Scaling Juniper Markets:
Sustainable Solutions for Rangelands and Rural Communities

Oregon State University, Oregon Wood Innovation Center

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Tomáš Pipíška, Scott Leavengood, and Fred Kamke

Executive Summary

Significant efforts have been made to foster market development for solid wood products from western juniper. However, viable markets are needed for juniper mill residues such as sawdust, shavings, slabs, and non-merchantable logs as well. Markets for juniper residues are currently non-existent or very limited at best. A survey of western juniper enterprises revealed that the highest volumes of non-merchantable residues are sawdust and slabs/edgings. Therefore, this project sought to develop two common products, particleboard and strandboard, using these residues, to assess the mechanical and physical properties of the products and to compare the properties to panels made using commercially available species.

Particleboard was produced using the small/fine residues (i.e., sawdust) and testing was conducted in 4 phases:

- Phase 1 - particle size, a key factor in particleboard manufacturing, was measured for 6 different types of materials – commercial Douglas-fir material from a local particleboard mill (for comparison), juniper sawdust produced using a bandsaw, sawdust without bark from a circular saw, circular sawdust with bark, heartwood sawdust, and sapwood sawdust. Particleboard test specimens were produced from these materials and the panels were tested for density, moisture content, thickness swelling, and water absorption.
- Phase 2 - the same raw materials as in phase 1 were used and the focus was on refining the 'recipe' for producing the panels. Specifically, differing levels of wax additives were used and the particles were screened to mimic the particle size composition of commercially-produced Douglas-fir panels. Density, thickness swelling, and water absorption were again measured from the test panels.
- Phase 3 – Commercial particleboard in Oregon is produced using Douglas-fir and ponderosa pine. Given the relatively small volumes of juniper available, the most likely use of juniper sawdust is as a 'blend' with these other species. In this phase, varying percentages (5, 10, and 20%) of juniper were added to panels made from Douglas-fir and ponderosa pine and the moisture-related properties (density, moisture content, thickness swell, water absorption, and linear expansion) of these panels were assessed.
- Phase 4 – the prior 3 phases focused on production of relatively small test specimens. In this phase, larger (in length and width) as well as thicker panels were made such that additional properties could be assessed including density, thickness swelling, water absorption, bending strength and stiffness, and internal bond strength.

Results from the particleboard trials indicate that panels made from sapwood and sawdust from an edger showed higher thickness swelling and water absorption compared to panels made from commercially-produced Douglas-fir particles. Panels from bandsaw and circular saw sawdust, the majority of which were heartwood, showed comparable moisture behavior to panels made from commercially-produced Douglas-fir particles. Results of blends of juniper at 5, 10, and 20% with Douglas-fir and ponderosa pine revealed no difference in thickness swell compared to control panels (i.e., 100% fir and pine panels) after a 24-hour water soak. Based on these results, we conclude that juniper sawdust particles can be used successfully to produce particleboard, whether as a mixed-species panel or as a 100% juniper panel. Further, given that no efforts were made to remove bark, we also conclude that it is acceptable, from the standpoint of mechanical and physical properties, to include small percentages of bark as well.

Strandboard was produced by first producing strands on a veneer slicer from the larger residues (e.g., slabs, edgings) and producing test panels from the strands. Testing was conducted in 3 phases:

- Phase 1 – strandboard was produced from 2 materials: aspen (for comparison) and mixed juniper heartwood and sapwood. Test panels were assessed for density, internal bond strength, thickness swell, water absorption and linear expansion.
- Phase 2 – strandboard was produced from 5 distinct materials: southern yellow pine (for comparison), juniper sapwood, juniper heartwood, mixed heartwood and sapwood without bark, and mixed heartwood and sapwood with bark. Test panels were evaluated for density, density profile through the thickness (via x-ray), thickness swelling, water absorption, bending strength and stiffness, internal bond strength, and screw withdrawal strength from both the face and edge.
- Phase 3 – durability (resistance to fungal decay) was evaluated of strandboard produced from southern yellow pine, mixed juniper heartwood and sapwood, juniper sapwood, juniper heartwood, and juniper panels produced from sapwood strands impregnated with juniper essential oil prior to manufacture as well as juniper sapwood panels impregnated with oil after pressing. Internal bond strength of the panels was tested to determine if the inclusion of essential oils had a negative impact on bond strength and hence panel integrity.

Results of strandboard testing indicate that heartwood and sapwood strands can be used to successfully produce panels even with approximately 10% bark included. Properties of the juniper panels were equivalent or slightly better than panels produced from southern yellow pine with one exception - bending stiffness (modulus of elasticity, MOE) was higher for high-density southern yellow pine panels than for all-heartwood juniper panels. With respect to durability, results indicate that, like juniper heartwood (solid wood), juniper strandboard produced from heartwood is also highly decay resistant. Impregnating juniper sapwood strands or finished panels led to increased decay resistance to one of the two brown rot fungi tested but not to the other brown rot fungus or a white rot fungus. Impregnating strands with essential oil prior to pressing resulted in panels with reduced internal bond strength compared to panels impregnated with oils after pressing. At the same time, the bond strength for all of the juniper panels (with and without the addition of essential oil) exceeded those of southern pine panels.

Juniper manufacturers should consider collecting and segregating residues by process (e.g., primary breakdown saw vs. edger) and can use the information in this report in discussions with local particleboard producers. For the larger residues like slabs and edgings, an entrepreneurial venture will be required that is able to acquire materials, produce strands, and produce decorative panels from the strands. Future work should look at the economic feasibility and supply. In particular, haul distance and the value of alternative uses should be assessed, and detailed estimates of potential supply of material by region should be developed.

Summary of Project Outputs:

- Outreach
  - Web-based meeting of interested industry stakeholders (March 18th, 2020, notes)
  - Plans to hold a final webinar with key stakeholders to recap project findings; date to be coordinated with the sponsor
  - Page on the Oregon Wood Innovation Center website to share project results (http://owic.oregonstate.edu/western-juniper-composites)
- Conference Presentations
  - Society of Wood Science & Technology, Virtual International Convention, July 12-15, 2020 - Utilization of Western Juniper Residues for Strandboard Manufacturing (poster)
  - 10th European Conference on Wood Modification, February 24-25, 2022, Nancy, France (postponed from 2020) – Impregnation of Strands with Juniper Essential Oil for Strandboard Manufacturing
- Journal publications
  - Properties of western juniper (*Juniperus occidentalis*) strandboard. 2021. *BioResources* 16(2): 2853-2860.
  - Utilization of western juniper (*Juniperus occidentalis*) in strandboard to improve decay resistance. Accepted for publication in *Bioresources* 4/3/2021

INTRODUCTION

Significant efforts have been made over several decades to foster market development for solid wood products from western juniper. For example, engineers require published design values for a species before they can specify lumber produced from the species in a structure. These design values for western juniper have recently been developed[1]. However, profitability of sawmills often hinges on their ability to achieve 'full utilization' of the resource. That is, viable markets are needed for solid wood as well as for residues like edgings and trim ends (material removed in trimming a board to width and length, respectively), slabs (half-round shapes produced as logs are first sawn from round shapes into squares), sawdust, and shavings (Figure 1). Market opportunities for such residues from western juniper are currently very limited. Common juniper residues and their current market options are shown in Table 1 below.

Table 1. Residues from western juniper harvesting and manufacturing

Explored in this project	Residue	Description	Current Market(s)
Yes	Slabs (Figure 1a)	From outer diameter of tree, predominantly sapwood with bark	Firewood
Yes	Edgings (Figure 1b)	Generated as boards with rough edges are trimmed to width; heartwood and sapwood, some bark	Often burned as fuel at sawmills
Yes	Peeler shavings – with bark (Figure 1c)	Sapwood	Garden mulch
Yes	Peeler shavings – without bark (Figure 1d)	Produced by pole peeler, primarily sapwood	Can be sold to particleboard mills[2]
Yes	Sawdust (Figure 1e)	Includes sapwood, hardwood, and some bark Note: the geometry of these particles varies with the type of saw used	None
No	Planer shavings	Sap heart	Very limited production (from secondary manufacturers using juniper)
No	Limbs	Generally left in the forest when the trees are harvested	Firewood
No[3]	Foliage	Generally left in the forest when the trees are harvested	Essential oil

The primary objectives of this project were to develop and test the material properties of prototype panels (conventional particleboard and strandboard) from a variety of western juniper residues, i.e., those noted in column 1 of Table 1 above.

In general, the biggest challenge for sawmills is disposal of sawdust since there are currently no markets for this material. Mills typically store sawdust for years. Juniper sawmills, produce approximately 6,000 m^3 (2000-2500 MBF) of lumber (personal communication with Sustainable Northwest) each year. Given that

[1] See https://www.plib.org/american-lumber-standards-committee-board-of-review-approves-structural-design-values-for-western-juniper/
[2] Integrated Biomass Resources sells to Woodgrain Millwork's particleboard mill in Island City, OR
[3] While foliage itself was not directly explored in this project, commercially-available "juniper leaf oil" was tested in the project.

sawdust is about 22% of the volume of lumber produced, the estimated volume of sawdust from these enterprises is approximately 1,300 m^3 (500-600 tons) per year.

Slabs are another key residue for juniper sawmills. Depending on technology (i.e., if a mill also uses an edger), there may also be edgings. Slabs and edgings are partially covered with bark, which is usually around 10-15 mm (1/2") thick. Slabs are usually used as firewood, which the sawmill sells to the local market. Edgings are typically processed into hog-fuel and burnt in the mill. From the production of the lumber, we can say that this residue is around 40-60% of the volume from each log. From one sawmill, slabs and edgings account for around 5,000 to 11,500 m^3 every year, which is equivalent to between approximately 2000 and 5000 tons of material.

a. Juniper slabs

b. Juniper edgings

c. Juniper peeler shavings (with bark)

d. Juniper peeler shavings (without bark)

e. Juniper sawdust

Figure 1. Juniper residues used in the project.

The project spanned 2 years and involved completion of several phases for each product tested.

Particleboard - Manufacture and testing of properties of particleboard from juniper sawdust; comparison of juniper panels with those produced using common commercial species and materials in Oregon, specifically Douglas-fir and ponderosa pine. The 4 phases and accompanying activities were:

- Phase 1 - particle size, a key factor in particleboard manufacturing, was measured for 6 different types of materials – commercial Douglas-fir material from a local particleboard mill, juniper sawdust produced using a bandsaw, sawdust from a circular saw without bark, circular saw sawdust with bark, heartwood sawdust and sapwood sawdust. Particleboard was then produced from these materials and the panels were tested for density, moisture content, thickness swelling, and water absorption.
- Phase 2 - the same materials were used and the focus was on refining the 'recipe' for producing the panels. Specifically, differing levels of wax additives were used and the particles were screened to mimic the particle size of commercially-produced Douglas-fir panels. Density, thickness swelling, and water absorption were again measured from the test panels.
- Phase 3 – varying fractions (5, 10, and 20%) of juniper were added to Douglas-fir and ponderosa pine particles to measure the impact on moisture-related panel properties such as thickness swelling and linear expansion.
- Phase 4 – larger-sized test panels were made such that additional properties were assessed including density, density profile through the thickness (via x-ray), thickness swelling, water absorption, bending strength and stiffness, internal bond strength, and screw withdrawal strength from both the face and edge.

Strandboard - Manufacture and testing of properties of strandboard (similar to OSB, but without attempts to orient the strands) from strands produced by slicing juniper slabs and edgings. Panels were compared to those produced using commercially available aspen strands, the species commonly used to produce OSB in the Lake States region of North America as well as southern yellow pine strands, the species commonly used in the southeastern US. The 3 phases and accompanying activities were:

- Phase 1 – strandboard was produced from 2 materials: aspen and juniper (mixed heartwood and sapwood). Test panels were assessed for density, internal bond strength, thickness swell, water absorption and linear expansion.
- Phase 2 – strandboard was produced from 5 distinct materials: southern yellow pine (the other dominant species used for OSB, besides aspen/poplar), juniper sapwood, juniper heartwood, mixed heartwood and sapwood without bark, and mixed heartwood and sapwood with bark. Test panels were evaluated for density, density profile through the thickness (via x-ray), thickness swelling, water absorption, bending strength and stiffness, internal bond strength, and screw withdrawal strength from both the face and edge.
- Phase 3 – assessment of durability (resistance to fungal decay) of strandboard produced from southern yellow pine, mixed juniper heartwood and sapwood, juniper sapwood, juniper heartwood, and juniper panels produced from sapwood strands impregnated with juniper essential oil prior to manufacture as well as juniper sapwood panels impregnated with oil after pressing. Internal bond strength of the panels was tested to determine if the inclusion of essential oils interfered with panel integrity.

Structure of this Report

The authors determined that the particleboard research was likely not sufficiently 'new and novel' such that scientific journals would be interested in publishing the findings. Therefore, in-depth information is presented here on the results of the particleboard testing. By contrast, the results of phases 2 and 3 of the strandboard research were believed to be sufficiently novel such that the results were submitted, and have been published, as two articles in the journal *Bioresources*. Therefore, rather than provide in-depth information on the strandboard testing in this report, we have opted to simply report the results of phase 1 here and provide the articles resulting from phases 2 and 3 as appendices.

