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Suitability of live and fire-killed small-diameter ponderosa and lodgepole pine trees for manufacturing a new structural wood composite

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ABSTRACT

Finding alternative uses for raw material from small-diameter trees is a critical problem throughout the United States. In western states, a lack of markets for small-diameter ponderosa pine *(Pinus ponderosa)* and lodgepole pine *(Pinus contorta)* can contribute to problems associated with overstocking. To test the feasibility of producing structural composite lumber (SCL) beams from these two western species, we used a new technology called steam-pressed scrim lumber (SPSL) based on scrimming technology developed in Australia. Both standing green and fire-killed ponderosa and lodgepole pine logs were used in an initial test. Fire-killed logs of both species were found to be unsuitable for producing SPSL but green logs were suitable for producing SPSL For SPSL from green material, ponderosa pine had significantly higher modulus of rupture and work-to-maximum load values than did SPSL from lodgepole pine. Modulus of elasticity was higher for lodgepole pine. The presence of blows was greater with lodgepole pine than with ponderosa. Blows had a negative effect on the mechanical properties of ponderosa pine but no significant effect on the mechanical properties of SPSL from lodgepole pine. An evaluation of non-destructive testing methods showed that X-ray could be used to determine low density areas in parent beams. The use of a sonic compression wave tester for NDE evaluation of modulus of rupture showed some promise with SPSL but requires further research.

1. Introduction

A history of fire suppression, changes in the intensity and type of land management activities being performed on forest land, and prolonged periods of climatic change (e.g., drought) have contributed to conditions in national forests leading to an unnatural build-up of brush and small trees (Levan-Green and Livingston, 2001). These conditions make stands prone to disturbances such as insect epidemics and uncharacteristically severe wildfires. Densely stocked stands of live and dead trees have compromised the ability of these forests to meet current and future demand for solid wood products (Wolfe, 2000). Reducing stand density by thinning suppressed trees could restore them to a more natural state, improve resiliency to attack by insects, and reduce adverse effects from fire. Finding alternative uses and/or markets for small-diameter raw materials is a critical problem. In western states, lack of markets for small-diameter lodgepole pine *(Pinus contorta)* and ponderosa pine *(Pinus ponderosa)* is impacting silvicultural practices on millions of acres of forests.

Wildfires in the western United States have always been a significant problem. Over the past decade, there has been a substantial increase in the number of wildfires and the acreage burned by them (Hill, 1999). There are many factors that have contributed to this increase of wildfires. Severe drought conditions along with the long-term effects of a national wildfire suppression policy, has led to an unnatural buildup of brush and small trees in our forests (Levan-Green and Livingston, 2001).

Insect attacks are also a major problem in western states. From 2001 to 2003, Arizona and New Mexico experienced a major bark beetle outbreak that attacked ponderosa pine stands and left the standing timber dead and prone to wildfire (Zausen et al., 2005). Many experts believe that prolonged drought conditions and overstocked forests were the major contributors to the severe outbreak (Parker et al., 2006). Thinning ponderosa and lodgepole pine stands would significantly help reduce the number of acres affected by wildfires and insect attack. Currently it is not economically feasible for landowners to thin trees, because they have little value in today's market (Parker et al., 2006). Canada is experiencing an outbreak of mountain pine beetle attacking lodgepole pine that has already moved into the US.

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Both fire and insects affect the quality of wood and utilization opportunities when harvested. At a basic level, heat from the fire can cause significant changes in wood. The outer surface of the stem, or the wood immediately under the bark, is probably most affected with the effect decreasing toward the pith. The depth of thermal effect is a function of both the properties that affect internal heat flow and the intensity of the fire. The temperature would logically be most elevated where the stem is small, the bark thin, and boundary temperatures most severe and long lasting. For wood scientists, this effect might be observed as changes in wood properties. while for foresters and entomologists, the effect might be observed as delayed tree mortality. post-fire insect activity, and rate of deterioration of standing injured and dead trees.

Fire-damaged and fire-killed trees provide host material to a number of deterioration agents including, but not limited to, numerous insect species and decay and stain fungi. Beetles are vectors of stain and decay fungi. Infestations typically will follow fire and are not confined to trees that have been killed by the fire. Many species will attack stressed trees and even adjacent green trees leading to an increase in mortality.

