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Enhanced Resistance to Fire of the Bark-Based Panels Bonded with Clay

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Abstract: The aim of this study was to investigate the flammability of ecologically friendly, 100% natural larch and poplar bark-based panels bonded with clay. The clay acted as a fire retardant, and it improved the fire resistance of the boards by 12–15% for the surface and 27–39% for the edge of the testing specimens. The thermal conductivity was also analyzed. Although the panels had a density ranging from 600 to 900 kg/m^3, thermal conductivity for the panel with a density of 600 kg/m^3 was excellent, and it was comparable to lightweight insulation panels with much lower densities. Besides that, the advantage of the bark clay boards, as an insulation material, is mostly in an accumulative capacity similar to wood cement boards, and it can significantly improve the climatic stability of indoor spaces that have low ventilation rates. Bark boards with clay, similar to wood cement composites (wood wool cement composites and wood particle cement composites), have low mechanical properties and elasticity. Therefore, there their use is limited to non-structural paneling applications. These ecologically friendly, 100% natural and recyclable composites can be mostly used with respect to their thermal insulation, acoustics and fire resistance properties.

Keywords: wood composites; bark clay composite; wood cement composites; flammability; fire-resistant treatment

1. Introduction

The susceptibility to fire of bio-composites has not been broadly researched yet. There is a lot of potential for the use of biomass in different engineered products for buildings where the main concern is fire hazards [1]. The natural wood fiber reinforcement starts decomposition at about 200 °C, compared to the hydrocarbon backbones of most polymeric adhesives, which degrade without leaving any residue [2]. Novel bio-based reinforcements should be developed, which are simultaneously fire resistant and mechanically sound [3].

Bio-fiber composites are renewable, partially or completely recyclable, lightweight and relatively cheap [4–9]. Their disadvantages include their hydrophilic nature and poor fire resistance [10–12]. The latter has remedies through physical or chemical modifications, such as the adding of flame-retardant additives [13–18]. Flame retardancy is the capacity of a material to prevent or impede the propagation of fire [19]. The inhibition of chemical reactions responsible for the flame or the set-up of a surface protective layer are two solutions in this case [20]. The flame retardancy depends on the alterations that occur inside the material and on the substances identified after the exposure of an inflammable material to high temperatures [21].

There are different techniques to test fire resistance. Flammability tests (small, medium and full-scale) are used in both academic and industrial laboratories. These methods are cone calorimetry, pyrolysis combustion flow calorimetry (PCFC) and the limiting oxygen index (LOI) [1].

Various additives can be blended in the bio-composite matrix: phosphorus additives (e.g., intumescent systems) [22], halogen additives (e.g., organibromine) [23], silicon additives (e.g., silica) [24], nanometric particles (e.g., nanoclay) [25] and mineral-based additives (e.g., metal hydroxide) [26–29]. Cement is an alternative to these costlier additives, in the case of wood-based composites [30,31]. Wood wool panels, bonded with cement, were developed around the beginning of the 20th century [32]. These composites are made of wood particles, fibers and excelsior wood and bonded with Portland cement, and they were developed as panels, bricks and other products for construction [33–36]. Nowadays, wood wool cement boards are reinforced with smart materials (e.g., nano-minerals) [37]. An alternative to wood wool as a sustainable raw material can be tree bark, a by-product of the wood industry. The resistance to fire of bark-based composites was analyzed by [38–40]. The phenolic compounds in tree bark contribute to the fire-retardant properties of composites. It is worth mentioning the transfer potential provided for biomimetic heat insulation and fire-stopping behavior found in many species of tree bark [41].

Clay has been studied recently, even if it has been used for centuries as construction material. It is considered a binder due to its cohesive behavior [42,43] and can improve the mechanical and fire retardancy properties of the composite material [44].

The aim of this study was to investigate the flammability and heat insulation properties of larch bark-based panels, with different grain sizes, bonded with clay. This new bark-based composite is ecologically friendly, 100% natural and recyclable. It can be mostly used with respect to its thermal insulation, acoustics and fire resistance properties.

2. Materials and Methods

The raw materials used for these trials were larch and poplar bark particles (mesh sizes shown in Table 1), a urea–formaldehyde (UF) adhesive (10F102 MetaDynea Austria GmbH, Krems, Austria) with 66% solid content, pH 8.3–9 and viscosity 60–90 mPa*s and clay (Sibelco, Germany) with 40% chamotte and 0–0.5 mm grit and de-ionized water (pH value 7). Commercial corn starch was added for the adhesive formulations with poplar bark.

