Thermal conductivity of wood-plastic composites as insulation panels: theoretical and experimental analysis

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Abstract

The aim of this study is evaluating the thermal performance of wood plastic composites (WPCs) as insulation panels depending on the values of thermal conductivity (k). Three types of wood flour taken from (pine, oak and walnut) trees with concentrations (10, 20, 30 %), and two types of thermoplastics; high density polyethylene (HDPE) and polypropylene (PP), have been selected for the evaluation. Theoretical work uses mathematical relations in the calculation of thermal conductivity of WPCs. Experimental work includes the manufacturing of the specimens, the measurements of k-values. The results show that the increasing in wood content leads to a reduction in k-values for WPCs by 6-8.5% for each 10% addition of wood. The k-values of WPCs tend to increase, when temperatures rise from 25-75 °C, by 20-25% for HDPE-wood composites, and by 15-20% for PP-wood composites. Furthermore, 10 % of water content will increase the k-value by 10-20%.

Keywords: wood, plastic, composite, thermal conductivity, insulation

Kulcsszavak: fa, műanyag, kompozit, hővezetőképesség, szigetelés

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1. Introduction

There are many technical solutions to decrease energy consumption and reduce greenhouse emissions, which is necessary also because of the need for the energy balance improving [1]. Thermal insulation is an essential part in the residential building to prevent heat transfer between outside and inside. Most of insulation materials are synthetic materials which consume extra sources of raw materials, and spend a lot of money and effort. Recently, many investigations have been developed to invest the natural materials or recycled materials. Wood plastic composites (WPCs) are relatively new family of composites and environmentally friendly materials, where they can be manufactured from recycled plastics and waste woods. The wooden materials are usually: wood fiber, flour fiber, kenaf hemp and sisal. While, the plastics are usually: polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC) [2]. Wood contents in WPCs may reach 50% of the composition. The wood and thermoplastics are usually compounded above the melting temperature of the thermoplastic polymers and then further processed to make various products. WPC can be manufactured in a variety of shapes and sizes, and with different surface textures depending on the processing method [3]. Factors attributes to mechanical and thermal properties of WPCs depend on [4]: wood content, type of polymer, type of additives and processing temperature. Studies conducted in WPCs show that the presence of wood contents increases the thermal properties, i.e. thermal resistance [5]. On the other hand, the mechanical properties, i.e. tensile strengths, decrease with the increasing of wood fibers for a certain range [6].

Researchers have been looking for the development of plastics with natural wooden materials as reinforcement.

In this context, wood is usually used as flour or fiber in the composition of composite material. Several promising studies [7-24] have taken place in the evaluation of thermal properties of wood plastic composites (WPCs), for several wood types, wood contents, and polymer types as well as additives contents. Most of the studies were experimental investigations, while some others were theoretical and numerical studies or models. The major outcome of the previous works, which related to thermal properties, had focused on the thermal stability of WPC material or the variation in phase change zone and the corresponding melting point, temperature of crystallization and glass transition temperature. Less concentration had taken place for the effect of wood content on the thermal conductivity. Hence, the present study focuses on the thermal conductivity as a preferable parameter in thermal resistance calculation. The present study includes both: theoretical and experimental works. The plan suggested three types of wood flour in different concentrations (10, 20 and 30 %) with two types of thermoplastics, high density polyethylene (HDPE) and polypropylene (PP).

2. Theoretical analysis

The coefficient of thermal conductivity is the most important property of any material which indicates whether it is an insulator or not. Material with relatively low thermal conductivity, less than 0.2 W/m.K, consider as a thermal insulator [25]. The reciprocal of thermal conductivity called thermal resistivity, which is a measure of material resistance to the heat transfer. The other thermal properties are: heat reflectivity, heat capacity, coefficient of thermal expansion, thermal stability and phase-change points.

