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Effect of moisture on thermal conductivity of bio-based materials (Samaar fibers)

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Abstract

The building sector is the dominant energy consumer with a total 30% share on the overall energy consumption and is responsible for the one-third of the greenhouse gas emissions around the world. Moreover, the energy consumption due to winter heating and summer cooling is increased very rapidly in recent years. Thus, the increase in energy demands of the building sector, the shortage of fossil fuels and the environmental impact requires developing a sustainable envelope in order to improve the energy efficiency of buildings. Thermal insulation is undoubtedly the best ways to reduce energy consumption and CO_2 emissions. The development of eco-friendly concrete using particles from agricultural resources gives desirable environmental and thermal insulation qualities. However, the major drawbacks of the use of vegetable fibers are their hydrophilic character and the susceptibility to moisture absorption. To reduce the water absorption and the perturbation of thermal properties upon a change of relative humidity, the chemical treatment of vegetable fibers can be a solution.

The objective of this work is to develop a new building material lightened by the chemically treated fibers, used as a heat insulator. The short Samaar fibers have been incorporated into a sand-cement mixture in order to prepare several samples with different fiber concentration, which have been examined herein with box method. The obtained results showed that the addition of the Samaar fibers to mortar matrix increase its thermal insulation capacity by decreasing the thermal conductivity and thermal diffusivity. The comparison of three most used models showed that the value of the thermal diffusivity depends on the counting models. However, the water content has a strong effect on thermal conductivity and density of these samples; they increase rapidly. The effect of chemical on water absorption of the Samaar fibers and composites was also investigated, indeed The water uptake of fibers and composites decreased compared to untrated composites.

Keywords

Composites, chemical treatment, thermal conductivity, Samaar fibers, Juncus acutus, Water content

1. Introduction

Nowadays, the energy consumption is increasing continuously in all fields such as the industry, buildings, agriculture… At the same time, the cost of energy increased due to the shortage of energy sources and heavy environment impact (ozone layer depletion, climate change, global warming, etc..). In order to overcome the high energy consumption, particularly, in building, we have required to elaborate a new composite materials based on agriculture waste. Therefore, the green solution is to use natural fibers as reinforcements in composite matrices as substitutes to synthetic fibers such as glass and carbon fibers. Indeed, they have advantage to improve the thermal insulation properties and allow a gain in weight and in cost and can be recycled. There are a lot of papers that studied the effect of the incorporation on the thermal properties of matrices (clay, mortar, gypsum, polypropylene, etc,) [1,2, 3,4]. The results showed that the addition of natural fibers improves the thermal insulation performance, while decreasing its mechanical properties. Nevertheless, the strong water absorption by the natural fibers can conducted to high hygroscopic behavior of the materials when it is submitted to wet atmosphere. Accordingly, the materials in this case can undergo significantly a damage and reduce the materials strength [5]. Also, an important interaction between the moisture transfers and the different thermal properties. For a range of water content, the thermal conductivity can increase rapidly. The same conclusion can be drawn by some reviews that used the composite reinforced natural fibers such as wood concrete [4]. Many researches have been conducted to find a methods and means treatment of the natural fibre to increase their resistance to humidity and to improve the surface between fibers and matrices such as the alkali treatment [5]. El Abbassi et al [6] showed that the alkali treatment has a significant enhancement of the tensile properties and reduce the water absorption compared to untreated composites. It is within this context, we will study the impact of the polymerization treatment on water absorption of fibers and the composites in order to assess their efficiency. We try to take advantage of Samaar fibers plant in order to elaborate a new bio based concrete as thermal insulating materials for buildings. For this purpose, we elaborated different composites reinforced with treated and untreated fibers by varying fiber weight fractions. We study experimentally the thermal conductivity and the thermal diffusivity of composites filled with treated fibers. We calculate the value of thermal diffusivity using three models found in the literature. Then, the treated and untreated composites were immersed in water in order to evaluate the impact of the polymerization treatment on reduce of water uptake by theses composites. The influence of water content on thermal conductivity and density of samples was also investigated.