Table 1. Overall experimental schedule for larch-based boards bonded with and without clay.

Board	Particle Size (mm)	Density (kg/m^3)	Thickness (mm)	Adhesive	Press Time (min)	Moisture Content (%)
A	4–11	700	20	10% UF + 5.2%water	7	8.6
B	<4	600	19	55.5%clay + 11%water	7	8.2
C	>11	900	24.5	51.3%clay + 8.2%water	7	8.5
D	4–11	950	33	54.8%clay + 8.7%water	11	8.6
E	4–11	518	19.4	10% + 5.2%water	7	3
F	4-11	720	24.3	40.7%clay + 13.68%water + 4.91%starch	7	3.5
G	4–11	913	22.4	43.66%clay + 7.27%water + 5.38%starch	7	3.9
H	4–11	750	25.4	33.7%clay + 16.85%water + 15.73%starch	7	4.4

Source: Authors' compilation.

The larch bark originates from a sawmill in Unternberg, Salzburg, Austria specialized in larch processing. The poplar bark was provided by Holz Deisl, Adnet, Austria. The bark was dried by means of a vacuum kiln dryer (Brunner–Hildebrand High VAC-S, HV-S1, Hannover, Germany) from 100% to 9% moisture content. The drying temperature was 60 °C at a pressure of 200–250 mbar. The bark was subsequently crushed in a 4-spindle shredder (RS40) at the Untha Co. in Kuchl, Austria, and repeatedly screened to obtain 0.5–20 mm particles.

The bark grains were mixed with UF (A, E) and with clay, water (B, C, D, F, G, H) and starch (for the poplar boards), respectively, in a ploughshare mixer ENT type WHB-75 for 10 min. In the case of clay-bonded larch boards, the mineral and the water were added gradually. 1% ammonium sulphate hardener was used for the UF adhesive.

Consequently, the glued particles were discharged and spread in a 45 cm × 45 cm mold and pressed at 170 °C in a Hofer HLOP 280 (Taiskirchen, Austria) computer-controlled press for 7 min.

A total of 16 boards (450 × 450 mm), two for each type, were manufactured (Table 1), with a thickness ranging from 19 to 33 mm [38].

The properties of all boards were compared to wood wool cement-bonded boards (Isolith and Knauf) and wood particle cement boards (Heraklith) (Table 2).

Table 2. Properties for wood cement boards.

Board	Density (kg/m^3)	Thickness (mm)	Composition	Moisture Content (%)
Isolith	470	25	50% wood (m.c. 20%); 50% cement	11
Heraklith	740	50	40% wood (m.c. 30%); 15% water; 45% cement	12
Knauf	460	25	26% wood, 34% water 33% MgO, 5% $MgSO_4$,	16

Source: [45–47].

Thickness swelling (TS) and water absorption (WA) were determined according to EN 317:2005 [48]. The 50 × 50 mm test samples were weighed and their thicknesses were measured, with a level of accuracy of 0.01 g and 0.1 mm. The specimens were immersed in de-ionized water (pH = 7 ± 1) at 20 °C for 1 and two hours. Afterwards, the test samples were taken out and rinsed to remove excess water. Each sample was reweighed; the sample´s size was taken from the same location prior to immersion in water. Based on the measurements, thickness swelling and water absorption after 1 and 2 h were calculated.

To determine the internal bond (IB, Figure 1) of the test samples, the transverse tensile strength was tested according to EN 319:1993 [49]. Five 50 × 50 × 7 mm samples were fixed on testing plates with hot melt glue. The experiment was performed with a Zwick/Roell Z250 (Ulm, Germany) universal testing machine.

The screw withdrawal resistance was made according to EN 320:2011 [50]. For this test, a wood screw (4.2 × 38 mm) was drilled into both the surface and the edge (Figure 2) and the pull-out force was measured. A hole of 3 mm in diameter was drilled in the center of the 75 × 75 mm samples. Then, the fastener was screwed in 20 mm deep. The test was carried out with a Zwick/Roell Z250 universal testing machine.

The thermal conductivity was measured according to EN 12667:2001 [51], by means of the lambda-meter EP500 of Lambda Measurement Technologies Corporation (Cincinnati, OH, USA). The measurements were taken at 10 °C, 25 °C and 40 °C. The cooling plate had a temperature of 2.5 °C, and there was a temperature difference of 15 K between plates. The tested boards had a size of 250 × 250 mm and a thickness of 18 to 25 mm, with a moisture content of 12% and a standard deviation of 0.5%. The density of these boards varied between 600 and 900 kg/m^3.

