

PHYSICAL AND MECHANICAL PROPERTIES OF NANOREINFORCED PARTICLEBOARD COMPOSITES

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ABSTRACT

Novel composite materials having desired performance properties can be developed by nanotechnology. The major objective of this research was to produce nanomaterial-reinforced particleboard composites with enhanced physical and mechanical performance. Urea formaldehyde adhesive used to produce particleboard composites was reinforced with nanoSiO₂, nanoAl₂O₃, and nanoZnO at loading level of 0%, 1%, and 3%. To evaluate physical properties density, thickness swelling, water absorption, and equilibrium moisture content were determined while modulus of rupture, modulus of elasticity, bonding strength, and screw withdrawal strength tests were carried out to evaluate mechanical properties of the particleboard composites. The results acquired in this work revealed that nanomaterial reinforcement technique significantly affected the physical and mechanical performance properties of the particleboard composites. The findings showed that the modulus of rupture, modulus of elasticity, bonding strength, and screw withdrawal resistance of the composites improved by all the nanomaterials used in this study, except 3% nanoZnO. It was also determined that using 1% nanoSiO₂ or 1% nanoAl₂O₃ in the composites had the best results in the bonding strength and screw withdrawal resistance. The findings indicate that it is possible to produce novel wood composites by using proper nanomaterial type and loading level.

Keywords: Nanoparticles, nanoreinforced adhesives, nanoscience, nanotechnology, particleboard, wood composites.

INTRODUCTION

Nanotechnology has been identified as a technological revolution by scientists from all over the world (Ciraci 2005). It is expected to be a critical driver of global economic growth and development in this century because it is a multi-disciplinary field of research (USDA 2005). Because of its potential for business development, nanotechnology is of global interest (Shand 2010). The National Science Foundation of the United States predicts that within a decade, nanotechnology will be a one trillion dollar market and provide two million new jobs (USDA 2005). Nanoscience and nanotechnology also have numerous advantages for renewable biomaterials such as wood and wood composites (Candan 2012, USDA 2005, Roughley 2005).

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Nanoparticles can be used as fillers or additives in various polymers so that different enhancements in material properties can be achieved. They can also be used to reinforce thermosetting polymers to improve final performance properties. Therefore nanoparticles are receiving increased interest for research and development activities. Nanoparticles can extend application area of polymers. Polymer nanocomposites are multidisciplinary and promptly developing research area (Candan 2012, Gacitua *et al.* 2005, Uddin 2008). Formaldehyde-based adhesives including urea-formaldehyde, melamine-urea formaldehyde, and phenol-formaldehyde are the three most commonly used adhesives in wood-based panels industry (Moubarik *et al.* 2010). The influence of nanoparticle modified thermosetting adhesives on the mechanical performance properties of wood composite panels has been evaluated by several authors. Nanoparticle-reinforced composite sandwich panels and laminate flooring were developed by Candan (2012). Dimensional stability characteristics of nanoparticle-reinforced composite sandwich panels were investigated by Candan and Akbulut (2012a). Formaldehyde emission properties of the nanoparticle-reinforced laminate flooring were studied by Candan and Akbulut (2012b). It was stated that the nanomaterials significantly affected the formaldehyde emission of the laminate flooring. It was indicated that the lowest formaldehyde emission value was determined in the laminate flooring reinforced with nanoAl₂O₃ (1%). Candan (2014) investigated the effect of nanocellulose on the formaldehyde emission of wood-based composite panels. It was revealed that environmentally friendly wood composites could be produced using nanocellulose.

The formaldehyde emission properties of particleboard and plywood panels reinforced with various nanoparticles at different loading levels were examined by Candan and Akbulut (2013). The authors reported that the nanoparticle type and loading level significantly affected the formaldehyde emission values of the particleboard and plywood panels. It was stated that the formaldehyde emission values of the plywood panels using 1% nanoZnO, 1% nanoAl₂O₃, and 3% nanoSiO₂ decreased by around 50%, 30%, and 20%, respectively. It was also concluded that the maximum decrease in formaldehyde emissions values of the particleboard panels was 82%. Physical and mechanical performance properties of nanoparticle-reinforced plywood panels were examined by Candan and Akbulut (2014). It was stated that the nanomaterial-reinforcement technique significantly affected the physical and mechanical performance of the plywood panels. It was reported that modulus of rupture of the plywood panels have been improved by around 20% using 3% nanoAl₂O₃. The authors also concluded that the nano-engineered plywood panels had higher bonding strength values than those of the unreinforced plywood panels. Wood material was modified with montmorillonite nanoclay-reinforced melamine urea formaldehyde to obtain nanocomposites by Cai *et al.* (2008). Kordkheili *et al.* (2013) examined physical and mechanical properties of polymer type panels made from single wall carbon nanotubes and wood flour. Candan *et al.* (2013a) and Candan *et al.* (2014b) developed nanobiocomposites from carbon nanotubes (CNTs) and liquefied wood. Dynamic mechanical thermal analysis (DMTA), thermogravimetric analysis (TGA), and scanning electron microscope (SEM) analysis were carried out to characterize the novel nanocomposites.

