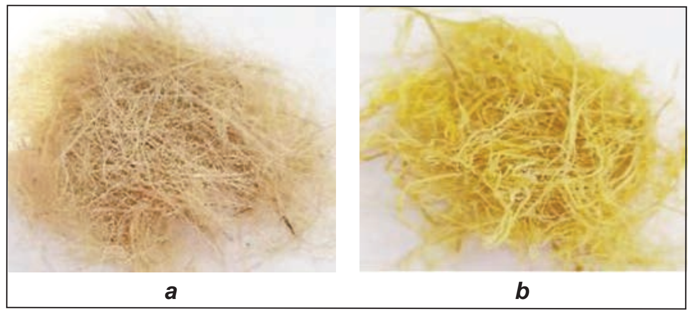


Fig. 1. Image of: *a* – Kenaf fibres; *b* – Alfa fibres

The fibres were soaked in a 35 g/l NaCl solution for 1 hour at room temperature and then drained and dried in a special oven, equipped with a ventilator and a thermostat, at 80°C for 4 hours. Table 1 presents the extraction process applied to kenaf and alfa.

Fibre characterization

The gravimetric method was used to determine the linear density of the fibres according to the standard NF G07-007. Also, 300 randomly selected fibres were examined to measure the diameter using an optical microscope according to standard NF G 07-004. Finally, the tensile test was carried out according to NF G07-002 to determine the mechanical properties of the fibres.

Development of the nonwoven panels

The "Airlaid machine" used to make nonwoven panels from kenaf and alfa is a lab-scale machine developed in the Textile Engineering Laboratory (National Patent Number: TN 2013/117) [12]. Panels are then thermally consolidated. So, two types of nonwovens were made by mixing kenaf and alfa fibres with 10 wt % of PLA fibres (polylactic acid). The fibrous mixtures, composed of either binding fibres mixed with alfa fibres or binding fibres with kenaf fibres, are well homogenised to make an air-laid nonwoven.
Structures are finally submitted to a temperature of 180°C for 60 s to ensure melting of the bonding polymer, then cooled to room temperature.

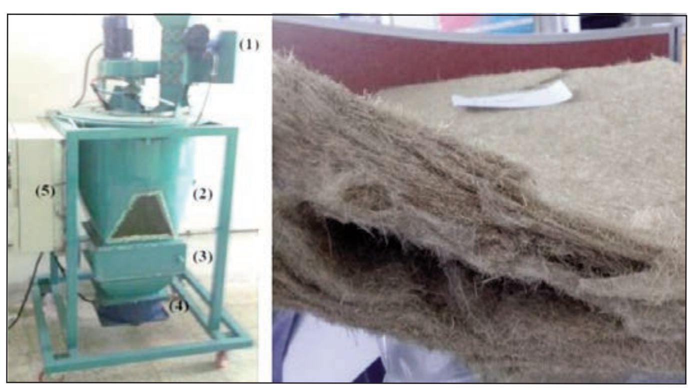


Fig. 2. Airlaid machine and Kenaf panel K1

Table 1

EXTRACTION PROCESS FOR BOTH ALFA AND KENAF FIBRES		
Phase	**Kenaf**	**Alfa**
1	Mechanical separation: Horizontal opener + Shirley analyser	Chemical extraction: NaOH concentration: 80 g/l Duration: 2 h Temperature: 80°C + Sodium hypochlorite NaClO: 100 ml/l Duration: 1 h Temperature: 70°C
2	Chemical extraction: NaOH concentration:120 g/l Duration: 2 h Temperature: 80°C	Finishing: Washing fibre with hot water Neutralised by 2 ml/l H_2O_2 Drying in a special oven at 80°C for 4 h
3	Finishing: Washing fibre with hot water Neutralised with 10 ml/L acetic acid Drying in a special oven at 80°C for 4 h	Mechanical separation: Shirley analyser
4	Fibre treatment for fire retardancy: NaCl concentration: 35g/l duration: 1 h Temperature: at room temperature (25°C) Finishing: Drying in a special oven at 80°C for 4 h	

Table 2

THE THERMOBINDER FIBRES "PLA" PROPERTIES				
Linear density (dtex)	**Length (mm)**	**Melting point (°C)**	**Tenacity (cN/tex)**	**Elongation (%)**
1.5	6	160	32±2.5	55±5

The properties of the thermobinder fibres are presented in table 2.