Although several theoretical works have been conducted to determine the thermal conductivity of composite materials, there is still some inaccuracy in the predicted values due to several important parameters like: operational conditions (temperature and water content), particle features (size and distribution) as well as interface quality (adhesion). For this reason, some of these effects will be discussed through numerical simulations. The effective thermal conductivity of a composite material k depends on the thermal conductivities of both: the reinforcement k_r and the matrix k_m , as well as concentration ϕ of each material. The simplest model assumes that the particles are placed in series manner with respect to the heat flow direction. This gives [26];

$$k = k_r \phi_r + k_m \phi_m \quad (1)$$

The coefficient of thermal conductivity mainly depends on: temperature, water content and some other thermo-physical properties of the material [27]. The thermal conductivity is measured in W/m.K. In general, the material with a small k -value is a good thermal insulator; on the other hand, the material with a large k -value is a good heat conductor.

2.1 Temperature rise effect

In the case of solid materials, the variation of thermal conductivity due to the change in medium temperature predominantly depends on electronic effect. The coefficient of thermal conductivity is affected by heat transport characteristics, where the microstructure of molecules affects the heat transfer. Thermal conductivity is proportional to the pore size; smaller pores will lead to lower heat conductivity [28].

In general, as temperature increases, both number of free electrons and lattice vibrations increase. Thus the thermal conductivity of the material is expected to increase. Many studies have shown that thermal conductivity of wooden materials increases with the temperature rise for a certain range, as shown in Fig. 1 [29].

Fig. 1 Variation of thermal conductivity with the temperature for some wooden materials [29]

1. ábra A hővezető képesség változása a hőmérséklet függvényében különböző faanyagok esetében [29]

Prisco U. (2014) [14] has shown that, in wooden materials, the thermal conductivity has general linear increasing as temperature increases before degradations, as following;

$$k = k_o + 1.9 \times 10^{-4} T \quad (2)$$

Where k_o refers to the initial k -value for the selected wood in the study in a limitation of temperature not exceeds 80 °C.

Heat conduction in polymers is considered as the propagation of anharmonic elastic waves through a continuum. The temperature dependent term is interpreted as the intrinsic thermal conductivity due to the Umklapp process (an anharmonic phonon-phonon scattering process), and the temperature independent term as conductivities due to the collective contribution of all point defect scattering terms. The conductivity decreases with temperature increase because “Anharmonic Umklapp” process becomes more frequent, and hence the phonon mean free path decreases [30]. Many recent investigations [30-32] indicated that, for crystalline polymeric materials, the thermal conductivity has reciprocating relation with respect to the temperature rise. The direct effect of temperature rise on the thermal conductivity of polymers is studied efficiently in reference [33], where the study presented the behavior of some polymers, as shown in Fig. 2. It can be concluded, from these studies, that the relationship between the thermal conductivity and the temperature may have the simple linear interpolation formula:

$$k = k_o - m T \quad (3)$$

Where, k_o is the reference k -value at standard conditions. While, m is the index of variation and it has different values from polymer to another.

Fig. 2 Variation of thermal conductivity with the temperature for some polymers [33]

2. ábra A hővezető képesség változása a hőmérséklet függvényében különböző polimerek esetében [33]

2.2 Water content effect

In humid conditions, materials absorb moisture from the air, and that causes to crack, less resistance and failure [34]. When material absorbs moisture, heat begins to leak. It is noticed that the increasing of water content increases the density of the material, thus the thermal conductivity. This behavior has been extracted from many investigations [35-40]. A study conducted by Goss W. and Miller R. (1992) [39] to investigate the effect of water content on the thermal conductivity of wood has proposed the following formula;

$$k = k_o + 0.004 w \quad (4)$$

Where k_o refers to the initial k -value for the selected wood in the study, while w is the water content up to 20% limit. This behavior is in line with a study carried out by Kawasaki T. and Kawai S. (2006) [40], where the increasing in the value of thermal conductivity for ply sandwich wood (PSW) with density range between 100–800 kg/m³ was about 10-25% for a water content ranged between 5–10%.

