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Research Article

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Effects of Nano-Wollastonite on Thermal Conductivity Coefficient of Medium-Density Fiberboard

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Abstract

Effect of wollastonite nanofibers on the improvement of thermal conductivity coefficient of Medium-Density Fiberboard (MDF) was studied here to find a possible solution to decrease hot-press time as a bottle-neck during composite production. Nanowollastonite (NW) was applied at 10%, based on the dry weight of wood fibers. Density of the control MDF boards was 0.66 g/cm³. Thermal conductivity coefficient was measured using an apparatus based on Fourier's Law for heat conduction. Results indicated that thermal conductivity was increased by 11.5% in NW-treated MDF boards in comparison to the control boards; thermal conductivity of control MDF was 0.099, whereas that of the NW-treated MDF boards was 0.110 $\left(\frac{w}{mk}\right)$. It may then be concluded that higher thermal conductivity of wollastonite nanofibers, spread all over the MDF-matrix, resulted in the increased thermal conductivity coefficient of NW-treated boards. This increased thermal conductivity contributed to better resin cure in the core section of the MDF mat, resulting in improved physical and mechanical properties reported in prior studies.

Keywords

Nano-biotechnology; Minerals; Nanoscience; Medium-Density Fiberboard (MDF); Wollastonite; Wood-composite

Introduction

Wood has been used over centuries as fuel, constructional materials, ship building material, as well as in art and paper-making industry. However, some of its inherent properties (such as water absorption due to the hydroxyl groups of holocellulose, sensitivity to fire and biological decay, etc.) make its usages limited. Various modifications were therefore initiated to overcome these disadvantages [1-3]. Furthermore, physical and mechanical properties of wood significantly depend upon the direction it is cut due to its orthotropic structure. Although composite-boards, as isotropic materials, offer a homogeneous structure [4], and therefore, there have been many studies to overcome its shortcomings and comply with its rapid expansion over the last decades [5-7], but transfer of heat to the core section of the mat is still considered a major concern in wood-composite manufacturing factories. In this connection, heat-transfer property of silver nanoparticles [8], was reported to decrease press time and improve mechanical properties in particleboard [9], as well as significantly decrease its liquid and gas permeability [10]. Nanotechnology was used in many sciences, such as fluid transfer in porous media [11-13], enhancement of antibacterial and antimicrobial effects of silver [14], thermal conductivity [15], heat treatment [16], filtration, wood densification [17], DNA detection [18], shape controlling [19], extraction of materials [20], surface functionalization [21], fire-retarding treatment [22], electro-deposition, electronics and semiconductors [23,24], biocomputing and missing data [25,26], manipulation of atomic force [27], cleaning technologies [28,29], cellulose and composite material production, and many others. In this connection, the heat-transfer property of silver nanoparticles [30-35], was also reported to improve some of the physical-mechanical and fire-retarding properties in solid woods and composite-boards [8].

Fire-retarding properties of nano-wollastonite, as a silicate mineral ($CaSiO_3$), were reported to be promising when used in MDF [36,37]. Some studies were also carried out on its effects on physical and mechanical properties in Medium-Density Fiberboard (MDF), made from wood fibers mixed with chicken-feather fibers [38]. The present study was, therefore, planned to evaluate the effects of wollastonite nanofibers on thermal conductivity of MDF, so that the heat could more rapidly be transferred to the core section of the MDF-mat, helping the resin to be cured more easily, and resulting in an improvement in the physical and mechanical properties.

Materials and Methods

Specimen procurement

Wood fibers were procured from Sanaye Choobe Khazar Company in Iran (MDF Caspian Khazar). The fibers comprised a mixture of five species of beech, alder, maple, hornbeam, and poplar from the neighboring forests. Boards were 16 mm in thickness and 0.66 g/cm³ in density. The total nominal pressure of the plates was 160 bars. The temperature of the plates was fixed at 175°C. Hot-pressing continued for 6 minutes. Urea-Formaldehyde resin (UF), as a thermosetting resin, was procured from Pars Chemical Industries Company, Iran. 10% of UF with 200-400 cP in viscosity, 47 seconds of gel time, and 1.277 g/cm³ in density was used. Specimens were kept in conditioning chamber (30°C and 45% relative humidity), for 2 weeks before the tests were carried out on them. The moisture content of the specimens at the time of testing was 7.5%. Ten boards were made for each treatment. From each board, two specimens were cut.