Nanoclay-reinforced phenol formaldehyde (PF) was used as adhesive in manufacture of oriented strand lumber by Zhang and Smith (2010). The impact of nanoclay on the properties of the PF and phenol urea formaldehyde (PUR) was determined by Lei *et al.* (2010). It was stated that the addition of small percentages of nanoclay did not increase much the performance of PF and PUR resins used as adhesives for plywood and particleboard panels. Lei *et al.* (2008) reinforced urea formaldehyde (UF) with nanoclay and manufactured wood composite panels such as particleboard and plywood. Urea formaldehyde was reinforced with nanocellulose and used to produce plywood panels by Zhang *et al.* (2011). Urea formaldehyde and melamine urea formaldehyde were modified with nanocellulose and used in manufacture of particleboard and oriented strandboard by Veigel *et al.* (2012). Candan *et al.* (2013b) studied on nanocellulose-reinforced adhesives for wood composite panels. Candan *et al.* (2014a) developed nanocellulose-modified urea formaldehyde adhesives. The authors determined DMTA performance of the nanocellulose-modified adhesives.

Particleboard composites are a type of wood-based composites which are made from wood particles as a renewable biomaterial. Particleboard composites are commonly used to produce furniture in Europe. The production capacity of particleboard is increasing year by year. Turkey is one of the biggest wood-based composite producers in Europe. Particleboard production capacity was 5,771,100 cubic meters in 2012 with 28 production lines (Candan 2012, Turkish Wood Based Panels Association 2013, Yildirim *et al.* 2013, Yildirim *et al.* 2014). Improving final performance properties of particleboard composites is of a great importance. For this aim, using nanotechnology application in wood composite manufacturing has a novelty. It can also be affect wood-based industry positively.

There is only limited work in the literature developing particleboard composites reinforced with nanoparticles such as nanoSiO₂, nanoAl₂O₃, and nanoZnO. The objective of this present study was to develop particleboard composites having enhanced physical and mechanical properties by using nanoparticles. The effects of the nanoparticle type or nanoparticle loading level on the physical and mechanical properties of the particleboard composites were determined in this research.

EXPERIMENTAL

Materials

Wood particles, urea formaldehyde adhesive, hardener, and paraffin were supplied by Kastamonu Integrated Wood Industry and Trade Inc., located in Kastamonu, Turkey. The nanoSiO₂, nanoAl₂O₃, and nanoZnO particles used to reinforce urea formaldehyde adhesive were provided by a chemical company. The purity of the nanoparticles used in this study was 99,9%. The average particle size (APS) values of the nanoSiO₂, nanoAl₂O₃, and nanoZnO were 15 nm, 15 nm, and 20 nm, respectively.

Nanoreinforced composite manufacturing

Urea formaldehyde adhesive was modified with nanoSiO₂, nanoAl₂O₃, and nanoZnO particles. The nanoparticles were added to adhesive at loading levels of 1% and 3%. The nanoSiO₂, nanoAl₂O₃, and nanoZnO were mixed in the urea formaldehyde adhesive using a mechanical stirrer. Urea formaldehyde, NH₄C₁, and paraffin were used as adhesive, hardener, and hydrophobic additive, respectively, in the manufacture of the composites. Unreinforced composites as a control group without nanoparticles were also produced for comparison. Each composite group was produced with the three types of nanoparticles at the two tested loading levels. All composite groups were made in triplicate, giving a total of 21 composites for evaluation. The final thickness of the composites was 8 mm.

Testing procedure

Nanoreinforced or unreinforced composites were cut into test samples which were then conditioned in a climate controlled chamber with a relative humidity of 65% and a temperature of 20°C until they reached an equilibrium moisture content, prior to the physical and mechanical tests. In this study, the dimensions of the all composite samples were determined according to TS EN 325 (2012).

Physical and structural properties

Density (TS EN 323, 1999), thickness swelling (TS) (TS EN 317, 1999), and water absorption (WA) (ASTMD1037, 2006) of the composites were determined according to national or international standards. Firstly, all TS and WA samples were weighed and measured in thickness. Specimens were immersed vertically in water bath with a temperature of 20±1°C. TS and WA performance of the composites were determined after 2 hours or 24 hours water immersion period. Equilibrium moisture content (EMC) test was also conducted according to ASTM D1037 (2006). The TS/WA samples were dried after the 24 hour water soaking period in an oven at 103°C until constant weights were reached and then weighed. The EMC values of the specimens after 2h or 24h water soaking period were calculated based on the oven-dry weight of each specimen.