PARTICLEBOARD

MATERIALS AND METHODS – Phase 1

Juniper sawdust is decay-resistant and therefore decomposes slowly. Hence storage of sawdust onsite at the mill is a problem. As stated previously, currently there is no market for juniper sawdust. For this part of the project, material from three different types of saws (bandsaws, circular saws - both for primary breakdown as well as edging) was used for the manufacturing of particleboard. Two different types of circular saw sawdust were tested as the primary breakdown saws produce sawdust that is mixed heartwood, sapwood, and bark, whereas the edger circular saws produce sawdust that is primarily sapwood with a smaller percentage of bark.

Materials were obtained from sawmills operating in eastern Oregon, specifically In the Sticks Juniper Sawmill (Kendall Derby) for the bandsaw and edger materials and from David and Tony Hand for the circular saw sawdust. After arrival at OSU, all materials were placed in cloth bags and dried in a rotating dryer. Drying of the material was at 60 °C for 60-120 minutes to a final moisture content of 6%. After drying, the particles were screened to remove fines and large particles. For manufacturing panels, particles between 0.180 mm and 2 mm were used, i.e., materials were passed through a screen with 2 mm openings and were retained on a screen with 0.180 mm openings. Six particle types were used (Figure 2):

- Douglas-fir: Commercially-produced, surface particles (courtesy of Arauco Particleboard, Albany, OR)
- Juniper:
    - bandsaw sawdust (bark, sapwood, heartwood)
    - edger circular saw sawdust (sapwood)
    - circular saw sawdust (bark, sapwood, heartwood)
    - heartwood particles (produced on a Wiley brand laboratory mill)
    - sapwood particles (produced on a Wiley brand laboratory mill)

a. Douglas-fir surface particles

b. Juniper from bandsaw

c. Juniper from edger circular saw

d. Juniper from circular saw

e. Juniper heartwood (as processed by a Wiley mill)

f. Juniper sapwood (as processed by a Wiley mill)

Figure 2. Different types of sawdust used for analysis

Fraction analysis was conducted of these materials to assess the particle size; particle size is a key factor considered by particleboard manufacturers. Analysis of the sawdust was conducted by measuring the weight (in %) of material passed through varying mesh sizes for screens: 2; 0.85; 0.5; 0.425; 0.355; 0.25; and 0.18 mm. The juniper materials were compared with the Douglas-fir surface particles from Arauco's particleboard mill in Albany, OR.

Thin 'surface layer' particleboard panels were then produced in the wood composites laboratory at OSU. Commercial particleboard is a 3-layer product – a surface layer (face and back) composed of finer particles to provide a smooth surface and a core layer of coarser particles. We opted to produce panels to mimic the fine surface layer in this first phase of the project.

The panels were produced with a thickness of 2 mm and dimensions 267 × 267 mm from all of the particle types shown in Figure 2. Three panels were made from each of the 6 particle types, for a total of 18 panels. Panels were conditioned in an environment controlled room (20°C, 65% RH) to an equilibrium moisture content prior to testing.

Pressing parameters were as follows:

- Target density: 750 kg/m^3
- Resin solids: 10%
- Catalyst solid: 2% (35% concentration)
- Wax solid: 1%
- Temperature: 140 °C
- Time: 100 seconds
- Pressure: 3.5 MPa

Test specimens that were 50 × 50 mm were then tested for:

- Density (to assess if target density was achieved)
- Moisture content of finished panels
- Thickness swelling (after 2 hours, 24 hours, 48 hours, and 7 days water soak)
- Water absorption (after 2 hours, 24 hours, 48 hours, and 7 days water soak)

Analysis of variance (ANOVA) was used to test for statistical significance using a 95% confidence level (alpha = 0.05).

RESULTS – Phase 1

Figure 3 below shows the results of the fraction analysis. It was noted that the sawdust from the bandsaw contained a lot of stones (presumably rocks from the gravel road) – both large and small. The edger sawdust, by comparison was quite fluffy and light in color. Particles from the circular saw were quite dark due to the inclusion of bark and heartwood.

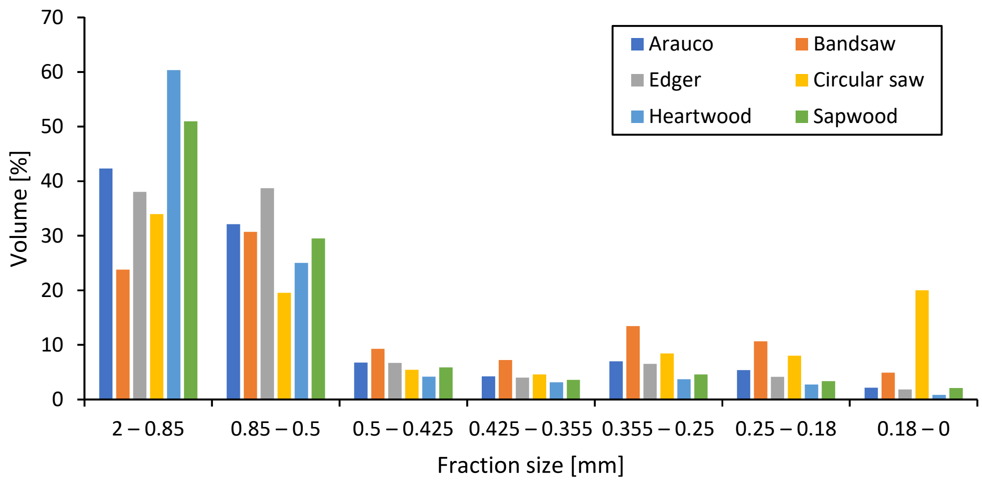


Figure 3. Fraction analysis of different particles

Density results are presented in Figure 4. Statistical analysis indicated there was no statistically significant difference in panel density based on particle type, which was the goal. Equal density allow for a fair comparison of panel strength and water adsorption properties.

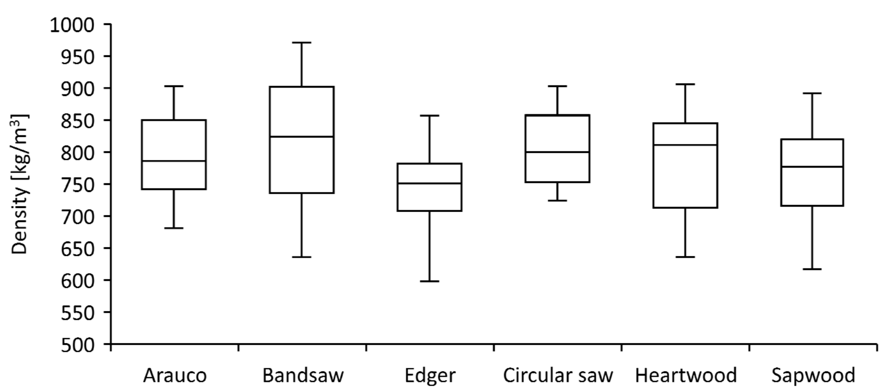


Figure 4. Density of different produced panels

Table 2 presents the results of the moisture content testing. Results indicate that the moisture contents are similar, with those for sawdust produced by the bandsaw and circular saw being the lowest at approximately 6.2%, while those for the laboratory-produced heartwood and sapwood materials was slightly higher at approximately 7.1%. In general, any differences here are likely of little practical significance and we may conclude that the panels were between 6 and 7% moisture content with minimal variability in moisture content.

Table 2 Moisture content of the panels

	EMC [%]
Douglas-fir	6.68 (0.20) B, C
Bandsaw	6.37 (0.19) A, B
Edger	6.76 (0.11) C, D
Circular saw	6.12 (0.40) A
Heartwood	7.26 (0.46) E
Sapwood	7.02 (0.42) D, E

Means with the same letter in column do not differ statistically by the Tukey´s test ($\alpha = 0.05$).

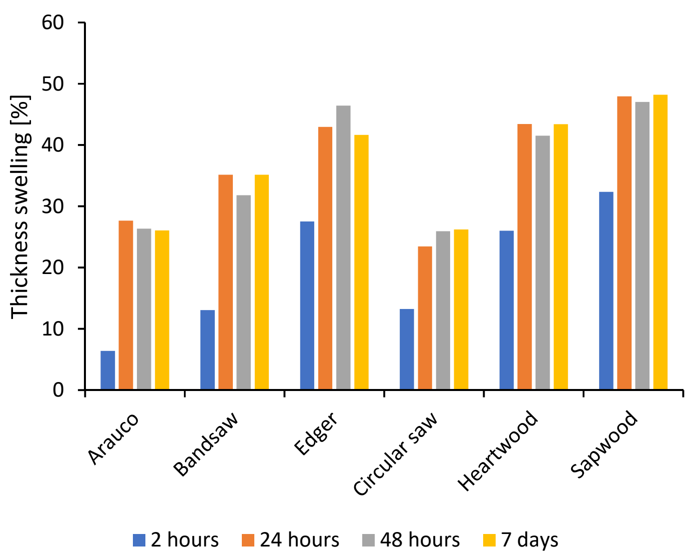


Figure 5. Thickness swelling of panels after 7 days

Figure 5 and Table 3 present the results of tests of thickness swelling for phase 1. In general it can be seen that Douglas-fir panels performed the best (least amount of thickness swelling), although after 24 hours, the panels made from circular sawdust swelled at a rate comparable to that of the Douglas-fir panels.

Table 3 Statistical analysis of thickness swelling

	Thickness swelling [%]			
	2 hours	24 hours	48 hours	7 days
Douglas-fir	6.39 ^{A}	27.66 ^{A}	26.35 ^{A}	26.06 ^{A}
Bandsaw	13.05 ^{B}	35.17 ^{B}	31.82 $^{A, B}$	35.16 ^{B}
Edger	27.51 $^{C, D}$	42.95 ^{C}	46.43 ^{C}	41.66 $^{B, C}$
Circular saw	13.24 ^{B}	23.46 ^{A}	25.95 ^{A}	26.21 ^{A}
Heartwood	26.03 ^{C}	43.44 ^{C}	41.52 $^{B, C}$	43.42 ^{C}
Sapwood	32.36 ^{D}	47.95 ^{C}	47.02 ^{C}	48.20 ^{C}

Means with the same letter in column do not differ statistically by the Tukey´s test (α = 0.05).

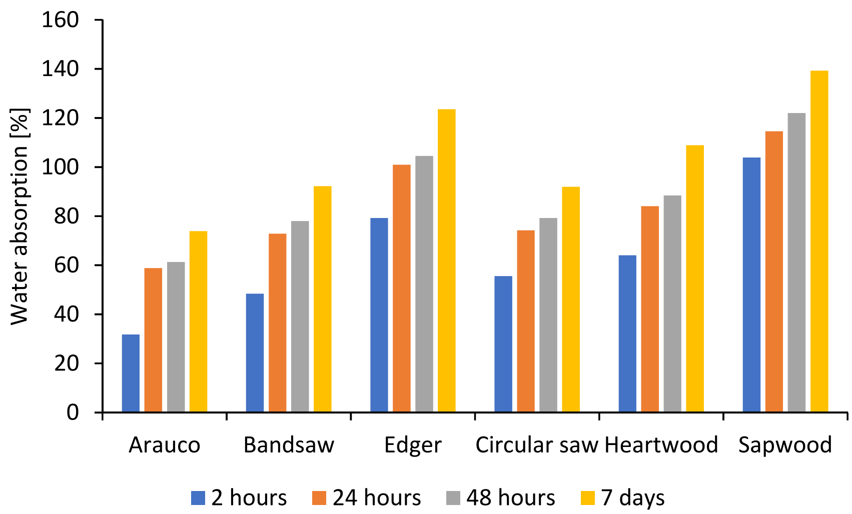


Figure 6. Water absorption of panels after 7 days

Figure 6 and Table 4 present the results of water absorption testing. The Douglas-fir panels again performed the best (least amount of water absorption). Panels produced from bandsaw sawdust and circular saw sawdust were comparable to one another, and next lowest with respect to amount of water absorbed.

Table 4 Statistical analysis of water absorption

	Water absorption [%]			
	2 hours	24 hours	48 hours	7 days
Douglas-fir	31.81 ^{A}	58.52 ^{A}	61.27 ^{A}	73.93 ^{A}
Bandsaw	48.40 ^{B}	72.83 ^{B}	77.98 ^{B}	92.21 ^{B}
Edger	79.25 ^{D}	101.00 ^{D}	104.52 ^{D}	123.58 ^{D}
Circular saw	55.63 $^{B, C}$	74.24 $^{B, C}$	79.27 $^{B, C}$	91.96 ^{B}
Heartwood	64.09 ^{C}	84.05 ^{C}	88.48 ^{C}	108.93 ^{C}
Sapwood	103.86 ^{E}	114.60 ^{E}	122.01 ^{E}	139.33 ^{E}

Means with the same letter in column do not differ statistically by the Tukey´s test (α = 0.05).

Particleboard – Phase 2

Results of phase 1 led to the decision to pursue additional testing with the same materials, however with four different particleboard recipes used for each particle type. These included varying wax levels (0, 0.5, 1%). In addition, the results for the Douglas-fir particles described above led to the decision to produce panels using 1% wax and a custom particle size classification; specifically, the goal was to produce juniper panels for which the particle size (shown in Figure 3) mimicked that of the commercially-produced Douglas-fir particles. Two panels from each group were made, for a total of 48 panels.

Pressing parameters were as follows:

- Dimensions - 267 × 267 × 2 mm (10.5 x 10.5 x 0.079 inch)
- MUF resin LEAF C2 670A08
- Target density: 750 kg/m^3 (46.8 lb./ft^3)
- Resin solid: 10%
- Catalyst solid: 2% (35% concentration)
- Temperature: 140 °C
- Time: 100 seconds
- Press time 100 seconds, plus 10 seconds of vent time

Panels were conditioned in standard conditions of 20°C and 65% relative humidity after manufacturing.