Nano-wollastonite application

Nanowollastonite (NW) gel was produced in cooperation with Vard Manufacturing Company of Mineral and Industrial Products, Iran. The size range of wollastonite nanofibers was 30–110 nm. Specifications of wollastonite combination are in table 1. NW was

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Table 1: The compounds and formulation of the nanowollastonite gel used in the present study.

Nano-wollastonite compounds	Mixing ratio (%)
CaO	39.7
SiO_2	46.96
Al_2O_3	3.95
Fe_2O_3	2.79
TiO_2	0.22
K_2O	0.04
MgO	1.39
Na_2O	0.16
SO_3	0.05

mixed with the UF resin and sprayed on to the wood fibers, before the hot press (internal application of NW). The mixed resin-NW suspension was stirred using a magnetic stirrer for 20 minutes, to make sure the suspension was adequately homogenized. The spraying of the mixed resin-nanowollastonite suspension was carried out using a rotating drum. Spraying of the suspension took 15 minutes for each of the panel, making sure that the dispersion of resin-NW would be the most uniform possible, throughout the MDF-mat. Thermal conductivity tests were carried out also one month after the production of MDF boards. Consumption level of wollastonite gel was 10% based on the dry weight of wood fibers. A prior study on production of MDF with wollastonite nanofibers indicated that this NW-content level (NW-10%) was the optimum level [38].

Thermal conductivity measurement

Thermal conductivity was measured based on Fourier's Law for heat conduction, using thermal conductivity apparatus for solids made by Iranian Precise System Co. (IPS) (Figure 1). Circular specimens were prepared, 30 mm in diameter and 16 mm in length (Figure 2); all around the specimens were covered with silicone adhesive for better insulation. Specimens were then inserted in a Teflon holder, to be placed between the heating and absorbing brass rods. The heating brass bar heated the specimen from one side at 130°C (Figure 1), while the other face of the cylindrical specimen was touched by the absorbing brass bar. The heating continued until the thermistor read a constant temperature. Furthermore, in order to measure the rate of heat-transferring, temperature was at the middle of the specimen, and registered with 5-second intervals. Thermal conductivity was then calculated using Equations 1 and 2. Temperatures were measured with 0.1°C precision.

$$Q = KA\frac{\Delta T}{L} \quad (1)$$

$$K = \frac{Q \times L}{A \times \Delta T} \quad (2)$$

Where:

K=Thermal conductivity $\left(\frac{w}{mk}\right)$

Q=Heat transfer (W)

L=Specimen thickness (m)

A=Cross section area of specimens (m^2)

ΔT=Temperature difference (T_1–T_2) (°k)

SEM imaging

SEM imaging was done at thin-film laboratory, FE-SEM lab (Field Emission), School of Electrical and Computer Engineering, The University of Tehran; a field-emission cathode in the electron gun of a scanning electron microscope provided narrower probing beams at low, as well as high electron energy, resulting in both improved spatial resolution and minimized sample charging and damage.

Statistical analysis

Statistical analysis was conducted using SAS software program, version 9.1. Two-way analysis of variance (ANOVA) was performed on the data, to conclude significant differences at the 95% level of confidence.

Results

Thermal conductivity coefficient of control MDF boards was measured to be 0.099 $\left(\frac{w}{mk}\right)$; that of NW-treated MDF boards were 0.110 $\left(\frac{w}{mk}\right)$ (Figure 3). In fact, wollastonite nanofibers increased thermal conductivity in NW-treated boards by 11.5%. This increase was statistically significant at 95% level of confidence. Standard deviation of thermal conductivity in control boards was 0.005; in the NW-treated MDF boards, standard deviation was reduced to 0.003. SEM imaging of the boards showed even formation of wood fibers along the MDF-matrix (Figure 4).

