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Nanotechnology in Wood-based Composite Panels

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ABSTRACT

Wood is a naturally renewable material with both continuous and isolated pore systems. Wood-composite panels have the privilege of offering a homogeneous structure to be used as constructional and structural materials. However, its nature makes it susceptible to biological wood-deteriorating agents, water absorption and thickness swelling, fire, etc. Using nano-materials are very easy in the wood-composite industry due to the possibility to apply nano-material suspensions as in-process treatment. An overview of the research project carried on applying nano-materials in wood-composite panels proved numerous potential applications of nano-technology in this industry. The use of metal (nanosilver, nanocopper, and nano zinc-oxide) and mineral nanomaterials (nano-wollastonite) with high thermal conductivity coefficient helped improving thermal conductivity and better cure of the resin, resulting in a significant decrease in hot-press time, an improvement in physical and mechanical properties, as well as a decrease in gas and liquid permeability values. The water repellent property of silane nano-particles prevented the penetration of water and vapor into wood-composite matrix, resulting in a potential increase in the service life of the parts used in the furniture or structure would significantly increase. The applications are expected to rapidly expand and cover many other areas in the near future.

Keyword: Nanotechnology; Porous Structure; Renewable materials; Thermal conductivity; Wood-composite panels.

1. INTRODUCTION

Wood resources in the world are limited, and the insufficient natural regeneration of forests does not satisfy the huge demands for the wood and wood-composite panel industry (Ruprecht et al. 2012). Moreover, the total area of world's forests is also decreasing in an alarming manner whilst the consumption of wood in the world is progressively increasing along with the exponential growth of the world population and the rising prosperity in several continents. It was estimated that the total area of the world's forests to be under four billion hectares (Kues 2007). Logical utilization and protection of the limited resources are therefore necessary.

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In this connection, wood can be modified to improve its durability against biological deterioration by fungi (Schmidt 2006 & 2007) and insects (Hickin 1975), its susceptibility against fire (Taghiyari 2012a), and its dimensional instability in moist and humid conditions. Nanotechnology was utilized in many sciences in the recent decades (Ayesh & Awwad 2012; Drelish 2013; Saber et al. 2013); it is arguably the most actively and extensively developing research areas at the beginning of the present century (Guz 2012). It was similarly used to improve the quality of many materials, including wood and wood-composites panels. It should, however, be kept in mind that when the size of a particle or the size of grains in a solid is reduced to the nanometer scale, unusual changes in its properties may occur (Li 2012).

Solid woods have a disadvantage; their strength properties vary in different directions (Doost-hosseini et al. 2014). The term wood-composite panels (or wood-composites, panels boards, …) refers to any product, which can be manufactured on the basis of mechanically chopped, milled, and grinded or refined wood (such as veneers, strands, particles, fibers, etc.) that are bonded by adhesives usually through a process at high temperature and pressure (Youngquist et al. 1997; Kharazipour 2004). During the production process of wood-composite panels, the homogenized raw materials can be formed in a desired shape, size, dimension, and amount (Kues 2007). The in-process treatment (IPT) treatment provides a benefiting opportunity to use different nano-materials in wood-composite panels to overcome its shortcomings (Taghiyari 2014a).

This review presents some of the recent applications of nanotechnology and nano-materials to improve physical and mechanical properties in agricultural and wood-based composite panels.

Thermal conductivity in wood-composite mat

Wood has a very low thermal conductivity coefficient in comparison to metal and mineral materials (0.055-0.17 W/mK depending on the direction of wood texture, in comparison to 429 W/mK in silver (Yu et al. 2010). In a study on MDF (Taghiyari et al. 2013a), thermal conductivity coefficient of control MDF boards was 0.099 (W/mK). Adding 10% of nano-wollastonite (NW) to the MDF-mat (based on the dry weight of wood fibers) increased thermal conductivity coefficient to about 0.110 (W/mK); that is an increase of about 11.5%. Addition of NW decreased standard deviation in thermal conductivity among the replications of NW-treated MDF panels. This means that NW resulted in more homogeneity in the composite matrix. The moisture content was equal in all treatments due to the thermo-hygromechanical behavior of wood (Figueroa et al. 2012).