3. Experimental work

In the current study, composite materials made of recycled wood and plastic, known as wood-plastic composites (WPCs), have proposed as thermal insulation materials. For this purpose, an experimental work has been done to manufacture and evaluate the thermal performance of WPCs as thermal insulations. The work includes collecting a group of materials (some woods and some plastics) and manufacturing a set of specimens with different mixing ratios, as well as different conditions. The tests include measuring the coefficient of thermal conductivity in room temperature and when temperature rises for certain ranges as well as water content.

3.1 Materials

A bunch of dried wood samples has been collected from the local market and this includes: Pine Wood (PW), Oak Wood (OW) and Walnut Wood (WW). It is worth noting that these samples of wood must be cut, spread, dried and grinded in order to obtain pure wood flour, as shown in Fig. 3.

Fig. 3 Wood flour used in the study
3. ábra A tanulmányban használt fa őrlémények

Initially, some solid samples of the woods had taken to calculate their densities, by measuring both: volume (by ruler) and mass (by weight scale). These values have been compared with average values that taken from reliable sources [41-43], as shown in Table 1. The comparison indicates a slight percentage of variation and that is mostly due to the difference in the features of wood.

Wood type	Density (g/cm ³) as solid [41-43]	% Variation to the type used
Pine Wood (PW)	0.45	+11 %
Oak Wood (OW)	0.70	+6 %
Walnut Wood (WW)	0.78	+5 %

Table 1 Densities of woods
1. táblázat A vizsgált faanyagok sűrűsége

Other thermo-physical properties such as: specific heat, thermal conductivity and degradation temperature, are shown in Table 2.

Wood type	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)	Degradation Temp. (°C)
Pine Wood (PW)	1500-1800	0.12-0.13	200-235
Oak Wood (OW)	2000-2400	0.14-0.16	200-220
Walnut Wood (WW)	2000-2400	0.17-0.19	200-225

Table 2 Some properties of woods from references [43-45]
2. táblázat A vizsgált faanyagok fontosabb tulajdonságai az irodalom alapján [43-45]

Thermoplastics that have melting point less than wood degradation temperature are commonly used with WPCs. Two types of thermoplastic materials have been purchased from the local market, which are: High Density Polyethylene (HDPE) and Polypropylene (PP). In order to ensure sufficient wood-plastic composites, granular raw materials of these plastics have been used, as shown in Fig. 4.

Fig. 4 Plastic grains used in the study
4. ábra A vizsgált műanyag szemcsék

Initially, some solid pieces of these types of plastics were formed using the oven with certain dimensions, where their volumes and weights have been measured to calculate the density, as shown in Table 3. The average values that extracted from references [46-48] indicated an acceptance percentage of variation due to the difference in the features of plastics. Other thermo-physical properties, would be useful in the study, are shown in Table 4.

Plastic type	Density (g/cm ³) as solid [46-48]	% Variation to the type used
High density polyethylene (HDPE)	0.95	+1 %
Polypropylene (PP)	0.90	+2 %

Table 3 Densities of plastics
3. táblázat A vizsgált műanyagok sűrűsége

Plastic type	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)	Melting point (°C)
High density polyethylene (HDPE)	2000-2500	0.44-0.48	140-160
Polypropylene (PP)	1500-2000	0.19-0.22	160-180

Table 4 Some properties of plastics from references [49-53]
4. táblázat A vizsgált műanyagok fontosabb tulajdonságai az irodalom alapján [49-53]

The variation in the thermo-physical properties of polymers is attributed to the features of type used which may be commercial or in accordance to a standard code. However, it is easy to recognize a certain type of polymer by comparing the values of several properties where there is similarity in the whole type used.

3.2 Manufacturing

The experimental work included manufacturing several specimens using different compositions of wood and plastic at different conditions. The work has conducted at Chemical Lab in Materials Engineering Department, Mustansiriyah University. Several devices and instruments have been used like, oven, thermometer, weight scale and molds. Some tools and auxiliaries have been used as well.

