MECHANICAL PROPERTIES OF *PAULOWNIA FORTUNEI* WOOD IMPREGNATED WITH SILVER, COPPER AND ZINC OXIDE NANOPARTICLES

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AKHTARI M, GHORBANI-KOKANDEH M & TAGHIYARI HR. 2012. Mechanical properties of *Paulownia fortunei* wood impregnated with silver, copper and zinc oxide nanoparticles. Mechanical properties are usually considered the most important characteristics of wood products for structural applications. Paulownia is known as a fast growing tree and can be used in several applications. This study was conducted to investigate effects of impregnation with silver, copper and zinc oxide aqueous nanofluids, with size range from 10 to 80 nm, on mechanical properties of *Paulownia fortunei* with dry density of 0.37 g cm^{-3}. Specimens were impregnated with a 400 ppm aqueous suspension of nanosilver, nanocopper and nanozinc oxide at 2.5 bars in a pressure vessel for 20 min. Results showed that modulus of rupture (MOR), modulus of elasticity (MOE) and compression strength parallel to the grain were significantly increased in all cases. The highest increase was observed in nanocopper-impregnated specimens. Cluster analysis clearly showed the similarity of nanosilver-impregnated specimens with control treatment. However, nanocopper and nanozinc oxide-impregnated specimens were clustered differently which may imply the formation of chemical bonds between wood cell structure and components with these nanoparticles.

Keywords: Nanosilver, nanocopper, nanozinc, nanofluids, MOR, MOE

AKHTARI M, GHORBANI-KOKANDEH M & TAGHIYARI HR. 2012. Ciri mekanik kayu *Paulownia fortunei* yang diimpregnat nanozarah perak, kuprum dan zink. Ciri mekanik biasanya dianggap ciri terpenting bagi produk kayu yang diguna untuk aplikasi struktur. Paulownia dikenali sebagai pokok yang tumbuh cepat dan mempunyai beberapa kegunaan. Kajian ini bertujuan untuk menyelidik kesan impregnasi nanocecair akues perak, kuprum dan zink oksida yang bersaiz antara 10 nm hingga 80 nm terhadap ciri mekanik *Paulownia fortunei* yang mempunyai ketumpatan kering sebanyak 0.37 g cm^{-3}. Spesimen diimpregnasi dengan 400 ppm ampaian akues nanoperak, nanokuprum dan nanozink oksida di dalam bekas tekanan pada 2.5 bar selama 20 minit. Keputusan menunjukkan bahawa modulus kepecahan (MOR) dan modulus kekenyalan (MOE) serta kekuatan mampatan yang selari dengan ira meningkat dengan signifikan dalam semua ujian. Peningkatan paling tinggi diperhatikan untuk spesimen yang diimpregnat nanokuprum. Analisis gugusan jelas menunjukkan persamaan antara spesimen diimpregnat nanoperak dengan kawalan. Bagaimanapun, spesimen yang diimpregnat nanokuprum dan nanozink oksida tergugus secara berbeza. Ini menyarankan bahawa terdapat ikatan kimia antara struktur sel dengan komponen nanozarah ini.

INTRODUCTION

Nanotechnology is defined as the development and application of materials, devices and systems with fundamentally new properties in the range of 1 to 100 nm (Siegel et al. 1999). The nanometer scale of nanoparticles with very high surface area and energy can change the original properties of materials and give rise to new functionalities. Nanoparticles have been incorporated into surface coatings, polymer composites, inks and plastics (Cayton & Sawitowski 2006). Research has found that nanoparticles can improve mechanical strength (abrasion resistance and toughness), fire resistance and UV resistance of polymers (Yang et al. 2005, Cayton & Sawitowski 2006). Nanometal characteristics may be totally different from the characteristics of the elemental metals and may, in turn, perform in an unusual manner. Nanometal preparations have several characteristics (e.g. size and charge) that may improve their performance in wood protection applications (Clausen 2007). Wood treated with micronised preservatives (dispersed solutions) shows some advantages such as lower leachability and less corrosion of metal fixings compared with wood treated with dissolved solutions (Freeman & McIntyre 2008, Cooper & Ung 2009). Decrease in modulus of rupture (MOR) and modulus of elasticity (MOE) values of nanosilver-impregnated heat-treated specimens may imply that nanosilver impregnation of wood accelerates the process of heat transfer and it can be considered as an increase in heating periods of wood (Taghiyari 2011).

Paulownia is as a fast-growing tree and can reach about 15–25 m high in 5 years (Caparro et al. 2008). Paulownia wood is used for a variety of applications such as furniture, construction, musical instrument, shipbuilding, aircraft, packing boxes, coffins, paper, plywood, cabinet and molding (Flynn & Holder 2001). The wood of paulownia is soft, lightweight, ring porous straight grained and mostly knot free with a satiny luster (Kalaycioglu et al. 2005). Paulownia timber is easily air dried without serious drying defects. It has high strength-to-weight ratio, a low shrinkage coefficient and does not easily warp or crack (Flynn & Holder 2001).