Thermal conductivity coefficient was measured based on Fourier's Law for heat conduction (Figure 1). Circular specimens were cut (30 mm in diameter and 16 mm in length); all around the specimens were covered with silicone adhesive to insulate from the surrounding atmosphere. Thermal conductivity was 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 (W/m.K)
Q = Heat transfer (W)
L = Specimen thickness (m)
A = Cross section area of specimens (m^2)
ΔT = Temperature difference ($T_1 - T_2$) (°k)

The cited authors indicated that NW decreased the cure time of the resin in the core section of the MDF-mat, resulting in a significant increase in the physical and mechanical properties (Taghiyari et al. 2013b). Heat-transferring property of metal (Khojier et al. 2012; Sadeghi & Rastgo 2012) and mineral nanomaterials (Haghighi et al. 2013) improved some properties in solid woods as well as wood-composite materials. Effects of a 400 ppm aqueous suspension of silver nanoparticles on the heat-transferring rate from the hot-press plates to the core section of medium-density fiberboards (MDF) was studied by Taghiyari et al. (2013c). Nanosilver suspension was sprayed on the mat at three consumption levels of 100, 150, and 200 mL/kg based on the dry weight of wood fibers.

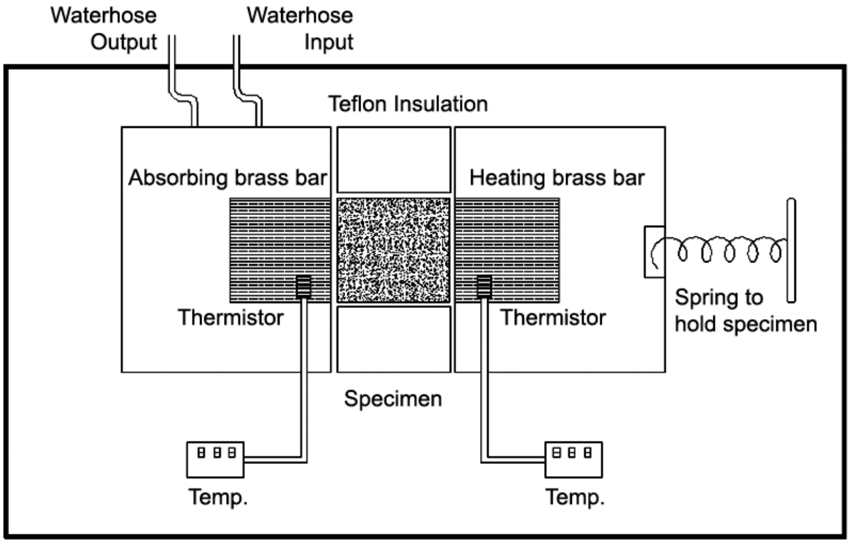


Figure 1: *Schematic drawing of the thermal conductivity measurement apparatus (Taghiyari et al. 2013a).*

SEM micro-graphs showed uniform spread of silver nanoparticles over wood fibers (Figure 2). A digital thermometer with temperature sensor probe was used to measure the temperature at the core section of the mat at 5-second intervals (Figure 3). The probe of the thermometer was directly inserted for about 50 mm into the core of the mat (from the edge boarder of the mat), in the horizontal direction. Temperature measurement was started immediately after the two hot plates reached the stop-bars. Measurement of temperature at the core section of the mat (immediately after the upper plate of the hot press reached the stop-bars) indicated significant difference between the temperatures of the four treatments of control, NS100, NS150, and NS200 (Figure 4). The cited authors reported that temperature at the core section of NS150 and NS200 were both higher than both NS100 and control treatments. The depolymerization of the surface resin bonds in the surface layers of panels with high metal nanoparticle-content can be related to the increasing trend in the final minutes of the hot-pressing; that is, in the final minutes when all moisture content was nearly evaporated in the surface layers, the heat resulted in the depolymerization and breaking down of resin bonds. The depolymerization increased the fluid flow in the composite-matrix. As to the fact that rapid transfer of heat to the surface layers of the mat would eventually result in the depolymerization of resin, ending up in decrease in some of the physical and mechanical properties, further studies should be carried out on possible spread of metal nanoparticles or mineral nanofibers in only the core section of composite mats to facilitate the heat transfer to this part; this would also prevent over-heating of the surface layers and the consequent resin break-down.

