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Effects of Nanosilver Impregnation on Impact Bending Strength of Ice-Blasted Beech and Poplar Woods

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Abstract

Ice-blasting (frozen CO_2 at minus 78.5 ºC) is one of the modern methods of cleaning for industrial purposes without any contamination or hazard to the environment. Effects of ice-blasting were studied here on the basis of normal solid wood as well as nanosilver-impregnated *Populus nigra* and *Fagus orientalis*. The size range of silver nanoparticles was 20 - 90 nm. Specimens were free from any knots, splits, rot, or other visual defects. Results showed that ice-blasting made impact strength decrease in beech by 8.4 %; however, an insignificant increase of 0.8 % was observed in poplar. Impregnating the specimens with a nanosilver suspension before ice-blasting made impact strength increase by 25.8 % in poplar; it also mitigated the impact loss in beech (5.2 % in comparison to control specimens). It can be concluded that the negative effect of ice-blast treatment is less in lower-density poplar wood; also, impregnation with nanosilver can even increase its impact strength. In higher-density beech wood, however, the impregnation can mitigate the significant negative effect of the ice-blast treatment on impact bending strength.

Keywords: Cleaning, ice-blasting, impact bending strength, nanosilver, solid wood

Introduction

The wood produced by trees does not usually have radial and axial uniformity, and the quality of wood can be affected by many factors, including natural regeneration and fungal attack [1], rotation period, mono- or mixed-species cultivation, light and soil, initial spacing and nitrogen fixation in soil, drying procedures, moisture content and hygroscopicity, as well as interactions between clone-type and site, and even length of specimens. The biological resistance of wood as well as the extent of mass loss is also highly affected by the species [2]. Therefore, any processing methods can easily have significant effects on the physical and mechanical properties of wood [3,4].

Ice blasting, or dry ice-blasting, is a modern method for cleaning a variety of materials without any contamination or hazard to the environment. This method is a form of abrasive blasting, where dry ice, the solid form of carbon dioxide, is accelerated in a pressurized air stream and directed at a surface in order to clean it. The method is similar to other forms of abrasive blasting such as sand blasting, plastic bead blasting, or soda blasting but substitutes dry ice as the blasting medium. Dry ice blasting is environmentally clean and leaves no chemical residue as dry ice sublimes at room temperature. The frigid temperature of the dry ice -109.3 °F or -78.5 °C "blasting" against the material to be removed, causes it to shrink and loose adhesion from its sub surface. Additionally when some dry ice penetrates through the material to be removed, it comes in contact with the underlying surface. The warmer sub surface causes the dry ice to convert back to carbon dioxide gas. The gas has 800 times greater volume and expands behind the material speeding up its removal. Paint, oil, grease, asphalt, tar, decals, soot, dirt, ink, resins, and adhesives are some of the materials removed by this procedure. Only the removed material must be disposed of, as the dry ice sublimes into the atmosphere. Damage to the workpiece with a resultant effect on the function was not detected [5].

Little scientific field tests have so far been carried out on the effects of ice-blasting on the physical and mechanical properties of wood. Scientific reports indicate that ice-blasting makes mechanical properties (MOR, MOE, and compression strength parallel to the grain) decrease in solid woods. The heat-transferring property of metal nanoparticles [6,7] was reported to decrease the amount of mechanical loss in higher density solid woods (with a density of more than 0.55 g/cm^3), and would even increase a little in lower density solid woods. The amount of decrease in the nanosilver-impregnated specimens was not statistically significant and therefore this method could be used for structural purposes [8]. Impact strength is one of the important mechanical properties for structural purposes; however, little or no study has so far been carried out on the effect of ice-blasting on the impact strength of commercial solid woods. The present study was therefore conducted to find out if ice-blast cleaning, as a modern cleaning method, would have any negative effects on impact strength; and if the heat-transferring property of nanosilver can decrease the possible negative effects of ice-blasting.