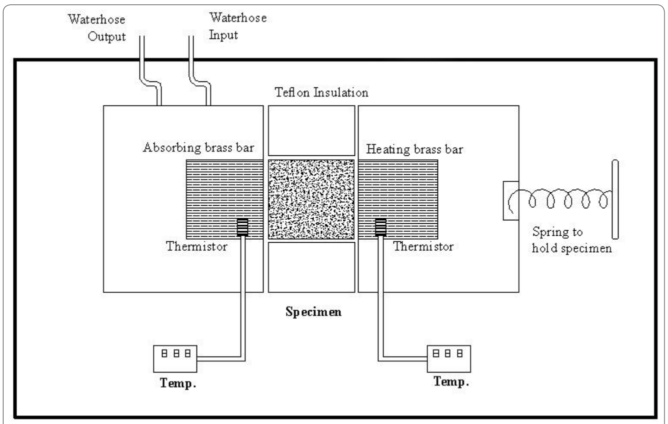

Figure 1: Schematic drawing of the thermal conductivity measurement apparatus in the present study.

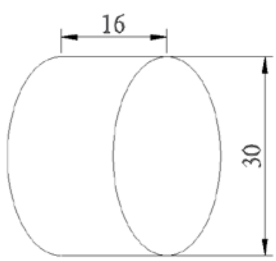

Figure 2: Schematic drawing of the cylindrical specimen placed in-between the heating brass bar and absorbing brass bar (mm).

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Discussion

Prior studies on the effect of wollastonite nanofibers reported significant increase in mechanical properties, such as Modulus Of Rupture (MOR), Modulus Of Elasticity (MOE), Internal Bond (IB), and hardness, as well as significant decrease in Water Absorption (WA) and Thickness Swelling (TS) [37,38]. This improvement can be viewed from two distinct perspectives: first, the increased thermal conductivity of the MDF-matrix due to the wollastonite nanofibers; and second, formation of bonds between the nanowollastonite and wood compounds, namely hydroxyl and methoxy groups of lignin and cellulose.

In fact, it is hypothesized that wollastonite composition (Table 1), made bonds with the hydroxyl and methoxy groups of the benzene cycles in lignin and cellulose, resulting in the improvement of physical and mechanical properties. Two types of similar bonding were also reported between nanoclay compounds and lignin network, significantly improving the properties of the composite [39]. From one side, the Al of $Al(OH)_3$ made reaction with methoxy groups in lignin; and from the other side, the hydroxyl groups of $Al(OH)_3$ made a complex bond with the lignin. The formation of the bonds was to be continued, significantly fortifying the composite-matrix. This network of bonds better integrated the MDF-matrix, resulting in better transferring of heat, and consequently higher thermal conductivity. That is, the individual fibers in the MDF-matrix were better connected to each other through a network of bonds formed between the wollastonite compounds and wood functional groups, facilitating the heat transfer. However, Al_2O_3 made up only about 4% of the wollastonite composition used in the present study, and the two main oxides making up more than 95% of the composition were CaO and SiO_2. So, in order to come to a final firm conclusion of how the bonding happened, the authors are planning to further work on the FTIR analysis of the treatments.

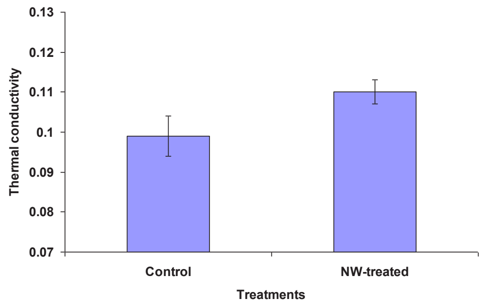

Figure 3: Thermal conductivity coefficients of control and 10% Nanowollastonite-Treated (NW-T) Medium-Density Fiberboards (MDF) ($\frac{w}{mk}$).