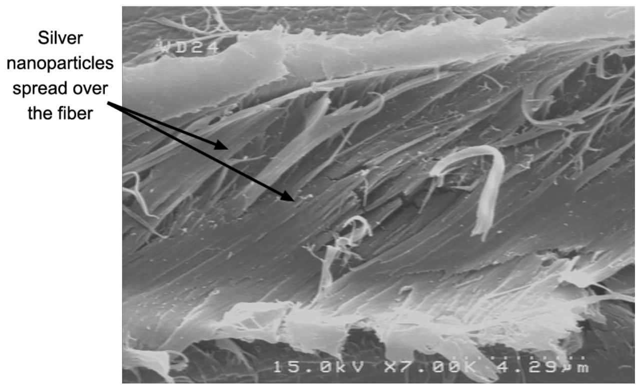


Figure 2: *SEM micrograph showing silver nanoparticles (↓) scattered all over the fibers (Taghiyari et al. 2013c).*

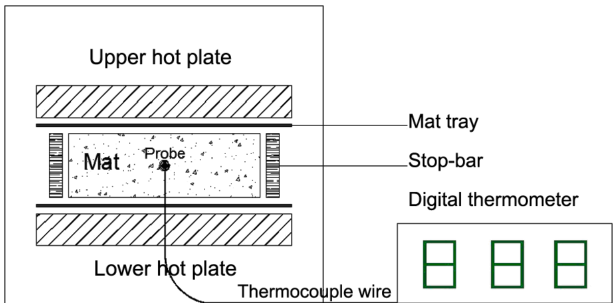


Figure 3: *Temperature measurement using a digital thermometer with its sensor probe inserted into the core section of the composite-board mat (Taghiyari et al. 2013c).*

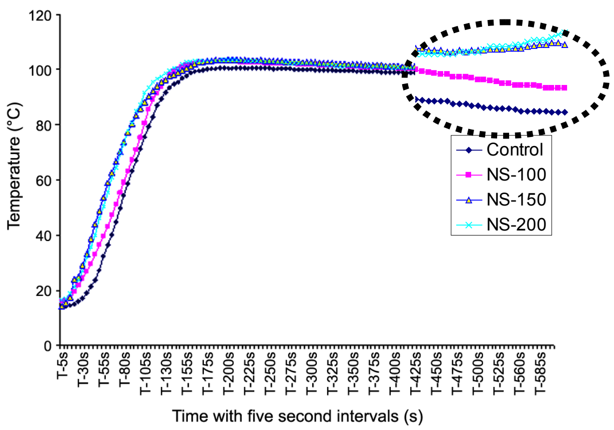


***Figure 4:** Temperature at the core section of the medium-density fiberboard mat after the third minute of hot-pressing with five-second intervals (NS= nanosilver content mL/kg) (Taghiyari et al. 2013c).*

It may therefore be concluded that addition of metal nanoparticles to increase the heat-transferring rate to the core section of composite mats should not necessarily improve all physical and mechanical properties. Furthermore, the optimum consumption level for metal nanoparticles is dependent on many factors, including the hot press temperature, hot-press duration, thermal conductivity coefficient of metal nanoparticles, and the type and density of composite panels.

Reduction in hot press time

Hot press time is considered the bottle-neck in wood-composite manufacturing factories. It is dependant on many factors, including the thickness of the composite mat, press temperature, closing rate, and most importantly, moisture distribution throughout the mat (Taghiyari et al. 2011). Moisture of the mat can not always be increased as it in turn increases the hot press time. It is therefore necessary to try to decrease the time of hot-pressing to speed up wood-composite manufacturing process; however, higher moisture contents increase the time significantly. Increase in the moisture content also causes many damages to panels as blows; high volume of water vapor and gases should be withdrawn from the mat to the surrounding atmosphere. If the volume is too high, permeability in the composite matrix would not be enough to have a timely withdrawal of vapor and gases. Accumulated vapor within the composite matrix would eventually blows, once the hot press plates open. Furthermore, for urea-formaldehyde (UF) resin, there is a limitation of moisture content (MC) level (Papadopoulos 2006); that is, higher MC than standard level for UF resin would eventually weakens the strength of resin. Finding new ways to increase the heat transferring rate to the core section of the composite mat has always been a challenge before the wood-composite manufacturing industry. Silver nano-particles decreased hot press time by 10.9% when 100 mL of nano-silver suspension was used for each kg of wood particles (dry weight basis). Copper nano-particles also decreased hot press time. Nano-copper decreased hot press time by 5.7% when 100 mL nano-copper suspension was used. Considering the lower thermal conductivity coefficient of copper in comparison to silver, this was reasoned (Bray 1947; Menezes Nunes et al. 1991).