The widespread use of wood in the construction of buildings has both economic and aesthetic basis. The ability to construct wood buildings with minimal amount of equipment has kept the cost of wood-frame buildings competitive with other types of construction (Breyer 1993). However, as a naturally-produced organic material, wood may be subject to decay, fungal stains, insect infestation and fire which can cause the useful life of a building or a product to be greatly reduced. Consequently, wood used in houses must be treated with preservatives. Various chemical processes have been applied to enhance wood properties. However, there is not enough information about effects of nanometals on mechanical properties of wood, especially the MOE and MOR which are the primary criteria for the selection of wood materials. Thus, the effects of these new preservatives on mechanical properties of wood have now become an important issue. The purpose of this study was to determine the effects of nanometals, namely, nanosilver, nanocopper and nanozinc oxide on some mechanical properties of paulowina wood. In addition, the obtained results were compared with untreated wood samples.

MATERIALS AND METHODS

Raw materials

For this study, three sample trees of *Paulownia fortunei* were harvested from the north part of Iran (Mazandaran Province). The sample trees were conditioned for approximately two weeks. Lumbers were cut parallel to the grain from logs obtained from the three sample trees. The boards were dried in a conventional kiln until moisture content of about 12%. Specimens were conditioned and cut for MOR, MOE, hardness and compression parallel to grain tests in accordance to the ASTM D 143-94 specifications (reapproved 2007). Specimens were free from checks, knots, rots and blue stains. Specimens were randomly separated into four groups with 10 replications: control samples, nanosilver, nanocopper and nanozinc oxide-impregnated specimens. The density of paulownia wood was 0.37 g cm^{-3}.

Nanomaterials

Nanofluids used in the study were obtained from Nano-Jahan Mavad Corporation. Solutions were provided as an aqueous dispersion containing 400 ppm nanosilver, nanocopper or nanozinc oxide particles.

Impregnation process

Test specimens were impregnated with the aqueous nanosolutions in a pressure vessel. Rueping (empty cell) process was used with no initial or final vacuum pressure. The specimens were impregnated under 2.5 bar vacuum pressure for 20 min. Five impregnated specimens were cut to evaluate the penetration of nanofluids. The impregnated specimens were kept for 1.5 months at room condition (30 °C and 45–50% relative humidity) to final moisture content of 8.5%. After conditioning, mechanical properties of paulownia wood were determined. Retention for each compound was calculated based on initial and final weights of each specimen and the treating solution concentration. Retention values of nanoparticles were 0.140, 0.137 and

0.142 kg m^{-3} for nanosilver, nanocopper and nanozincoxide respectively.

Statistical analysis

Two-way analysis of variance (ANOVA) was conducted to discern significant difference at 99% using SAS software program (version 9.1). Hierarchical cluster analyses including dendrogram using Ward methods with squared Euclidean distance intervals were carried out by SPSS/16.

RESULTS AND DISCUSSION

Modulus of rupture (MOR)

Bending strength (MOR) determines the load a beam will carry. In this study MOR for nanocopper-treated specimen was not statistically different than MOR of nanozinc oxide-treated specimen according to Duncan's multiple range test ($p < 0.01$) (Figure 1). MOR of nanosilver-impregnated specimen was 45.1 N mm^{-2} while for nanocopper and nanozinc oxide treatments, 49.3 and 49.2 N mm^{-2} respectively. MOR value in the control samples was the lowest at 40.4 Nmm^{-2}.

Modulus of elasticity (MOE)

MOE measures of the resistance to bending, which directly relates to the stiffness of a beam. Based on results obtained, there were no significant differences in MOE between the different treatments. MOE was highest in specimens impregnated with nanocopper (3922.5 N mm^{-2}) in comparison with control (3882.5 N mm^{-2}) and the rest of the samples (nanozinc oxide = 3903.8 N mm^{-2} and nanosilver = 3878.5 N mm^{-2}) (Figure 2). It was reported that there was no significant difference in MOE values between treated and untreated ammoniacal copper quaternary compound (ACQ) and CCA preservatives of Scots pine timber (Yildiz et al. 2004).

Hardness

Hardness strength test is required if the products are used in flooring or paving or as bearing blocks. Statistical analysis showed that there were significant differences in hardness between control and treatments (Figure 3). Control had higher hardness value (2.60 kN) than impregnated samples. Hardness value of samples impregnated with nanozinc oxide (1.86 kN) was higher than nanosilver (1.76 kN) and nanocopper (1.79 kN) samples. However, there were no significant differences in average hardness between treatments. Hardness values were not affected by many ways by waterborne preservative treatments (Winandy 1995).