Testing was conducted on 20 specimens per treatment, with dimensions of 50 × 50 mm. Density was measured on specimens after conditioning at 20°C and 65% relative humidity. Thickness swelling (TS) and water absorption (WA) were measured after 2, 24, 48 hours and 7 days submersion in water.

RESULTS – Phase 2

The target oven-dried density for all panels was 750 kg/m^3, however final density after conditioning was higher on average (Table 5). Mat formation during manufacture was difficult due to the small thickness of the panel. Edges of the panels tended to be low density, with higher density in the center. The edges were trimmed away, leaving the higher density center for test specimens. There was also a high variability of density in each group. Due to the high variability, statistical differences were not detected between particle types, even though the average density values appear different.

Table 5. Average density of laboratory panels (kg/m^3)

	Wax Content			
	1%	0.5%	0%	Recipe 1%
Douglas-fir	926 (107) $^{B, C}$	878 (107) $^{A, B, C}$	857 (143) $^{A, B, C}$	886 (130) $^{A, B, C}$
Bandsaw	942 (142) ^{C}	915 (163) $^{B, C}$	920 (132) $^{B, C}$	890 (141) $^{A, B, C}$
Edger	823 (127) $^{A, B, C}$	735 (98) ^{A}	760 (89) $^{A, B}$	801 (108) $^{A, B, C}$
Circular saw	899 (116) $^{A, B, C}$	852 (116) $^{A, B, C}$	839 (127) $^{A, B, C}$	851 (108) $^{A, B, C}$
Heartwood	893 (130) $^{A, B, C}$	846 (143) $^{A, B, C}$	828 (122) $^{A, B, C}$	889 (140) $^{A, B, C}$
Sapwood	874 (133) $^{A, B, C}$	877 (113) $^{A, B, C}$	844 (120) $^{A, B, C}$	873 (101) $^{A, B, C}$

Means with the same letter do not differ statistically by the Tukey´s test ($\alpha = 0.05$). Numbers in parentheses represent standard deviation

Thickness swelling

Thickness swelling after 2 hours (Table 6) was the same for panels with 1% wax and the panels made from the custom particle size fraction with 1% wax. Similarly, there was no difference between the Douglas-fir materials and the custom particle size recipe (with 1% wax) using bandsaw and circular saw particles.

Panels made from edger sawdust, as well as heartwood and sapwood, showed almost twice the thickness swell after 2 hours. As mentioned above, particles were screened for size, however, the shape of the particles and ratio between thickness and length can influence water relations in these panels.

Table 6. Average thickness swelling after 2 hours water soak (%)

	Wax Content			
	1%	0.5%	0%	Custom 1%
Douglas-fir	19.0 (5.5) A, B	27.1 (7.3) A, B, C, D, E	24.1 (8.0) A, B, C, D	19.9 (5.5) A, B, C
Bandsaw	17.7 (6.9) A	27.3 (8.8) B, C, D, E, F	40.3 (9.1) H, I	24.1 (4.4) A, B, C, D
Edger	35.0 (7.8) E, F, G, H, I	35.5 (3.9) E, F, G, H, I	34.2 (4.3) E, F, G, H, I	31.2 (5.3) D, E, F, G, H
Circular saw	20.6 (7.0) A, B, C	28.3 (5.5) B, C, D, E, F	31.3 (6.4) D, E, F, G, H	20.1 (7.1) A, B, C
Heartwood	29.2 (10.5) C, D, E, F, G	32.3 (8.2) D, E, F, G, H	38.7 (9.5) G, H, I	35.0 (11.0) E, F, G, H, I
Sapwood	36.8 (10.8) F, G, H, I	39.8 (5.6) H, I	42.5 (6.7) I	39.2 (7.0) H, I

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

Thickness swelling after 24 hours showed the same results for bandsaw, circular saw and heartwood in comparison with panels made from Douglas-fir particles with 1% wax (Table 7). The same thickness swelling was observed on all panels except sapwood made with 0.5% wax. The average values for panels made from juniper were higher than Douglas-fir panels, particularly panels made exclusively from juniper sapwood.

Table 7. Average thickness swelling after 24 hours water soak (%)

	Wax Content			
	1%	0.5%	0%	Custom 1%
Douglas-fir	29.0 (6.1) A, B	31.9 (9.3) A, B, C, D, E	28.0 (9.2) A	28.7 (4.7) A
Bandsaw	35.4 (9.5) A, B, C, D, E, F	36.7 (8.1) A, B, C, D, E, F	42.8 (10.4) F, G, H, I	31.2 (9.6) A, B, C, D, E
Edger	41.0 (5.7) E, F, G, H, I	37.6 (6.2) A, B, C, D, E, F, G	39.5 (5.2) C, D, E, F, G, H	37.7 (4.5) A, B, C, D, E, F, G
Circular saw	29.7 (4.6) A, B, C	30.8 (7.4) A, B, C, D	34.2 (9.4) A, B, C, D, E, F	30.9 (6.1) A, B, C, D, E
Heartwood	39.1 (7.0) B, C, D, E, F, G, H	36.2 (8.7) A, B, C, D, E, F	40.1 (8.8) D, E, F, G, H, I	39.3 (10.0) C, D, E, F, G, H
Sapwood	43.1 (8.3) F, G, H, I	50.0 (9.3) I	48.3 (7.2) H, I	47.4 (8.0) G, H, I

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

Thickness swell after 48 hours (Table 8) showed the most consistent results, except for the sapwood. The comparison between the sapwood and heartwood panels is important because better properties were expected for heartwood due to the extractive chemicals (that impart odor and decay resistance) in juniper heartwood. The same results for particles from Douglas-fir, bandsaw, edger, and circular sawdust were obtained for 1%, 0.5% and the custom particle size recipe (Custom 1%). Heartwood panels showed the same results for 1% and 0.5% wax.

Table 8. Average thickness swelling after 48 hours water soak (%)

	Wax Content			
	1%	0.5%	0%	Custom 1%
Douglas-fir	36.5 (6.7) A, B, C, D	38.2 (8.5) A, B, C, D	34.9 (10.4) A, B	34.5 (6.9) A
Bandsaw	40.6 (8.3) A, B, C, D, E	40.6 (9.4) A, B, C, D, E	51.5 (7.3) G, H	37.7 (7.3) A, B, C, D
Edger	43.8 (5.6) B, C, D, E, F, G, H	43.1 (7.1) A, B, C, D, E, F, G, H	44.3 (4.8) C, D, E, F, G, H	42.6 (5.1) A, B, C, D, E, F, G
Circular saw	36.1 (4.9) A, B, C	42.0 (6.1) A, B, C, D, E, F	39.5 (6.7) A, B, C, D, E	37.8 (4.6) A, B, C, D
Heartwood	42.9 (6.4) A, B, C, D, E, F, G	43.2 (7.9) A, B, C, D, E, F, G, H	45.5 (10.1) D, E, F, G, H	45.6 (7.2) D, E, F, G, H
Sapwood	48.4 (7.2) E, F, G, H	51.0 (4.3) F, G, H	50.7 (5.4) F, G, H	52.2 (7.3) H

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

Thickness swelling after 7 days showed similar results in comparison to the swelling after 48 hours (Table 9).

Table 9. Average thickness swelling after 7 days water soak (%)

	Wax Content			
	1%	0.5%	0%	Custom 1%
Douglas-fir	35.0 (7.0) ^{A}	37.6 (8.8) $^{A, B, C}$	36.6 (10.2) $^{A, B}$	36.4 (8.8) $^{A, B}$
Bandsaw	44.3 (8.5) $^{A, B, C, D, E, F, G}$	42.2 (10.2) $^{A, B, C, D, E, F}$	50.6 (10.2) $^{E, F, G, H}$	41.7 (9.7) $^{A, B, C, D, E, F}$
Edger	48.0 (6.4) $^{C, D, E, F, G, H}$	46.5 (5.9) $^{B, C, D, E, F, G, H}$	44.9 (4.6) $^{A, B, C, D, E, F, G}$	43.2 (6.2) $^{A, B, C, D, E, F}$
Circular saw	38.4 (4.8) $^{A, B, C, D}$	39.5 (6.7) $^{A, B, C, D}$	40.7 (7.8) $^{A, B, C, D, E}$	40.2 (5.5) $^{A, B, C, D, E}$
Heartwood	48.2 (8.9) $^{D, E, F, G, H}$	44.3 (9.8) $^{A, B, C, D, E, F, G}$	52.3 (12.7) $^{F, G, H}$	48.3 (9.9) $^{D, E, F, G, H}$
Sapwood	54.0 (7.9) $^{G, H}$	55.7 (7.6) ^{H}	55.6 (5.2) ^{H}	54.5 (8.3) $^{G, H}$

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

Water absorption

In the results of the water absorption testing, we can see the important role of the wax. The difference of the water absorption for Douglas-fir particleboard was from 39.3% to 76.1% for panels with and without wax, respectively (Table 10).

Table 10. Average water absorption after 2 hours water soak (%)

	Wax Content			
	1%	0.5%	0%	Custom 1%
Douglas-fir	39.3 (12.9) $^{A, B}$	66.5 (13.3) $^{C, D, E}$	76.1 (16.8) $^{D, E, F, G}$	31.5 (10.7) ^{A}
Bandsaw	41.6 (14.8) $^{A, B}$	69.7 (24.3) $^{C, D, E, F}$	89.1 (15.7) $^{E, F, G, H}$	54.0 (18.5) $^{A, B, C, D}$
Edger	75.4 (21.8) $^{D, E, F, G}$	102.8 (18.2) ^{H}	101.2 (15.7) ^{H}	72.7 (18.4) $^{D, E, F, G}$
Circular saw	48.0 (21.0) $^{A, B, C}$	74.9 (17.1) $^{D, E, F, G}$	86.1 (19.3) $^{E, F, G, H}$	52.5 (17.3) $^{A, B, C, D}$
Heartwood	54.2 (20.1) $^{A, B, C, D}$	76.5 (24.4) $^{D, E, F, G}$	93.3 (22.2) $^{F, G, H}$	56.7 (22.8) $^{B, C, D}$
Sapwood	83.1 (23.1) $^{E, F, G, H}$	88.9 (18.4) $^{E, F, G, H}$	96.5 (22.4) $^{G, H}$	85.2 (16.8) $^{E, F, G, H}$

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

Water absorption after 24 hours showed the same results for Douglas-fir, bandsaw, circular, and heartwood sawdust (Table 11). The edger material, being primarily sapwood, showed the same results as sapwood particles made in a laboratory mill.

Table 11. Average water absorption after 24 hours water soak (%)

	Wax Content			
	1%	0.5%	0%	Custom 1%
Douglas-fir	62.6 (10.5) $^{A, B}$	81.5 (11.2) $^{B, C, D, E, F}$	85.4 (15.5) $^{B, C, D, E, F, G, H}$	55.3 (10.1) ^{A}
Bandsaw	68.8 (14.6) $^{A, B, C}$	85.1 (19.9) $^{B, C, D, E, F, G}$	97.3 (14.9) $^{D, E, F, G, H, I, J}$	77.0 (17.3) $^{A, B, C, D, E}$
Edger	93.7 (21.7) $^{D, E, F, G, H, I, J}$	116.2 (18.0) ^{J}	113.3 (16.3) $^{I, J}$	92.9 (18.4) $^{C, D, E, F, G, H, I, J}$
Circular saw	75.7 (22.2) $^{A, B, C, D, E}$	89.2 (16.8) $^{C, D, E, F, G, H, I}$	97.4 (19.8) $^{D, E, F, G, H, I, J}$	79.4 (16.1) $^{A, B, C, D, E, F}$
Heartwood	74.6 (20.6) $^{A, B, C, D}$	91.4 (25.4) $^{C, D, E, F, G, H, I}$	107.8 (23.8) $^{G, H, I, J}$	74.7 (22.2) $^{A, B, C, D}$
Sapwood	97.6 (23.3) $^{D, E, F, G, H, I, J}$	101.7 (19.6) $^{F, G, H, I, J}$	109.3 (23.4) $^{H, I, J}$	99.2 (17.4) $^{E, F, G, H, I, J}$

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

Water absorption after 48 hours showed the same trends as after 24 hours, with higher absorption for panels made from edger and sapwood particles (Table 12).

Table 12. Average water absorption after 48 hours water soak (%)

	Wax Content			
	1%	0.5%	0%	Custom 1%
Douglas-fir	65.8 (10.1) A, B	83.1 (11.1) A, B, C, D, E, F	87.1 (15.4) B, C, D, E, F, G	59.2 (9.8) A
Bandsaw	73.6 (14.1) A, B, C	88.5 (19.3) B, C, D, E, F, G	99.3 (14.4) D, E, F, G, H, I, J	80.7 (16.5) A, B, C, D, E
Edger	99.2 (22.1) D, E, F, G, H, I, J	122.3 (18.9) J	118.7 (16.2) I, J	96.5 (18.3) C, D, E, F, G, H, I
Circular saw	81.0 (22.4) A, B, C, D, E	93.3 (17.1) C, D, E, F, G, H	102.2 (20.6) D, E, F, G, H, I, J	86.0 (16.1) B, C, D, E, F
Heartwood	80.7 (21.3) A, B, C, D, E	95.6 (25.7) C, D, E, F, G, H, I	111.1 (23.6) G, H, I, J	80.2 (22.5) A, B, C, D
Sapwood	102.3 (23.8) D, E, F, G, H, I, J	105.0 (22.1) E, F, G, H, I, J	113.0 (23.8) H, I, J	105.4 (18.2) F, G, H, I, J

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

Water absorption after 7 days showed similar results as water absorption after 48 hours (Table 13).