Scanning electron microscopy (SEM) analysis was carried out to determine structural characteristics of the nanoreinforced composites. SEM images were taken with a Field Emission-SEM (FEI Quanta FEG 450, The Netherlands) operated at 20 kV. All the specimens were coated with gold prior to the analysis.

Mechanical properties

Modulus of rupture (MOR) (TS EN 310, 2011), modulus of elasticity (MOE) (TS EN 310, 2011), bonding strength (TS EN 319, 1999), and screw withdrawal resistance (TS EN 320, 2011) tests were performed to evaluate mechanical properties of the nanoreinforced or unreinforced composites.

Statistical analysis

All comparisons were first performed using an analysis of variance (two-way ANOVA) at $p < 0,05$ to determine the effects of the nanoreinforcement technique on the physical and mechanical properties of the particleboard composites. Significant differences between the mean values of nanoreinforced and unreinforced composite groups were determined using Duncan's multiple range test.

RESULTS AND DISCUSSION

Physical and morphological properties of the nanoreinforced composites

The average density values of the nanoreinforced or unreinforced composites ranged between $0,65 \text{ g/cm}^3$ and $0,69 \text{ g/cm}^3$. The composite groups had similar density values. There was no important difference between the composite groups. Duncan's groupings also show that there was no significant difference in density values of the composites reinforced with nanoSiO₂, nanoAl₂O₃, and nanoZnO at a significance level of 0,05. It can be also concluded that the composite manufacturing procedure has meticulously performed which is of a great importance to be obtained the composites having homogeneous performance properties in a group.

Average thickness swelling (TS) values of the nanoreinforced and unreinforced composites after 2h, 24h, 48h, and 96h water soaking period were given in Table 1. The findings clearly indicate that the TS values of the composites increased with increasing water soaking period from 2h to 96h. The results show that the TS values of the nanoreinforced composites were significantly higher than those of unreinforced composites for 2h, 24h, 48h, and 96h water soaking period. TS values after all water immersion periods of the nanoreinforced composites increased with increasing nanomaterial loading level. In case of nanoparticle type, the nanoSiO₂ reinforced composites had the lowest TS values, followed by nanoAl₂O₃ and nanoZnO reinforced composites. To investigate the effect of the nanomaterial loading level and nanomaterial type, a two-way ANOVA was carried out in this study. The results indicate that the TS values of the composites after all water soaking periods were significantly affected by the nanomaterial loading level, nanomaterial type, and combined effect of these factors. Duncan's groupings revealed that there was significant difference in all TS values of the composites reinforced with 0%, 1%, and 3% nanomaterials. There were not significant differences between the composites reinforced with nanoSiO₂ and nanoAl₂O₃ at a significance level of 0,05.

Table 1. Average thickness swelling values of the nanoreinforced or unreinforced composites.

Composites	Thickness Swelling (%)			
	2h	24h	48h	96h
Unreinforced	17,67 (1,15)	21,73 (1,45)	22,72 (1,60)	23,82 (1,71)
NanoSiO ₂ (1%)	20,85 (2,03)	25,23 (2,42)	26,27 (2,35)	27,92 (2,58)
NanoSiO ₂ (3%)	22,99 (3,43)	28,01 (4,40)	29,30 (4,66)	30,52 (4,53)
NanoAl ₂ O ₃ (1%)	23,06 (2,42)	27,92 (2,84)	29,26 (2,81)	30,75 (3,04)
NanoAl ₂ O ₃ (3%)	24,05 (2,68)	28,30 (3,05)	29,23 (2,92)	31,03 (3,26)
NanoZnO (1%)	24,58 (3,26)	29,19 (3,75)	31,15 (3,25)	34,31 (2,68)
NanoZnO (3%)	33,47 (6,44)	40,42 (7,23)	41,02 (6,94)	44,76 (6,23)

Standard deviation values are in parentheses

Effect of Al₂O₃ nanoparticles on thickness swelling properties of medium density fiberboard was examined by Kumar *et al.* (2013). It was reported that when the loading level of Al₂O₃ nanoparticles increased from 0% to 0,5%, thickness swelling values of the panels decreased but further increase in nanoparticle loading level to 1% increased thickness swelling values of the panels. In this present study, the nanoparticles were used in the composites at a loading level of 1% or 3%. It was obvious that lower loading level of nanoparticles had positive effect on thickness swelling while higher loading levels had adverse effect on the thickness swelling properties.

