# Effects of Pressing Temperature and Particle Size on Bark Board Properties Made from Beetle-Infested Lodgepole Pine (*Pinus contorta*) Barks

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**Abstract**

Mountain pine beetle (*Dendroctonus ponderosae*)–infested lodgepole pine (*Pinus contorta*) bark was used to make particleboard panels (bark board) without synthetic resins. The effects of pressing temperature and particle size on the mechanical properties of the bark boards were examined. The study revealed that pressing temperature and particle size have great influence on mechanical, physical, and hygroscopic properties of self-bonded bark boards. Higher pressing temperatures resulted in improvements in all properties studied, including increases of modulus of elasticity and modulus of rupture by approximately 4 times and an increase of internal bond strength by nearly 10 times when comparing boards pressed at 170°C versus 230°C. Boards produced from fine bark particles showed better mechanical performance than boards produced from coarser bark particles except for internal bond strength, which was highest in boards containing bark particles of mixed sizes. Scanning electron microscopic images of fractured surfaces of bark boards derived from different particle sizes and pressed at different temperatures indicated that fine and mixed particles and higher pressing temperatures led to denser packing.

With the increasing concerns regarding environmental issues and sustainable development, maximum utilization and value recovery of forest residues and waste materials are highly desirable. Use of bark has long been attempted in manufacturing of panel products with or without synthetic resins. However, many issues still limit its effective utilization on a commercial scale. In this study, mountain pine beetle (*Dendroctonus ponderosae*)–infested lodgepole pine (*Pinus contorta*) bark was used as a raw material for producing particleboard products without any synthetic resin, and the effects of pressing temperature and particle size on panel properties were investigated. The requirement for high pressing temperatures is one of the main obstacles in the production of bark board on a commercial scale; therefore, studies on the impact of furnish and processing conditions are highly beneficial for the utilization of bark in panel production.

Bark is a mill-waste residue that is available in large quantities. It has limited uses and can sometimes cause disposal problems (Harkin and Rowe 1971). In addition to the normal production of bark by forest industries, the recent outbreak of the mountain pine beetle in various parts of North America also contributes to the availability of a tremendous amount of beetle-infested bark because of the high mortality rate of lodgepole pine trees. Approximately 50 percent of the bark is currently burned for energy production, but due to environmental concerns and its low calorific value, using bark as a fuel is not the most desirable application (Deppe and Hoffmann 1972). Bark possesses a large amount of phenolic compounds, which can act as an adhesive in making panels. However, only limited research has been done in this area.

In general, bark constitutes about 9 to 15 percent of a typical log by volume (Harkin and Rowe 1971). In terms of chemical composition, bark differs from wood by the presence of polyphenols and suberin, a lower percentage of

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polysaccharides, and a higher percentage of extractives (Weissmann 1983, Fengel and Wegener 1984, Sjostrom 1993, Rowell 2007).

Bark board is a panel product quite similar to particleboard. In this article, bark board is referred to as boards made exclusively from bark particles by using heat and pressure to generate cohesion from the bark's natural chemicals without adding a synthetic adhesive. Past studies have demonstrated the feasibility of full or partial use of bark as the raw material for particleboard production, but the manufacturing conditions and the properties of the resulting products have not been attractive enough for commercialization. However, bark board has very high dimensional stability in water and does not have an issue with formaldehyde emissions (Anonymous 1999). Thus, it is a more environmentally friendly product.

Making bark boards without synthetic resins has been studied by Burrows (1960), Chow (1972, 1975), Wellons and Krahmer (1973) and Troughton and Gaston (1997). Research in this area was pioneered by Heritage (1956) and Burrows (1960). Heritage worked on thermal plasticization principle, while Burrows reported plasticization of lignin by adding moisture.

During the study of bark extractive-lignin polymerization at high temperatures, Chow (1975) found that the most effective pressing temperature for making bark boards was in the range of 250°C to 300°C. Important board properties, such as dimensional stability, moisture absorption, and strength, were found to be similar to or better than those of bark boards made with 4 to 7 percent urea-formaldehyde resin or phenol-formaldehyde resin using a pressing schedule similar to that of commercial particleboard production. The study also found substantial moisture release during bark board pressing, caused by condensation and dehydration of the bark chemical components. As a result, the bark boards were susceptible to blow and moisture blisters when pressed at high temperatures. Later, Troughton and Gaston (1997) and Troughton (1998, 2000, 2003) produced self-bonded bark boards under different manufacturing conditions (different pressures, temperatures and catalysts; US patents 5,725,818, 6,120,914, and 6,544,649).

Various researchers, including Alvang and Johanson (1965), Dost (1971), Deppe and Hoffmann (1972), Place and Maloney (1975, 1977), Blankenhorn et al. (1977), Wisherd and Wilson (1979), Muszynski and McNatt (1984), and Blanchet et al. (2000, 2008), attempted to use various resins as binding agents to bond the bark particles together. Dost (1971) studied the effects of bark fibers on properties of particleboard and reported that most of the mechanical properties and board performance became poorer as bark fiber content increased. Deppe and Hoffman (1972) performed particleboard experiments and utilized softwood bark residues, and they noticed that bending strength decreased with increased bark content. Deppe and Hoffman also tried to utilize the self-gluing ability of the bark by testing ammonia-disintegrated spruce bark but did not find satisfactory results with this approach.

Maloney (1973) performed various experiments on bark boards of US West Coast softwood species. Anderson et al. (1974) studied the suitability of ponderosa pine (*Pinus ponderosa*) bark extract as a bonding agent for particleboard. Place and Maloney (1975) manufactured three-layer particleboards from combinations of wood and bark. Their investigation evaluated the role of specific gravity and press closing time on the mechanical properties of the board. Place and Maloney (1977) also studied a variety of three-layer composite boards that were made by using two bark species for the core and varying the pressing conditions. Blankenhorn et al. (1977) investigated some of the compressive and flexural properties of bark board and polymer-impregnated bark board. The objective of their study was to compare the properties of nonimpregnated bark board with those of bark board impregnated with epoxy and methylmethacrylate.