Materials and methods

Poplar (*Populus nigra*) specimens were procured from 11 year old planted trees in the local gardens of Rasht city, and beech (*Fagus orientalis*) specimens from 60 year old trees of the natural forest near Roodbar city. These 2 species were chosen due to their great applications for different structural and industrial purposes. Geographical specifications of the region are as follows: the altitude is 10 m below sea level and 15 m above Caspian Sea level; 49° and 57' Eastern longitude; 37° and 19' Northern latitude. The soil was composed of alluvial settlements and silty loam having neutral pH to somehow alkaline. Average annual precipitation is 1,186 mm, and average annual temperature is 17.5 degrees centigrade; averages for maximum and minimum temperatures are 26.6 and 8.6 degrees centigrade respectively. Specimen dimensions and testing were in accordance with ASTM D 143-94 [9]. As to the important effect of nanosilver absorption, sampling was done from sapwood so that uniform absorption of aqueous nanosilver suspension would achieve. Specimens were divided into 3 treatments of: 1. Control specimens (without nanosilver impregnation, and ice-blast cleaning), 2. Ice-blasted specimens, 3. Nanosilver impregnated and ice-blasted specimens. For each treatment, 20 sound specimens were prepared; specimens were free from any splits, fissures, or knots. Mechanical tests were fulfilled at laboratories of the Wood Industries department at Shahid Rajaee Teacher Training University.

A 200 ppm aqueous dispersion of silver nanoparticles (NS) was produced and applied to the specimens using an electrochemical technique in collaboration with Mehrabadi Mfg. Company. The size range of the silver nanoparticles was 20 - 90 nm; the nanoscale size dispersion of silver particles facilitated easier and more even transfer of heat to all parts of the impregnated specimens. Larger scales of metal particles may result in the heat being concentrated at points nearest to the metal particles, causing uneven transfer of heat throughout the specimens. The pH of the suspension was 6 - 7; 2 kinds of surfactants (anionic and cationic) were used in the suspension as stabilizers; the concentration of the surfactants was 3 times the nanosilver particles. Empty-cell impregnation process (Lowry method) was done in a 3 bar pressure vessel for 20 min by Afshar Wood Machinery Mfg. Co. (Ltd.). Specimens were weighed just before and after impregnation with a digital scale having 0.0001 g precision to measure the amount of NS-absorption. Moisture content (MC) of specimens was 8.5 % before NS-impregnation and when they were tested, because wood has a thermo-hygromechanical behavior and its deformation properties depends on the combined action of temperature, relative humidity, and mechanical local variations [10]. After impregnation, all specimens were kept at room temperature for 3 months along with control samples before ice-blasting treatment as well as mechanical tests.

Ice-blasting was done using apparatus designed and built by Ice-Palayesh Co. in Iran (patented). The system used small pellets of dry ice forced under pressure out of a medium size flat nozzle (3.5 cm) using compressed air (3 bar). Middle parts of the 4 sides of specimens were ice-blasted for 3.5 s.

Impact bending tests were performed according to ASTM D 143-94 [9]; impact strength of the specimens was measured in terms of J/cm using a pendulum impact testing machine, and then converted to Newtons. The nominal dimensions of the specimens were $50 \times 50 \times 760$ mm^3 with 20 replications; center loading was used with a span length of 710 mm. Specimens were placed so that the load was applied through the bearing block to the tangential surface nearest the pith.

Scanning Electron Microscope (SEM) imaging was done at the 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 provides 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 was conducted using SAS software program, version 9.2 (2010). Two-way analysis of variance (ANOVA) was performed on the data to conclude significant differences at the 95 % level of confidence. Hierarchical cluster analysis, including dendrogram and using Ward methods with squared Euclidean distance intervals, was carried out by SPSS/18 (2010). Cluster analysis was carried out to find the similarities and dissimilarities between treatments based on more than one property, simultaneously. The scaled indicator in each cluster analysis shows how much treatments are similar or different; lower scale numbers show more similarities, while higher ones show dissimilarities [11]. Fitted-line and scatter plots were created using Minitab software, version 16.2.2 (Minitab Inc., USA).