Water absorption (WA) results of the nanoreinforced or unreinforced composites after 2h, 24h, 48h, and 96h water soaking period was shown in Table 2. The results reveal that WA values of the nanoreinforced composites were significantly higher than those of unreinforced composites for all water soaking periods. WA values after 2h, 24h, 48h, and 96h water soaking period of the nanoZnO-reinforced composites increased with increasing nanomaterial loading level. In case of nanomaterial type, the composites reinforced with nanoSiO₂ had the lowest WA values, followed by the composites reinforced with nanoAl₂O₃, and the composites reinforced with nanoZnO. The highest WA values for all water soaking periods was determined in the composites reinforced with 3% NanoZnO. Two-way ANOVA was performed to evaluate the influence of the nanomaterial loading level, nanomaterial type, and combined effect of the factors on WA properties of the composites. The results indicate that the nanomaterial loading level, nanomaterial type, and combined effect of the two factors significantly affected the WA values of the composites after 2h, 24h, 48h, and 96h water soaking period. Duncan's groupings showed that there was no significant difference in 2h, 24h, 48h, and 96h WA values of the composites reinforced with 1% and 3% nanomaterials at a significance level of 0,05.

Table 2. Average water absorption values of the nanoreinforced or unreinforced composites.

Composites	Water Absorption (%)			
	2h	24h	48h	96h
Unreinforced	71,72 (6,70)	88,23 (7,45)	91,31 (8,47)	101,70 (10,39)
NanoSiO ₂ (1%)	77,81 (4,44)	91,81 (4,94)	92,86 (3,43)	103,58 (6,12)
NanoSiO ₂ (3%)	75,07 (3,58)	88,62 (3,14)	89,30 (2,64)	99,52 (7,15)
NanoAl ₂ O ₃ (1%)	82,07 (7,08)	96,21 (7,01)	98,38 (4,48)	108,12 (7,63)
NanoAl ₂ O ₃ (3%)	80,58 (5,66)	96,03 (5,53)	98,60 (5,25)	109,06 (6,89)
NanoZnO (1%)	79,60 (6,46)	99,05 (7,81)	103,00 (6,10)	113,14 (9,87)
NanoZnO (3%)	86,89 (9,56)	107,89 (11,29)	112,02 (9,90)	126,10 (10,62)

Standard deviation values are in parentheses

Table 3 shows equilibrium moisture content (EMC) properties of the nanoreinforced or unreinforced composites after 2h, 24h, 48h, and 96h water soaking period. The findings indicated that the nanoreinforced composites had significantly higher EMC values than those of unreinforced composites. EMC values after all water soaking periods of the nanoZnO-reinforced composites increased with increasing nanomaterial loading level. As for nanomaterial type, the nanoSiO₂ reinforced composites had the lowest EMC values, followed by nanoAl₂O₃ reinforced composites and nanoZnO reinforced composites. A two-way ANOVA was carried out to determine the influence of the nanomaterial loading level, nanomaterial type, and combined effect of the two factors on the EMC values of the composites. The findings obviously show that EMC values of the composites after all water soaking periods were significantly affected by the nanomaterial loading level, nanomaterial type, and combined effect of these factors. Duncan's groupings revealed that difference in 2h, 24h, 48h, and 96h EMC values of the composites reinforced with 1% and 3% nanomaterials was no significant at a significance level of 0,05. There was significant difference in 24h, 48h, and 96h EMC values of the composites reinforced with nanoSiO₂, nanoAl₂O₃, and nanoZnO at a significance level of 0,05.

Table 3. Average equilibrium moisture content values of the nanoreinforced or unreinforced composites.

Composites	Equilibrium Moisture Content (%)			
	2h	24h	48h	96h
Unreinforced	91,54 (8,13)	110,29 (9,48)	112,09 (9,71)	123,62 (11,90)
NanoSiO ₂ (1%)	96,75 (5,46)	112,97 (6,24)	112,63 (4,94)	125,28 (7,37)
NanoSiO ₂ (3%)	94,44 (4,27)	109,48 (3,82)	110,26 (3,18)	123,83 (6,41)
NanoAl ₂ O ₃ (1%)	102,36 (8,22)	118,08 (8,17)	120,46 (3,04)	130,60 (8,66)
NanoAl ₂ O ₃ (3%)	101,40 (6,92)	118,63 (6,82)	120,49 (6,42)	133,18 (8,95)
NanoZnO (1%)	100,58 (8,99)	122,32 (9,98)	124,67 (10,19)	138,05 (12,25)
NanoZnO (3%)	111,43 (12,22)	135,19 (14,29)	138,56 (12,66)	153,40 (14,06)

Standard deviation values are in parentheses

Figure 1 indicates scanning electron microscopy (SEM) micrographs of the nanoSiO₂, nanoAl₂O₃, and nanoZnO particles used to produce the nanoreinforced composites. It clearly shows that all the nanoparticles are at nano-scale. Figure 2a, b, and c show SEM micrographs of the composites reinforced with nanoSiO₂ (1%), nanoAl₂O₃ (1%), and nanoZnO (1%), respectively. The SEM micrographs show that the nanomaterials were found to be embedded in the adhesive. It was also determined that the nanomaterials used to reinforce the composites were well dispersed in the matrix. On the other hand, it was observed that the nanomaterials tended to agglomeration when its loading level increased from 1% to 3%.