The behavior against fire was analyzed with a small flame test (Figure 3), according to EN ISO 11925-2:2011 [52]. Three specimens, sized 250 × 90 mm from each panel, were clamped in a frame and their entire surface was exposed to the flame of a Bunsen burner at distance of 20 mm for 15 and 30 s.

Following the flame exposure, the heat behavior of the sample was evaluated, observing (1) if ignition took place, and (2) if the flame reached a height of 150 mm above the burning point and in the specified time span. Additionally, any possible yielded droplets leading to ignition of the filter paper, located below the sample, were evaluated. Overall damage of the samples due to fire exposure was also inspected.

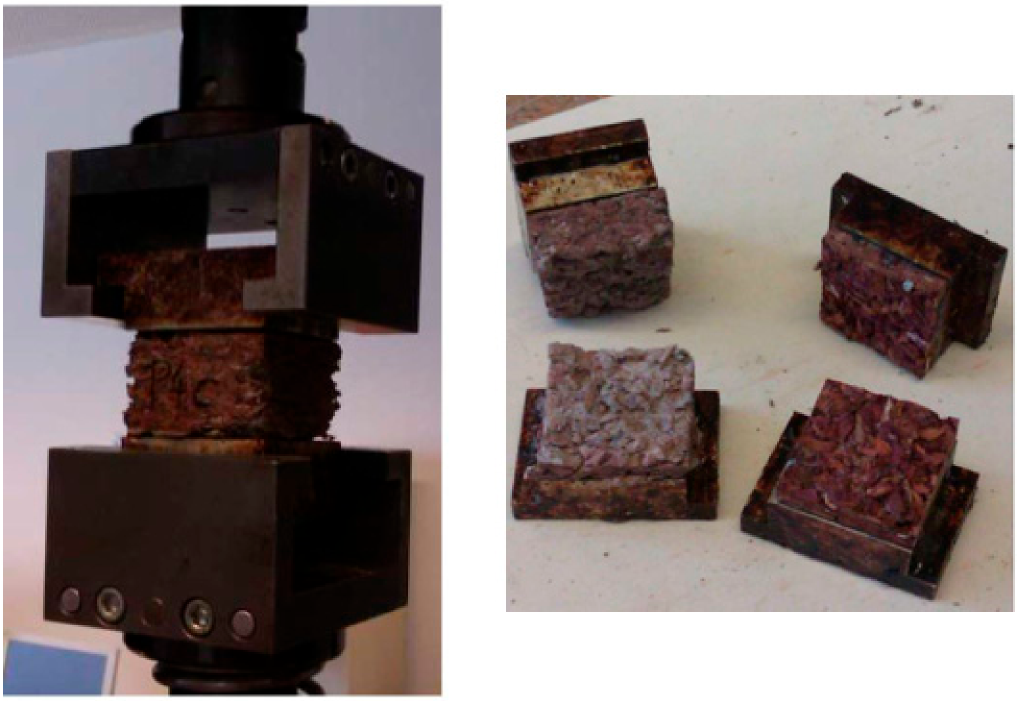

Figure 1. Internal bond test of one sample with larch bark bonded with clay (**left**) and two tested samples bonded with clay and urea–formaldehyde (**right**).

Figure 2. Screw withdrawal resistance of a bark clay sample tested on the edge.

Figure 3. Experimental setup for the small flame test (**left**) and the tested sample (**right**).