Table 13. Average water absorption after 7 days water soak (%)

	Wax Content			
	1%	0.5%	0%	Custom 1%
Douglas-fir	67.0 (8.5) A, B	84.5 (8.9) A, B, C, D, E, F	90.9 (16.4) C, D, E, F, G, H	63.3 (9.4) A
Bandsaw	78.5 (12.1) A, B, C	89.7 (17.3) C, D, E, F, G	100.2 (12.9) C, D, E, F, G, H, I	83.0 (12.8) A, B, C, D, E
Edger	104.0 (19.6) E, F, G, H, I, J, K	125.4 (18.8) K	122.9 (15.1) J, K	103.6 (17.8) E, F, G, H, I, J, K
Circular saw	81.1 (12.7) A, B, C, D	94.7 (14.7) C, D, E, F, G, H, I	102.4 (16.7) D, E, F, G, H, I, J	89.4 (14.3) C, D, E, F, G
Heartwood	84.2 (20.5) A, B, C, D, E	96.1 (22.4) C, D, E, F, G, H, I	112.8 (22.5) H, I, J, K	87.1 (21.3) B, C, D, E, F, G
Sapwood	106.4 (23.8) F, G, H, I, J, K	108.7 (16.5) G, H, I, J, K	113.8 (21.9) I, J, K	112.0 (19.4) H, I, J, K

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

Particleboard – Phase 3

Commercial particleboard producers in Oregon currently use either Douglas-fir or ponderosa pine to produce their panels. Given the very large volumes used in these mills, for juniper sawdust to be used commercially in particleboard, the most likely scenario is that juniper would be mixed with commercial species. However, there is always a question of species compatibility. Therefore, for this phase, varying fractions of juniper (5, 10, and 20%) were added to panels made from both Douglas-fir (provided by Arauco, Albany OR) and ponderosa pine (provided by Collins Companies, Klamath Falls OR). Panels were then tested for density, moisture content, thickness swell, water absorption and linear expansion.

Pressing parameters were as follows:

- Dimensions - 267 × 267 × 4 mm (10.5 x 10.5 x 0.079 inch)
- MUF resin LEAF C2 670A08
- Target density: 700 kg/m^3 (43.7 lb./ft^3)
- Resin solid: 10%
- Catalyst solid: 2% (35% concentration)
- Temperature: 160 °C
- Time: 190 seconds
- Press time 180 seconds, plus 10 seconds of vent time

Panels were conditioned in standard conditions of 20°C and 65% relative humidity after manufacturing.

Testing was conducted on 20 specimens per treatment, with dimensions of 50 × 50 mm. Density was measured on specimens after conditioning at 20°C and 65% relative humidity. Thickness swelling (TS), water absorption (WA) and linear expansion were measured after 24, 48 hours and 7 days submersion in water.

RESULTS – Phase 3

The target oven-dried density for all panels was 750 kg/m^3, however as in Phase 2, final density after conditioning was higher on average (Table 14), though only slightly so in this phase. Also as with Phase 2, due to the high variability, statistical differences were not detected between particle types, even though the average density values appear different. For moisture content, only the control panels were significantly different (higher) than other panels.

Table 14. Density and moisture content of Douglas-fir particleboards with addition of juniper particles

	Density (kg/m^3)	MC (%)
Control	774 (33) ^{A}	9.2 (0.3) ^{B}
5% Bandsaw	761 (22) ^{A}	7.1 (1.3) ^{A}
10% Bandsaw	764 (30) ^{A}	7.1 (0.6) ^{A}
20% Bandsaw	762 (21) ^{A}	6.9 (0.7) ^{A}
5% Edger	763 (17) ^{A}	6.9 (0.8) ^{A}
10% Edger	764 (32) ^{A}	6.8 (0.8) ^{A}
20% Edger	757 (34) ^{A}	6.6 (0.7) ^{A}
5% Circular saw	774 (25) ^{A}	6.9 (0.6) ^{A}
10% Circular saw	775 (39) ^{A}	6.9 (0.7) ^{A}
20% Circular saw	770 (47) ^{A}	6.7 (0.5) ^{A}

Means with the same letter in column do not differ statistically by the Tukey´s test ($\alpha = 0.05$). Numbers in parentheses represent standard deviation

There was no significant difference in thickness swelling after 24 hours for any of the panels (Table 15). However, after 48 hours control panels swelled significantly less than panels made with 10% and 20% circular saw sawdust. Swelling for the other panel types was similar and intermediate to the controls and 10 to 20% circular saw sawdust panels. While as expected, average swelling was greater after 7 days compared to 48 hours, the comparisons were identical as for 48 hours, i.e., control panels swelled less than panels with 10 and 20% circular saw sawdust.

Table 15. Thickness swelling (%) of Douglas-fir particleboards with addition of juniper particles

	Douglas-fir		
	24 hours	48 hours	7 days
Control	24.8 (2.8) ^{A}	26.5 (3.5) ^{A}	28.4 (3.5) ^{A}
5% Bandsaw	26.6 (3.1) ^{A}	29.3 (2.7) $^{A, B}$	32.4 (2.9) $^{A, B}$
10% Bandsaw	25.4 (2.6) ^{A}	27.8 (2.2) $^{A, B}$	31.5 (3.0) $^{A, B}$
20% Bandsaw	26.5 (1.9) ^{A}	29.4 (1.3) $^{A, B}$	33.1 (2.1) $^{A, B}$
5% Edger	25.9 (2.8) ^{A}	28.8 (2.3) $^{A, B}$	32.5 (2.4) $^{A, B}$
10% Edger	26.2 (2.7) ^{A}	28.9 (3.1) $^{A, B}$	32.3 (3.6) $^{A, B}$
20% Edger	27.5 (2.7) ^{A}	30.1 (3.3) $^{A, B}$	33.6 (4.2) $^{A, B}$
5% Circular saw	25.2 (3.3) ^{A}	28.8 (3.6) $^{A, B}$	32.4 (3.5) $^{A, B}$
10% Circular saw	27.2 (3.1) ^{A}	31.4 (3.4) ^{B}	35.2 (3.8) ^{B}
20% Circular saw	27.7 (2.9) ^{A}	31.4 (3.7) ^{B}	35.6 (5.1) ^{B}

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05).
Numbers in parentheses represent standard deviation

Results of water absorption testing are more complex than those for thickness swelling (Table 16). After 24 hours, absorption is lower for panels made with 5% edger sawdust and 5% circular saw sawdust than for panels made with 5% bandsaw dust and 20% edger sawdust. Average water absorption for other test panels (including controls) are similar and intermediate to these values. After 48 hours, more differentiation occurs such that absorption for controls and panels with 5% edger and 5% circular saw sawdust are similar, and lower than panels made with 20% edger sawdust. Comparisons after 7 days of soaking are nearly identical to the comparisons after 48 hours, with the exception that absorption for panels made from 5% circular saw sawdust (superscripts highlighted in red text) are more similar to other panels.

Table 16. Water absorption of Douglas-fir particleboards with addition of juniper particles (%)

	24 hours	48 hours	7 days
Control	66.4 (6.8) $^{A, B}$	70.7 (5.2) ^{A}	82.4 (6.2) ^{A}
5% Bandsaw	68.3 (4.0) ^{B}	75.3 (3.7) $^{A, B, C}$	86.6 (3.7) $^{A, B, C}$
10% Bandsaw	64.5 (3.6) $^{A, B}$	72.6 (2.9) $^{A, B}$	83.4 (2.9) $^{A, B}$
20% Bandsaw	65.7 (3.1) $^{A, B}$	74.6 (3.2) $^{A, B, C}$	85.8 (2.9) $^{A, B, C}$
5% Edger	60.9 (1.7) ^{A}	70.5 (1.3) ^{A}	82.8 (1.7) ^{A}
10% Edger	64.0 (5.1) $^{A, B}$	73.7 (5.0) $^{A, B, C}$	85.1 (4.7) $^{A, B, C}$
20% Edger	69.5 (4.1) ^{B}	78.6 (3.0) ^{C}	90.4 (2.9) ^{C}
5% Circular saw	61.1 (2.7) ^{A}	71.0 (2.3) ^{A}	83.9 (2.2) $^{A, B}$
10% Circular saw	64.7 (4.6) $^{A, B}$	74.6 (3.3) $^{A, B, C}$	86.4 (3.0) $^{A, B, C}$
20% Circular saw	66.6 (4.3) $^{A, B}$	77.2 (3.3) $^{B, C}$	88.7 (3.6) $^{B, C}$

Means with the same letter in column do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

As with water absorption, results for linear expansion were somewhat complicated (Table 17). After all time periods, control panels expanded significantly less than all other panel types with the exception of panels made with 5% circular saw sawdust at 24 hours. All panel types expanded similarly after 7 days of water soak, again, with the exception of the controls which expanded less.

Table 17. Linear expansion of Douglas-fir particleboards with addition of juniper particles (%)

	24 hours	48 hours	7 days
Control	1.18 (0.03) A	1.30 (0.04) A	1.40 (0.07) A
5% Bandsaw	1.34 (0.03) C, D	1.47 (0.05) B, C	1.60 (0.05) B
10% Bandsaw	1.30 (0.04) B, C	1.44 (0.03) B, C	1.58 (0.05) B
20% Bandsaw	1.39 (0.06) D	1.51 (0.06) C	1.65 (0.05) B
5% Edger	1.26 (0.04) B, C	1.41 (0.05) B	1.55 (0.06) B
10% Edger	1.28 (0.06) B, C	1.43 (0.07) B, C	1.56 (0.08) B
20% Edger	1.32 (0.06) B, C, D	1.49 (0.05) B, C	1.62 (0.07) B
5% Circular saw	1.25 (0.04) A, B	1.42 (0.05) B, C	1.57 (0.07) B
10% Circular saw	1.30 (0.04) B, C	1.46 (0.07) B, C	1.62 (0.09) B
20% Circular saw	1.32 (0.05) B, C, D	1.47 (0.08) B, C	1.63 (0.09) B

Means with the same letter in column do not differ statistically by the Tukey´s test ($\alpha = 0.05$). Numbers in parentheses represent standard deviation

As with ‘Douglas-fir/juniper blend’ panels, target oven-dried density for ponderosa pine/juniper blend panels was 750 kg/m^3, however final density after conditioning was again slightly higher on average (Table 18). As with Douglas-fir, there was no significant difference in density between panel types. Control panels again had significantly different (higher) moisture content than the other panels. And there were other differences as well, for example, panels made from 20% circular saw sawdust had higher moisture content than panels made with 5% bandsaw sawdust.

Table 18. Density and moisture content of ponderosa pine particleboards with addition of juniper particles

	Density (kg/m^3)	MC (%)
Control	761 (21) A	9.6 (0.2) D
5% Bandsaw	757 (23) A	7.2 (1.0) A
10% Bandsaw	766 (30) A	7.4 (0.3) A
20% Bandsaw	762 (22) A	7.3 (0.3) A
5% Edger	762 (23) A	7.5 (0.4) A, B
10% Edger	754 (39) A	7.5 (0.2) A, B
20% Edger	762 (19) A	7.2 (0.1) A
5% Circular saw	761 (33) A	7.8 (0.1) A, B
10% Circular saw	763 (18) A	8.1 (0.3) B, C
20% Circular saw	760 (28) A	8.7 (0.4) C

Means with the same letter in column do not differ statistically by the Tukey´s test ($\alpha = 0.05$). Numbers in parentheses represent standard deviation

As with Douglas-fir, there was no significant difference in thickness swelling after 24 hours for any of the panel types (Table 19). However, unlike with Douglas-fir, this lack of differentiation in swelling continued throughout the test, i.e., after 48 hours and even after 7 days.

Table 19. Thickness swelling of ponderosa pine particleboards with addition of juniper particles (%)

	Pine		
	24 hours	48 hours	7 days
Control	30.9 (4.3) ^{A}	32.2 (4.1) ^{A}	34.8 (4.5) ^{A}
5% Bandsaw	32.4 (4.7) ^{A}	34.6 (3.7) ^{A}	38.8 (5.0) ^{A}
10% Bandsaw	31.5 (2.4) ^{A}	34.0 (4.5) ^{A}	38.8 (5.3) ^{A}
20% Bandsaw	32.7 (3.5) ^{A}	35.5 (2.8) ^{A}	40.6 (3.0) ^{A}
5% Edger	33.0 (4.0) ^{A}	35.7 (3.1) ^{A}	40.0 (3.9) ^{A}
10% Edger	32.7 (5.7) ^{A}	35.4 (5.2) ^{A}	40.1 (6.1) ^{A}
20% Edger	33.8 (2.5) ^{A}	37.4 (3.4) ^{A}	41.2 (3.2) ^{A}
5% Circular saw	32.0 (5.8) ^{A}	34.5 (4.2) ^{A}	39.0 (4.3) ^{A}
10% Circular saw	32.4 (2.5) ^{A}	35.2 (1.7) ^{A}	40.6 (2.6) ^{A}
20% Circular saw	30.5 (5.0) ^{A}	32.8 (3.7) ^{A}	39.2 (4.8) ^{A}

Means with the same letter do not differ statistically by the Tukey´s test ($\alpha = 0.05$).
Numbers in parentheses represent standard deviation

And again, the results of water absorption testing are far more complex than those for thickness swelling (Table 20). After 24 hours, absorption is lower for panels made with 20% circular saw sawdust than for panels made with 5% or 10% bandsaw, 5 or 10% edger, and 10% circular saw sawdust. Average water absorption for other test panels are similar and intermediate to these values. After 48 hours, more differentiation occurs (as was the case with Douglas-fir panels) such that absorption for controls is significantly lower than for panels with 10% edger sawdust. Comparisons after 7 days of soaking are similar for many of the panels to 48-hour results, however the absorption for bandsaw panels and 5% edger sawdust panels are now more similar to the controls whereas at 48 hours, these panel types were significantly higher than controls.