Results and discussion

The amount of nanosilver solution absorption was 0.289 and 0.352 g/cm^3 in poplar and beech respectively (**Table 1**). A significant difference was observed in nanosilver absorption between the 2 species.

On the surface layers of ice-blasted specimens, a slight abrasion was observed by the naked eye caused by ice-blasting treatment. The abrasion effect of ice-blasting was deeper in poplar which had less density in comparison to beech (0.43 and 0.62 g/cm^3 in poplar and beech, respectively). Fissures and splits were also observed in SEM micrographs of the ice-blasted specimens (**Figure 1**).

Figure 2 shows the results of impact strength for 3 groups of control, ice-blasted, and nanosilver-impregnated ice-blasted specimens for poplar and beech species. Ice-blasting decreased the impact strength in beech by 8.4 %; however, in poplar it was increased by 0.8 %, although this is not significantly different. Nanosilver impregnation of the specimens before ice-blasting significantly increased the impact strength by 25.8 % in poplar, and it also mitigated the negative impact of ice-blasting in beech specimens (5.2 % decrease in comparison to control specimens).

Table 2 shows the impact strength values of control specimens in the present study with a previous comprehensive study on other mechanical properties of the same native species in Iran [12]. The effects of ice-blasting and nanosilver impregnation on MOR, MOE, and compression strength parallel to the grain of these 3 treatments are also added for comparison [8].

Impact strength represents the strength of materials against breaking. The more the value is, the more energy the specimen absorbs. Results of the present study showed that the impact strength of normal untreated poplar wood did not decrease by ice-blasting; in fact, the value significantly increased due to the impregnation with nanosilver suspension. In beech wood however, a significant decrease may be expected in the untreated wood specimens; nanosilver-impregnation decreased the amount of loss, although not significantly. Similar improvement in other mechanical properties (MOR and MOE) was previously reported [8]. The Ag ions in nanosilver suspension made some bonds with the hydroxyl groups of cellulose, hemi-cellulose, and even lignin [13]. These extra bonds made the surface layer of wood more stiff and strong than normal not-ice-blasted wood. Consequently, as it happened, higher mechanical properties were found.

Table 1 Nanosilver solution absorption in the 2 wood species studied in the present research.

Species	***Populus nigra***	***Fagus orientalis***
Nanosilver Absorption (g/cm^3)	0.289 (0.025)*	0.352 (0.023)
Density (g/cm^3) [present study] (MC 8.5%)	0.43 (0.031)	0.62 (0.045)
Density (g/cm^3) [12]	0.41	0.63

*Figures in parentheses are the standard deviations.

Table 2 Comparison between impact strength, MOR, MOE, and compression strength parallel to the grain values in the present study with previous studies.

Mechanical strength	***Populus nigra***		***Fagus orientalis***	
	Present study	**Parsapajouh***	**Present study**	**Parsapajouh***
Impact strength (N)	0.40	0.50	1.15	0.92
MOR (N/mm^2)**	66.8	63.77	112.89	85.35
MOE (N/mm^2)**	6,745.8	8,632.8	11,550	12,262.5
Compression strength parallel to the grain (N/mm^2)**	45.63	34.34	70.48	63.18

*Parsapajouh 1984 [12].
**Taghiyari *et al*. 2012 [8].

All mechanical properties measured in the present study and the previous study [8] showed an increase in the nanosilver-impregnated specimens in comparison to the ice-blasted specimens, though not all the increases were statistically significant. Therefore, it may be concluded that cold was transferred through nanosilver particles [14,15] from the surface layers to the deeper parts of the specimens, and consequently, ultra-structure fissures and splits caused by extreme cold and frozen water crystals in the wood structure could be prevented to a great extent.