Wisherd and Wilson (1979) studied the effects of bark as a supplement to wood furnish in production of particleboard. Muszynski and McNatt (1984) made single-layer wood particleboards from Scots pine (*Pinus sylvestris*) with the addition of Norway spruce (*Picea abies*) bark in varying proportions and found that a 30 percent spruce bark combination performed best. Blanchet et al. (2000) studied particleboard made from hammer-milled black spruce (*Picea mariana*) bark residues, and their results showed the technical possibility of making particleboard from bark residues.

In another study, Blanchet et al. (2008) discussed the effects of pressing time, particle geometry, and melamine overlay on bark particleboard properties. Yemele et al. (2008b) studied the effects of hot-water treatment on black spruce and trembling aspen (*Populus tremuloides*) barks on the bark particles/phenol-formaldehyde adhesive system. Their results showed that the hot-water treatment affected physical and mechanical properties of the resulting bark particleboards. In a separate study, Yemele et al. (2008a) also discussed the effect of hot-water–extracted bark particle content and size on the physical and mechanical properties of bark particleboards. The thermal behavior of bark has been studied by various researchers as well (Chow and Pickles 1971, Place and Maloney 1975, Koch 1985).

Past research on self-bonded bark boards has focused mostly on the alteration of pressing temperature and the use of various catalysts to lower the pressing temperature. However, other issues associated with bark boards, including the effects of particle size and optimization of process parameters, require further examination. This study aimed to explore some of these issues and to develop bark boards from beetle-infested lodgepole pine barks.

The main objectives of this study were to investigate effects of temperature and particle size on bark board properties, optimize process parameters, conduct board characterization and evaluation, and compare mechanical and physical properties of the resulting bark boards. It was hypothesized in this research that

1. Mountain pine beetle–infested lodgepole pine barks can be used for making bark boards without any synthetic resin by utilizing the polymerization and softening reactions of its constituents at higher temperatures.
2. Both pressing temperature and bark particle morphology can impact bark board performance.

## Materials and Methods

### Raw material preparation

Beetle-infested lodgepole pine bark, acquired from a saw mill in Whitecourt, Alberta, was used throughout this research project. When received, the bark material had a moisture content of about 40 percent and was initially air dried under

shades for a week, followed by grinding in a Wiley mill and then separation using different mesh sizes. They were further dried in a forced-air oven at 80°C for 24 hours to a moisture content of around 2 to 3 percent. The chemical composition of the beetle-infested lodgepole pine bark was determined according to Technical Association of the Pulp and Paper Industry (TAPPI) Standards T264 om-82 (TAPPI 1982) and T204 os-76 (TAPPI 1976), which showed that this bark contained around 46.7 percent hollocellulose and 42.6 percent Klason lignin.

## Board development

Bark particles were shaped in the form of mats with a thickness of approximately 18.75 mm and a size of 30 by 30 cm, in a wooden mould, using 600 g of dry bark. So, the standard size of targeted boards was fixed to 30 by 30 cm, with a targeted board thickness of 6.25 mm and a density of 0.8 to 1 g/cm$^3$. This board size was large enough to allow the samples to be cut for different mechanical tests.

According to the experimental design, in the beginning of the experiments boards were pressed at varying pressures and temperatures, ranging from 170°C to 230°C. Some boards were also pressed at higher temperatures of up to 300°C, but it was observed that at 300°C, the bark boards had highly charred surfaces, likely due to degradation of the main chemical constituents, which is supposed to adversely affect the strength properties. However, in a few past studies (e.g., Chow 1975, Troughton and Gaston 1997), this higher temperature was found to be favorable by contributing to self-adhesion of the bark particles. In the present study, bark boards were highly susceptible to blowing and cracking. That problem was controlled by alterations in pressing parameters and by the use of special caul screens, which helped in releasing moisture and gases.

## Experimental design

Experiments were designed on the basis of the following two objectives:

1. Determination of the effects of pressing temperature on board properties
2. Determination of the effects of particle size on board properties

To achieve these objectives, the following two factors were considered in the experimental design (Fig. 1):

1. Three pressing temperatures (170°C [338°F], 200°C [392°F], and 230°C [446°F]) with mixed particles (passing through a 4.75-mm sieve) pressed at 28.1 kg/cm$^2$ (400 psi) for 1 minute, followed by 12.3 kg/cm$^2$ (175 psi) for 19 minutes[1]
2. Three particle sizes (coarse, medium, and fine; Table 1 and Fig. 2) with a temperature of 230°C[2]

For the study of the temperature effect, three replications were made for each temperature, so a total of nine boards were pressed. Three replications were also made for each group of particles, so a total of nine boards were pressed in that portion as well.

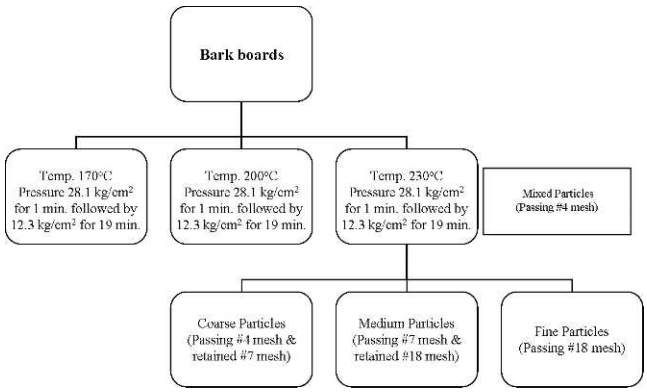


*Figure 1.—Experimental design for studying the temperature and particle size effects on the bark boards.*

*Table 1.—Particle sizes used in the experiments.*

| | Mesh size (sieve opening size, mm) | |
|---|---|---|
| Particle size | Passing | Retaining |
| Coarse | #4 (4.75) | #7 (2.81) |
| Medium | #7 (2.81) | #18 (1) |
| Fine | #18 (1) | — |
| Mixed | #4 (4.75) | — |

## Board pressing parameters

A total of 18 bark boards (nine each for the temperature and particle size studies) with targeted dimensions and densities were prepared in a hot press at the wood composite laboratory in the Faculty of Forestry, University of Toronto. Mixed-type particles, which contained all particles passing through a #4-mesh screen, were used in the temperature study. A thermocouple sensor was inserted in the middle of the mat before pressing to get the core temperature and core gas pressure. The core temperature, core gas pressure, and platen pressure and position were recorded. Pressman software was used to control and measure the pressing parameters. Table 2 summarizes the mat and pressing parameters.