Table 20. Water absorption of ponderosa pine particleboards with addition of juniper particles (%)

	24 hours	48 hours	7 days
Control	87.1 (2.2) $^{A, B}$	89.1 (2.2) ^{A}	98.8 (2.7) ^{A}
5% Bandsaw	90.5 (3.2) ^{B}	95.3 (2.6) $^{B, C}$	103.7 (2.5) $^{A, B, C}$
10% Bandsaw	89.9 (4.3) ^{B}	94.9 (3.5) $^{B, C}$	102.9 (3.6) $^{A, B, C}$
20% Bandsaw	88.9 (3.7) $^{A, B}$	94.6 (2.9) $^{B, C}$	102.9 (3.0) $^{A, B, C}$
5% Edger	89.6 (2.8) ^{B}	94.7 (2.5) $^{B, C}$	103.1 (2.4) $^{A, B, C}$
10% Edger	92.0 (4.6) ^{B}	97.5 (5.0) ^{C}	106.5 (4.9) ^{C}
20% Edger	87.8 (2.8) $^{A, B}$	93.7 (2.7) $^{A, B, C}$	103.2 (2.7) $^{A, B, C}$
5% Circular saw	87.7 (4.2) $^{A, B}$	93.5 (4.3) $^{A, B, C}$	102.2 (4.2) $^{A, B, C}$
10% Circular saw	89.4 (2.7) ^{B}	95.4 (2.6) $^{B, C}$	104.3 (2.4) $^{B, C}$
20% Circular saw	83.4 (3.3) ^{A}	90.1 (4.0) $^{A, B}$	99.8 (3.9) $^{A, B}$

Means with the same letter do not differ statistically by the Tukey´s test ($\alpha = 0.05$).
Numbers in parentheses represent standard deviation

As was the case for Douglas-fir panels, results for linear expansion were complicated for ponderosa pine panels as well (Table 21). However, for pine, panels made with 20% circular saw sawdust expanded significantly less than all other types after all time periods with a few exceptions – linear expansion was similar for these panels as for control panels (for all time periods) as well as for panels made with 10% circular sawdust after a 7-day water soak.

Table 21. Linear expansion of ponderosa pine particleboards with addition of juniper particles (%)

	24 hours	48 hours	7 days
Control	1.19 (0.06) $^{A, B}$	1.26 (0.06) $^{A, B}$	1.35 (0.08) $^{A, B}$
5% Bandsaw	1.26 (0.08) $^{B, C, D}$	1.34 (0.09) $^{B, C}$	1.47 (0.10) $^{C, D}$
10% Bandsaw	1.32 (0.06) $^{C, D, E}$	1.40 (0.08) $^{C, D}$	1.54 (0.09) $^{C, D}$
20% Bandsaw	1.37 (0.06) ^{E}	1.45 (0.06) ^{D}	1.58 (0.05) ^{D}
5% Edger	1.27 (0.04) $^{B, C, D}$	1.35 (0.06) $^{B, C, D}$	1.48 (0.06) $^{C, D}$
10% Edger	1.34 (0.05) $^{D, E}$	1.41 (0.06) $^{C, D}$	1.56 (0.06) ^{D}
20% Edger	1.30 (0.04) $^{C, D, E}$	1.39 (0.05) $^{C, D}$	1.53 (0.06) $^{C, D}$
5% Circular saw	1.24 (0.03) $^{B, C}$	1.33 (0.05) $^{B, C}$	1.46 (0.06) $^{B, C, D}$
10% Circular saw	1.24 (0.05) $^{B, C}$	1.32 (0.07) $^{B, C}$	1.42 (0.07) $^{A, B, C}$
20% Circular saw	1.13 (0.07) ^{A}	1.20 (0.07) ^{A}	1.32 (0.06) ^{A}

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

<u>Particleboard – Phase 4</u>

Lastly, for particleboard research, phases 1 through 3 explored smaller specimen dimensions and enabled testing of a variety of physical properties. In this final phase, three-layer particleboard specimens manufactured from 100% juniper with regular and lower amounts of resin were made; Douglas-fir particleboard specimens served as a control.

Pressing parameters were as follows:

- Dimensions - 560 × 560 × 18 mm (22 x 22 x 0.75 inch)
- MUF resin LEAF C2 670A08
- Target density: 650 kg/m^3 (40.6 lb./ft^3)
- Resin solid: surface 10%, core 6%;
lower resin (LR) surface 8%, core 4%
- Catalyst solid: 2% (35% concentration)
- Temperature: 180 °C
- Time: 280 seconds
- Press time 240 seconds, plus 40 seconds of vent time

Panels were conditioned in standard conditions of 20°C and 65% relative humidity after manufacturing.

Testing was conducted on 20 specimens per treatment, with dimensions of 50 × 50 mm. Density was measured on specimens after conditioning at 20°C and 65% relative humidity. EMC (%), bending strength and stiffness (MOR and MOE, respectively), and internal bond were measured according to ASTM 1037. These are important properties for particleboard that are not easily measured on smaller test specimens.

RESULTS – Phase 4

Moisture content was statistically similar for all test panels at an overall average value of 7.8% (Table 22). Bending stiffness (modulus of elasticity – MOE) and bending strength (modulus of rupture – MOR) were statistically similar for all panel types as well.

Table 22. Moisture content and bending properties of Douglas-fir and Juniper particleboards with regular and lower resin content (LR)

	EMC (%)	MOE (MPa)	MOR (MPa)
Douglas-fir	8.1 (0.4) A	2458 (491) A	13.0 (2.3) A
Juniper 1%	7.8 (0.3) A	2781 (266) A	15.6 (1.3) A
Juniper 0.5%	7.7 (0.3) A	2705 (270) A	15.4 (1.6) A
Juniper 0%	7.8 (0.3) A	2698 (238) A	15.6 (1.7) A
LR Juniper 1%	7.8 (0.3) A	2721 (295) A	14.3 (2.2) A
LR Juniper 0.5%	7.8 (0.3) A	2885 (283) A	14.4 (1.9) A
LR Juniper 0%	7.9 (0.2) A	2656 (300) A	14.7 (1.7) A

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

Internal bond strength varied between panel types (Table 23). Bond strength was significantly lower for panels made with lower resin content with 1% juniper blend than for Douglas-fir panels and for juniper panels with regular resin content.

Table 23. Internal bond strength of Douglas-fir and Juniper particleboards with regular and lower resin content (LR)

	IB (N/mm^2)
Douglas-fir	0.53 (0.04) D
Juniper 1%	0.46 (0.07) B, C, D
Juniper 0.5%	0.45 (0.07) B, C, D
Juniper 0%	0.50 (0.06) C, D
LR Juniper 1%	0.36 (0.08) A
LR Juniper 0.5%	0.38 (0.05) A, B
LR Juniper 0%	0.41 (0.05) A, B, C

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

Particleboard – Summary & Conclusions

The primary objective for the particleboard panel prototype development and testing were to determine if panels with 'adequate properties' (defined below) could be made from juniper residues using standard industrial methods – with respect to adhesive type and quantity, press time and temperature, etc. Juniper heartwood contains extractive chemical compounds that impart color, aroma, and decay resistance. Such compounds alter the chemistry of the wood and therefore can sometimes interfere with adhesive bonds. Similarly, bark can interfere with bonding as well. At the least, the testing conducted here indicates particleboard with adequate properties can be produced from western juniper sawdust as a pure juniper panel and/or mixed with Douglas-fir or ponderosa pine, even without efforts to screen out bark. To provide more detail, we summarize the results of the specific material properties that were evaluated.

Thickness Swelling

For pure juniper panels (100% juniper sawdust), panels made from sapwood and edger saw sawdust (which again, is primarily sapwood) showed higher thickness swelling compared to panels made from commercially-produced Douglas-fir particles. Panels produced from circular sawdust, where the majority of the particles were heartwood, showed comparable thickness swelling behavior to panels made from commercially-produced Douglas-fir particles.

For panels produced from mixtures of juniper and Douglas-fir or juniper and ponderosa pine, there was no significant difference in thickness swelling after 24 hours for any of the panels. And for ponderosa pine, there were no differences in swelling behavior even after longer soak times (48 hours and 7 days). However, Douglas-fir control panels swelled significantly less than Douglas-fir/juniper panels soaked 48 hours and longer (i.e., 7 days) for panels made with 10% and 20% circular saw sawdust.

Linear Expansion

After all time periods, Douglas-fir control panels expanded significantly less than all other panel types with the exception of panels made with 5% circular saw sawdust at 24 hours. By contrast, for ponderosa pine, panels made with 20% circular saw sawdust expanded significantly less than all other types after all time periods with a few exceptions – linear expansion was similar for these panels and to control panels as well as those made with 10% circular sawdust after a 7-day soak.

Bending Properties

Bending stiffness (modulus of elasticity – MOE) and bending strength (modulus of rupture – MOR) were tested for juniper blended with Douglas-fir. The results were statistically similar for all panel types.

Internal Bond

Internal bond strength was tested for panels made with juniper blended with Douglas-fir. The results varied between panel types. Bond strength was significantly lower for panels made with lower resin content with 1% juniper blend than for Douglas-fir panels and for juniper panels with regular resin content.

As a general observation, given that no efforts were made to remove bark, we can also conclude that it is acceptable to include small percentages of bark, at least with respect to moisture-related properties, bending strength and internal bond strength. Aesthetic concerns that may be related to bark were not considered in this project.

STRANDBOARD

Strands, such as those used to manufacture oriented strandboard (OSB), are produced from roundwood. Logs suitable for OSB strands typically have a small-end diameter of 5 to 25 cm (2 to 10 inch). Standers require a substrate that can be held in position to cut the strands parallel to the grain. With respect to sawmill residues (as opposed to logs), juniper slabs, and possibly edgings, have the potential to be converted into strands. The application could be a structural panel. However, it is highly unlikely that a greenfield commodity OSB mill would be built in Oregon based on the supply of western juniper residues. The economy of scale, haul distance for raw material, and distance to market would seem a significant disadvantage in the commodity OSB market. A more likely scenario would be development of a small-scale facility producing specialty nonstructural panels for decorative applications or for aromatic closet and drawer liners.

Research related to strandboard proceeded in 3 phases. The first phase assessed the feasibility of producing juniper strands and then test panels from the strands. Mechanical properties were evaluated and compared to panels produced from aspen, one of the two primary species used to manufacture commercial OSB. Phase 2 then followed by delving into much greater depth with the raw materials, e.g., juniper sapwood strands, heartwood strands, and mixed heartwood and sapwood with and without bark. Southern yellow pine (the other common commercial species) served as the control for phase 2. Numerous mechanical and physical properties were assessed for these panels as well. Lastly, phase 3 explored a unique property of juniper, namely its decay resistance. Durability (in terms of decay resistance) was evaluated for juniper strandboard. Decay resistance of pure heartwood panels was tested as was that of sapwood panels produced from strands impregnated with juniper leaf oil, as well as sapwood panels that were impregnated with the leaf oil after they were pressed.

Strandboard – Phase 1

Materials and Methods

Slabs (with bark), were cut to a length of 127 mm and immersed in water for 48 hours at a temperature of 40°C to soften the wood. A vertical veneer slicer was used to cut strands from the small wood blocks. The strands had average dimensions of 127 × 50.8 × 0.89 mm (5 inches x 2 inches x 0.035 inches, length × width × thickness). Drying of the strands was done in a rotating dryer to a final moisture content of 6%. The rotary dryer also serves as a screen, where small particles are separated from the strands. Bark typically broke down into small particles that were separated in the dryer and removed. After drying, the strands retained approximately 0-20% of the initial bark.

Panels were then made from both juniper strands as well as aspen strands, to serve as a control for comparison. Aspen strands were obtained from an OSB mill and had a different geometry than the laboratory-produced juniper strands. The aspen strands had approximate dimensions 85 x 25 x 0.8 mm, and contained no bark.

Strandboard panels were made at 3 target density levels from each wood species with 3 panel replications (as described below) and pressing parameters were as follows:

- Panel dimensions: 267 × 267 × 7.67 mm (10.5 x 10.5 x 0.3 inch)
- Phenol-formaldehyde resin RESI-STRAND 265C08 (Georgia-Pacific Chemical)
- Oven Dry Density: 600, 650, 700 kg/m^3 (37.2, 40.3, 43.4 $lb./ft^3$)
- Resin solid: 5%
- Wax solid: 0.5%
- Temperature: 160 °C
- Press time 200 seconds, plus 15 seconds of vent time

Test panels were conditioned in standard conditions of 20°C and 65% relative humidity prior to testing.