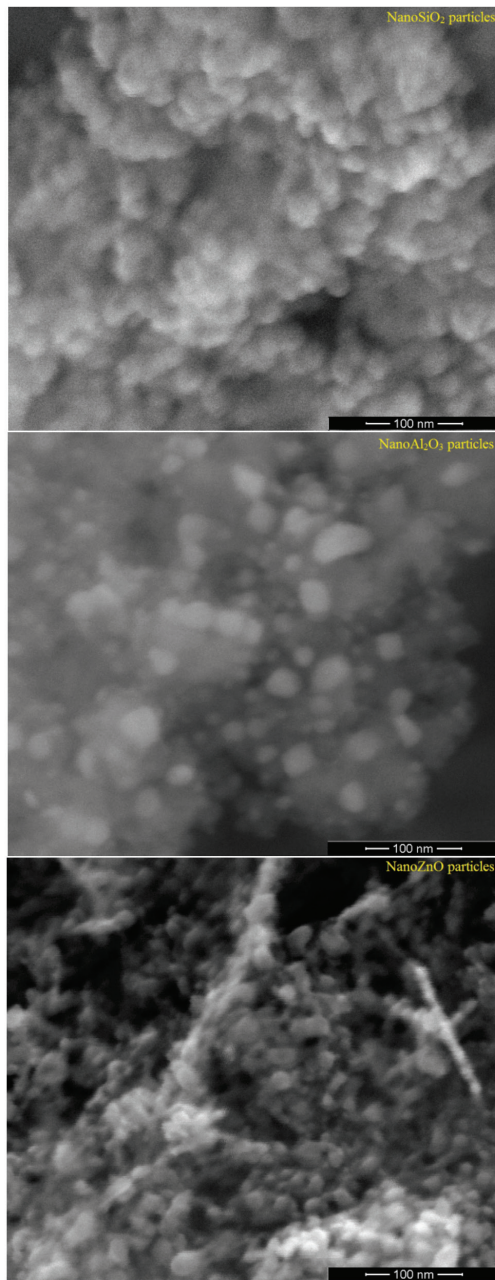


Figure 1. SEM micrographs of the nanoparticles.

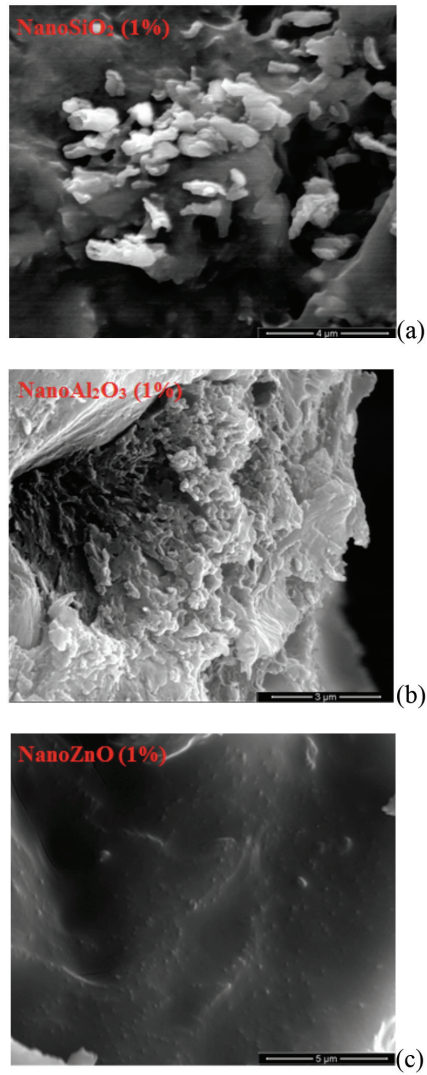


Figure 2. SEM micrographs of the nanoreinforced composites.

Mechanical properties of the nanoreinforced composites

The modulus of rupture results of the nanoreinforced or unreinforced composites are given in figure 3. It clearly indicates that the nanomaterial reinforcement technique affected the modulus of rupture performance the composites.

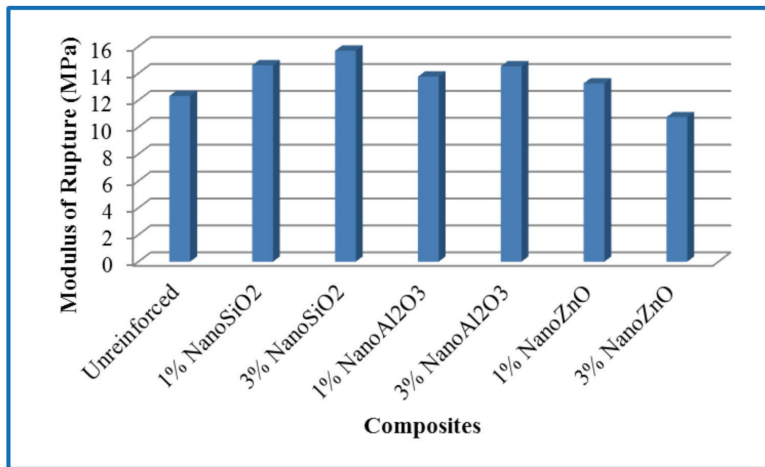


Figure 3. Modulus of rupture results of the nanoreinforced composites.