Cluster analysis based on the 4 mechanical properties measured in this study and previous study (impact strength, MOR, MOE, compression strength parallel to the grain) showed that nanosilver-impregnated ice-blasted specimens were closely clustered to the control specimens (**Figure 3**). This proves the potentiality of the heat-transferring property of silver nanoparticles in solid woods [16] on mitigation of negative effects of dry-ice blasting on solid woods. However, cluster analysis of beech specimens alone showed that nanosilver-impregnated ice-blasted specimens were clustered with the ice-blasted treatment (**Figure 4**). Furthermore, cluster analysis for poplar species showed close clustering of nanosilver-impregnated ice-blasted specimens with the control treatment (**Figure 5**). It may therefore be concluded that the effect of ice-blasting as well as nanosilver-impregnation would vary according to the density and/or structure of wood species, because the density of the wood determines the depth of abrasion caused by ice-blasting. In the meantime, cluster analysis of both species based on the impact strength showed that ice-blasted specimens were closely clustered with NS-IB specimens (**Figure 6**). This indicated that the overall improving effect of nanosilver impregnation on the impact strength may not be high enough to be recommended on an industrial scale (**Figure 3**). Still, with due consideration to the significant difference of nanosilver-impregnated ice-blasted poplar treatments (**Figure 2**), it will be noticed that the final decisive outcome of nanosilver-impregnation may quite be dependent on the species and density of wood, as well as the specific mechanical property in question. It would therefore be recommended studying each property of every species separately for a final conclusion.