Testing procedures

Testing was performed on specimens with dimensions of 50 × 50 mm. Density and internal bond tests used 20 replications for each treatment (i.e., combination of species and target density). Thickness swell (TS), water absorption (WA) and linear expansion (LE) tests were measured after 24, 48 hours and 7 days of water soak. The water soak test specimens were smaller than specified in ASTM D1037, which calls for 152 x 152 mm (6 x 6 inch) specimens.

Analysis of variance (ANOVA) was used to test for statistical significance using a 95% confidence level (alpha = 0.05).

RESULTS – Phase 1

Juniper panels were marked as J600, J650, J700, and aspen panels as A600, A650, A700, where the number represents the target density in kg/m^3. Analysis of the results of density showed the lowest density for juniper panels (Table 24) and density levels were higher than the targets. Formation of the strand mats in this project was challenging due to the small size of the mat in comparison to the length of the strands. The panel edges were low in density, while the center of the panel tended to have higher density. There was also high variability of density within panels.

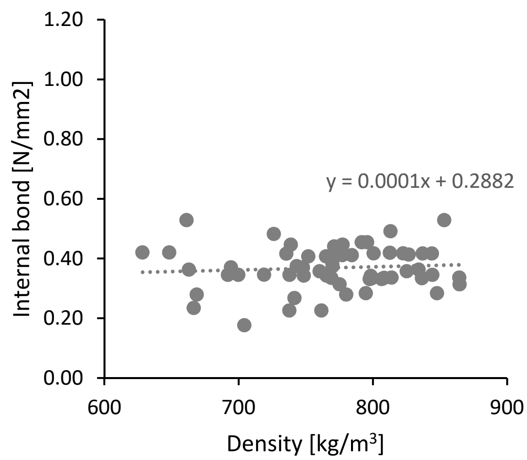
Table 24. Panel density and internal bond strength

	Density [kg/m^3]	Internal Bond [N/mm^2]
A600	705 (38) $^{B, C}$	0.35 (0.09) ^{A}
A650	775 (12) $^{C, D}$	0.38 (0.07) ^{A}
A700	828 (21) ^{D}	0.38 (0.06) ^{A}
J600	637 (27) ^{A}	0.64 (0.21) ^{B}
J650	687 (11) ^{A}	0.76 (0.19) ^{B}
J700	727 (16) $^{A, B}$	0.69 (0.18) ^{B}

Means with the same letter do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation

One objective in this phase was to explore the relationship between panel properties and density. Another objective was to compare juniper panels to aspen panels of the same density. After observing the high variability in density, results for the panel properties were plotted as a function of their density; a linear trend line was fitted to the data and extrapolated to obtain adjusted panel properties at equal density.

Figures 7 through 9 show the results of the internal bond (IB) testing. The highest average IB value obtained in these tests was 0.76 N/mm^2 (112 psi) for juniper panels J650. Internal bond strength for aspen was lower than for juniper. These results indicate that it is possible to make panels with adequate integrity (internal bond) from juniper strands.



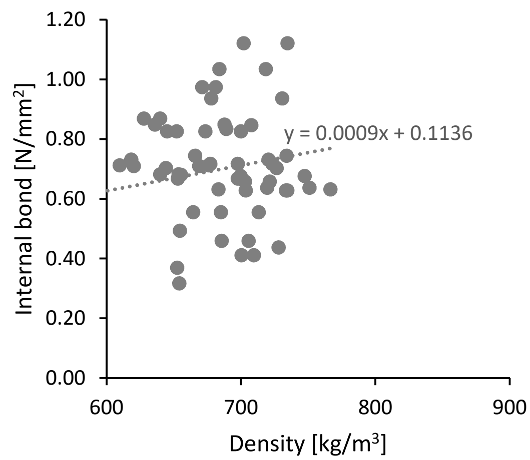


Figure 7. Chart of Internal bond versus density of aspen specimens

Figure 8. Chart of Internal bond versus density of juniper specimens

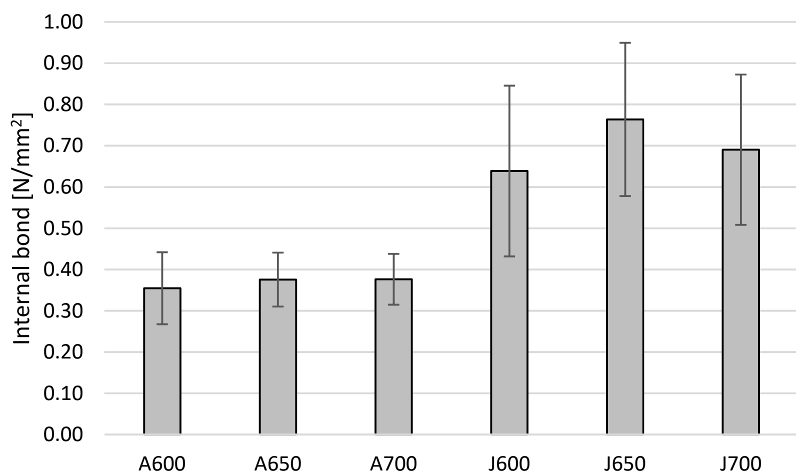


Figure 9. Average values of internal bond for aspen and juniper strandboard

Results for thickness swelling (Figure 10) showed higher values for aspen (averaging approximately 60-70%) than for juniper (approximately 30-35%) after 7 days.

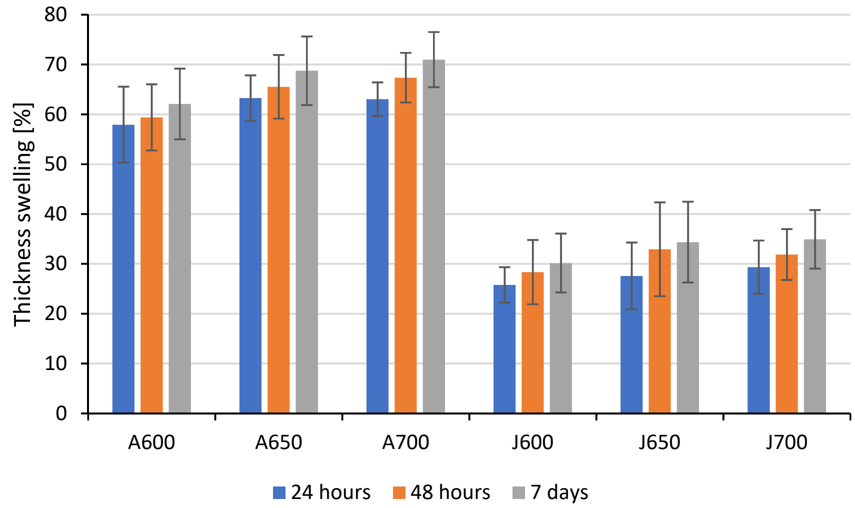


Figure 10. Average values of thickness swelling

Water absorption increased with time (Figure 11) with an average value of 52% for juniper J700 after 24 hours and 65% after 7 days. For aspen A700 water absorption was 58% and 92% after 24 hours and 7 days, respectively. Overall, aspen panels showed higher values of water absorption than juniper panels (approximately 90% compared to 60%).

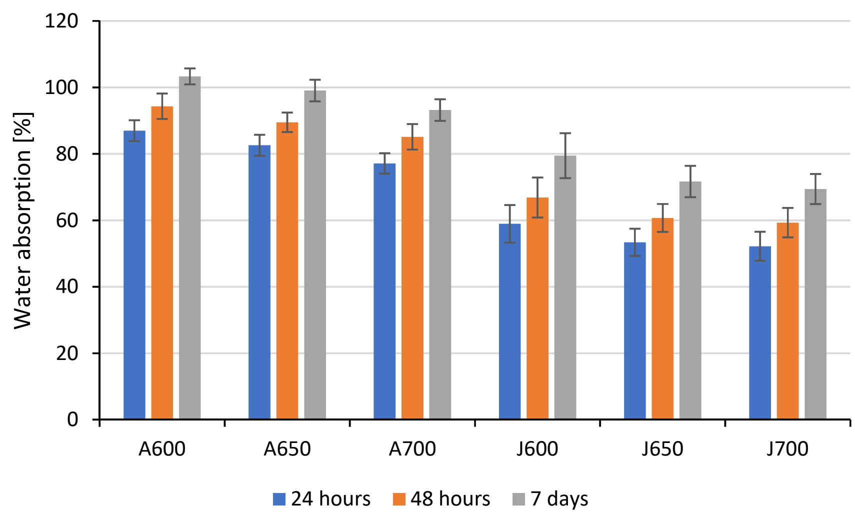


Figure 11. Average values of water absorption

Figure 12 shows that linear expansion of aspen and juniper specimens decreased with increasing panel density after 24 hours water soak.

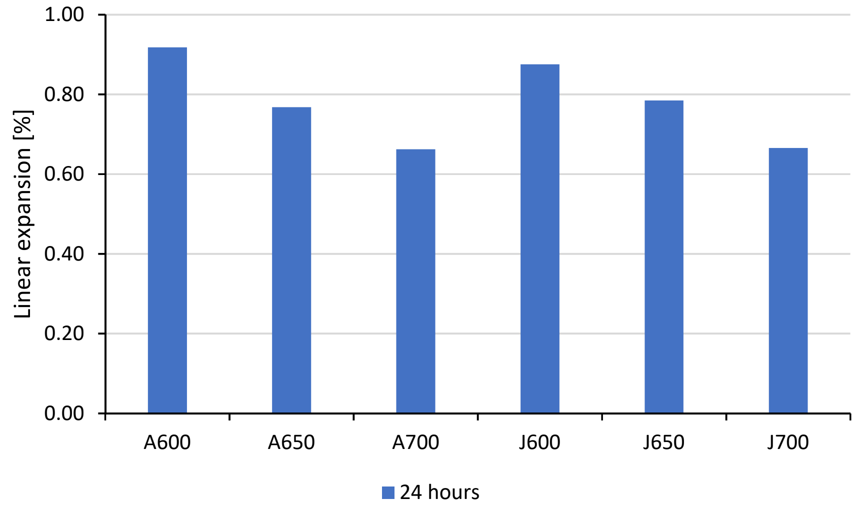


Figure 12. Linear expansion of juniper and aspen strandboard after 24 hours

Differences in geometry between the commercially produced aspen strands and laboratory produced juniper strands (Figure 13) may be responsible for some differences in panel performance. Longer strands may improve linear expansion, but this was not observed. Difference in wood density could have been a factor. Handbook values for specific gravity of aspen and western juniper are about 0.35 and 0.44, respectively. This means the compaction ratio for aspen panels would be about 25% greater than juniper panels. Greater compaction ratio should improve IB, if all else is equal, because there would be better surface contact and fewer voids. On the other hand, the denser juniper strands would mean fewer strands in the blender than aspen strands. Therefore, with equal resin loading by weight, there would be greater resin coverage on the juniper strands. Given the difference in density, resin coverage could have been 26% greater for juniper. These factors may explain the improved IB strength and reduced thickness swell for juniper panels compared to aspen panels. Strand geometry can be controlled, but wood density is what it is.

Figure 13. Aspen strands (left) and juniper strands (right)

Conclusions

Two significant outcomes related to strandboard are:

1. Producing strands from slabs - we demonstrated the feasibility of making strands from juniper slabs. While we do not have a commercial strander, OSU's vertical veneer slicer has the same cutting geometry as a knife in a commercial strander. Also, strand thickness was precisely controlled.
2. Bark removal – there were some concerns with how bark would impact strandboard production along with challenges (and hence costs for manufacturers) of removing bark from odd-shaped surfaces like slabs. However, the drying procedure resulted in reducing the percentage of bark in the strands. While our lab dryer is different from a commercial rotary dryer, the procedure demonstrated that the bark easily detaches from the juniper strands and can be removed via a screening process, which is typical in a commercial OSB mill.

With respect to bonding properties and wood water relations, test results showed that juniper slabs can be used to make strandboard for which the bonding properties and moisture behavior are equal to, or better, than strandboard made from aspen.

<u>Strandboard – Phases 2 and 3</u>

As mentioned above, results of strandboard phases 2 and 3 have been published in the journal *Bioresources*. Those articles are provided in the Appendix.

SUMMARY & RECOMMENDATIONS

Particleboard
Based on the results presented above, we conclude that it is technically feasible to use juniper sawdust for particleboard production, even if the sawdust includes some small quantities of bark. The sawdust may be used either pure or blended with Douglas-fir or ponderosa pine.

For moisture behavior to be comparable to that of panels made using existing commercial species (i.e., Douglas-fir and ponderosa pine), manufacturers should use either sawdust produced from mills that use circular saws (for pure juniper panels) or mix juniper sawdust with commercial species in blends less than 10%. Moisture-induced thickness swell and linear expansion are better for heartwood than sapwood. Therefore, manufacturers are advised to minimize use of sawdust produced by edger saws given that it is likely to be primarily sapwood.

When blended with Douglas-fir, there are no significant reductions in internal bond strength or bending strength or stiffness.

Strandboard
Based on the results, we conclude that it is also technically feasible to produce a high quality (with respect to bonding properties and moisture-related behavior) strandboard panel from western juniper slabs and edgings. With respect to bonding properties and moisture-related behavior, results demonstrated that juniper slabs can be used to make strandboard for which bonding properties and moisture-related behavior are equal to, or better, than strandboard made from aspen and southern yellow pine, with one exception. Bending stiffness (MOE) of juniper panels was less than that of panels produced from southern yellow pine.

Durability, in terms of resistance to common decay fungi, is very good for heartwood panels as well as for panels that are impregnated with essential oils from juniper foliage ('leaf oil').