The modulus of rupture values of all the nanoreinforced composites were higher than those of the unreinforced composites, except than the composites reinforced with 3% nanoZnO. The modulus of rupture values of the composites reinforced with nanoSiO₂ or nanoAl₂O₃ increased with increasing the nanomaterial loading level from 1% to 3%. Whereas the values decreased with increasing the nanomaterial loading level in the composites reinforced with nanoZnO. The highest results in modulus of rupture were determined in 3% nanoSiO₂-reinforced composites with an improvement of around 27%. Two-way ANOVA was carried out to evaluate the effect of the nanomaterial loading level, nanomaterial type, and the combined effect of the two factors on the modulus of rupture values of the composites. Table 4 indicates that the modulus of rupture values of the composites were significantly affected by the nanomaterial loading level, nanomaterial type, and combined effect of two factors. The synergetic effect was the most effective factor influencing the modulus of rupture of the composites with a partial eta squared value of 0,129. It was followed by nanomaterial type and nanomaterial loading level with a partial eta squared values of 0,118 and 0,073, respectively. Duncan's groupings indicated that difference in the modulus of rupture values of the nanoreinforced composites and unreinforced composites was significant while difference between 1% and 3% nanomaterial-reinforced composites was not significant at a significance level of 0,05. It was also obtained that no significant difference was found in the modulus of rupture values of the composites reinforced with nanoSiO₂ and nanoAl₂O₃ at a significance level of 0,05.

Table 4. Two-way ANOVA results of the mechanical properties of the nanoreinforced or unreinforced composites.

Variable	MOR	MOE	Bonding Strength	Screw Withdrawal Resistance
Nanomaterial loading level	0,001*	0,000*	0,003*	0,000*
Nanomaterial type	0,000*	0,595 (NS)	0,000*	0,000*
Nanomaterial loading level × Nanomaterial type	0,000*	0,276 (NS)	0,004*	0,000*

* Indicates significance at 0,05

NS: Non significant at 0,05

×: Interaction between nanomaterial loading level and nanomaterial type

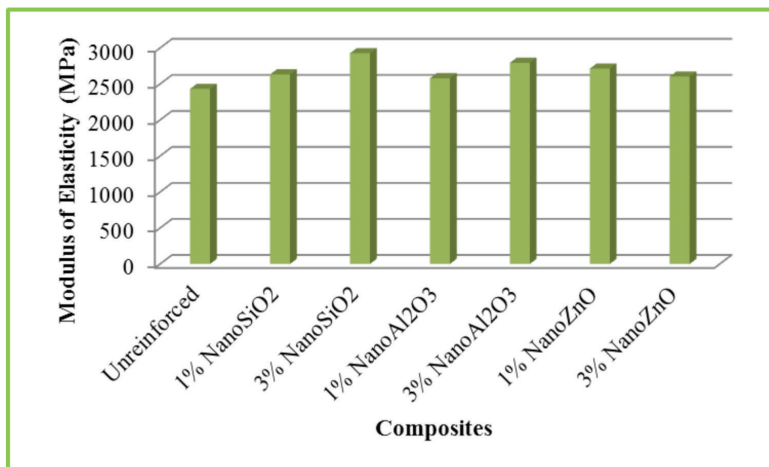


Figure 4. Modulus of elasticity results of the nanoreinforced composites.

Figure 4 shows the modulus of elasticity results of the nanoreinforced or unreinforced composites. It obviously indicates that all the nanoreinforced composite groups had higher modulus of elasticity values than those of the unreinforced composite group.

The modulus of elasticity values of the composites reinforced with nanoSiO₂ or nanoAl₂O₃ increased as the nanomaterial loading level increased from 1% to 3% while the modulus of elasticity values decreased as nanomaterial loading level increased in the composites reinforced with nanoZnO. The highest modulus of elasticity value was obtained in 3% nanoSiO₂-reinforced composites with an improvement of around 20%. To acquire the effect of the nanomaterial loading level, nanomaterial type, and the combined effect of the two factors on the modulus of elasticity performance of the composites, a two-way ANOVA was performed. As can be seen from table 4, the modulus of elasticity values of the composites were significantly affected by the nanomaterial loading level. It was obtained that both the nanomaterial type and the interaction between these factors had no significant effect on the modulus of elasticity values of the composites. Duncan's groupings showed that the nanoreinforcement technique significantly affected the modulus of elasticity values of the composites but difference in the modulus of elasticity values of the composites reinforced with 1% or 3% was not significant at a significance level of 0,05. It was revealed that no significant difference was obtained in the modulus of elasticity values of the composites reinforced with nanoSiO₂, nanoAl₂O₃, and nanoZnO at a significance level of 0,05. The findings determined in this work were similar with findings which were found by Kumar *et al.* (2013). It was stated that Al₂O₃ nanoparticles were used to reinforce medium density fiberboard at a loading level of 0,5% and 1%. It was reported that modulus of rupture and modulus of elasticity performance of the panels were affected by the reinforcement of Al₂O₃ nanoparticles. It was stated that modulus of elasticity values of the panels increased with increasing Al₂O₃ nanoparticles loading level from 0,5 to 1%.