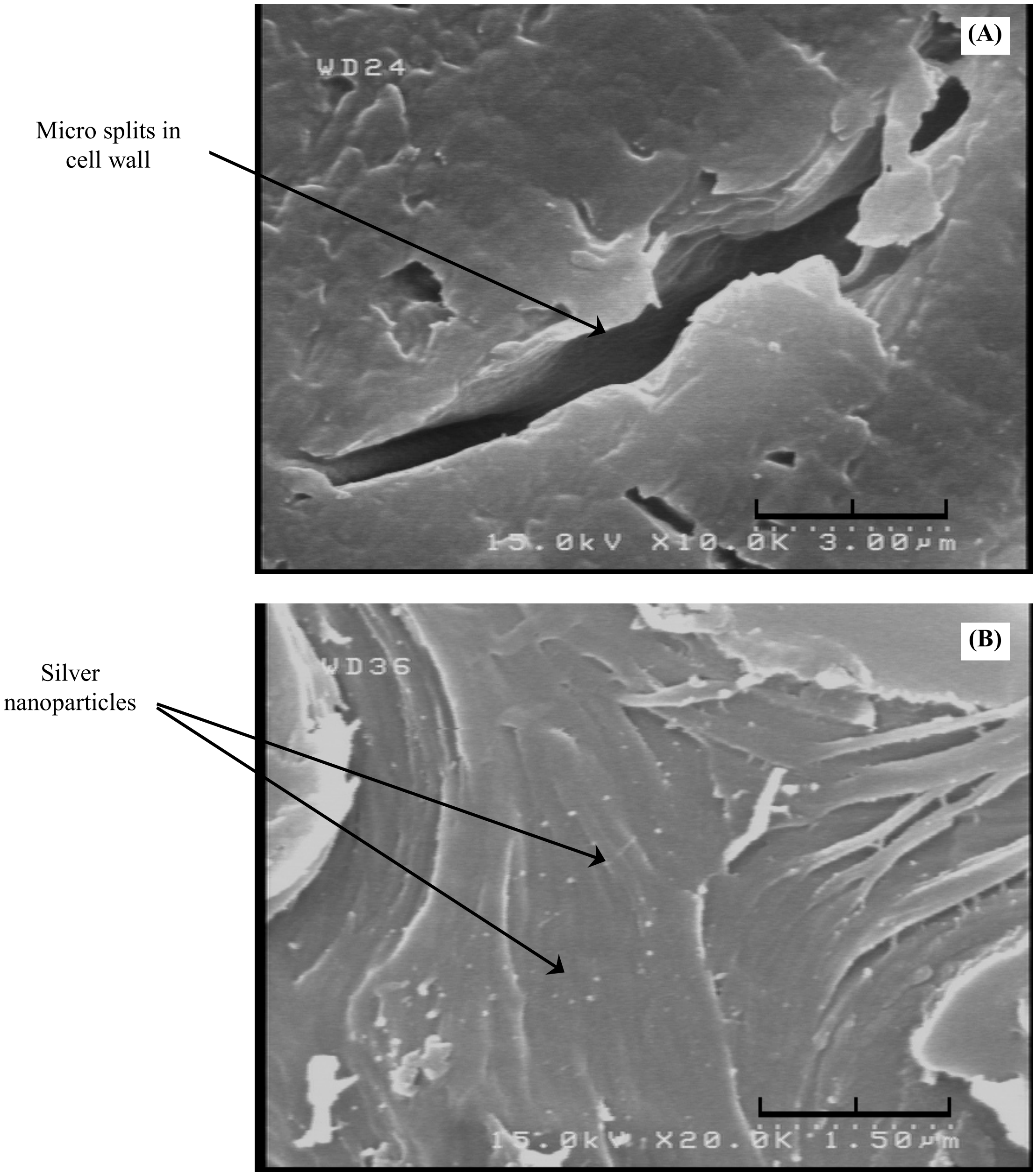

Figure 1 (a) Fissures and splits (↓) occurred in cell wall due to extreme cold shock caused by ice-blast treatment on beech specimen [8,17]; (b) silver nanoparticles (↓) spread all over the cell wall.

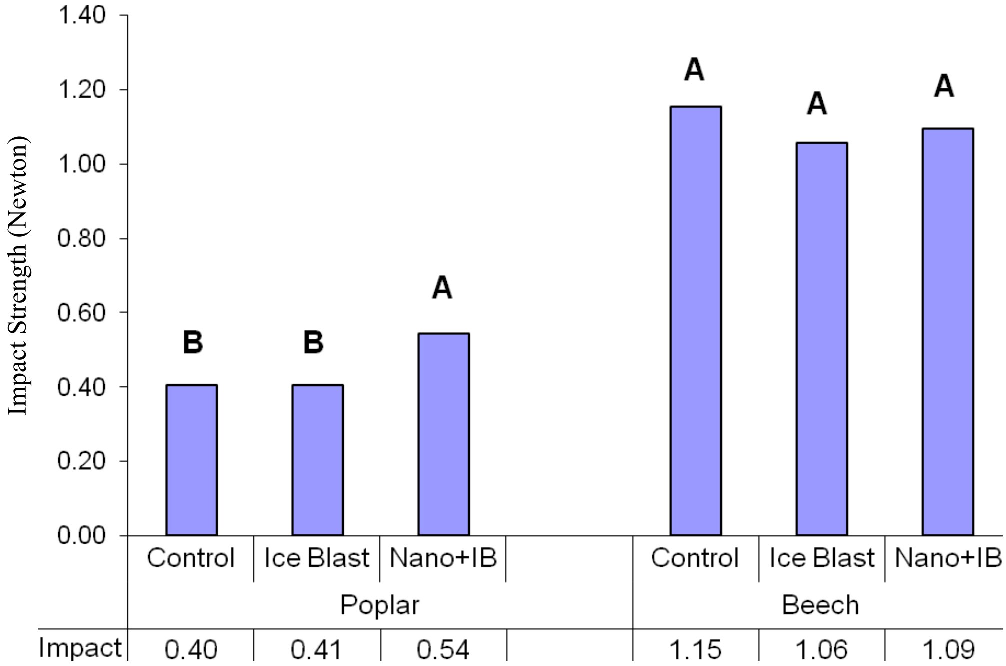

Figure 2 Impact bending strength values of 3 groups of control, ice-blasted, and nanosilver impregnated ice-blasted poplar and beech specimens (Newton) (IB = Ice-Blasted) (Letters on each column represent Duncan multiple range groupings at 95 % level of confidence).