What is lacking is information on the suitability of dead or dying trees as an input raw material for several new and emerging wood processing technologies. Wood unsuitable for solid wood appearance or structural-grade products could be suitable for engineered structural composite wood products (Yadama et al., 2009). Such value-added products, like steam-pressed scrim lumber (SPSL)(Forrest, 2003), are being developed. The emphasis in developing TimTek® scrimming technology[1] was utilization of green, low-value pulpwood-size raw material to manufacture a high-strength, engineered structural composite lumber product (SCL) for use in residential and home construction. A log may produce several hundred individual scrim pieces and the collection of the individual pieces is called a mat. Scrim mats are visually graded according to factors that impact manufacture of finished product. The average length and diameter are important because it impacts drying uniformity and bending properties in the final product. Defects in a log such as knots may create areas in the mat where the scrim pieces are shorter and smaller than the surrounding area and in some cases a knot in the log may result in a hole in the mat. Scrim quality is judged within and between mats in terms of uniformity. The process of scrimming is performed by two types of roll devices that apply pressure on the log. Logs are first processed in "crush" mills. Crush mills do not actually crush logs rather they apply just enough pressure to crack the log from end to end. Logs are processed through multi passes crush rolls and then processed on the scrim rolls. Scrim rollers are cylinders with flights that separate the cracked fiber into multi strand mats.

There is a lack of information on the suitability of dead or dying trees or mature, suppressed trees as an input raw material to this manufacturing process. If proven successful, it could be an option that would provide a market for small-diameter timber prices that would make it economically feasible for landowners to thin overstocked stands, thus reducing wildfire and insect attack risks. The purpose of that could offset fuel reduction treatment costs and compete with solid wood products in today's market.

This project focuses on evaluating small-diameter fire-killed and green trees (less than 177 mm diameter breast height) ponderosa and lodgepole pines for manufacture using the TimTek* process.

[1] TimTek® is the name given SPSL when it was developed in Australia. A diagram and pictures of the complete process may be found at http://www.cfr.msstate.edu/timtek/index.asp.

2. Methods

2.1. Materials

An initial shipment of ponderosa and lodgepole pine logs was shipped from study sites located on the Confederated Tribes of Warm Springs Indian Reservation and the Deschutes National Forest. both in central Oregon, to the TimTek* pilot plant located at Mississippi State University. Both 1 year dead (fire-killed and left standing prior to being harvested for the study) and live (green) logs of each species were sent. Each of these areas experienced major wildfires during the summer of 2003. The goal of the early research was to make two beams from each species and condition; *i.e.* two green and two fire-killed. Enough scrim was obtained to produce two beams from green logs of each species. After the beams were pressed, they were examined to see if there were any noticeable faults in them; *i.e.* blows. A blow is a physical defect in a manufactured billet that usually exhibits a longitudinal crack that follows the grain. Blows occur when internal gas pressure builds up during the pressing operation and exceeds the internal bond of the billet as the platens are removed. The root cause ofthe buildup in internal gas pressure is excess moisture that forms steam and builds pressure since it is sealed inside the billet being pressed. Blows in beams from the TimTek® process are not that uncommon when species are used which do not dry evenly producing wet pockets in the scrim. The ponderosa beams were blown, but had enough good wood in them to test small samples. The lodgepole beams were blown so badly that there was not enough good wood to test even small samples.

A second shipment of green lodgepole and ponderosa logs was sent to the pilot plant and was used to produce beams from which most of the data in this report is based. In this detailed study 10 lodgepole pine and eight ponderosa pine beams were produced. The data in this paper came from samples produced from the second shipment of logs.

Lodgepole billets produced in the study exhibited many blows due to the uneven drying particularly around knots. The lodgepole scrim did not separate into individual strands like ponderosa and/or southern yellow pine. The material was run through the scrim rollers multiple times in an attempt to increase separation but the scrim did not separate well especially around knots. It is believed that when a sample contains blows the mechanical properties are greatly reduced. Fig. 1 shows a lodgepole pine sample that contains a blow.