## Testing and evaluation of bark board properties

All boards were tested for their mechanical properties. All tests were conducted according to the procedure specified in American National Standards Institute (ANSI) A208.1-1999 (ANSI 1999) and American Society for Testing and Materials (ASTM) D-1037-06a (ASTM 1999). The panels were cut into samples to test static bending (modulus of elasticity [MOE] and modulus of rupture [MOR]), internal bond (IB) strength, tensile strength, thickness swelling, and water absorption properties according to the testing standards. All boards were also evaluated for their physical properties (e.g., density and moisture content) and their surface characteristics.

[1] Among these three temperatures, 230°C was selected for carrying out the particle size study, because boards pressed with other two temperatures were unsatisfactory.

[2] Mixed particles were used in the temperature study. Therefore, experiments with the mixed particles were not repeated.

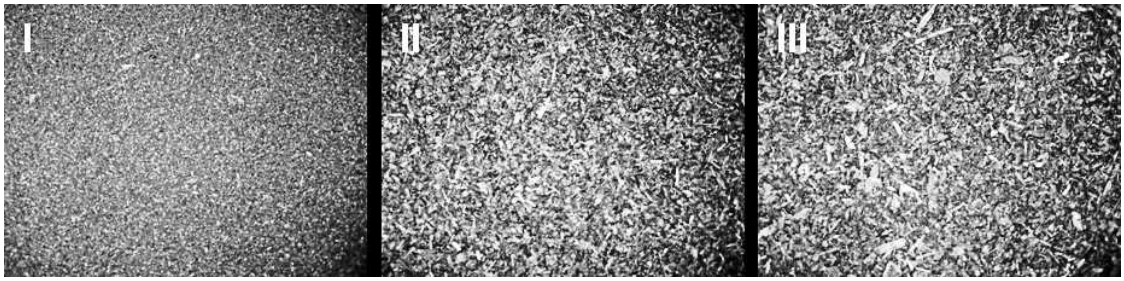


*Figure 2.—Bark particles of three different sizes (I = fine; II = medium; III = coarse).*

*Table 2.—Mat and pressing parameters.*

| Mat/press parameter | Value |
|---|---|
| Target panel density (g/cm$^3$) | 0.8–0.9 |
| Weight of bark particles in one sample (g) | 600 |
| Moisture content (%) | 2–3 |
| Particle type | Mixed, fine, medium, coarse |
| Resin content | Nil |
| Platen temperature (°C) | 170, 200, 230 |
| Pressing time (s) | 1,200 |
| Press closing time (s) | 50 |
| Average board thickness (mm) | 6.25 |
| Initial mat thickness (mm) | 18.75 |
| No. of layers in mat/board | 1 |

## Results and Discussion

### Effects of pressing temperature on board properties

Pressing temperature is one of the most important parameters in production of bark boards, because the binding of the bark particles without any synthetic resin is believed to occur due to the thermal effects. Various results related to pressing temperature effects on board properties are shown in Table 3 and Figures 3 through 8. In all these figures, results after normalization by panel density are also included for comparison. Density normalization was done by dividing the measured board property by the corresponding board density to account for the influence of densification.

As shown in Table 3 and Figures 3 through 8, all board properties improved significantly when the pressing temperature increased from 170°C to 230°C. The improvements were more substantial after 200°C, which supports the hypothesis of extractives and lignin polymerization and softening at higher temperature. It is also essential to mention here that moisture release occurred during hot pressing. Similar to Chow's results (Chow 1975), this release was greater at higher temperatures, which implies a higher degree of condensation reaction at higher temperatures. At a pressing temperature of 170°C, MOE and MOR were 420 and 2.01 MPa, respectively. However, they increased almost 4 times when pressing temperature was changed to 230°C. The IB strength was increased by nearly 10 times at 230°C. Similar trends were observed for thickness swelling and water absorption at both 2 and 24 hours. In the case of tensile strength, the increase was less significant. It was also observed for boards pressed at 170°C that their particles started to separate after a 24-hour water soaking, which indicated little or no chemical bonding between bark particles at this temperature. Perhaps the bark particles were just attached to each other by physical bonds or by the thermoplastic effects of some components in the bark, such as wax or resin. This phenomenon supports the opinion that chemical bonding only occurs at higher temperatures. Comparisons by statistical *t* tests among data obtained at 170°C, 200°C, and 230°C showed that the maximum difference was between data of 170°C versus 230°C.

It was also found that the board density increased with increasing temperature. To compensate, density normalization was applied to all graphs, which showed that the density increase was not responsible for the increase in mechanical properties but, rather, that temperature-related condensation reactions were the main factor.