The average bonding strength values of the nanoreinforced and unreinforced composites are given in figure 5. It shows that all the nanoreinforced composites had higher bonding strength values than those of the unreinforced composites, except the composites reinforced with 3% nanoZnO.

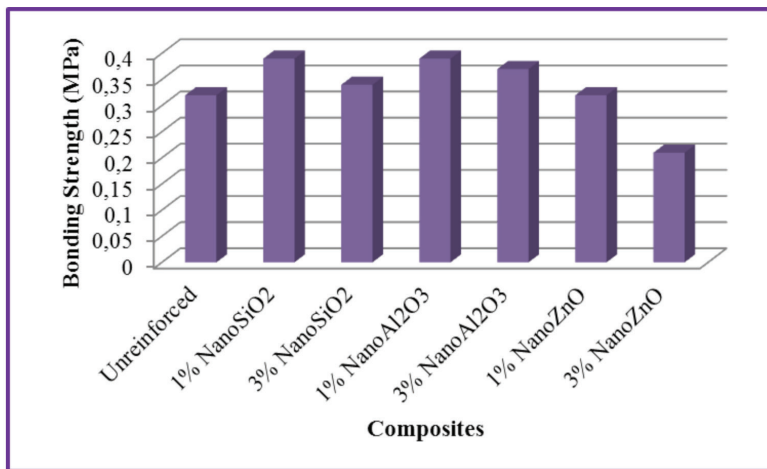


Figure 5. Bonding strength results of the nanoreinforced composites.

As can be clearly seen from figure 5, the bonding strength values of the composites reinforced with nanoSiO₂, nanoAl₂O₃, and nanoZnO decreased with increasing the nanomaterial loading level from 1% to 3%. The composites reinforced with 1% nanoSiO₂ or 1% nanoAl₂O₃ had the highest bonding strength values with an increase of around 22%. The results determined in this present study were supported by previous studies. Enhancement mechanism in bonding strength of nanoSiO₂-reinforced plywood panels can be related to the enhanced wood-adhesive interaction and the elimination of voids on the wood surface by nanoSiO₂ (Xu *et al.* 2011). Kumar *et al.* (2013) used Al₂O₃ nanoparticles at a loading level of 0,5% and 1% to enhance performance properties of medium density fiberboard. It was stated that internal bonding strength of the panels reinforced with Al₂O₃ nanoparticles was higher than those of the panels without nanoparticles. The improvement in the mechanical properties of the nanoAl₂O₃-reinforced composites can be due to improved heat transfer in the composites. Effect of nanoAl₂O₃ on the heat transfer properties of medium density fiberboard was also investigated by Kumar *et al.* (2013). It was reported that enhanced heat transfer influenced urea-formaldehyde curing in the composites which resulted in increased performance in the composites. A two-way ANOVA was executed to determine the effect of the nanomaterial loading level, nanomaterial type, and the synergic effect of these factors on the bonding strength of the composites. Table 4 obviously shows that the nanomaterial loading level, nanomaterial type, and synergic effect of these factors significantly influenced the bonding strength values of the composites. The most effective factor affecting the bonding strength of the composites was the nanomaterial type with a partial eta squared value of 0,112. It was followed by the synergic effect and nanomaterial loading level with a partial eta squared values of 0,082 and 0,062, respectively. According to Duncan's groupings, the reinforcing the composites with the nanomaterials significantly affected the bonding performance. No significant difference was found in the bonding strength values of the composites reinforced with 0% and 3% at a significance level of 0,05. It was also determined that difference between the bonding strength values of the nanoSiO₂ or nanoAl₂O₃ reinforced composites was not significant at a significance level of 0,05.

The screw withdrawal resistance results of the nanoreinforced or unreinforced composites are shown in Figure 6. The results acquired in this study obviously indicated that the screw withdrawal resistance of the composites reinforced with nanomaterials was higher than those of the unreinforced composites except the composites reinforced with 3% nanoZnO. The findings revealed that the highest screw withdrawal resistance values were determined in the composites reinforced with nanoSiO₂ at a loading level of 1%, whereas the lowest screw withdrawal resistance values were obtained in the composites reinforced with nanoZnO at a loading level of 3%. Maximum increase in the screw withdrawal resistance was around 7%.