2.2. Beam production

The process began with the harvesting of logs 76-178 mm in diameter from central Oregon. These were end-coated, and

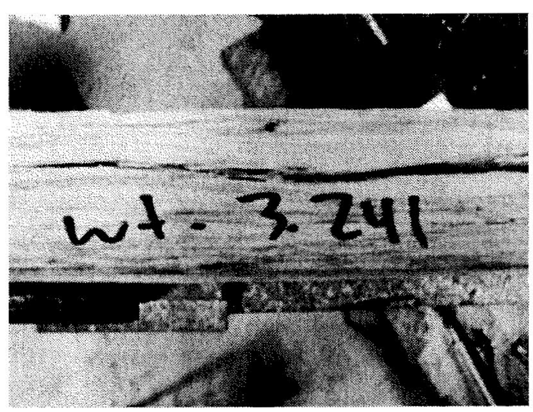

Fig. 1. Typical blow in a lodgepole pine sample.

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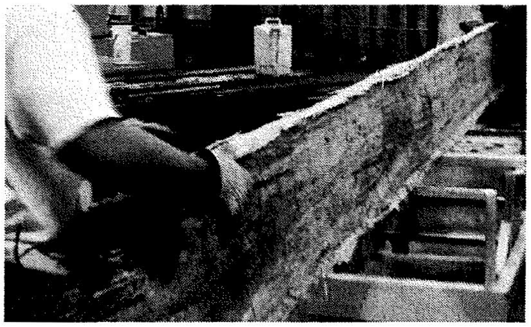

Fig. 2. Typical rough beam shown immediately after pressing.

shipped to Mississippi where they were stored under water spray until used. The storage period did not exceed 1 month. Logs were removed from water storage and debarked. The debarked logs were soaked in a hot water bath at *54-60°C* for 6 h (2 h for the initial study) prior to processing. This allowed any moisture lost from the air drying of the logs to be recovered before scrimming thus allowing for the highest yield of scrim out of each log.

After heating, logs were crushed and passed down the line through a series of scrimming heads of successively smaller size. These scrim mills produced scrim that was approximately 6.4 mm thick and 2.1-2.4-m long. A demonstration of the technique can be seen on the web at http://www.cfr.msstate.edu/timtek/index.asp. A process description can be found in the literature (Seale et al., 2006; Barnes et al., 2006).

After production, the scrim was loaded into a kiln and dried to a nominal 20% moisture content at *80°C* dry bulb temperature with no wet bulb control. The dried scrim was then coated with a stage B resole phenol formaldehyde resin to yield 12% resin solids. The resin is highly diluted with water and applied using a wand that literally floods the scrim with the resin mixture. Uptake of the resin is controlled with the initial drying process and with the dilution percentage of the applied resin. Since scrim is produced with rolls rather than a knife there are few smooth gluing surfaces. The resin must be the approximate viscosity of water to get application of resin solids into all the cracks and crevices of the material. The coated scrim was sent through a conveyor dryer at *115°C* to achieve a moisture content of 6% or less.

The scrim was laid into a mat in a forming box to get the correct beam weight and form. The finished mat was loaded into a proprietary steam press and consolidated. The rough beams were trimmed to a final size of 44.5 x 298-mm x 5.5-m. Fig. 2 shows a typical rough beam before trimming.

2.3. *Sample* testing

Samples measuring 44 x 64 x 1295-mm (width x depth x length) were cut from parent beams and tested in edgewise bending. Prior to testing, samples were also evaluated non-destructively using the Falcon Engineering A-Grader,[2] an instrument based on sonic resonance using compression wave technology. The A-Grader measures both the density of the timber and speed of the sonic waves in the timber to produce a stiffness value for the timber.

A total of 10 lodgepole pine beams and eight ponderosa pine full-sized beams were produced in the detailed study. Although the majority of the ponderosa and lodgepole beams were blown, a total of 160 lodgepole and 128 ponderosa bending samples were prepared from the large beams for testing. Prior to mechanical testing, each sample was non-destructively tested using the A-Grader.