And as was the case with particleboard, bark that is likely to be included with the feedstocks (sawmill slabs and edgings) does not appear to be a significant concern given that the bark tended to detach from strands during drying and was then easily removed during screening.

NEXT STEPS

Particleboard
Western juniper manufacturers are encouraged to collect and store sawdust in such a manner that it can be kept free of non-wood contaminants such as soil and rocks. They may also consider segregating sawdust based on the source such that materials most likely to be sapwood (e.g., from edger saws) can be separated from other materials. Producers are also encouraged to contact local particleboard manufacturers to gauge their interest in purchasing juniper sawdust. They can reference this report, the project website (http://owic.oregonstate.edu/western-juniper-composites) or the authors directly for particleboard manufacturers that may have questions about including juniper sawdust in their furnish.

Future work should look at the economic feasibility and supply. We were unable to complete that exercise for this project. In particular, haul distance and the value of alternative uses should be assessed, and detailed estimates of potential supply of material by region should be developed.

Strandboard
Next steps for strandboard require more significant investment than for particleboard, given there is existing particleboard manufacturing capacity in Oregon but no strandboard manufacturing. The results suggest

there is an opportunity for development of a firm to produce decorative juniper strandboard panels. Structural panels are a possibility as well, though more significant investment is required for such a facility and efforts such as additional testing or panels with oriented strands (i.e., for making OSB vs. strandboard) are likely to be needed to improve the bending properties.

At the least, a new entity will be needed with capabilities to:

- receive juniper slabs and edgings
- produce strands from the materials
- dry the strands
- screen to remove bark
- apply adhesive
- form loose mats of strands
- hot press to produce panels

Assuming that fungal durability is a desirable feature, additional capabilities that are needed will be:

- ability to accumulate juniper foliage
- distill essential oils from the foliage
- blend oils with a solvent such as ethanol
- pressure impregnate finished panels with oil
- dry panels

Unfortunately, we were unable to locate a lab with research capabilities to test panels for moth repellency for this project. Given that eastern redcedar (also a juniper species - *Juniperus virginiana*) is commonly used for cedar closet lining as both paneling and flakeboard, it is possible there are market opportunities for western juniper strandboard to be sold for closet lining as well. Future work may consider exploring the ability of juniper panels to repel moths.

Appendix A: Properties of the Western Juniper (*Juniperus occidentalis*) Strandboard

Tomáš Pipíška,[a,*] Scott Leavengood,[a] Frederick A. Kamke,[a] and Pavel Král [b]

This work investigated the feasibility of using western juniper (*Juniperus occidentalis*) as a material to manufacture oriented strandboard (OSB) panels. Four different material combinations of juniper sapwood, heartwood, and fibrous bark were compared with regular southern yellow pine (*Pinus* sp.) strands. The OSB panels were made at an oven-dry density of 560 kg/m^3. One pine control panel was also made at a higher density of 650 kg/m^3 with a 5% addition of phenol formaldehyde (PF) resin and a 0.5% addition of wax. The single-layer panels were formed with a hot press, and the physical and mechanical properties were tested according to the ASTM standard D1037 (2020). The testing indicated that western juniper is a potential material for manufacturing of OSB panels. The properties of the juniper panels were equivalent or slightly better than those of the southern yellow pine panels at the same density level, except for the modulus of elasticity (MOE). The lower density of the juniper OSB panels may have benefits in construction applications and can decrease transportation costs.

Keywords: Western juniper; Strandboard, OSB, Physical properties; Mechanical properties; Screw withdrawal

*Contact information: a: Department of Wood Science and Engineering, Oregon State University, 119 Richardson Hall, 3180 SW Jefferson Way, Corvallis, OR 97331, USA; b: Department of Wood Science and Technology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemědělská 3, 613 00 Brno, Czech Republic; *Corresponding author: tpipiska@gmail.com*

INTRODUCTION

Western juniper (*Juniperus occidentalis*) is an invasive tree species that is widespread in the western United States. Western juniper woodlands are in Oregon, California, Washington, Idaho, and Nevada (Bedell *et al.* 1993; Swan 1995). These woodlands occupy approximately 3.4 million hectares, and the majority (over 2.6 million hectares) are in Oregon (Azuma *et al.* 2005; Miyamoto 2017; Eastern Oregon Agricultural Research Center 2020). The highest concentration of western juniper woodlands is in central and eastern Oregon, with approximately 2 million hectares (Miller *et al.* 2005). The standing timber volume in Oregon, California, and Idaho is 18 million m^3, 6 million m^3, and 3.7 million m^3, respectively (Miyamoto 2017). Juniper trees are quite short compared to other Pacific Northwest conifer species, and the logs are highly tapered. The wood has an average density of 497 kg/m^3 and aromatic rose-red heartwood and yellow sapwood (Panshin and de Zeeuw 1980; Swan and Connolly 1998). Juniper heartwood is highly decay-resistant, and it is typically used as fencing, decking, and landscape timbers (Highley 1995; Swan 1995; Morrell *et al.* 1999; Morrell 2011). Design values for juniper lumber have been developed (Miyamoto *et al.* 2018), and there are now 6,000 m^3 of lumber produced every year. Due to the tapered structure of the logs, lumber production generates significant volumes of residues, such as slabs, edgings, and trimmer ends. Juniper harvest operations also result in a substantial volume of non-merchantable logs. These residues are primarily used as firewood or they are discarded.

Southern yellow pine species (primarily *Pinus taeda*, *P. palustris*, *P. elliottii*, and *P. echinata*) with average density 550 kg/m^3 are commonly used to produce oriented strandboard (OSB) in the southern United States. For OSB production, it is typical to use juvenile pine logs with small diameters. In 2019, the United States produced approximately 13.5 million m^3 of OSB (Food and

Agriculture Organization of the United Nations 2020). There is strong potential for manufacturing OSB from juniper based on the volume and availability of the wood. Previous research conducted on a similar species eastern redcedar (*Juniperus virginiana*) showed the possibility to use this wood for OSB manufacturing (Hiziroglu 2009, 2012).

Juniper logs, slabs, and branches are covered with very fibrous bark, and the logs often have deep bark pockets. The fibrous nature of the bark makes it difficult to remove. Furthermore, the bark can cause some challenges in the production of the strands (Swan and Connolly 1998). Due to the fibrous structure of the bark, there is an option to use it in OSB. Research by Moya *et al.* (2008) indicated that low volumes of bark did not change the final properties of OSB panels.

This study explored the uses for western juniper residuals to improve the economics of juniper harvesting and milling operations. In particular, markets were investigated for non-merchantable logs and sawmill residues. The objectives were to produce juniper OSB panels from sawmill and harvesting residues and compare the physical and mechanical properties of these boards with commercially available OSB panels produced from southern yellow pine. This research provides a comparison of OSB made from juniper sapwood, heartwood, and wood with and without bark.

EXPERIMENTAL

Manufacturing

The western juniper slabs, edgings, and low-quality/non-merchantable logs were obtained from two different locations in Oregon. All the materials contained a layer of bark that was approximately 10 mm thick. The materials were cut to 117 mm long, which is the typical average length of pine strands in OSB mills. The strands were sorted into four groups. The first group contained 100% sapwood (Sap), while the second group contained 100% heartwood (Heart). The third group contained a mixture of sapwood and heartwood without bark (Slabs). The fourth group contained a mixture of sapwood and heartwood with bark (Slabs-W). Approximately 10% of the fourth group was made up of bark.

The juniper blocks were submerged in water at a temperature of 30 °C for 72 h as a plasticization step before cutting the strands. The juniper blocks were cut to a thickness ranging from 0.6 to 0.9 mm using a veneer slicer. The strands were dried in a rotary dryer at 50 °C until they reached a moisture content (MC) of 4 ± 1%.

The pine strands were obtained from an OSB mill in Alabama. The pine strands had average dimensions of 0.6 mm × 25 mm × 117 mm (thickness × width × length). These strands were used as the control panels with a target density 560 kg/m^3 (Pine), which was the same as the juniper panels. The pine strands were used to make panels with a target density comparable to that used in commercial production (Pine-H) (650 kg/m^3).

The OSB panels were made using phenol formaldehyde (PF) resin with 49% resin solids (GP 265C08; Georgia Pacific Chemicals, Atlanta, GA, USA) with 5% resin by weight and 0.5% wax added. The resin was sprayed with a model EL-4 spinning disk atomizer (Coil Manufacturing, Surrey, BC, Canada) with a speed of 10,000 rpm. Three 12-mm thick panels and dimensions of 600 mm × 600 mm were made in each group. The target oven-dry density of the panels was 560 kg/m^3. Single layer OSB panels were formed on a wire mesh without any attempt to orient the strands. The panels were pressed at 180 °C with 30 s of closing, 240 s at position, and 80 s to vent.

Testing Procedures

The test specimens were conditioned at 20 °C and 65% relative humidity (RH) before the mechanical and physical properties were measured. All the mechanical and physical properties were tested according to the ASTM standard D1037 (2020), unless noted otherwise.

Density and density profile

The density was determined on 10 specimens from each board and the density profile was measured on three 50 mm × 50 mm × 12 mm specimens from each board. The density profile was measured at an interval of 0.01 mm through the sample thickness using an X-ray densitometer (QDP-01X; Quintek Measurement Systems, Knoxville, TN, USA) and the average density profile was calculated.

Physical properties

The MC was determined on 10 specimens with dimensions of 152 mm × 152 mm. The thickness swelling (TS) and the water absorption (WA) were measured using 10 specimens with the same dimensions.

Mechanical properties

The mechanical testing was carried out on an Instron 5582 universal testing machine with a 100 kN load cell (Norwood, MA, USA). Three-point bending tests were conducted to determine modulus of elasticity (MOE) and the modulus of rupture (MOR) on 10 specimens with dimensions 356 mm × 76 mm, with the span 305 mm. The specimens were loaded at a rate of 10 mm/min. The internal bond (IB) strength was measured on 10 specimens with dimensions 50 mm × 50 mm. The specimens were glued to the aluminum blocks and tested. The screw withdrawal resistance was tested on five specimens with 4.6 mm thread diameter type AB screws. Peak loads for the edge and face testing was recorded.

Statistical Analysis

The data was processed in Statistica 10 software (StatSoft Inc., Tulsa, OK, USA) and evaluated using a one-factor analysis of variance (ANOVA) test and Tukey's honest significance difference (HSD) test. The tests were conducted to determine if there were significant differences in the properties between the six groups, *i.e.*, the four groups of juniper materials and the two pine control groups.

RESULTS AND DISCUSSION

There were no challenges in manufacturing the OSB panels with respect to delamination (steam blows) in the press with the combination of density, resin concentration, wax, and press parameters used in this study. The juniper compression ratio for the sapwood and heartwood were 1.46 and 1.32, respectively.

Table 1 presents the results of the density and MC testing. The MC of the specimens after they were conditioned was significantly lower ($p < 0.5$) for the boards made from juniper compared to the pine strandboard made with the same average density. The MC for the higher density pine strandboard and juniper panels were not significantly different.

Table 1. Average Values of the Density and Equilibrium MC of the Boards at 20 °C and 65% RH

OSB panel	Density (kg/m^3)	MC (%)
Pine-H	707 (36) B	7.6 (0.3) A
Pine	629 (24) A	8.3 (0.6) B
Heart	643 (31) A	7.3 (0.4) A
Sap	614 (13) A	7.4 (0.3) A
Slabs	629 (18) A	7.1 (0.3) A
Slabs-W	636 (24) A	7.3 (0.3) A

Means with the same letter in column do not differ statistically by the Tukey's test (α = 0.05). The numbers in parentheses represent standard deviation

No attempts were made to conduct statistical analyses to compare the density profiles. The discussion here is therefore primarily qualitative in nature based on the examination of the density profile plots (Fig. 1). The density profiles for the juniper heartwood OSB panels were similar to the profiles of the pine OSB panels at comparable target densities. The juniper Sap, Slabs, and Slabs-W OSB panels had a higher density 1 mm from the surface compared to the surface density of the Pine-H OSB panels. These results show that strandboard can be made from mostly juniper sapwood with a high surface density (850 to 900 kg/m^3) and a low core density. Therefore, it may be possible to produce juniper OSB panels with comparable mechanical properties and lower densities than currently available commercial panels. This reduction in the OSB panel weight can be a significant advantage for the transportation of the panels and the feasibility of using them in building applications.