Nonwoven characterization

Some physical and thermal properties of nonwovens made, such as thickness, density, thermal conductivity, and air permeability, were investigated.

The nonwoven thickness was measured according to the standard ISO 5084 at different areas of each sample. The thickness was calculated as an average of the thickness measurements at five separate points with a Digmatic Thickness Meter ID-F 543-553. The samples were weighed using an electronic scale. The surface of each panel was 0.09 m^2, so nonwoven density was deduced using the following formula:

$$\textit{Density}\ (\text{kgm}^{-3}) = \frac{m}{V} \qquad (1)$$

where m is the sample weight (kg), and V is the sample volume.

The air permeability was measured according to ISO 9237 (1995) using an air permeability tester at five positions on the sample surface selected randomly. All measurements were performed on the same side (face) of the sample.

Also, the thermal conductivity is measured according to French Standard NF EN 12667 using a hot/cold plate apparatus, which measures the difference in temperature between the two surfaces of the tested sample. The principle behind measuring thermal conductivity consists of passing a uniform, unidirectional, and constant thermal flow through a flat sample and measuring the temperature on both sides of the sample. Samples were dried in an oven at 70°C to remove all humidity until their mass variation was equal to zero. Then it was placed between the hot and cold plates of the apparatus, ensuring direct contact to avoid heat dissipation, and the thermal conductivity was measured in two cases: the first for cold and hot plate temperatures of 0°C to 20°C and the second for 10°C to 30°C.

The thermal conductivity k ($\text{Wm}^{-1}\text{k}^{-1}$) is described by Fourier's law (equation 2):

$$q\ (\text{wm}^{-2}) = -k \times A \times \frac{dT}{dx} \qquad (2)$$

where q is unidirectional heat flow (w·m^{-2}), A – cross-sectional area of the sample (m^2), dT/dx – the temperature gradient (k/m).

Finally, to evaluate the efficiency of flame-retardant treatment applied on fibre, the flame test was carried out. It is a qualitative and subjective test. The test is conducted according to the standard ISO 694. So, the sample is placed vertically on a sample holder exposed to a burner placed horizontally at 7 mm from the sample. The material is exposed to flame for 20 s. The results of the examination are a subjective description of the behaviour of the samples during and after exposure to the burner flame.

RESULTS AND DISCUSSION

The results of fibre characterisation are presented in table 3.

Table 3

KENAF AND ALFA FIBRES PROPERTIES				
Fibre type	**Diameter (μm)**	**Linear density (dTex)**	**Tenacity (cN/tex)**	**Elongation (%)**
Kenaf	103.96	17.32	10.32	2.40
Alfa	281.19	49.97	20.53	1.7

By examining the properties of alfa and kenaf fibres, it was concluded that alfa fibres are thicker, more resistant, more rigid, and more difficult to deform.

These fibres were used to make nonwovens with two different densities. Alfa samples are noted A1 and A2, and kenaf samples are noted K1 and K2. Results of the nonwoven characterisation are presented in table 4.

The samples present density and thickness comparable to those of most commercial insulating products already used in buildings. It can be concluded through the results of table 4 that the air permeability increases when the density of nonwovens is contrary to what is expected. Typically, a higher density of the nonwoven reduces its air permeability because there is less space between the fibres, so they prevent air from passing through the structure. But in this case, the fibres used are rigid and thick, leading to an increase in the fibres' interspace in a given volume.

The kenaf and alfa fibre nonwovens have the same range of thermal conductivity, which varies from 0.034 $W{\cdot}m^{-1}{\cdot}K^{-1}$ to 0.041 $W{\cdot}m^{-1}{\cdot}K^{-1}$ and which is similar to other commercialised insulation materials.

Table 5 presents the thermal conductivity of some commercial products compared to those of the studied samples. Through the values presented in the table, kenaf and alfa panels present better thermal conductivity than glass fibre panels and values similar to those of rock wool and polystyrene panels, which are the most commonly used in building.