The majority of WPC researches suggested considering an amount of wood less than that of plastic to ensure sufficient bonding between the two components, thus the current study assumed a wood content not more than 30 % of the total weight. The wood was oven dried at 80 °C for 2 hours before processing to remove the moisture content (No more than 5%). However, WPC specimens prepared in the current study with their mixing ratios are shown in Table 5.

WPC type	Mixing ratio (%)	No. of specimens
HDPE	100	2
HDPE-PW	90-10, 80-20, 70-30	6
HDPE-OW	90-10, 80-20, 70-30	6
HDPE-WW	90-10, 80-20, 70-30	6
PP	100	2
PP-PW	90-10, 80-20, 70-30	6
PP-OW	90-10, 80-20, 70-30	6
PP-WW	90-10, 80-20, 70-30	6

Table 5 Mixing ratios of WPC specimens used in the study
5. táblázat A vizsgálatban használt WPC minták keverési arányai

For each WPC, two samples have manufactured for thermal conductivity test. Furthermore, four specimens have manufactured for temperature rise tests, and four specimens for water content tests. Besides that, three specimens have manufactured for pure wood evaluation. Thus, the total quantity reached to (51) specimens.

The desired quantities for each specimen components have weighted and combined in well mixing procedure, where two stages have proposed to ensure homogenous product as much as possible. In the first stage, some of the wood flour has mixed with the plastic grains in a bowl and then pour the mixture into a sheet of parchment paper to insert it easily to the oven for a period of time till the melting point. After that, the second stage of mixing is beginning by spreading the rest of the wood flour into the melted plastic and rolling it carefully. The oven used in the study is assigned for polymer melt-works which has the brand Jrad, with Italian thermostat operates up to 250 °C, as shown in Fig. 5.

Fig. 5 Oven used in the study
5. ábra A vizsgálatokhoz használt kemence

The period that the plastic grains spent in the oven to get melting, starting from room temperature, was ranged between 20-25 minutes at a constant rate of heat (10 °C/min). After that, the molten plastic-wood paste has ejected from the oven and inserted into the mold which has the dimensions: 5×5×1 cm³. The paste of wood-plastic should be pressed in the mold using an appropriate cap which holds a weight of 2 kg and for a period of 10 minutes. The advantage of pressing is to strengthen the produced specimen during heat transfer process in the product to ensure sufficient WPC formation. Parchment paper or aluminium foil could be used in the base of the mold to extract the specimens easily. Finally, the specimens should be exposed to the still air for a period of 5 minutes for cooling.

Measurements of thermal conductivity require specimens have circular shapes of 42 mm diameter. Therefore, the manufactured specimens should be cut using a circular hole-saw. The final shapes of specimens are shown in Fig. 6.

Fig. 6 Final shapes of WPC specimens (left: HDPE-wood; right: PP-wood)
6. ábra A WPC minták végső formája (balra: HDPE-fa; jobbra: PP-fa)

3.3 Measurements of thermal conductivity

The measurements of thermal conductivity for the specimens have conducted at the laboratory of Materials Research Department in Ministry of Science and Technology (MOST) according to ASTM C518 – 04, using Lee's disc apparatus, as shown in Fig. 7.

Fig. 7 Specimen is placed in the apparatus between hot and cold discs
7. ábra A készülékbe helyezett minták meleg és hideg lemezek között

The device consists of a chamber and a reader. The chamber has an electric heater, and there is a group of discs where the specimen should be placed between the hot and cold discs. The chamber has sufficient thermal insulation. The electric circuit was switched on until the equilibrium condition is reached. The reader recorded the temperatures across the specimen using sensors connected to a thermometer. The recorded values have compensated in a special equation approved for this device.