Permeability in wood-composite panels

One of the characteristics of wood is its water absorbing potentiality when being rained, in soil contact,

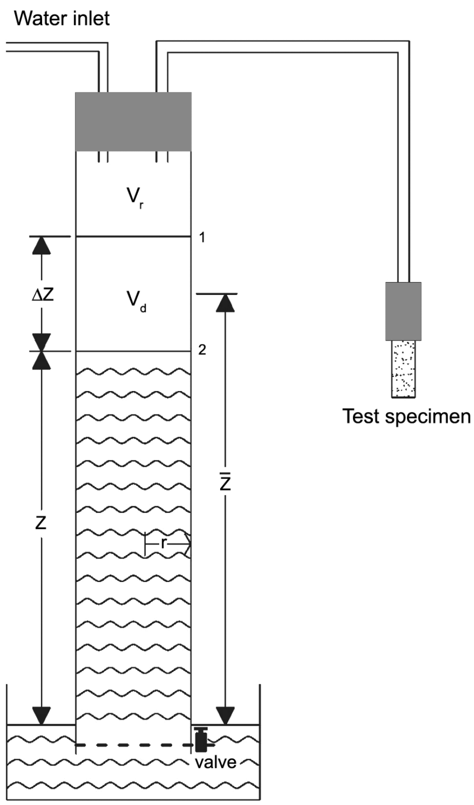


***Figure 5:** The overview of the gas permeability apparatus (USPTO No. US 8,079,249, B2) equipped with single-storey milli-second precision electronic time measurement device (approved by The Iranian Research Organization for Scientific and Technology under certificate No. 47022) (Taghiyari 2014).*

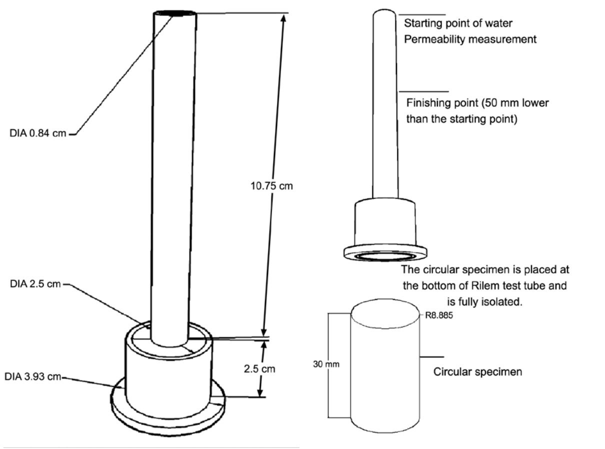


Figure 6: *Liquid permeability measurement apparatus (RILEM test tube) (Taghiyari 2012b; Taghiyari et al. 2014).*

dipped in water or even placed in moist areas. This affects wood-composite materials from different aspects. First, the dimensions of wood-composites panels and parts alter due to swelling. The swelling not only has undesirable side-effects on the design and dimensions of the wood-composite part that is used in the structure, but also the wood chips and fibers lose their integrity by micro-movements due to swelling. Secondly, water breaks down some of the resin bonds that have stuck wood chips or fibers together in the matrix, again decreasing the overall strength of the composite matrix.

In this connection, gas permeability measurement apparatus was invented to measure permeability values in porous media (including solid woods, wood-composite materials, carton and paper, light-weight cement, …) (Taghiyari, 2012b; Taghiyari & Efhami, 2011) (Figure 5). Falling-water volume-displacement method is used to calculate specific longitudinal gas permeability values based on the microstructure porosity of wood as well as wood-composite materials (USPTO No. US 8, 079, 249, B2) (Taghiyari 2013ab). Liquid permeability can be measured using Rilem test method II.4 (Figure 6).