3. Results and Discussion

Thickness swelling of the bark composites bonded with clay was observable because the test specimen (n = 10) started to disperse after water immersion within one hour. For this reason, only the results for the UF-bonded bark panel are available: thickness swelling after 1 h: 2.5%, after 2 h: 4% and after 24 h: 8.68%; water absorption after 1 h: 6%, after 2 h: 7.7% and after 24 h: 41.74%. Therefore, larch bark composites bonded with clay are suitable to dry or slightly wet environments only, similar to standard wood cement boards. In the case of poplar bark panels bonded with clay and starch (F, G and H), the dimensional stability is different. A lower swelling in thickness was measured for the board glued with UF (3%), while the values for the formulations with clay and starch ranged from 28% (G) to 43% (F). A similar trend was followed for the water uptake. The lesser value was reported for sample G (43%), while 66% water uptake was calculated for sample F. In Table 3 are the values of thickness swelling and water absorption for bark boards, wood particle cement and wood wool cement boards. In the case of needing to use bark boards in a wet environment, into the bark board with UF can be added a small amount of nanoclay, which can improve water absorption and thickness swelling. Extensive research in adding nanoclay to particleboard has taken place in recent years. Hosseyni et al. [53] investigated the effect of adding nanoclay particles (3% and 6%) to resin on the properties of particleboard. Their research results showed that WA decreased by adding small amounts of nanoclay to UF-bonded boards, and TS was lower by 36%. In case of TS, these results were also confirmed in research by Ismita and Lokesh [54]. The authors investigated the effects of different nanoclay loadings (2%, 4% and 6%) on the physical and mechanical properties of *Melia composita* particleboard.

Table 3. Thickness swelling and water absorption for bark, wood particle cement and wood wool cement boards.

Board	Thickness Swelling	Water Uptake
Larch bark board with UF (A)	2.5% (1 h), 4% (2 h), 8.68% (24 h)	6% (1 h), 7.7% (2 h), 41.74% (24 h)
Poplar bark board with UF (E)	1% (1 h), 2% (2 h), 3% (24 h)	3% (1 h), 6% (2 h), 19% (24 h)
Poplar bark board (F)	7% (1 h), 9% (2 h), 43% (24 h)	43% (1 h), 54% (2 h), 66% (24 h)
Poplar bark board (G)	7% (1 h), 9% (2 h), 28% (24 h)	28% (1 h), 34% (2 h), 43% (24 h)
Poplar bark board (H)	7% (1 h), 9% (2 h), 36% (24 h)	36% (1 h), 42% (2 h), 48% (24 h)
Wood wool cement board—Isolith	1.8% (24 h)	36% (24 h)
Wood particle cement board—Heraklith	2% (24 h)	36% (24h)
Wood wool cement bonded board—Knauf	N/A	N/A

Source: [42–44].

The internal bond of the clay-bonded larch bark panels is moderate (Figure 4). Values in the range of 0.010 N/mm^2 to 0.035 N/mm^2 were measured in the case of the UF-bonded larch bark board (A). When poplar bark was bonded only with UF (E), the internal bond was 0.334 N/mm^2. The board with a 913 kg/m^3 density (G) had an internal bond of 0.3 N/mm^2, comparable with panel E. One of the reasons for this is that the clay gains its hardness and consistency when fired at temperatures over 800 °C. If it is only dried, as in the test, it is brittle. Trial samples made of bark with UF resin (A) could achieve values similar to those of industrially manufactured products (internal bond of 0.51 N/mm^2). A raw particleboard with a similar thickness should have a minimum transverse tensile strength of 0.24 N/mm^2 (P1), according to EN 312:2010 [55] that states the requirements for particleboard. Similar to the cases of WA and TS, the internal bond can be improved by adding a small amount of nanoclay to UF-bonded bark boards. A statistically significant increase in IB occurred in the case of UF-bonded boards with the addition of nanoclay particles in the research by Hosseyni et al. [53]. Similar improvements can also be achieved in the cases of modulus of rupture (MOR) and modulus of elasticity (MOE). The authors also achieved a 39% increase in MOR by adding 6% nanoclay and a 73% increase in MOE with the same amount of nanoclay added. These results were confirmed by Ismita and Lokesh [54]. In their case, MOR showed the most significant improvement (34%) with 6% nanoclay loadings and MOE 65%, also with 6% nanoclay loadings. Bacigalupe et al. [56] investigated adhesives based on UF/soy protein reinforced with clay for wood particleboard. Their results showed that a small amount of nanoclay (1%) improved the modulus of both rupture and elasticity.