Since the produced WPC is assigned for residential applications (thermal insulation), thus the surface temperature on the hot side was limited not to exceed 80°C. It is important to refer here, that the thermal conductivity of pure solid wood specimens of (pine, oak and walnut) has measured as well in the same procedure. Furthermore, extra specimens of HDPE-PW and PP-PW, 10%, 20% and 30% wood content, have been selected for temperature rise tests. Moreover, four specimens of HDPE-PW and PP-PW, 30% wood content, have been selected for water content tests at 10% and 20% water content. For this purpose, the wood flour should be put in the water for certain period of time (several days) to insure increasing in wood mass due to water content by 10% or 20%.

4. Results and discussion

The thermal conductivity (k-value) is the property which indicates whether the material is a good insulator or not. The thermal conductivity of WPCs has been investigated in three situations; standard conditions, temperature rise effect and water content effect.

4.1 Standard k-values of WPCs

In general, the increasing in wood content leads to a reduction in k-value for WPC material because k-value of wood is less than that of polymer, thus the overall k-value of the composite tends to decrease. This decreasing was linear, as shown in Figs. 8-13. For HDPE-wood composites, it is noticed that there is a significant reduction in k-value when pine wood is used, due to the low k-value for pine wood ($k=0.12$ W/m.K) in compare to oak wood ($k=0.15$ W/m.K) and walnut wood ($k=0.17$ W/m.K). Theoretically, the reduction in k-value of HDPE-wood composite for every 10% addition of wood was about 8.5% when pine wood is used. On the other hand, it was 6.8% when oak wood is used. Furthermore, the using of walnut wood gave 6.2% reduction in k-value. This

amount of increasing is going to be double when there is 20% addition of wood, or triple when there is 30% addition of wood. For PP-wood composites, the reduction in the k-value by the increasing of wood content was small (3-4%) due to the fact that k-value of pure PP raw material is basically low ($k=0.22$ W/m.K) compared to that of HDPE ($k=0.48$ W/m.K). Hence, the addition of wood to PP has less reduction in k-value. So, it is concluded that the technique of WPC is useful with plastics that have relatively high k-values (more than 0.3 W/m.K) such as; HDPE, LDPE and PA in order to get clear benefits of wood addition, thus reasonable results. The experimental k-values of HDPE-wood composite were lower than that calculated theoretically by a range of 1-6%, while for PP-wood composites they were higher by 1%. The difference between experimental and theoretical values is due to the inaccuracy of mathematical equation used, since it is a simple relation, as well as a percentage of error in experimental readings. However, the range of difference was slight.

Fig. 8 Standard k-values for HDPE-PW
8. ábra A HDPE-PW szabványos k-értékei

Fig. 9 Standard k-values for HDPE-OW
9. ábra A HDPE-OW szabványos k-értékei

Fig. 10 Standard k-values for HDPE-WW
10. ábra A HDPE-WW szabványos k-értékei

Fig. 11 Standard k-values for PP-PW
11. ábra A PP-PW szabványos k-értékei

Fig. 12 Standard k-values for PP-OW
12. ábra A PP-OW szabványos k-értékei

Fig. 13 Standard k-values for PP-WW
13. ábra A PP-WW szabványos k-értékei

4.2 Effect of temperature rise on k-values

As mentioned theoretically, that the temperature rise has a negative impact on k-value of the wood and a positive impact on k-value of the polymer. Where k-value of wood increases proportionally when temperature rises for a certain range. On the other hand, k-value of polymer has a reciprocating relationship with temperature rise. Since the majority of the composition of WPC is polymer, hence the k-value of WPC tends to decrease with temperature rise. This theoretical behavior can be noticed clearly, as shown in Figs. 14-19, for HDPE-PW composites and PP-PW composites, where the temperature range was not exceeded 75 °C. The experimental results gave a contradictory behavior for the effect of temperature rise on k-value of WPCs. Where, the k-value

of WPC tends to increase with temperature rise due to the presence of H_2O which evaporated from the wood and filled the cavities, where $k_{\text{vapor}} > k_{\text{air}}$, thus increasing in the overall k-value of the composite material without focusing on the side of the majority of the polymer in the composition of WPC. So, it is very important to modify the mathematical equation that describes the k-value of WPC by adding the temperature rise effect in the consideration. Experimentally, the temperature rise from 25-75 °C leads to an increase in k-value by 20-25% for HDPE-PW composites, and by 15-20% for PP-PW composites. These percentages are effective and may increase further if extra wood content is included, thus it is recommended (in high temperatures) to use relatively low amount of wood comparing to the polymer in the composition of WPCs, if there is no stabilizers or coupling agents used.