2. Materials and methods

2.1. Materials

2.1.1. Samaar fibers

The Samaar plant used in this work is available in the Tunsia center from the Juncaceae family. Its scientific noun is Juncus acutus. It grows to a hight exceed 1.5 m. It was first dried for two days. Then, we continue the drying in oven at 60°C. The second step consists to cut manually the stems to bundles of 1-2 cm length. Next, these bundles were crushed mechanically so with the standard mills, either we get fibers with a large dimensions or an important quantity of dust. Then, the obtained product is sieved in order to keep only those with a size between 1mm and 2.5mm (Fig.1).

Figure1: General aspect of the Samaar particles

2.1.2. Composite preparation

The mortar samples consist of Portland CEMII/AL32.5R cement and a sand with a grain less to 1 mm. The samples are based on a mass ratio of 2/3 sand and 1/3 of cement. The ratio of water W/C is equal to 0.6. The natural fibers are polymerized by a chemical product. We immersed the small particle of Samaar fibers in amount of resinol OF/AR, then we dry it in a regulated oven. Finally, we polymerized it at high temperature. The mass of treated and untreated fibers were added gradually to the mortar in the portion of 2%, 5%, 7%, 10% by substitution to the equivalent percentage in mass of cement and sand mixture. All samples are molded into the dimensions 27cm*27cm*3cm. They dry in the laboratory conditions and we continue the drying in oven at 60°C until constant weight.

2.2.Methods

2.2.1. Thermal measurements

A box method is used to estimate the effective thermal conductivity in steady state (Fig. 2). The measuring principle is based on achieving a permanent unidirectional heat flow through the sample which is supposed to be homogeneous and without internal generation of heat, by generation a difference of temperature between its faces. The composite sample is fixed between two boxes one of which is heated and the other is cooled, in such way that the lateral flow are negligible. Once the permanent regime is established, the value of effective thermal conductivity value is given by the Fourier's law:

$$\lambda = \frac{qe}{S\Delta T} = \frac{e}{S\Delta T}\left(\frac{U^2}{R} - C\Delta T'\right) \qquad (1)$$

q: The heat flow through the sample (W).

e: thickness of sample (m).

S: the area of the faces of the sample perpendicular to the flow lines (m^2)

C: heat loss coefficient $W°C^{-1}$

R: Electrical resistance (Ω)

ΔT : Temperature gradient between the cold and hot faces of the sample, °C

ΔT': Temperature gradient between the inside and the outside of the box, °C

The thermal diffusivity was measured using a non-steady method. The flash technique was used. One of the box of the measurement apparatus used to measure the thermal conductivity in this study is fitted with an incandescent lamp of 1000 W. Its principle is to apply a uniform pulse of short duration t_0 on one face of the sample and recording the temperature evolution on the opposite face as function of time (Fig.3). Then, the thermal diffusivity *a* is evaluated from the temperature variation of the non irradiated face of sample, using existing theoretical models.