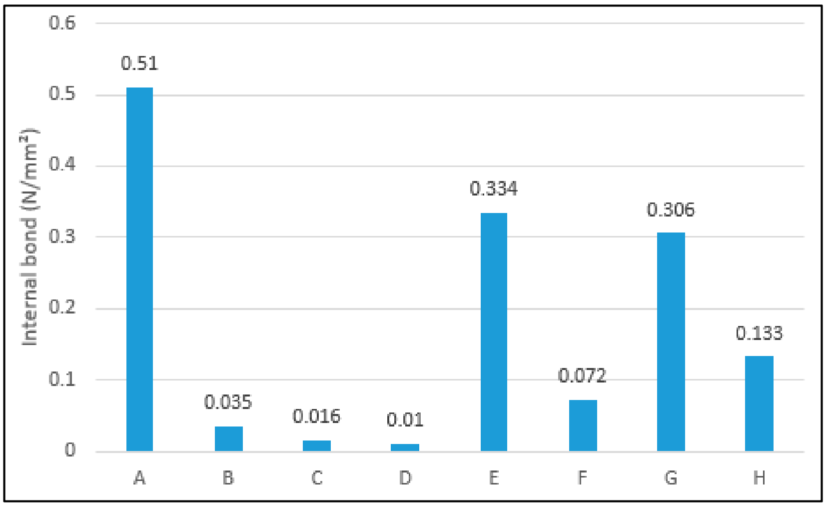

Figure 4. Internal bond of the larch bark panels bonded with UF (A) and clay (B, C and D) and poplar bark panels bonded with UF (E) and clay and starch (F, G, H).

For comparison, a cement-bonded particle board has a transverse tensile strength of 0.5 N/mm^2, according to the manufacturer [57]. The bending strength of an Isolith wood wool cement-bonded board is 3.2 N/mm^2 (lengthwise) and 1.7 N/mm^2 (across), with a compression strength (at 10%) of 0.6 N/mm^2. The bending strength of a Heraklith wood particle cement-bonded board is 2 N/mm^2 (lengthwise), with a compression strength (at 10%) of 2.2 N/mm^2.

The values of screw withdrawal resistance (Figure 5) were measured for both the surface and the edge, but only for the samples cut from the larch bark reference panel (16.3 N/mm for the surface and 12.6 N/mm for the edge). In the case of the other larch bark samples, the average value of screw withdrawal resistance at the surface was 1.4 N/mm, 87% lower than the value of the control sample. These values are within the required range for the boards' use in non-structural paneling applications. The measurements for the samples of the poplar bark boards bonded with UF (E) were similar for the edges (12.3 N/mm), but lower for the surface (10.76 N/mm). The board with a density of 700 kg/m^3 (F) and a thickness of 24.3 mm had the lowest values of screw withdrawal resistance from this series.

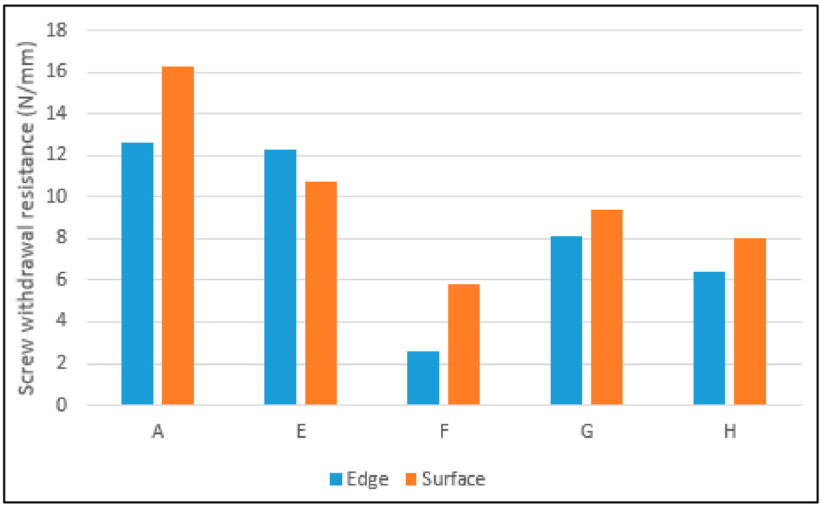

Figure 5. Screw withdrawal resistance of the larch bark panel bonded with UF (A) and poplar bark panels bonded with UF (E) and clay and starch (F, G, H).

All composite boards with larch and poplar bark and clay were exposed to fire, and they were compared with a reference panel manufactured with the same raw material and bonded with UF (Figure 6).