Full-sized beams were also non-destructively graded using an Inspex™ X-ray inspection system. The samples were X-rayed to determine number and location of any low density areas (LDAs). These areas of low density are formed during layup when scrim furnish bridges across pieces resulting in an uneven density mat. This causes parts of the scrim to not bond well with the other pieces that surround it and can cause a decrease in the mechanical properties of the sample. The X-ray procedure has been found to be effective for quality control of beams (Leng et al., 2006). Fig. 3 shows an X-ray image taken from a set of samples. Circled areas indicate LDAs where the scrim mat was not formed properly and resulted in areas not bonded well. Number 1 shows a sample that does not contain a LDA. Numbers 2. 3, and 4 show typical samples rejected because of LDA's in each piece. The light areas in each piece indicate LDA locations.

By using the X-ray scanner, we could determine where these LDA's were and use this information to determine where to cut the smaller bending samples. We can also determine where and how each large beam will break by looking at the X-ray.

After all non-destructive tests were completed; each sample was tested in static bending to determine the flexure properties. Testing was done using an Instron™ 5566 testing machine according to ASTM Standard D 4761-05 (2007) using third point loading on an 1143-mm span. The span to depth ratio was 18 and samples were tested at a machine speed of 24 mm/min. Bluehil™ software version 2.3 was used to acquire the data. Modulus of rupture (MOR), modulus of elasticity (MOE), work-to-maximum load (WML), specific gravity (SG) and moisture content (MC) were calculated for each sample. MC and SG (oven-dry basis) were determined on a small block cut from each sample after bending.

2.4. *Data analysis*

The data were analyzed using the GLM procedure in the SAS™ software system. By using this procedure, we were able to compare means of each species and property by using the least squares method. Data were analyzed using analysis of variance and means were separated using Tukey's test (SAS, 2008).

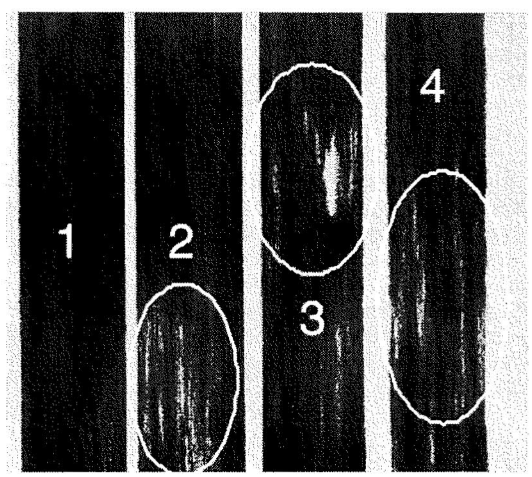

Fig. 3. X-ray images of SPSL beams showing areas of low density (denote by circles).

[2] http://www.falconengineering.co.nz/products/grading.php; the use of trade names is for the convenience of the reader only. Such use does not imply endorsement over other products equally suitable.

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3. Results and discussion

3.1. Initial study

The fire-killed logs did not scrim well. The logs broke and came apart when they were sent through the crush rolls. creating processing problems conveying short log segments and the resulting scrim was short and not uniform in diameter. Generally the process of converting logs to scrim works best with fresh raw material that has a high moisture content.

3.2. Non-destructive evaluation

In the initial study. an attempt was made to correlate A-Grader readings from logs to the modulus of elasticity (MOE) values obtained with the beams. but there was not enough bending data to successfully compare A-Grader averages with the MOE due to the high number of samples that were blown and not tested. Further studies need to be conducted to see if the A-Grader is a good method for predicting beam MOE properties from values obtained from the parent logs. An effort was made to correlate the stress wave timing results with the mechanical property values obtained from the testing program. Little correlation was found between property values and A-Grader output for lodgepole pine samples (Fig. 4). Reasonable correlation ($R2$ = 76%) between results was found for ponderosa pine samples where there seems to be a direct correlation between the two numbers. This can probably be attributed to many factors. but the most likely reason is there were a higher number of lodgepole beams blown than ponderosa. The blows in the samples may have altered the A-Grader numbers slightly and caused an offset in the results. Further tests need to be conducted to see how blown samples affect the A-Grader numbers compared with non-blown samples. When extreme outliers were excluded from the analysis. output from the A-Grader was reasonably correlated ($R2$ = 79%) with modulus of elasticity for all samples. This indicates that such a device may have some value in a quality control program.