In order to decrease water absorption in medium-density fiberboard (MDF), water-repellent property of nano-silane (NS) was used (Taghiyari 2013a). The nano-silane liquid was the resultant product of organo silane reacted with organic reactant. Nano-silane content was based on the solid parts in the suspension. For each treatment, the weight of nano-silane solids

Figure 7: *SEM image showing nanozycosil (↓) on the cell wall (× 6,000) (Taghiyari 2014).*

was deducted from the fiber used; this way, the density of panels in different treatments with different fiber-content was managed to be kept constant. The final mixture of nano-silane plus resin was smoothly sprayed on the fibers (Figure 7). The pH and viscosity of the resin were kept constant for all treatments in the present study. Density of all treatments was kept constant at 0.67 g/cm^3. The cited author reported that nano-silane significantly decreased liquid permeability in MDF (Figure 8) although the amount of wood fibers was lower in nano-silane-treated panels and micro-cavities formed in the composite-matrix (Figure 9). This resulted nano-silane 100-treatment to be clustered with the control panels (Figure 10). In another study, nano-silane decreased water absorption and thickness swelling in MDF (Taghiyari et al. 2013d). Nano-silane treatment affected the wood-composite in two ways. First, the water-repellant property of silane nano-particles acted as a physical barrier towards penetration of water. And second, na-

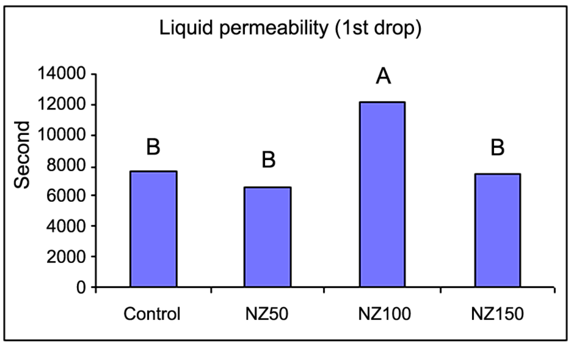
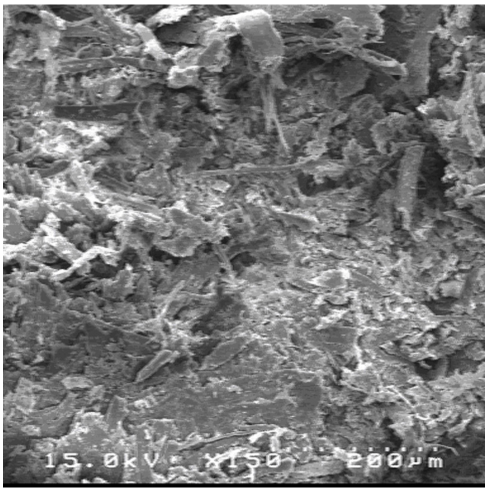
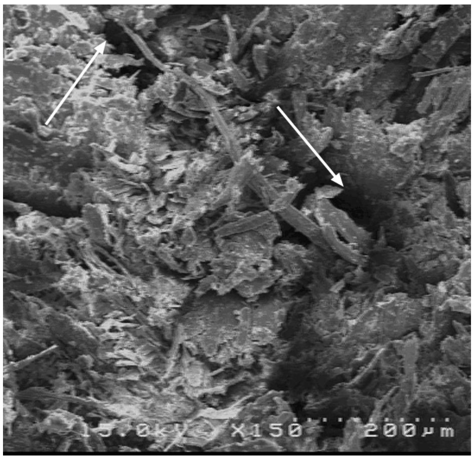


Figure 8: *The liquid permeability of the 1st-drop for the four treatments of control, NZ-50, NZ-100, and NZ-150 treatments (s) (NZ=nanozycosil) (Taghiyari 2013ab).*



(a)



(b)

Figure 9: *MDF texture (a) control specimen: fibers are integrated more intensely; (b) NZ-150: some void spaces (↓) are observed in the texture leading air to pass through much easier (Taghiyari 2013a).*

no-silane contributed in the process of sticking wood fibers together. However, silane-treated panels were susceptible to molds and therefore they were not recommended for moist climates (Figure 11).

Most of the fungi were identified as Aspergillus niger and Penicillium spp. (Taghiyari 2014b). As to the susceptibility of nano-silane to fungal attack, wollastonite nanofibers can be recommended to improve durability against wood-deteriorating fungi (Taghiyari et al. 2014b).