Fig. 14 Effect of temperature on k-values for HDPE-10%PW
14. ábra A hőmérséklet hatása a k-értékére HDPE-10%PW esetén

Fig. 15 Effect of temperature on k-values for HDPE-20%PW
15. ábra A hőmérséklet hatása a k-értékére HDPE-20%PW esetén

Fig. 16 Effect of temperature on k-values for HDPE-30%PW
16. ábra A hőmérséklet hatása a k-értékére HDPE-30%PW esetén

Fig. 17 Effect of temperature on k-values for PP-10%PW
17. ábra A hőmérséklet hatása a k-értékére PP-10%PW esetén

Fig. 18 Effect of temperature on k-values for PP-20%PW
18. ábra A hőmérséklet hatása a k-értékére PP-20%PW esetén

Fig. 19 Effect of temperature on k-values for PP-30%PW
19. ábra A hőmérséklet hatása a k-értékére PP-30%PW esetén

4.3 Effect of water content on k-values

The presence of water content in the wood will increase its k-value, because water molecules will fill the cavities, and since $k_{\text{water}} > k_{\text{air}}$ that means increasing in the overall k-value of the composite material. In this test, readings were taken at different percentages of water content (5, 10, 20%) in the pine wood mixed with either HDPE or PP. It is clearly that the increasing in the water content leads to increase the k-value of WPCs, as shown in Figs. 20 and 21. The increase in k-value of HDPE-PW composite was about 15-20% for each 10% addition of water content, and it was about 10-15% for PP-PW composite. The experimental results were relatively higher than the theoretical due to the fact that wet wood flour has spread over the entire WPC composition thus impacted more on the k-values. As a result, it is concluded that water content

is undesired parameter because it has a negative impact on the k-value of WPC insulation panel.

Fig. 20 Effect of water content on k-values for HDPE-30%PW
20. ábra A víztartalom hatása a k-értékére HDPE-30%PW esetén

Fig. 21 Effect of water content on k-values for PP-30%PW
21. ábra A víztartalom hatása a k-értékére PP-30%PW esetén

5. Conclusions

Wood plastic composites (WPCs) that manufactured from waste wood and recycled plastics have possessed some advantages since they are renewable and environmentally friendly, and present some desired thermo-physical properties. They are easy in manufacturing and can be produced as thermal insulation panels with a wide range of applications in the field of constructions, facilities and equipment. However, some specific points could be concluded from the recent study as following:

- The increasing in wood content leads to a decrease in k-value for WPC material because k-value of wood is less than that of polymer.
- The decrease in k-value of WPC was 6-8.5% for each 10% addition of wood.
- The k-value of WPC tends to increase with temperature rise due to the presence of H₂O which evaporated from the wood and filled the cavities, thus increasing in the overall k-value of the composite material.
- The temperature rise from 25-75 °C leads to an increase in k-value by 20-25% for HDPE-PW composites, and by 15-20% for PP-PW composites. These percentages are effective and may increase further if extra wood content is included.

- It is important to modify the mathematical equation that describes the k-value of WPC by adding the temperature rise effect in the consideration.
- The presence of water content in the wood will increase its k-value, because water molecules will fill the cavities, and since $k_{\text{water}} > k_{\text{air}}$.
- The increase in k-value due to water content in HDPE-PW composite was about 15-20% for each 10% addition of water content, and it was about 10-15% for PP-PW composite.

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