Compression strength parallel to grain

Compression strength parallel to grain is an important characteristic for determining the load a short post or column can carry. In this study compression strength for treated specimens was not statistically different from control specimens according to Duncan's multiple range test

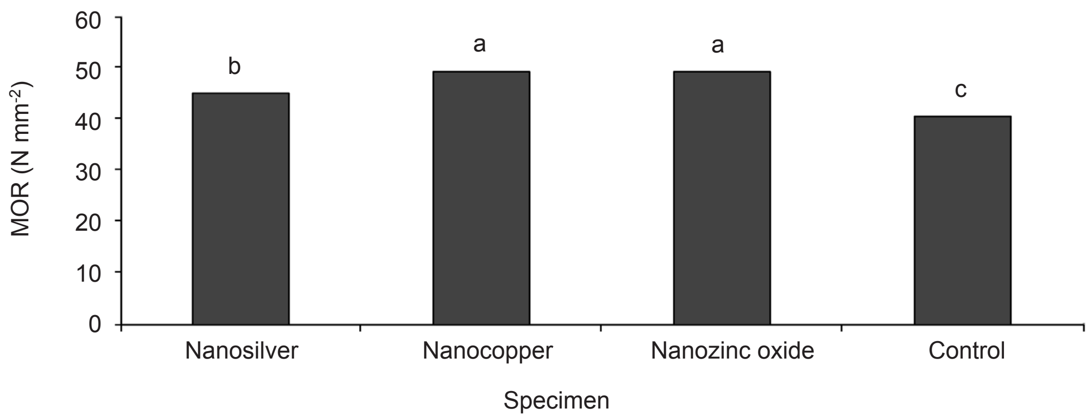

Figure 1 Modulus of rupture (MOR) values for control and impregnated specimens; bars with the same letter are not significantly different at $p < 0.01$

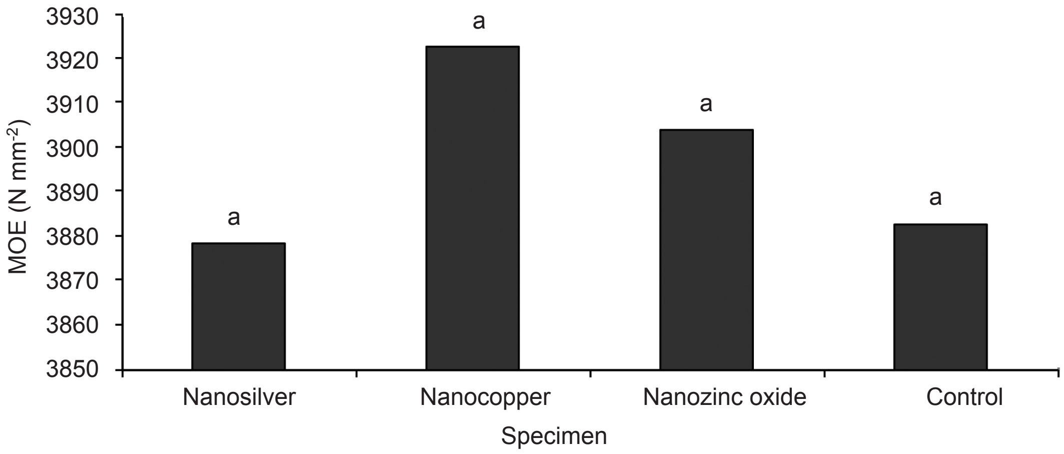

Figure 2 Modulus of elasticity (MOE) values for control and impregnated specimens; bars are not significant at $p \leq 0.01$

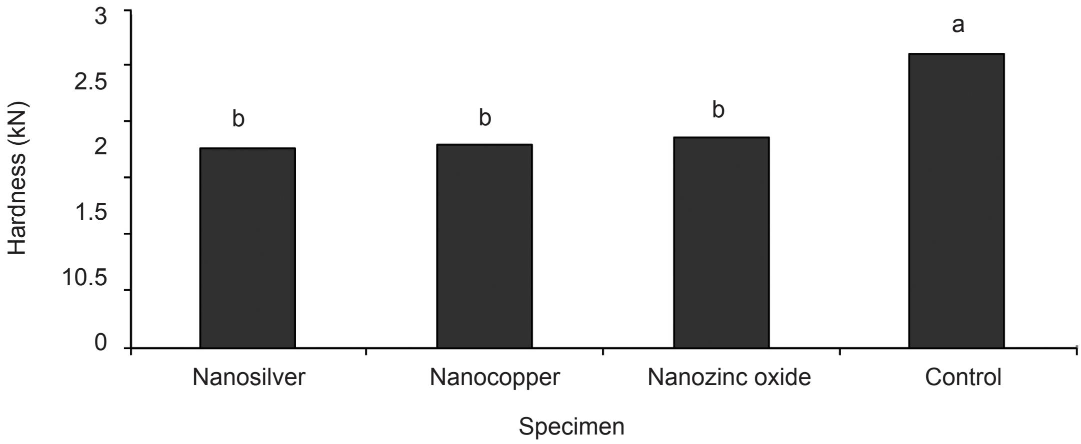

Figure 3 Hardness values for control and impregnated specimens; bars with the same letter are not significantly different at $p < 0.01$