The use of X-ray to determine low density areas (LDAs) within the large beams was successful. It allowed us to take samples with reasonable density variation for testing. As a quality control tool. it should prove invaluable in making sure high quality beams are supplied to the marketplace. These LDAs are created when the mat that forms the billet is not formed with uniform density. Compounding low density areas are issues associated with the first steam chamber press. First. notice the edges of scrim that run the length of each edge of the raw billet in Fig. 2. This scrim is called "squeeze out" because it is forced between the side dam and top platen while the hydraulic press is Closing. The cam system that closes the side dams is requires a modification to close the side dams before the top platen contacts the mat being pressed. Second. close inspection of the raw billet picture will indicate that there are 12 mm variations in width due to the internal configuration of the press. The side dam material is not stiff enough to prevent bulging between the internal supports and cam mechanisms. To stiffen the side dams. a thicker dam would be required and there is not enough physical space to thicken the side dams given the general arrangement. Finally. due to variations in delivered hydraulic pressure. there is thickness variation in the pressed billet. The hydraulic cylinders are custom made and located inside the steam chamber of the press. The ring seals are steel and the internal walls are scored which allows oil to escape to the low pressure side of the piston creating pressure variation. These three factors in combination greatly increase the difficulty to make a uniform density product and the differences in density significantly impact bending properties. The issues associated with the press are significant but could easily be remedied in production via engineering changes to another press. The existing press is the only one in existence that can test the technology. Given that the press has issues. methods to identify areas of low density are important so it can be excluded leaving the remaining material properties as representative of the technology with a press designed to overcome these deficiencies.

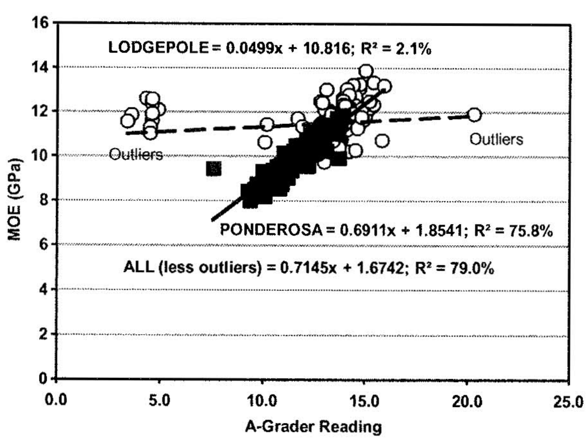

Fig. 4. Correlation between actual modulus of elasticity values obtained by destructive testing and the non-destructive Falcon A-Grader readings.

3.3. Blows

Blows occur when scrim does not bond well. therefore separating when pressure is released from the press. This allows steam and other gases to escape. It is believed that when a sample contains blows. the mechanical properties are greatly reduced. For samples tested. lodgepole pine samples had considerably more blows (155 out of 160) than did ponderosa pine (16 out of 128). Given our success with beams made from southern pine in an ongoing study. this result is somewhat surprising. The reasons for this are not entirely clear. especially given the almost identical anatomical characteristics of the two species. Additional research is required to determine the cause of this phenomenon. In all likelihood. it is process-related indicating that processing parameters will need to be altered to produce blow-free beams. We know that in scrimming lodgepole. the knots tend to stay in the scrim whereas with southern pine and ponderosa pine. the knots tend to fall out during the scrimrning process. Lodgepole tends to produce scrim which stays intact rather than form discrete fiber bundles as with southern and ponderosa pines.

3.4. Moisture content and specific gravity

For lodgepole pine samples. the moisture content had a range of 5.8-9.0% with a mean of 7.9%. Ponderosa pine samples had an identical range and a mean of 7.4%. Therefore. no correction to data for moisture content was required. Similar specific gravity distributions were found for both species so no correction was needed. Lodgepole pine sample specific gravity ranged from 0.615 to 0.869 with a mean of 0.700. For ponderosa pine. specific gravity had a range of 0.618-0.864 with a mean of 0.726. Moisture content .and specific gravity distributions are shown in Fig. 5.