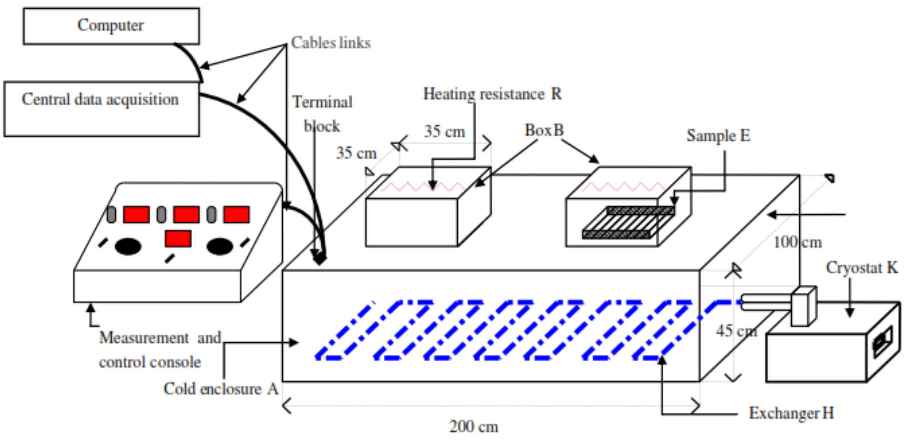

Figure 2 : Experimental setup of the box method

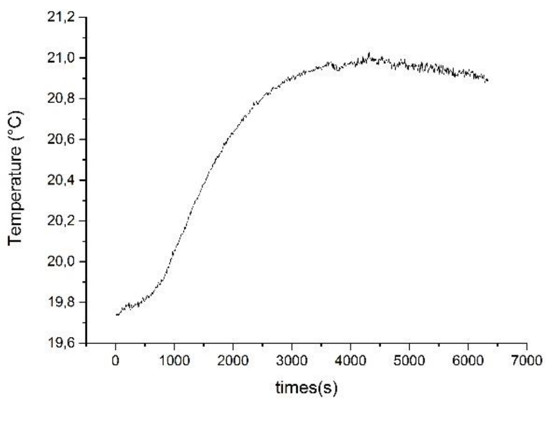

Figure3: The experimental thermo gram of opposite face

Fig.3 illustrated the temperature variation of the opposite face (case of the Samaar fibers). The exploitation of experimental thermogram allows us to estimate the thermal diffusivity of samples. Different models used in the literature are considered in this study.

2.2.2. Determination of the water absorption

The samples were immersed in bath of water at room temperature, we removed the sample at a regular time and before weighing (M_{wet}) is wiped with a soft cloth to rid the superficial water. The weight is considered constant when the mass variation still < 0.1°C. The water uptake is obtained using the following relationship:

$$Abs(\%) = \frac{M_{wet} - M_{dry}}{M_{dry}} \times 100 \qquad (2)$$

3. Results and discussions

3.1. Effect of fiber loading

Table 1**:** Thermal conductivity, thermal diffusivity of composites reinforced with treated Samaar fibers

Fiber weight fraction (%)	*K(W/m. K)*	*α(×10⁻⁷m²/s)*
0	0.520	2.6
2	0.39	2.01
5	0.248	1.726
7	0.212	1.25
10	0.185	1.106

Table 1 summarized the effective thermal conductivity and diffusivity measurements of composites reinforced with the treated Samaar fibres. The results show that the incorporation of vegetable fibers in the mortar matrix induces a decrease simultaneously of the effective thermal conductivity and the effective thermal diffusivity (i.e., from 0.52 W m^{-1} K^{-1} for neat mortar matrix and 0.185 W m^{-1} K^{-1} for 10 wt% (weight fraction). At 10% loading, the effective thermal conductivity and diffusivity decrease by almost 60%. This decrease can be explained by the air entrapped in the pockets of porous structure. Moreover, the hollow stucture of the fibers which act as insulators reduces the heat transport in the composites. The same behaviour for thermal conductivity has been noted by [1-2-3]. The thermal diffusivity behaviour follows the same trend ; Its value decreased when the fiber loading increased. The same trend is found by Taoukil et al [4].

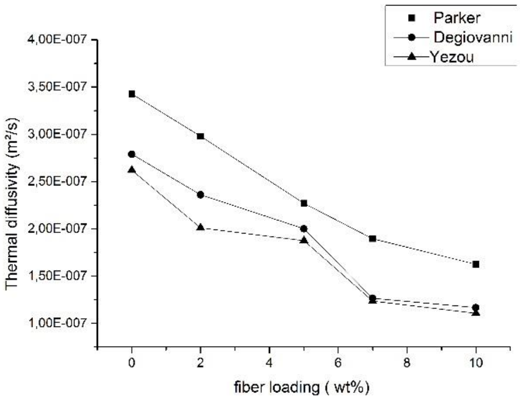

Figure 4: Comparison between thermal diffusivity of the various samples as a function of treated fibers content given by Parker, Degiovanni and Yezou models

Fig.4 shows a comparison between the thermal diffusivity values obtained by three counting models of experimental thermograms. It is worthy to note that thermal diffusivity of samples reinforced with treated fibers, which measured at dry state, decreases simultaneously with the increase of fiber loading. Thus, the Samaar particles has a positive effect on its thermal insulation capacity. For calculating the thermal diffusivity value, we use three models, which exist in the literature:

Parker model [7],

$$\alpha = \frac{0,139e^2}{t_{1/2}} \tag{3}$$

Degiovanni model [8],

$$a_{2/3} = e^2 \frac{1,150 * t_{5/6} - 1,250 * t_{2/3}}{{t_{5/6}}^2} \tag{4}$$

$$a_{1/3} = e^2 \frac{0,617 * t_{5/6} - 0,862 * t_{1/3}}{{t_{5/6}}^2} \tag{5}$$

$$a_{1/2} = e^2 \frac{0,761 * t_{5/6} - 0,926 * t_{1/2}}{{t_{5/6}}^2} \tag{6}$$

Yezou model [9],

$$a_{5/6} = \frac{e^2}{t_{5/6} + t_0/2}\left[0,713\left(\frac{t_{1/2} + t_0/2}{T_{5/6} + t_0/2}\right)^2 - 1,812\left(\frac{t_{1/2} + t_0/2}{T_{5/6} + t_0/2}\right) + 1,037\right] \tag{7}$$

$$a_{1/2} = \frac{e^2}{t_{1/2} + t_0/2}\left[-0,4032\left(\frac{t_{1/2} + t_0/2}{T_{5/6} + t_0/2}\right)^2 + 0,1103\left(\frac{t_{1/2} + t_0/2}{T_{5/6} + t_0/2}\right) + 0,2027\right] \tag{8}$$

Where $t_{i/j}$ is the time corresponds to the ratio i/j of the maximum temperature determined from the experimental thermograms (seen in Fig. 3), t_0 is the pulse duration.

For each model, the thermal diffusivity is calculated as the arithmetic mean of expressions.

It is observed in Fig.4 a significant difference between values of thermal diffusivity calculated using the three aforesaid models. These results can be explained by the difference between basic hypotheses retained in each model.

Firstly, for the development of Parker model, several aspects of the physical reality are neglected, the author supposed that the sample is homogeneous, isotropic, constant thermophysical characteristics and unidirectional heat transfer. They supposed that the heat loss on different faces of a sample is null. For these reasons, we can affirm that the value of thermal diffusivity given by Parker model is overestimated (as shown in Fig. 4) which presented the high value compared to Degiovanni and Yezou. Secondly, Degiovanni model supposed that the unidirectional heat transfers and takes account the heat losses on the face of cylindrical samples. But, he neglected the pulse duration. Finally, Yezou model, in addition to Degiovanni conditions, he used a parallelepepid sample and take account the pulse duration. This model is suitable for construction materials. The value of the thermal diffusivity in our case, are given by Yezou model.

3.2. Effect of chemical treatment on water absorption

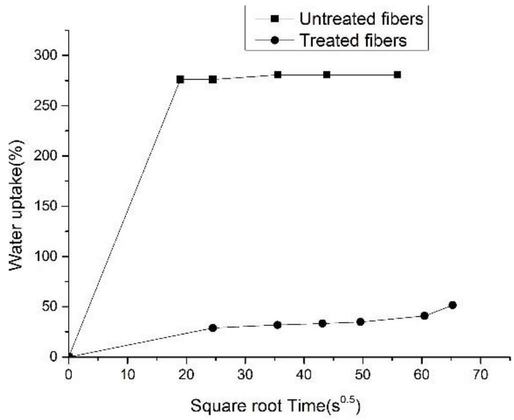

Figure 5 : Mass relative water absorption of treated and untreated fibers according to water immersion time

For the natural fibre composites, the water absorption is strongly related to fibre content because their hydrophilic character [10]. Accordingly, we present in Fig. 5, the water uptake of untreated and treated Samaar fibers according to water immersion. Two distinct stages can be observed. In the case of untreated fibers, a rapid weight gain is observed during the first few minutes (see Fig.5- stage 1). After 15 min we can observed an equilibrium stage (stage 2), 280,59 per cent higher wet mass compared to initial dry mass, However, the water uptake of treated fiber is very low compared to untreated fiber and its value can reach only 50% after 70 min.

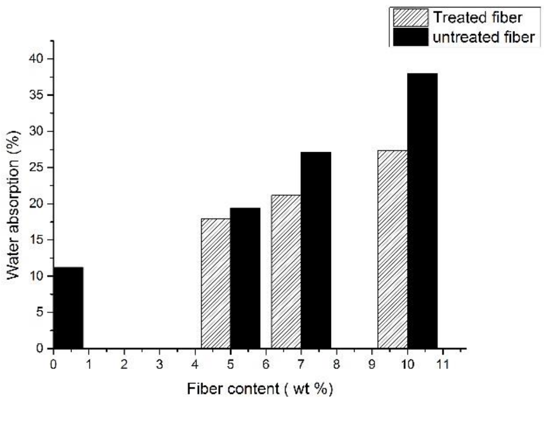

Figure 6 : the water uptake of composites according to Samaar content

Fig.6 shows the water absorption of composites reinforced with treated and untreated Samaar fibers. It shows that the incorporation of Samaar fibers in the mortar matrix is translated by an important increase of its water absorption. This increase is caused, among other factors, by the highly hydrophilic character of the Samaar fibers (see in Fig.5). It is clear to note that the treatment applied to natural fiber reduce the water uptake of the Samaar fibers and accordingly the decrease of the composite water absorption. Indeed, This reduction can be attributed to polymerization treatment by the improvement of surface between the Samaar fibers and mortar matrix. The same behaviour is noted [6] that used an alkali treatment to alfa fiber. They conclude that the alkali treatment lead to a reduction of water absorption by composites.