($p < 0.01$) (Figure 4). Compression strength values for control and treated samples were almost the same. The effects of wood preservatives on mechanical properties are directly related to several key wood material factors and pre-treatment, treatment and post-treatment processing factors. The key factors included preservative chemistry or chemical type, retention, post-treatment drying temperature, initial kiln drying temperature and grade of material (Yildiz et al. 2004).

CONCLUSIONS

This study was conducted with the main objective of determining the effects of nanometals, namely, nanosilver, nanocopper and nanozinc oxide on some mechanical properties of low-density paulowina wood. Based on findings of the present study, it was concluded that the impregnation of paulowina wood with nanoparticles had no negative effect on MOR, MOE and compression strength parallel to grain. Generally, impregnation with nanocopper resulted in the highest increase of these values. Only hardness was decreased by impregnation of nanofluid. Therefore, it is recommended that in future studies, the surface of the impregnated specimen should be planed before the hardness test is undertaken.

Cluster analysis of the four treatments in the present study based on MOR, MOE, compression strength parallel to the grain and hardness showed that nanosilver-impregnated specimens were closely clustered to the control treatment. This might imply that silver nanoparticles did not come into chemical bond with the cell wall structure and components. On the other hand, copper and zinc oxide nanoparticles were

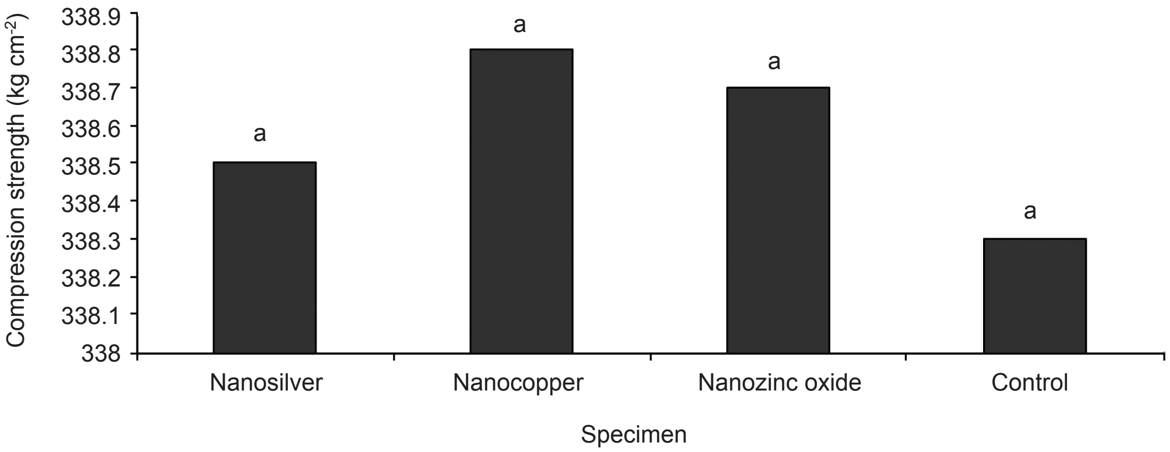

Figure 4 Compression parallel to grain values for control and impregnated specimens; bars are not significant at $p \leq 0.01$

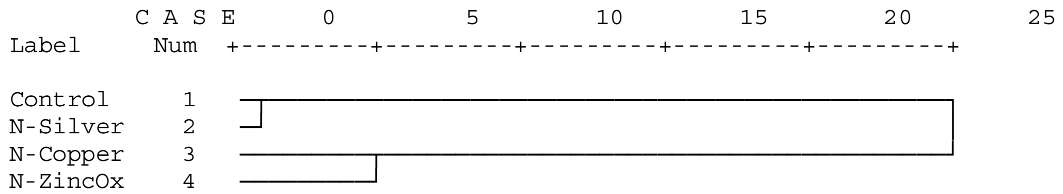

Figure 5 Cluster analysis of control and the three impregnation treatments based on MOR, MOE, compression strength parallel to the grain and hardness; N-Silver = nanosilver-impregrated, N-Copper = nanocopper-impregnated, N-ZincOx = nanozinc oxide-impregnated

clustered quite differently (Figure 5). Since no modification, physical or heat treatment, was carried out during or after the impregnation with nanofluids, it might be concluded that in one way or another, nanoparticles made bonds with cell wall structure or components so that mechanical properties were increased.

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