For all boards pressed at 230°C, all properties except IB strength were below the minimum requirement as set by

*Table 3.—Effects of pressing temperature on bark board properties.*[a]

| Bark board properties | Pressing temperature[b] | | |
|---|---|---|---|
| | 170°C | 200°C | 230°C |
| Density (g/cm$^3$) | 0.80 | 0.86 | 0.92 |
| Moisture content (%) | 2.52 | 2.44 | 1.46 |
| MOE (MPa) | 420 (104)[c] | 724 (108) | 1,684 (218) |
| MOR (MPa) | 2.01 (0.22) | 3.22 (0.4) | 7.18 (0.64) |
| IB strength (MPa) | 0.1 (0.03) | 0.15 (0.01) | 0.97 (0.22) |
| Tensile strength (MPa) | 1.55 (0.2) | 2.08 (0.23) | 3.82 (0.29) |
| Thickness swelling, 2 h/24 h (%) | 24.90/64.93 (0.34/3.1) | 13.17/41.77 (1.75/2.45) | 2.96/10.46 (0.08/0.61) |
| Water absorption, 2 h/24 h (%) | 29.78/72.82 (3.46/0.92) | 13.64/57.27 (1.56/0.21) | 3.64/15.36 (0.34/1.95) |

[a] Tested as per ASTM-1037D-06a (ASTM 1999). MOE = modulus of elasticity; MOR = modulus of rupture; IB = internal bond.
[b] Pressure of 28.1 kg/cm$^2$ for 1 minute, followed by 12.3 kg/cm$^2$ for 19 minutes.
[c] Values in parentheses are the standard deviations.

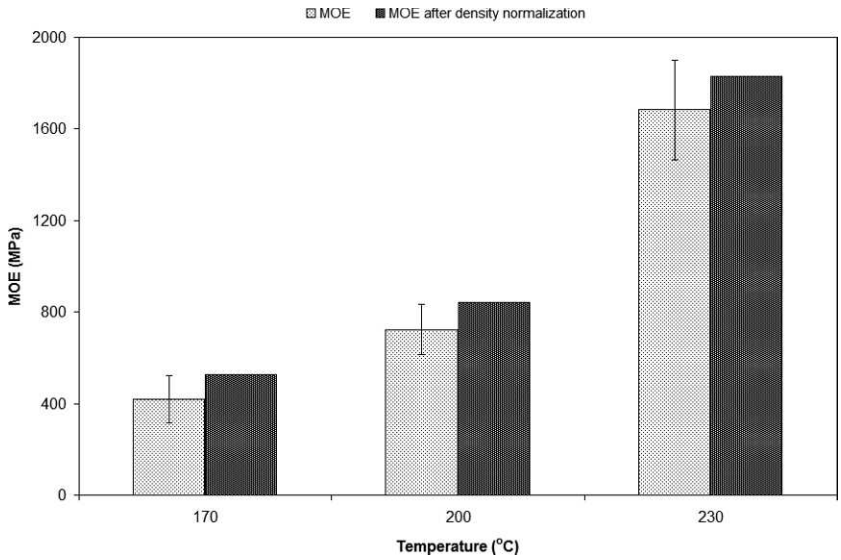


*Figure 3.—Effects of temperature on modulus of elasticity (MOE) of the bark boards.*

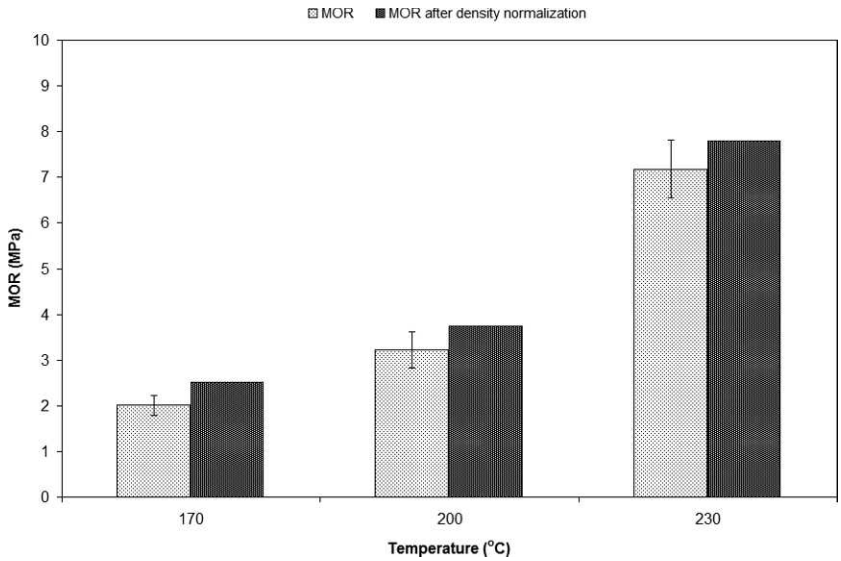


*Figure 4.—Effects of temperature on modulus of rupture (MOR) of the bark boards.*

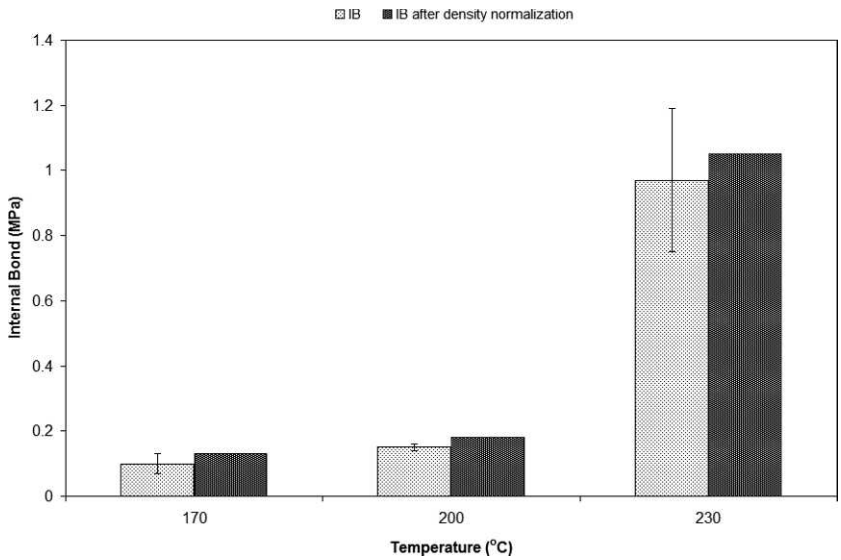


*Figure 5.—Effects of temperature on internal bond (IB) strength of the bark boards.*