Silver and copper nano-particles (NS and NC) significantly decreased both gas and liquid permeability in particleboards produced at industrial scale (Taghiyari 2011; Taghiyari & Farajpour 2013). NS and NC suspensions were added to the mat at two levels of 100 and 150 milli-liters/kg dry weight wood particles and compared with control boards. Permeability values were significantly decreased in all nano-treated composite panels. The decrease was due to the high thermal conductivity coefficient of metal nanoparticles, resulting in better heat-transfer to the mat, eventually causing better cure of the resin. However, the optimum consumption levels of NS and NC were not the same. Significant difference in the thermal conductivity coefficients of silver and copper was reported to be the reason. Water absorption and thickness swelling significantly decreased after addition of nanosilver (NS) and nanocopper (NC) to particleboard matrix (Taghiyari et al. 2011; Taghiyari & Farajpour 2013). The high thermal conductivity coefficient of metal nanoparticles helped UF-resin cure more effectively.

Accelerated heat-transfer in the NS- and NC-treated wood-composite panels can influence permeability from another point of view. Heat-treatment had significant effects on fluctuations of permeability in different woods (Taghiyari 2013b). In this connection, structural modifications and chemical changes of carbohydrates and lignin occur while heating woods (Repellin & Guyonnet 2005). Moreover, the irreversible hydrogen bonding in the course of water movements within the pore system also affects the fluid transfer process (Borrega & Karenhampi 2010). These processes caused permeability to increase when woods are heated from about 70°C up to 150°C. In these steps, higher temperatures increase high inter-

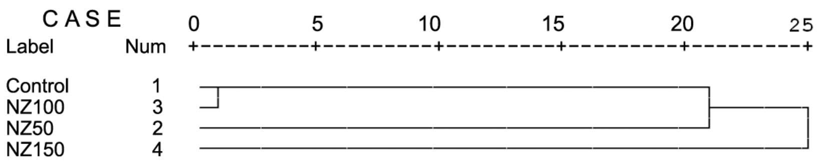
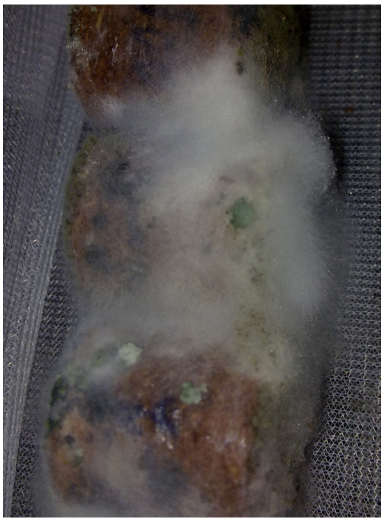


Figure 10: *Cluster analysis based on gas permeability value, as well as the two liquid permeability times for the four treatments of control, NZ-50, NZ-100, and NZ-150 (NZ = nanozycosil) (Taghiyari 2013a).*

(a)

(b)

(c)



(d)

Figure 11: *Photographs of molded specimen in vapor chamber; A, B: after 14 weeks; C, D: progressed growth after 18 months (Taghiyari 2014).*

nal stresses that are released as cracks (Oltean et al. 2007). These micro-cracks facilitate the process of fluid transfer through the porous material causing the gradual increase in permeability. Nanoclay had no significant effects on permeability in plywood; however, moisture diffusion decreased significantly (Dashti et al. 2012). The cited authors used nanoclay at two levels of 3 and 5%; hot press time was also studied at two levels of 4 and 5 minutes. It was concluded that due to the hydrophobic property of clay nanoparticles, increase in the level of consumption of filler resulted in reduction in thickness swelling and diffusion coefficient.

2. CONCLUSIONS

Wood-composite panels have the privilege of offering a homogeneous structure to be used as constructional and structural materials. Application of nano-materials is very easy due to the possibility to dissolve nano-material suspensions as in-process treatment. However, its biological nature makes it susceptible to biological wood-deteriorating agents, water absorption and thickness swelling, fire, etc. An overview of the research project carried on applying nano-materials in wood-composite panels proved numerous potential applications of nano-technology in this industry. The use of metal (nanosilver, nanocopper, and nano zinc-oxide) and mineral nanomaterials (nano-wollastonite) with high thermal conductivity coefficient helps improved thermal conductivity and better cure of the resin, resulting in a significant decrease in hot-press time, improvement in physical and mechanical properties, as well as decrease in gas and liquid permeability values. The water repellent property of organo silane nano-particles (nano-zycosil) can prevent the penetration of water and vapor into wood-composite matrix, resulting in an increased service life of the parts used in the furniture or structure would significantly increase.

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