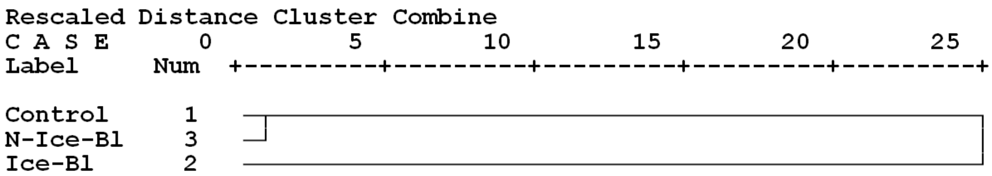

Figure 3 Cluster analysis based on impact strength, MOR, MOE, and compression strength parallel to the grain values of both species and all treatments: Control, Ice-Blasted (Ice-Bl), and nanosilver impregnated Ice-Blasted (N-Ice-Bl).

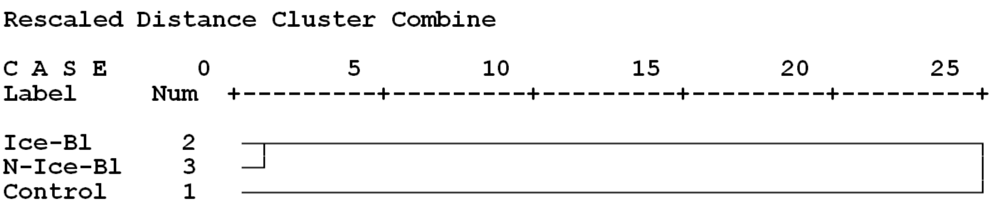

Figure 4 Cluster analysis of beech specimens based on impact strength, MOR, MOE, and compression strength parallel to the grain values.

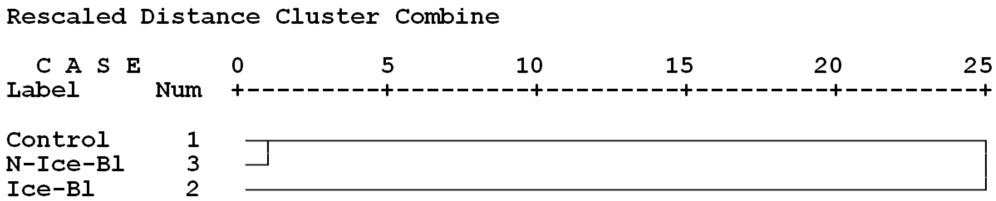

Figure 5 Cluster analysis of poplar specimens based on impact strength, MOR, MOE, and compression strength parallel to the grain values.

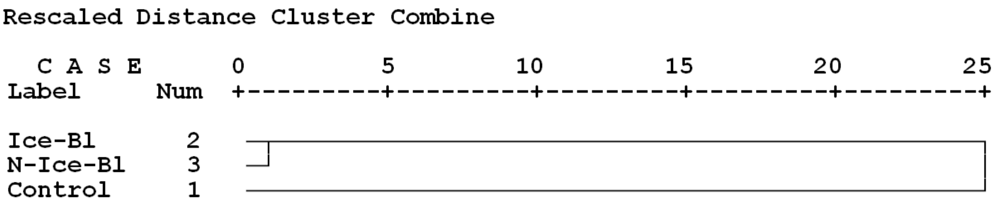

Figure 6 Cluster analysis of poplar and beech specimens based on impact strength values.