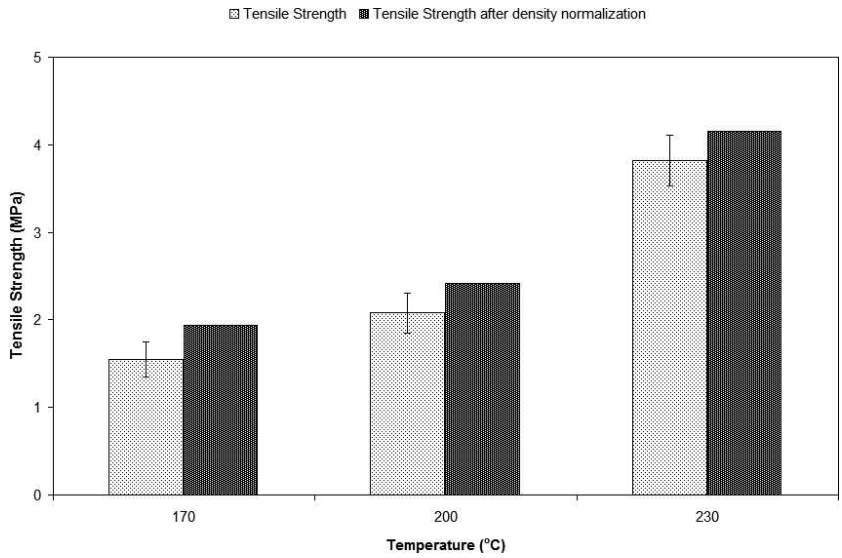


*Figure 6.—Effects of temperature on tensile strength of the bark boards.*

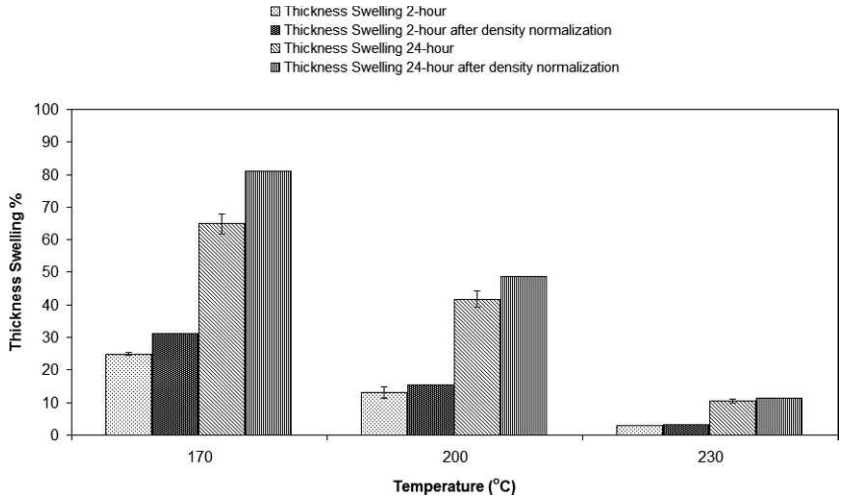


*Figure 7.—Effects of temperature on thickness swelling of the bark boards.*

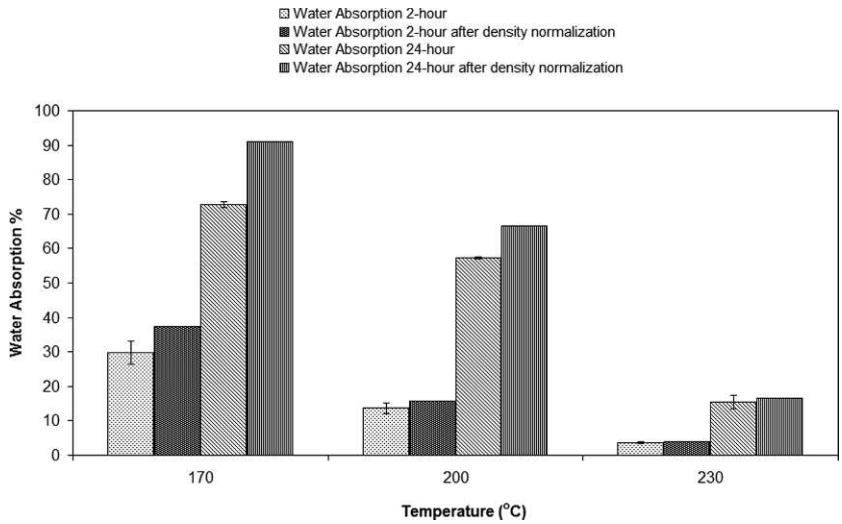


*Figure 8.—Effects of temperature on water absorption of the bark boards.*

ANSI A208.1-1999 for use in construction purposes, so it is obvious that these boards need further improvements in their properties. However, these boards can potentially be used for less stringent applications.

## Effects of particle size on board properties

In addition to pressing temperature, bark particle size and the packing of particles in boards should also affect the board properties. Poor packing will lead to most of the

*Table 4.—Effects of particle size on bark board properties.*[a]

| Bark board properties | Particle size | | | |
|---|---|---|---|---|
| | Coarse | Medium | Fine | Mixed |
| Density (g/cm$^3$) | 0.89 | 0.91 | 1.0 | 0.92 |
| Moisture content (%) | 1.21 | 1.29 | 2.2 | 1.46 |
| MOE (MPa) | 1,350 (145)[b] | 990 (47) | 1,871 (142) | 1,684 (218) |
| MOR (MPa) | 5.99 (1.33) | 4.65 (0.04) | 9.81 (1.25) | 7.18 (0.64) |
| IB strength (MPa) | 0.3 (0.04) | 0.26 (0.02) | 0.62 (0.1) | 0.97 (0.22) |
| Tensile strength (MPa) | 2.47 (0.16) | 3.29 (0.22) | 5.27 (0.41) | 3.82 (0.29) |
| Thickness swelling, 2 h/24 h (%) | 2.42/11.99 (0.86/2.33) | 8.47/18.44 (1.16/2.94) | 1.02/5.1 (0.17/0.3) | 2.96/10.46 (0.08/0.61) |
| Water absorption, 2 h/24 h (%) | 5.36/18.33 (0.45/0.95) | 13.97/31.8 (3.56/4.16) | 0.67/6.31 (0.07/0.4) | 3.64/15.36 (0.34/1.95) |

[a] Tested as per ASTM-1037D-06a (ASTM 1999). MOE = modulus of elasticity; MOR = modulus of rupture; IB = internal bond.
[b] Values in parentheses are the standard deviations.