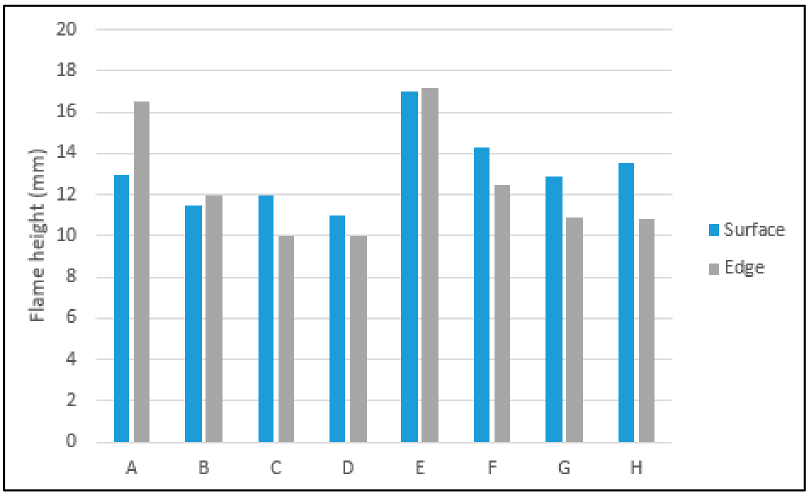

Figure 6. Small flame test after 30s, applied on the surface and edge of the composite boards with larch and poplar bark and clay.

These mineral-bonded larch bark boards revealed their properties against fire, both on the surface and edge, with a duration of flame propagation (flame height under 12 mm). The density of the panels and their thicknesses seemed to play non-significant roles when exposed to fire (from 10 to 12 mm) [38].

For the UF-bonded boards (A and E), the height of the flame was higher compared with the bark composites mixed with clay (B, C, D) and clay with starch (F, G, H). The clay acted as a fire retardant and improved the fire resistance of the boards by 12–15% for the surface and 27–39% for the edge [38]. The larch bark is lumpy [58] and the poplar bark more fibrous; for this reason, the flame height was lower for the former.

No drop formation was detected, and the filter paper placed under the testing frame did not ignite. It is in harmony with Liu et al. [25], who studied the effects of fiberboard coated with nano-kaolin-clay (NK). The results lead to the conclusion that finishing with NK, together with a phenolic resin, is an effective method for increasing fire safety and resistance. These findings are consistent with the results of [59], who emphasized the role of mineral coatings for wood composites in order to avoid fire hazards.

Therefore, the composites made of larch bark and clay could be a good solution for fire-resistant decorative boards, especially for different types of protection walls. Isolith, Knauf and Heraklith cement-bonded boards have a fire resistance of B s1 d0, which is comparable to the bark clay panels in this research.

Samples A, B, C, D, E, F, G and H were also tested for thermal conductivity (λ). They were not essentially designed for thermal insulation purposes because their target density is high (from 600 to 950 kg/m^3). The aim of this test (Figure 7) is to identify the λ values as a material property for the composite boards with larch bark, using three different particle sizes (<4 mm, 4 < × < 11 mm and >11 mm) [38].

The thermal conductivity of boards A and C (Figure 7) are relatively similar at measuring temperatures of 10 °C, 25 °C and 40 °C, respectively.

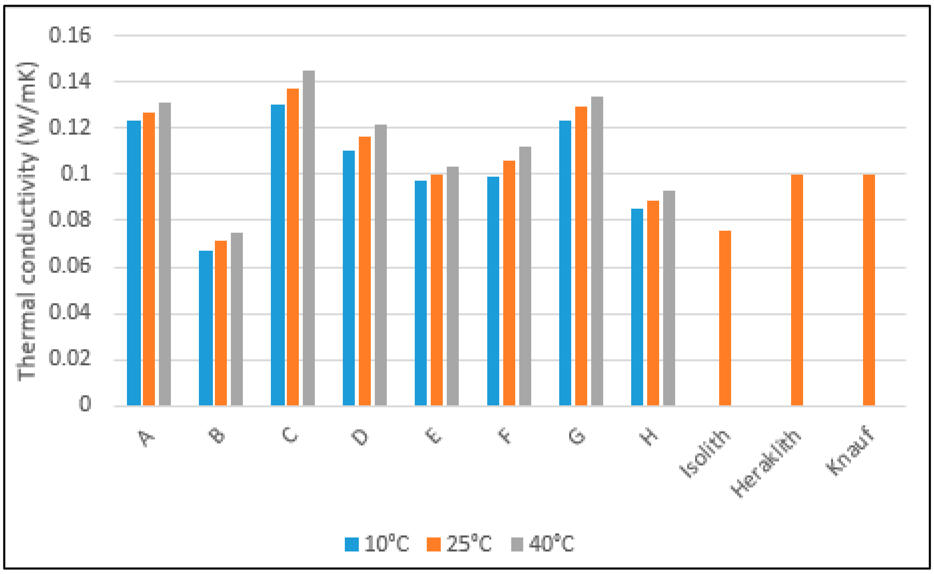

Figure 7. Thermal conductivity of the composite boards with larch bark and clay.