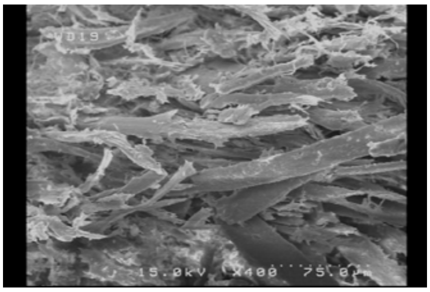

Figure 4: SEM imaging showing wood fibers in Medium-Density Fiberboard matrix (MDF-matrix).

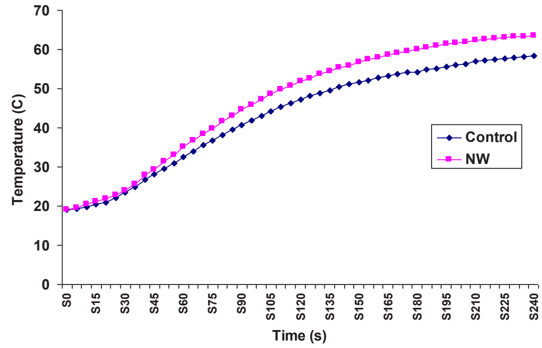

Figure 5: Temperature increase measured at the center of the specimens during 240 second exposure to 130°C.

From another perspective, the thermal conductivity of the compounds of the MDF-matrix can be studied. The thermal conductivity of wood is reported to be roughly 0.04-0.20$\left(\frac{w}{mk}\right)$, based on the species and direction from which it is viewed. However, wollastonite has a higher thermal conductivity of 2.5$\left(\frac{w}{mk}\right)$. So, the nanofibers spread all over the MDF-matrix significantly contributed to the thermal conductivity, increasing its coefficient by 11.5%.

In order to ensure the heat-transferring property of wollastonite nanofibers in the MDF-matrix, another test was carried out; one side of the specimens were exposed to 130°C, then the temperature of the core section of the specimens was measured with 5-second intervals. Total time of heat exposure was 240 seconds. The results also showed a significant increasing trend in the heat-transferring rate in the NW-treated specimens (Figure 5). This clearly proved the better cure of the resin in the core section of the MDF-mat, resulting in an increase in the physical and mechanical properties.

SEM imaging showed uniform formation of wood fiber in the MDF-matrix (Figure 4). However, as to the biological nature of wood as a natural material and the wood fibers formed from it and used in the MDF-matrix, rather high standard deviation could have been predicted. Wollastonite nanofibers helped reduce the standard deviation of thermal conductivity in the MDF-matrix; therefore, more uniform cure of resin can be expected in the matrix, resulting in the improvement of physical and mechanical properties.

The spreading pattern of wollastonite nanofibers in the composite matrix, as well as the quality of the bonds formed between different ingredients of wood with wollastonite, would give a better scope of its possible utilization on an industrial scale. The authors are therefore working on these aspects to be published in future scientific reports. In the meantime, as to the better improvement of physical and mechanical properties of wood-composites (MDF and particleboard), by nano-wollastonite, in comparison to nanoclay, the authors are also working on its possible usages in wood-plastic composites.

Conclusion

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Medium-Density Fiberboard (MDF) were studied in the present study. Wollastonite nanofibers increased thermal conductivity by 11.5% in NW-treated MDF boards. Based on the improvement in physical and mechanical properties of the NW-treated boards, this increase in thermal conductivity can significantly be correlated with the improvement in properties. In fact, the increase in thermal conductivity made better cure of the resin in the core section of the MDF-mat, resulting in the improved properties. Furthermore, higher thermal conductivity of wollastonite in comparison to wood contributed in the higher thermal conductivity of nanowollastonite-treated MDF boards.

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