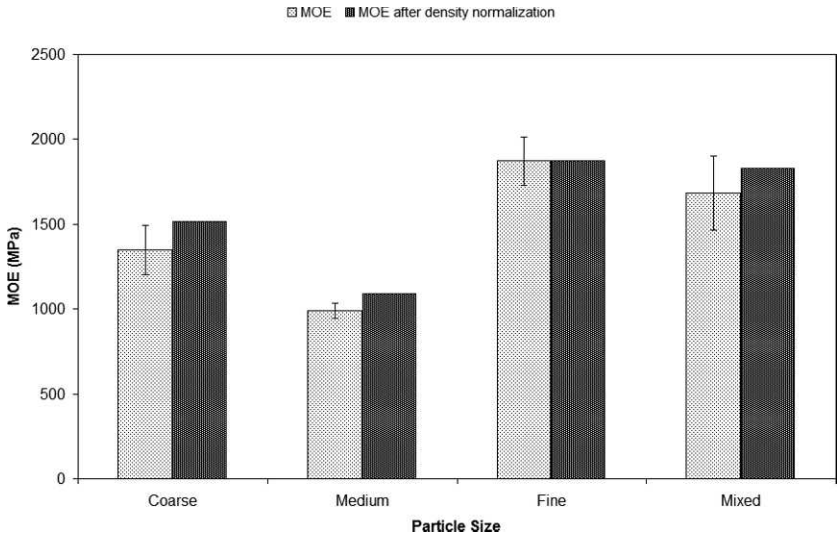


*Figure 9.—Effects of particle size on modulus of elasticity (MOE) of the bark boards.*

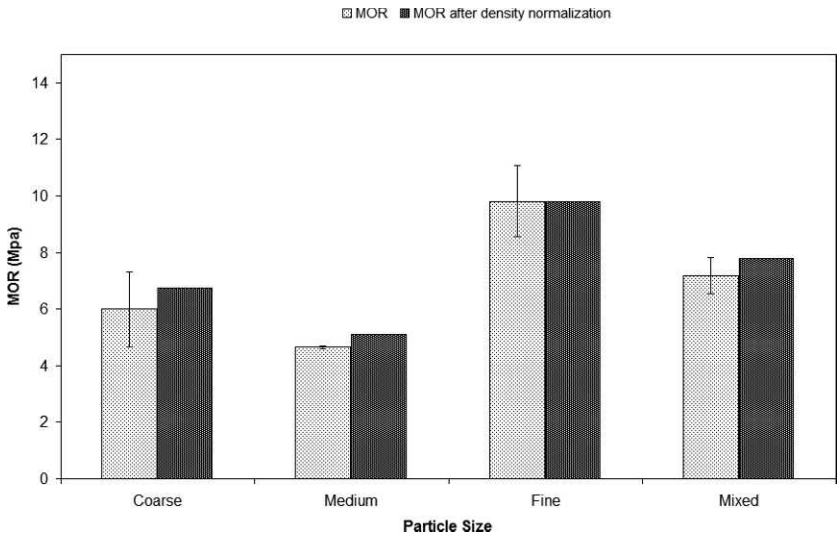


*Figure 10.—Effects of particle size on modulus of rupture (MOR) of the bark boards.*

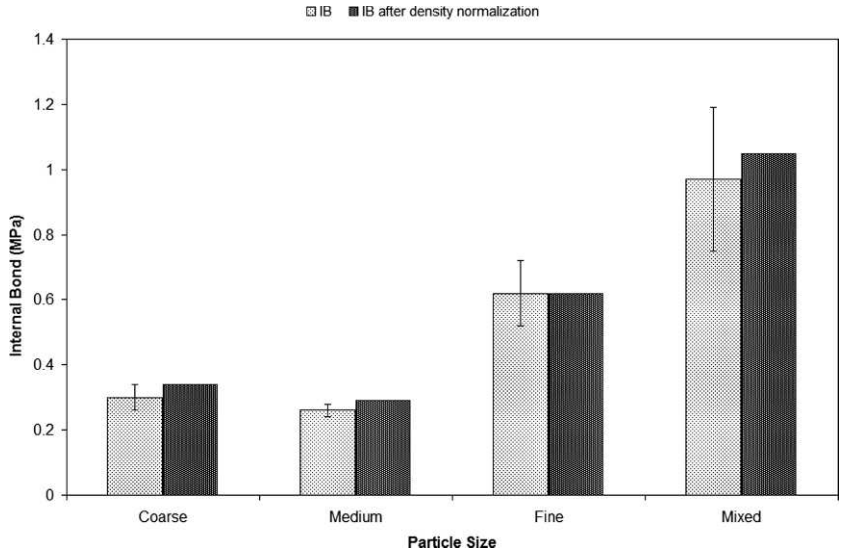


*Figure 11.—Effects of particle size on internal bond (IB) strength of the bark boards.*