A decrease of λ values was observed for panel B with 600 kg/m^3 [38]. Thermal conductivity for panel B has an excellent value despite a higher density, and can also serve as thermal insulating material [60]. The λ value of thermal insulation materials covers, although a higher spectrum, below 0.1 W/mK [61]. The measurements at 25 °C for panels B (0.07 W/mK), E (0.1 W/mK) and F (0.1 W/mK) are consistent with the values for the Isolith, Heraklith and Knauf panels, as well as with the findings of [62,63]. They studied the thermal conductivity of tree bark panels bonded with tannin adhesives and reported values between 0.06 and 0.09 W/mK. The advantage of the bark clay boards as an insulation material is mostly in the well-known accumulative capacity of clay, which can significantly improve the climatic stability of indoor spaces, mostly in spaces with low ventilation rates. Another advantage of clay, as a component in bark clay boards, is the excellent absorbance and diffusivity of water vapor [64]. In the analysis of fiberglass–urethane, fiberglass-rigid, urethane-rigid, perlite, extruded polystyrene and urethane-roof deck materials, Mahlia et al. [65] concluded that there should be a relation between the thermal conductivity and the thickness of the insulation panel for each material. They proposed a non-linear relationship between the λ value and optimal thickness (x_{opt}) that obeys a polynomial function:

$$x_{opt} = a + b \cdot k + c \cdot k^2 \tag{1}$$

where a = 0.0818, b = −2.973 and c = 64.4.

In the case of thermal conductivity, the thickness of the board plays an important role, correlated with density. The thickest board (33 mm) reached values that are consistent with the results from other recent studies.

4. Conclusions

These ecologically friendly, 100% natural and recyclable composites can be mostly used with respect to their thermal insulation, acoustics and fire resistance properties [66].

In this research, the thermal conductivity of the bark clay composites was investigated. The board with the lower thickness (19 mm) had a similar value as reported from Kain et al. [60,62] and Pasztory et al. [67]. The panel with density of 600 kg/m^3 has excellent thermal conductivity values despite a high density, and it can also serve as thermal insulating material. Another advantage of the bark clay boards as an insulation material is mostly in the accumulative capacity, similar to wood cement boards. Clay surfaces can regulate temperature because they are able to absorb and diffuse water vapor very well. Clay boards can significantly improve the climatic stability of indoor spaces that have low ventilation rates. Thus, moisture mass must have equal consideration to thermal mass in passive buildings. A few centimeters of clay absorbent material is sufficient to buffer a daily relative humidity (RH) cycle, and about 40 cm of an absorbent wall might buffer an annual cycle in a standard room [68]. Besides these properties, clay boards are excellent in absorbing odors. The same occurs for bark insulation boards [69].

In the case of sound absorption, bark-based panels can absorb sound better than OSB, particleboard, MDF and poplar plywood. Therefore, the values of the sound absorption coefficient confine their application as structural elements for reducing noise effects in residential buildings, and open new ways for deeper research in this field [6]. In addition, clay is very good at reducing noise levels.

Clay boards have excellent fire resistance properties, and they can be used, for example, as the fire protection of wooden or metal structure surfaces. The mixture between larch bark and clay generated a composite with enhanced resistance to fire. The results are consistent with the findings of Tudor et al. [40], regarding the role of bark composites as coating materials with acceptable fire resistance.

Bark boards with clay, similar to wood cement composites, have non-essential mechanical properties. Therefore, there is a limited use for non-structural paneling applications [70]. The disadvantage of the bark clay composite panels is also the tool wear (circular saw and band saw, milling head), that can be optimized by the reduction of the board's thickness of 1–2 mm, to obtain a thin fire-resistant coating. These layers can protect a flammable substrate from fire by the thermal insulation effect. A trend in recent years is that coatings represent the addition of clay to improve resistance against fire, especially formulations with nanoclay [71,72]. A new type of fire-resisting coating with bark and clay could be considered as a follow-up of this analysis.

The following research perspectives in this area should focus even more deeply on the synchronization of ecological, economic, and social aspects of sustainability of ecologically friendly, 100% natural and recyclable composites with respect to their thermal insulation, acoustics and fire resistance properties [73–76].

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