3.3. Effect of moisture on thermo physical properties of samples reinforced with treated fibers

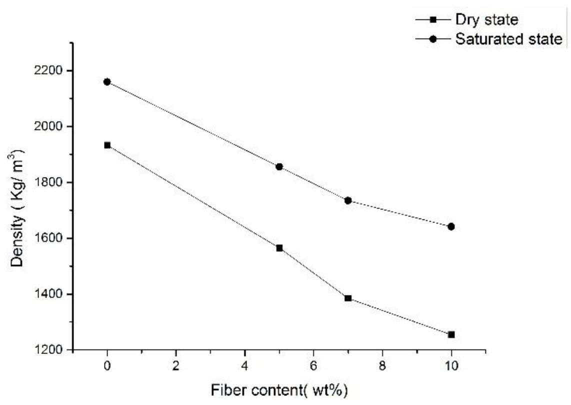

Figure 7: Variation of density at dry and saturated state as function of fiber content

The evolution of the density as function with fiber content as function at dry and saturated state is illustrated on the Fig. 7. It is worthy to note that the addition of the Samaar fibers in mortar matrix decrease their density. This could be attributed to the low density of natural fibers which substitue the mass of sand and cement. In spite of the advantage that the use of natural fiber can lighten the construction material, the experimental measurements shows (as shown in Fig.7) the high hydrophilic character of the natural fiber (the water uptake of treated fibers can reach to 50% se Fig. 5) lead to increase to density of samples due to infiltration of water into these materials.

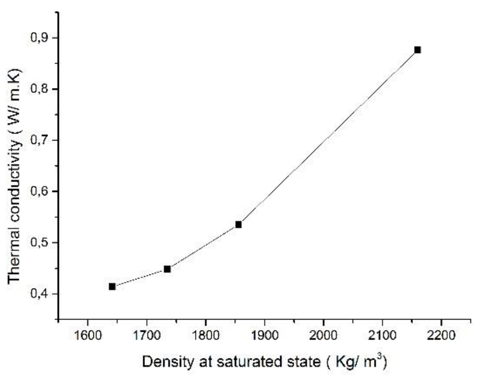

Figure 8 : Variation of thermal conductivity with density saturated state

Fig. 8 shows that the evolution of the thermal conductivity of compsites filled with untreated fibers. We notice that the moisture has a strong influence on the thermal conductivity. In fact, the thermal condutivity increases when the wet density increased. Indeed, the wet material conducts more heat than a dry one because the thermal conductivity of water is much greater than the air. These results are concordance with previous work [11,12,13] that bring to light the effect of moisture on thermal conductivity of kind material. Therefore, it is worthy to retain that the increasing of water content decreases the insulating capacity of materials in important proportions.

4. Conclusion

This work is a contribution to improve the energy efficiency of buildings by the development a eco-friendly composites as thermal insulators with reduction of the normally used quantity of sand and cement and valorization of natural resources. Short randomly mixed Samaar fibers/ mortar were prepared by varying the fiber weight fraction. The thermo physical properties of compsites reinforced with chemically modified fibers were measured. The increase of fiber content in mortar matrix resulted in decrease of the thermal conductivity and the thermal diffusivity of the composites. In this study, we remarked also that the value of the thermal diffusivity, which measured at dry state, depends on the model used for the counting of the experimental thermo gram recorded on the opposite face of the sample. The obtained results showed that the polymerization treatment applied to the Samaar fibers reduces their water uptake during their exposure to moisture, and accordingly this treatment reduce significantly the water absorption water compared to the untreated materials. The effect of moisture on the thermal conductivity and density of composites reinforced with treated fibers was also studied. The results showed that water content has an important effect on thermal conductivity and density of composites.

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