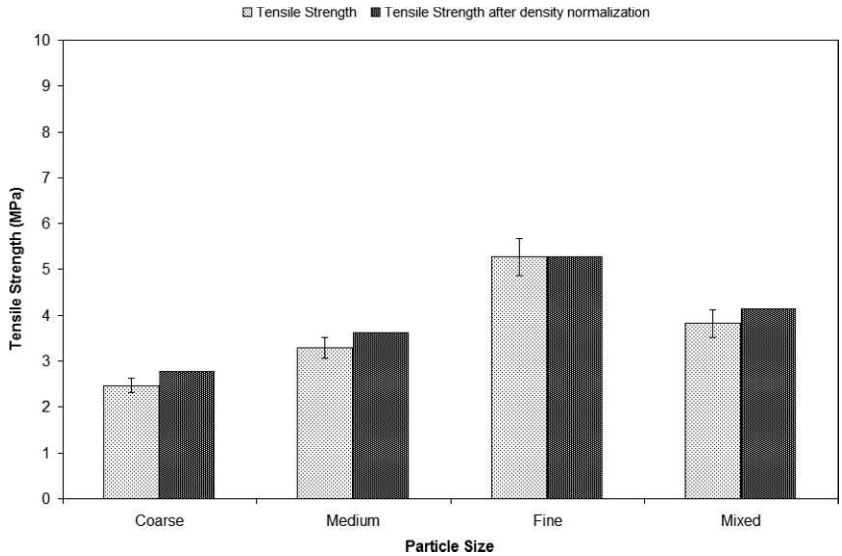


*Figure 12.—Effects of particle size on tensile strength of the bark boards.*

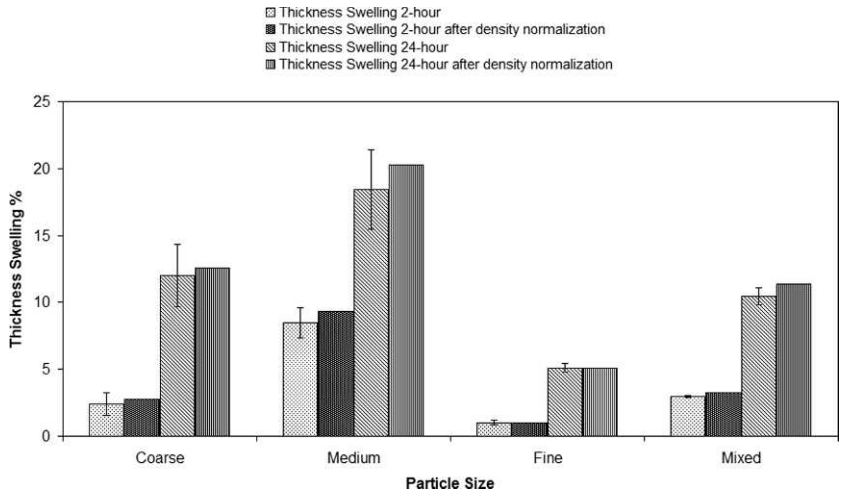


*Figure 13.—Effects of particle size on thickness swelling of the bark boards.*

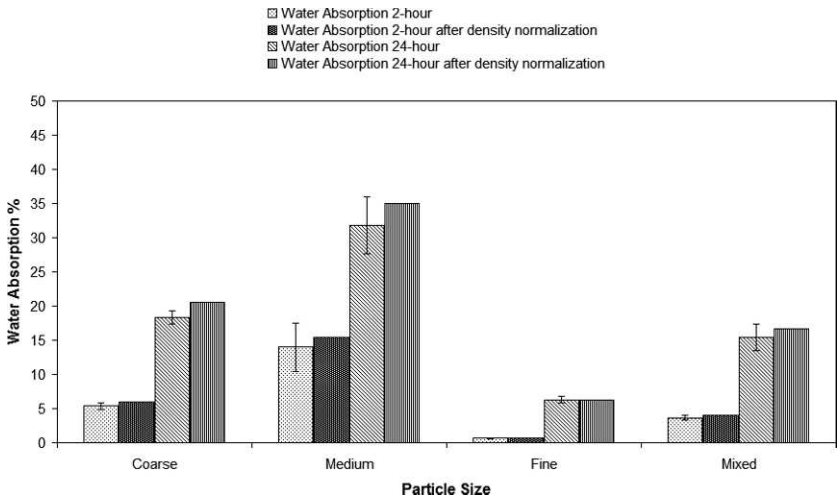


*Figure 14.—Effects of particle size on water absorption of the bark boards.*

interparticle spaces remaining as voids. For fine or mixed particles, the chance of tighter packing and closer contact among the particles is greater, which may positively contribute to bark board properties. The effects of particle size are presented in Table 4 and Figures 9 through 14.

Investigation of the effects of bark particle size on bark board properties revealed better mechanical properties for bark boards derived from fine particles. Boards made from fine particles (passing through a #18-mesh screen) showed superiority in almost all properties (except IB strength) when comparing boards made from coarse particles (passing through a #4-mesh screen and retained in a #7-mesh screen), medium particles (passing through a #7-mesh screen and retained in an #18-mesh screen), and particles of mixed sizes (passing through a #4-mesh screen). Boards of fine particles were aesthetically more appealing, with smooth and even surfaces. They also possessed the highest density, at about 1 g/cm$^3$.

Boards derived from fine particles were superior in terms of MOE and MOR, followed by boards of mixed particles and then boards of coarse particles. Boards of medium particles gave the lowest MOE and MOR values. However, boards of mixed particles exhibited the highest IB strength, followed, in order of decreasing IB strength, by those of fine, coarse, and medium particles. The reason may be that in the case of mixed particles, there were synergistic effects on the physical interlocking between particles due to both larger particle size and more favorable packing. For tensile strength, thickness swelling, and water absorption, boards made from fine particles gave the best values. Even after a 24-hour water soaking, their swelling and water absorption were much less, and the particle binding appeared to be intact. The superiority of fine particles exhibited in most of the board properties is possibly due to the close contact of particle surfaces, the larger surface areas, and the compact packing (and, hence, less void volume). Because no synthetic resin was used in the bark boards, there existed more void spaces or less surface interaction between coarse or medium particles as compared with fine or mixed particles, all of which were reflected accordingly in the resulting board properties.