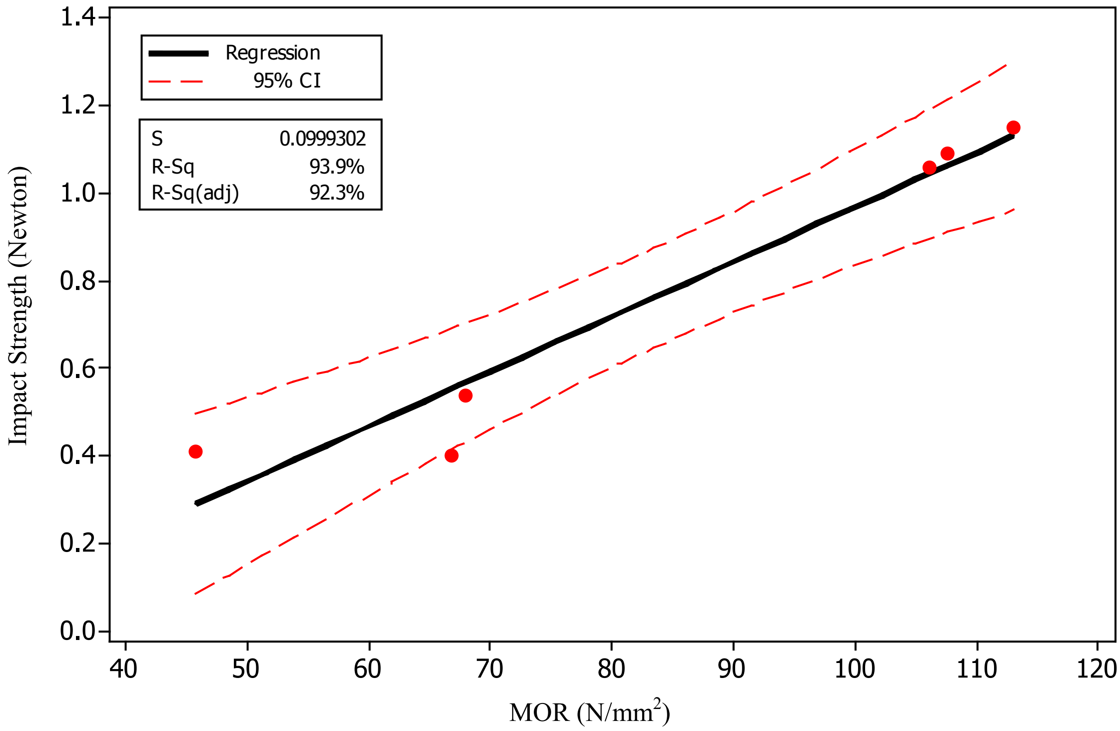

Figure 7 Fitted-line plot between impact strength versus modulus of rupture (MOR).

The fitted-line plot between impact bending strength versus corresponding values of MOR, parallel to grain of the previous study [8] showed a high significant correlation between all the mechanical properties with impact strength (**Figure 7**). The highest R-square was found between impact strength versus compression strength parallel to the grain (98 %). This indicated that alteration caused by ice-blasting are rather the same in nearly all mechanical properties.

Conclusions

The effects of ice-blasting, as a modern method of cleaning, were studied on the impact strength of 2 commercial wood species (poplar and beech). The results showed that ice-blasting did not have a significant effect on the impact strength of poplar wood; however, it made the impact strength decrease in beech wood, although not statistically significant. It was concluded that the effects of ice-blasting on the impact strength of solid wood species would be significantly dependent on the density and species of wood that determines the depth of surface abrasion caused by ice-blasting. Furthermore, the heat-transferring property of silver nanoparticles prevented accumulation of cold on the surface of the specimens, mitigating the negative effects of ice-blasting in beech caused by micro-cracks; it also significantly improved the impact strength in poplar, as a lower-density hardwoods.

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