Low thermal conductivity values lead to good insulation properties of both alfa and kenaf fibres, and this can be explained by the fact that these fibres present a porous microstructure [14] as presented in figure 3 for kenaf fibres and as reported in the work of Ayadi et al. [15] for alfa fibres. The fibre structure is porous (figure 3), allowing air to be stored and trapped in the fibre, which prevents heat transfer through the panel [13, 16, 17].

A flame test was carried out on a panel made of treated and untreated kenaf and alfa fibres. Results of this test are illustrated in figure 4 for samples made from kenaf fibres and figure 5 for those made from alfa fibres.

For untreated kenaf fibre, the sample begins to burn after 1 s of exposure and ignites after 10 s. The flame continues to spread slowly after the burner is removed. But for treated kenaf fibre, there is a superficial burn in the presence of a burner, and when it is removed, sparks appear and disappear in fractions of a second. By exploring the photos in figure 4, it can be seen that the flame impact on the panels has diminished, and the damaged area is smaller.

For untreated alfa fibre, the sample begins to burn after 1 s and ignites after 4.8 s. The flame continues to spread after the burner removal. For treated alfa fibres, there is a superficial burn in the presence of the burner, and the flame extinguishes simultaneously with burner removal. Figure 5 illustrates the damaged area for both untreated and treated alfa fibre panels. The damaged area in the treated fibre panel is smaller.

NaCl has the potential to be used as a fire extinguishing agent. It can form a thin layer of sodium chloride on the surface of the fibre. This layer acts as a physical barrier to the burning material, stopping the oxygen supply and extinguishing the fire [13].

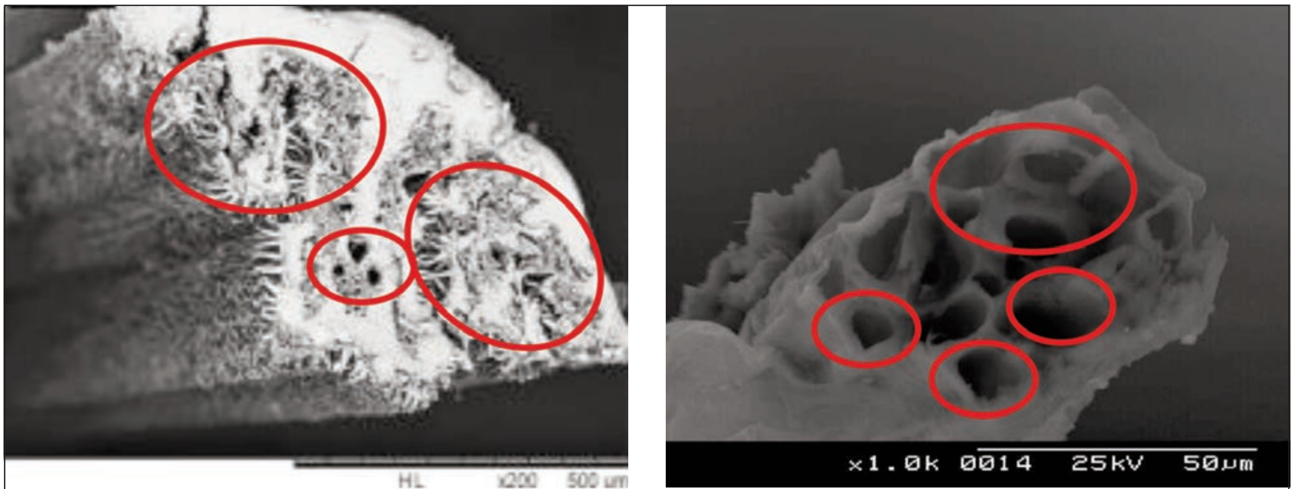
Table 4

NONWOVEN PROPERTIES						
Sample	**Mi (g)**	**Ms (g)**	**Air permeability (mm/s)**	**Thickness (mm)**	**Density ($kg{\cdot}m^{-3}$)**	**k ($W{\cdot}m^{-1}{\cdot}K^{-1}$)**
A1	203.81	191.72	1116.69 ± 108.31	12.55 ± 2.16	180.43 ± 13.08	0.040
A2	234.73	222.26	453.80 ± 95.75	18.83 ± 0.22	138.07 ± 1.61	0.039
K1	206.18	194.65	546.81 ± 35.15	20.57 ± 0.25	111.32 ± 1.39	0.034
K2	65.42	61.71	1866.63 ± 268.27	8.04 ± 0.40	90.38 ± 4.56	0.041

Note: Mi: initial panel weight; Ms: panel weight after drying at 70°C.