Similar to the effects of temperature, particles size affected the densities of these bark boards. It was found that the density of boards made with fine particles was the highest. However, density normalization on all graphs showed that density increase alone cannot account for the improvements in board properties.

## Bark board characterization by SEM

Scanning electron microscopic (SEM) images of fractured surfaces of bark boards pressed under different conditions of temperature and particle size were obtained to observe the extent of particle packing and board

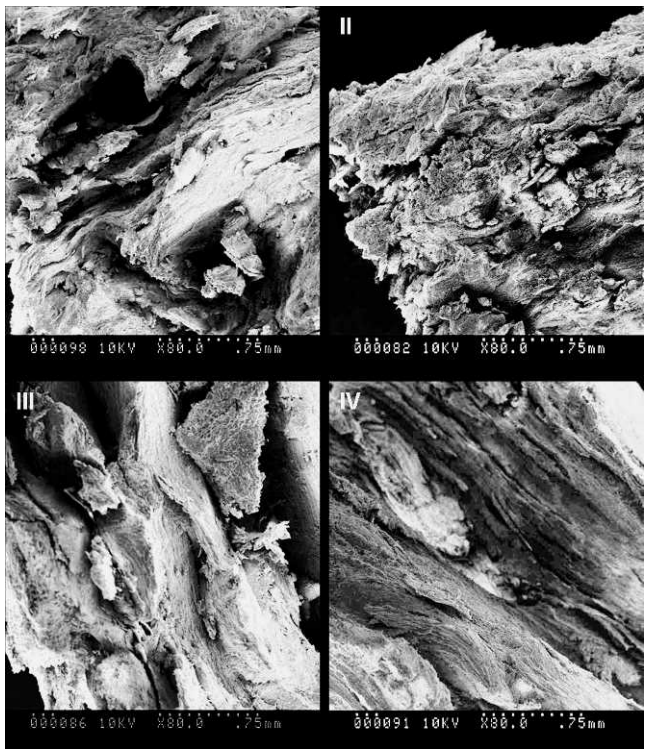


*Figure 15.—Scanning electron microscopic images of fractured surfaces of bark boards pressed at 230°C (I = mixed particles; II = fine particles; III = medium particles; IV = coarse particles).*

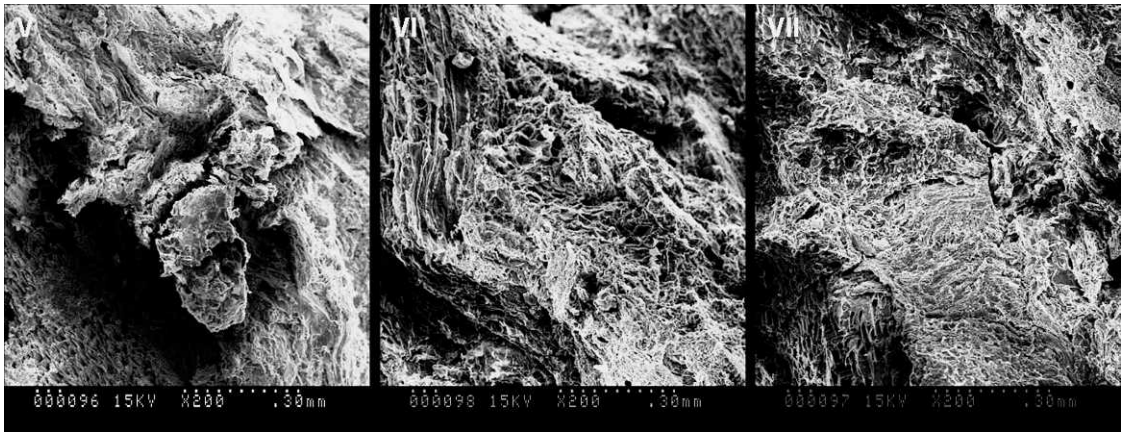


*Figure 16—Scanning electron microscopic images of fractured surfaces of bark boards made with mixed particles (V = pressed at 170°C; VI = pressed at 200°C; VII = pressed at 230°C).*

structures. Figure 15 shows that mixed (Image I) and fine (Image II) particles were more closely packed than medium (Image III) and coarse (Image IV) particles. Similarly, tight packing was observed for boards pressed at higher temperatures (Fig. 16). Such tight packing of particles as shown in SEM images of boards derived from a higher temperature (230°C) and fine particles was consistent with the higher board densities. Additionally, many void volumes or interparticle spaces are visible in all SEM images, probably due to no synthetic resin being used in the bark boards. It was also observed in the SEM images that an increase in pressing temperature resulted in higher alteration of the bark's anatomical structure. This can be explained by the phenomenon of plasticization and polymerization of bark components, which is more extensive at temperatures above 200°C.

## Conclusions

This study aimed to develop environmentally friendly bark boards from mountain pine beetle–infested lodgepole pine bark without using any synthetic resin. The development of auto-adhesion techniques and the manipulation of thermal conditions and furnish particle sizes are important for the manufacturing of bark boards. As hot pressing occurs, moisture, mass transfer, heat transfer, chemical changes, and bark particle densification interact with each other, resulting in continuing changes in the board's physical, chemical, and mechanical properties. This study provides experimental results for bark boards derived from mountain pine beetle–infested lodgepole pine bark and sheds light on the technical feasibility of producing bark board from this resource.

Based on this study of the effects of pressing temperature and bark particle size on bark board properties, the following conclusions can be drawn.

1. Pressing temperature has a great influence on properties of particle boards made from beetle-infested lodgepole pine bark. Board mechanical and physical properties improved significantly with an increase of pressing temperature within the temperature range of this study.
2. Boards made with fine particles possess the best physical and mechanical properties as well as good IB strength. They also have better physical appearance and smooth surfaces, with the highest density. Mixed particles resulted in bark boards with the highest IB strength.

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