3.5. Flexure properties

A comparison of the various property values between species is shown in Table 1. As shown. the two species differed significantly

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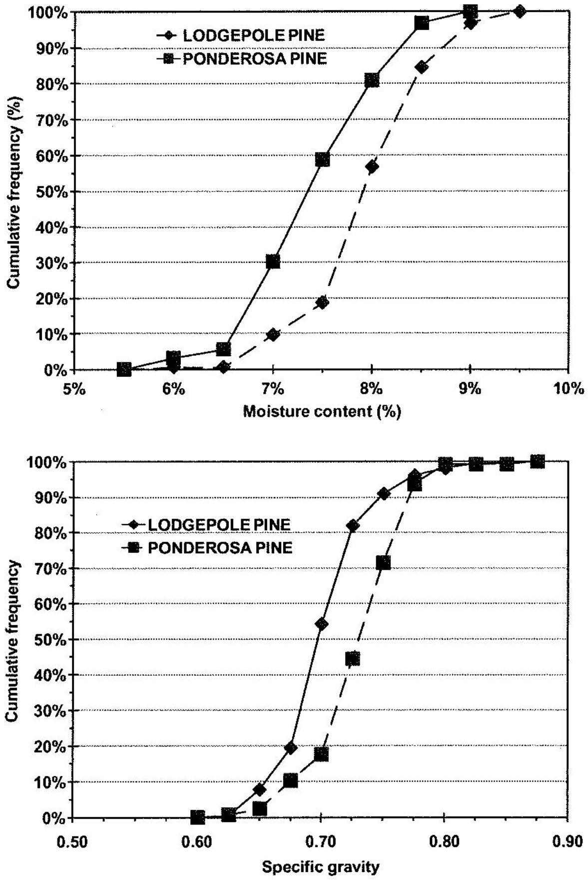

Fig. 5. Distribution of moisture content and specific gravity for all samples tested in static bending.

Table 1
Comparison of mean mechanical property values between species.[a]

Analysis	*p*-Value	Ponderosa	Lodgepole
MOR (MPa)	<0.0001	51.7 A	48.1 B
MOE (GPa)	<0.0001	9.6 B	11.5 A
WML (kJ/m^3)	<0.0001	16.7 A	12.1 B

[a] Means not followed by a common letter are significant different at *p* level indicated.

Table 2
Effect of blows on properties by species.[a]

Analysis	*p*-Value	Blow	No blow
Ponderosa pine			
MOR (MPa)	0.0192	48.1 B	52.2 A
MOE (GPa)	0.0132	9.1 B	9.7 A
WML (kJ/m^3)	0.1241	15.2 A	16.9 A
Lodgepole pine			
MOR (MPa)	0.1874	48.2 A	44.2 A
MOE (GPa)	0.0828	11.4 A	12.1 A
WML (kJ/m^3)	0.0503	12.2 A	9.3 A

[a] Means are significantly different at *p* level indicated.

in all three properties when all samples for each species were analyzed as a group, MOR and work values were higher for the ponderosa pine samples while lodgepole pine samples were stiffer. Within each species, the impact of the presence of blows can be seen in Table 2. Blows caused a reduction in MOR and MOE for ponderosa pine. No effect on WML was observed. For lodgepole pine, no significant difference between blown and non-blown samples was shown for any property. Some caution should be taken by the reader in interpreting these results since the numbers in each category differ widely by species.

When comparing across species (ponderosa *vs.* lodgepole) with and without blows, all properties were significantly different one from another (Table 3) with the exception that no difference between was found for the MOR of samples with blows.

Table 3
Comparison of species with and without blows.[a]

Analysis	*p*-Value	Ponderosa	Lodgepole
Between species with blows			
MOR (MPa)	0.9619	48.1 A	48.2 A
MOE (GPa)	<0.0001	9.1 B	11.4 A
WML (kJ/m^3)	0.0003	15.2 A	12.2 B
Between species without blows			
MOR (MPa)	0.0095	52.2 A	44.2 B
MOE (GPa)	<0.0001	9.7 B	12.1 A
WML (kJ/m^3)	0.0001	16.9 A	9.3 B

[a] Means not followed by a common letter are significant different at *p* level indicated.

4. Conclusions

Our results suggest that only green, small-diameter lodgepole and ponderosa logs are suitable for producing SPSL. Moisture content in fire-killed logs was too low for the logs to serve as furnish for SPSL using the current technology.

Lodgepole and ponderosa beams had reasonable MOR values, but MOE values were relatively low for each species, especially for the lodgepole pine samples owing to the blows in beams from this species. Changes in operating parameters need to be made to optimize properties.

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