Table 5

EXAMPLES OF THERMAL CONDUCTIVITY OF COMMERCIALISED PRODUCTS [13]					
	Kenaf	**Alfa**	**Glass fibre**	**Polystyrene**	**Rock wool**
k ($W{\cdot}m^{-1}{\cdot}k^{-1}$)	0.034 – 0.041	0.039 – 0.040	0.030 – 0.060	0.030 – 0.040	0.030 – 0.040



a b

Fig. 3. SEM image of: *a* – Alfa Fibre cross-section; *b* – Kenaf fibre cross-section

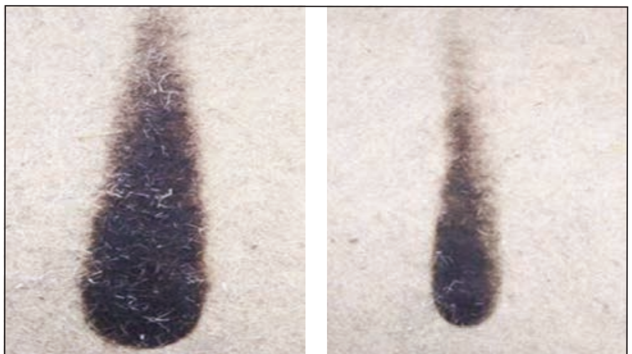


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Fig. 4. Image of Kenaf nonwoven panel after flame test: *a* – untreated fibre; *b* – treated fibre

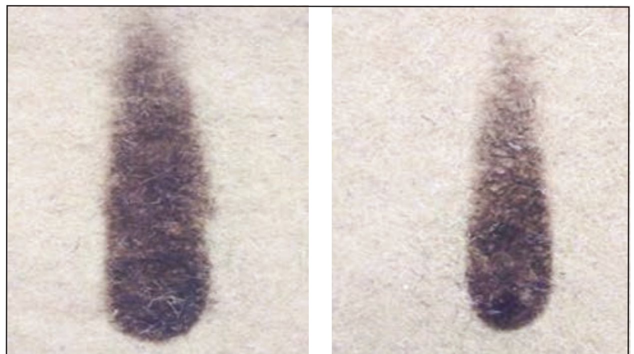

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Fig. 5. Image of alfa nonwoven panel after flame test: *a* – non-treated fibre; *b* – treated fibre

CONCLUSION

Eco-friendly nonwoven insulation panels were successfully produced from alfa and kenaf fibres. The results demonstrate that these biobased materials exhibit thermal properties comparable to conventional commercial insulation panels, especially in thermal conductivity values ranging from 0.034 $W \cdot m^{-1} \cdot K^{-1}$ to 0.041 $W \cdot m^{-1} \cdot K^{-1}$ for our panels and from 0.030 $W \cdot m^{-1} \cdot K^{-1}$ to 0.060 $W \cdot m^{-1} \cdot K^{-1}$ reported for commercialised products.

Among the developed nonwovens, kenaf-based panels displayed the most efficient thermo-insulation performance, highlighting the potential of this fibre in eco-friendly building.

Air permeability measurements highlighted the strong dependency on fibre.

Kenaf-based panels generally exhibit higher air permeability than alfa-based panels, indicating a more open and porous structure. This characteristic can enhance vapour transfer and breathability, which is beneficial in certain building applications.

Additionally, an ecological fire retardancy treatment applied to the fibres and based on the use of NaCl (salt) improved the behaviour of the panels when exposed to the flame, confirming its effectiveness as a simple and non-toxic enhancement method.

Overall, Kenaf and alfa natural fibres proved their competitive alternatives to the commercial insulation products from a thermal insulation performance standpoint.

Future work should focus on evaluating the effects of moisture absorption on the panels' mechanical and physical properties and ensuring long-term durability in real building conditions.

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