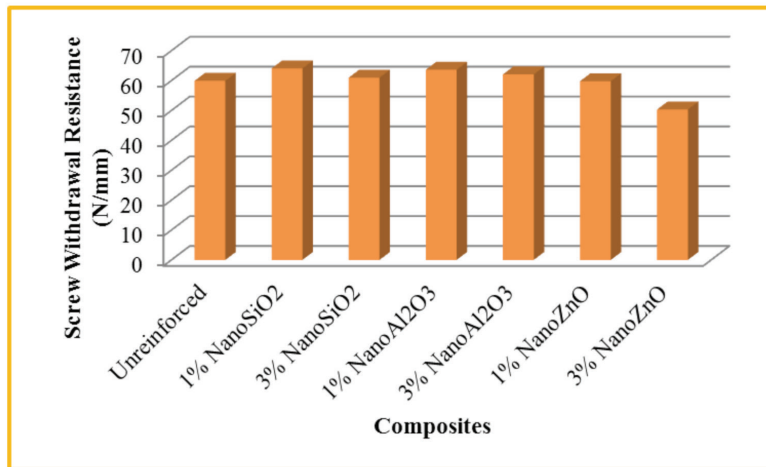


Figure 6. Screw withdrawal resistance results of the nanoreinforced composites.

Figure 6 also indicates that the screw withdrawal resistance values of the nanoreinforced composites decreased with increasing nanomaterial loading level. Statistical analysis was carried out to determine effect of the factors on the screw withdrawal resistance of the composites (Table 4). It shows that the nanomaterial loading level, nanomaterial type, and the synergic effect of these factors significantly affected the screw withdrawal resistance of the composites. The nanomaterial type was found to be the most effective factor influencing the screw withdrawal resistance of the composites with a partial eta squared value of 0,233. It was followed by the synergic effect of the two factors and nanomaterial loading level with a partial eta squared value of 0,198 and 0,158, respectively. Duncan's grouping findings showed that significant difference was found in the screw withdrawal resistance values of the composites reinforced with 0%, 1%, and 3% nanomaterial at a significance level of 0,05. It was also obtained that there was no significant difference in the screw withdrawal resistance values of the composites reinforced with nanoSiO₂ or nanoAl₂O₃ at a significance level of 0,05.

The results obtained in this present work are supported by a previous work by Salari *et al.* (2013). That work investigated the effect of SiO₂ nanoparticles on the mechanical properties of oriented strandboard. In that study, urea-formaldehyde was reinforced with SiO₂ nanoparticles at loading level of 1, 3 and 5 phc. It was reported that bonding strength and screw withdrawal resistance of the oriented strandboard reinforced with SiO₂ nanoparticles were higher than those of the control panels. Jiang *et al.* (2013) examined the influence of SiO₂ nanoparticles on the properties of nanoSiO₂/urea-formaldehyde-performed polymer composites. It was reported that the bonding strength of the wood modified by nano-UFP significantly improved. Xu *et al.* (2011) modified soy protein adhesive with SiO₂ nanoparticles at a loading level of 0; 0,5; 1; and 2% and then produced plywood panels. It was concluded that dry bonding strength of the panels significantly increased by addition of SiO₂ nanoparticles up to 1%. It was also reported that further increase in SiO₂ nanoparticle loading level decreased the bonding strength of the panels.

CONCLUSIONS

It is well known that bonding performance, modulus of rupture, modulus of elasticity, and screw withdrawal resistance are important performance characteristics for composites which are made from renewable biomaterials. Nanotechnology offers a number of opportunities to producing novel materials. Therefore developing new composites having enhanced performance properties was objected in this present work. NanoSiO₂, nanoAl₂O₃, and nanoZnO were used to reinforce particleboard composites at different loading levels in this study.

The findings obtained in this research clearly indicated that the nanoreinforcement technique significantly affected the physical and mechanical properties of the composites. It was determined that the modulus of rupture, modulus of elasticity, bonding strength, and screw withdrawal resistance of the composites improved by all the nanomaterials used in this study, except 3% nanoZnO. It was concluded that using 1% nanoSiO₂ or 1% nanoAl₂O₃ in the composite matrix had the best results in the bonding strength and screw withdrawal resistance. As for modulus of rupture and modulus of elasticity, the highest performance was obtained in the composites reinforced with 3% nanoSiO₂. It was suggested that nanoZnO can be used to enhance performance properties of the composites with a lower loading level.

The results showed that the nanoparticles had a negative effect on the dimensional stability properties such as thickness swelling and water absorption of the composites. When lower nanoparticle loading levels are used, the negative effect of the nanoparticles on the dimensional stability can be minimized but it can be produced composites with improved mechanical performance. It was concluded that the physical and mechanical performance properties of the composites can be enhanced using proper nanomaterial loading level and nanomaterial type.

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