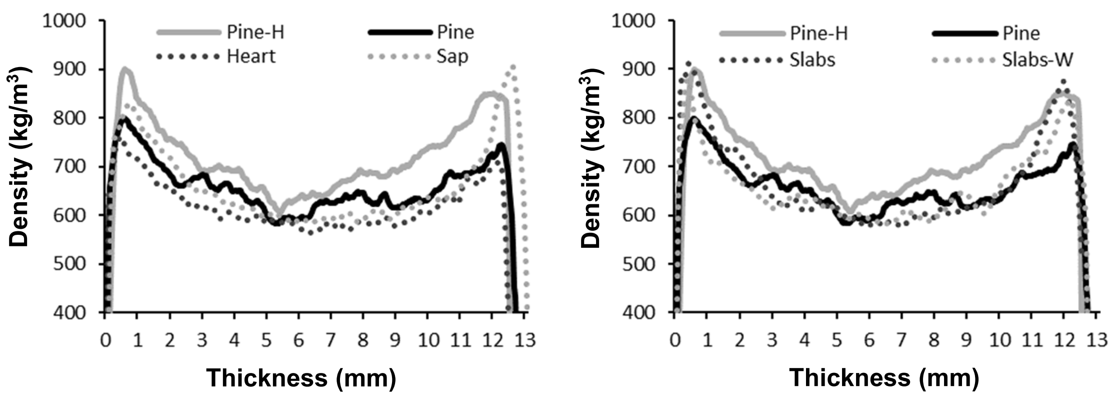


Fig. 1. Density profile of the juniper and pine strandboard at 20 °C and 65% RH

The results of the TS and WA tests are shown in Table 2. The OSB made from the pine had a higher TS and WA after 24 h. The pine OSB also had TS and WA values that were 2.5 and 2 times higher than those of the Sap OSB, respectively. The OSB made from the Sap had the lowest TS and WA values after 24 h. The TS values after 7 d of water immersion showed more consistent results for the juniper and pine OSB at the same density level. The higher density pine OSB had the greatest TS (33.3%) after 7 d. After 7 d of water immersion, the pine and juniper OSB panels had significantly different WA values. The juniper OSB WA values were approximately 15% lower than those of the pine OSB.

The OSB panels that were made from the eastern redcedar (*J. virginiana*) with PF resin from strands that included bark, had TS values of 15.2% after 24 h of water immersion (Hiziroglu 2009). This is comparable to the TS values of the OSB panels that were made in this research, especially for the Slabs-W panels.

Table 2. The TS and WA Values after 24 h and 7 d of Water Immersion

	24 h		7 d	
OSB Panel	TS (%)	WA (%)	TS (%)	WA (%)
Pine-H	29.7 (2.4) D	67.8 (8.5) C	33.3 (4.6) B	88.1 (6.9) B, C
Pine	20.2 (2.5) C	70.8 (8.1) C	21.5 (2.7) A	95.0 (6.4) C
Heart	15.3 (3.1) B	43.2 (6.1) B	19.4 (3.7) A	72.4 (7.6) A
Sap	11.8 (2.5) A	33.6 (4.5) A	21.5 (3.6) A	75.1 (9.2) A
Slabs	14.4 (1.8) A, B	36.6 (1.6) A, B	22.2 (2.8) A	76.6 (2.8) A
Slabs-W	15.1 (2.2) A, B	39.0 (4.8) A, B	24.1 (2.3) A	81.4 (9.3) A, B

Means with the same letter in column do not differ statistically by the Tukey's test (α = 0.05). The numbers in parentheses represent the standard deviation

Figure 2 presents the results of the static bending tests. The OSB made from the juniper sapwood had MOE values that were comparable to the Pine-H OSB. According to Haataja and Laks (1995), northern white-cedar (*Thuja occidentalis*) OSB bonded with polymeric diphenyl methane diisocyanate (pMDI) resin had MOE values of 4,275 MPa. The MOE of the panels made from eastern redcedar (Hiziroglu 2009) was 2,845 MPa, which is at the low end of the results from the research presented in this paper.

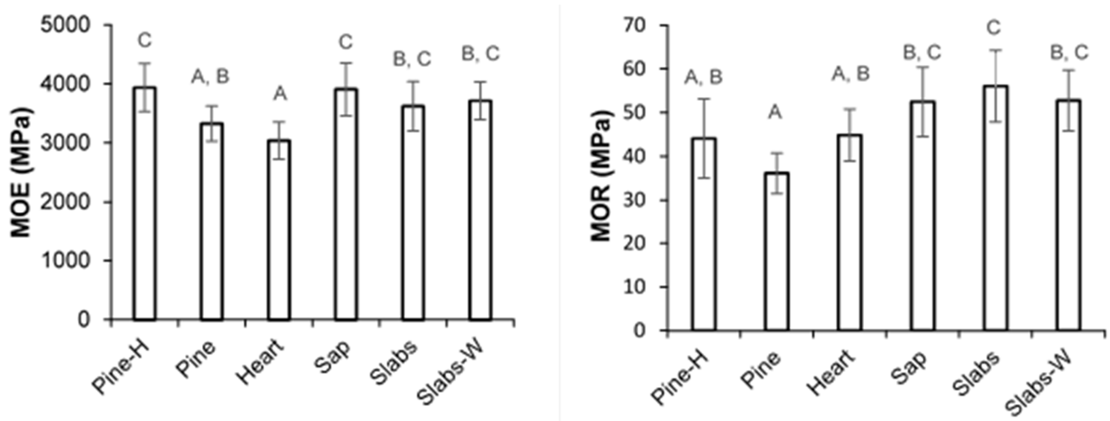


Fig. 2. The average values of the bending properties of the juniper and pine OSB panels at 20 °C and 65% RH

The OSB panels made from Slabs had the highest average MOR of 56 MPa, which is approximately 12 and 20 MPa higher than the MOR values of the Pine-H and Pine boards, respectively. Haataja and Laks (1995) found that the MOR of northern white-cedar panels made with pMDI resin was 39 MPa, which is lower than the results in this research. Hiziroglu (2009) found that the MOR for eastern redcedar OSB, with a density of 650 kg/m^3, was 17.5 MPa (Hiziroglu 2009).

The IB values of the OSB panels are shown in Table 3. The juniper samples had an average value of 0.85 MPa, which is significantly higher (1.7 times), than the average value of the pine samples. Research on the utilization of northern white-cedar bonded with pMDI resin reported IB values of 0.72 MPa, which are comparable with the OSB panels made from slabs with bark (Slabs-W) in this research (Haataja and Laks 1995). Hiziroglu (2009) reported IB values of 0.77 MPa for OSB panels made from eastern redcedar with bark, which is comparable with the Slabs-W panels made in this research. The utilization of low-density species increases the number of strands used, resulting in a higher total wood surface area of the strands and a lower area covered by the adhesive (Barbuta *et al.* 2011).

Table 3. Average IB Values of the Juniper and Pine OSB Panels at 20 °C and 65% RH

OSB Panel	IB (MPa)
Pine-H	0.47 (0.13) A
Pine	0.53 (0.09) A
Heart	0.85 (0.14) B
Sap	0.90 (0.12) B
Slabs	0.91 (0.08) B
Slabs-W	0.74 (0.20) B

Means with the same letter in column do not differ statistically by the Tukey´s test (α = 0.05). The numbers in parentheses represent the standard deviation

The results of the screw withdrawal resistance tests are presented in Table 3. The juniper OSB panels showed comparable or higher results for the screw withdrawal resistance, especially for the Sap and Slabs-W panels, which had significantly higher peak loads for the edge screw withdrawal resistance. The screw withdrawal with pilot hole 2.4mm and torque level 1.5 Nm for southern yellow pine OSB in the research of Tor *et al.* (2016) was 1859N, 1477N, and 2469N for edge-grain, end-grain, and face-grain respectively.

Table 4. Average Values of the Screw Withdrawal Resistance of the Juniper and Pine OSB Panels at 20 °C and 65% RH

	Peak Load: Edge (N)	Peak Load: Surface (N)
Pine-H	1119 (340) A	1455 (491) A
Pine	1185 (250) A	1254 (136) A
Heart	1568 (144) A, B	1417 (364) A
Sap	2127 (29) B	1752 (420) A
Slabs	1651 (235) A, B	1551 (361) A
Slabs-W	2010 (574) B	1598 (365) A
Means with the same letter in column do not differ statistically by the Tukey´s test (α = 0.05). Numbers in parentheses represent standard deviation		

CONCLUSIONS

1. The testing in this study indicated that heartwood and sapwood western juniper residues can be used to successfully produce OSB panels, even at lower densities and a small amount (approximately 10%) of bark in the strands.
2. There were no indications that the lower density of the western juniper (compared to southern yellow pine) require a higher amount of resin. This is beneficial for the utilization of juniper to manufacture OSB panels.
3. All the physical and mechanical properties presented in this work support the potential for manufacturing juniper OSB panels. The properties of the juniper panels were equivalent or slightly better than higher density panels made from southern yellow pine, apart from the MOE. Specifically, higher density pine panels had higher MOE values than the pure heartwood juniper panels. However, the MOE values were equivalent for the other juniper materials tested in this study.
4. The lower density of the juniper OSB panels may be beneficial in construction applications and can reduce transportation costs.

ACKNOWLEDGMENTS

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Appendix B: Utilization of the Western Juniper (*Juniperus occidentalis*) in Strandboards to Improve the Decay Resistance

Tomáš Pipíška, [a,]* Jed Cappellazzi,[a] Scott Leavengood,[a] Frederick A. Kamke,[a]
Gerald Presley,[a] and David Děcký [b]

Naturally durable wood species such as western juniper (*Juniperus occidentalis*) are a potential source of bio-based wood preservatives for the improvement of non-durable timber species. This research investigated the durability of southern yellow pine (*Pinus* sp.) and western juniper lumber or strandboard. Single layer panels were made with six different types of wood or wood treatments: southern yellow pine, mixed juniper sapwood and heartwood, sapwood, heartwood, sapwood strands impregnated with juniper oil prior to and after panel manufacturing. Panels were fabricated with 560 kg/m^3 oven-dry density with 5% of PF resin and 0.5% of wax. Durability testing was performed with the brown rot fungi *Gloeophyllum trabeum* and *Rhodonia placenta* and the white rot fungus *Trametes versicolor*. Internal bond as a crucial parameter of OSB was measured. Tests revealed that juniper heartwood and juniper heartwood strandboards were highly decay resistant, and juniper oil pre- and post-impregnation strandboard manufacture imparted increased resistance to decay against one brown rot fungus, *Gloeophyllum trabeum*. Juniper strandboard manufactured from non-impregnated strands showed significantly higher internal bond than pine. These results suggest there is excellent potential for manufacturing highly decay-resistant OSB from juniper, especially from heartwood and that juniper oil can increase the durability of juniper sapwood strandboard.

Keywords: Natural durability; Western juniper; Strandboard; Decay resistance; Internal bond

*Contact information: a: Department of Wood Science and Engineering, Oregon State University, 119 Richardson Hall, 3180 SW Jefferson Way, Corvallis, OR 97331, USA; b: Department of Wood Science and Technology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemědělská 3, 613 00 Brno, Czech Republic; *Corresponding author: tpipiska@gmail.com*

INTRODUCTION

Western juniper (*Juniperus occidentalis* Hook.) is an invasive tree species that is widespread in the western United States including Oregon, California, Washington, Idaho, and Nevada (Bedell *et al*. 1993; Swan 1995; Gedney *et al*. 1999). The wood has an average density of 497 kg/m^3, with yellow sapwood and aromatic rose-red heartwood that is commonly used to manufacture posts, poles, fencing, decking, and other products (Panshin and Zeeuw 1980; Swan and Connolly 1998). The heartwood is highly decay-resistant and can remain in-service for 56 years or more without preservative treatment (Hemmerly 1970; Highley 1995; Swan 1995; Morrell and Schneider 1999; Morrell 2011; Kirker *et al*. 2013; Adams 2014). The durability of juniper heartwood is attributed to the high lignin content and presence of the cedrol and other terpenes that can be extracted by steam distillation (Kurth and Ross 1954; Adams 1987; Highley 1995). Sapwood has little inherent durability, but some data suggest that juniper sapwood adjacent to heartwood is more durable than sapwood further removed from the heartwood (Morrell 2011).

Manufacturing lumber from these highly tapered trees with many small branches results in extensive waste material as low-quality logs, slabs, branches, and foliage. In addition to low-value uses like firewood, waste materials may be used to manufacture strandboard with high decay-resistance. Developing higher value end-uses for juniper processing wastes would help improve the economic viability of lumber production for this species.

Substantial residual juniper foliage can be generated during harvesting with little utilizable value; however, juniper foliage is a rich source of biocidal terpenes, some of which impart durability to juniper heartwood (Acda *et al*. 1998). Extracts of juniper foliage and heartwood have activity against fungi and subterranean termites (Adams *et al*. 1988; Sichamba *et al*. 2012; Ateş *et al*. 2015; Scouse *et al*. 2015; Lipeh *et al*. 2020). Impregnating juniper wood with juniper essential oil diluted in a solvent to improve the decay-resistance of slabs/branches (primarily sapwood) can be an avenue to utilize the entire tree in the manufacture of a highly decay-resistant strandboard.

Wood decay that leads to strength loss is predominantly caused by basidiomycete fungi, which can be grouped into two main categories, lignin-degrading white-rot and carbohydrate-selective brown-rot (Zabel and Morrell 2020). These two types of fungi differ in what components they are able to degrade in wood, which stems from a difference in the genetic and enzymatic profiles (Floudas *et al*. 2012). The physiology of these two groups of fungi is different enough for them to both be included in standard durability testing protocols. White rot fungi are capable of depolymerizing all major cell wall components (lignin, cellulose, and hemicelluloses), primarily attack hardwoods, and the resultant wood tends to be spongy. Brown rot fungi mainly depolymerize cellulose and hemicelluloses, primarily attack softwoods, and leave decayed wood looking brown, brittle and fractured into distinct zones (Goodell *et al*. 2020; Zabel and Morrell 2020).

Natural durability (decay resistance) is defined here as “the inherent resistance of wood to fungal attack” (Scheffer and Morrell 1998). The utilization of naturally occurring wood extractives/oils from unused harvest residues to enhance the durability of the less decay-resistant sapwood is a bio-based alternative to other chemical treatment methods. Treatment with juniper oil may potentially redistribute the natural durability, thereby generating a greater amount of durable wood from western juniper harvest. This study explored ways in which the whole juniper tree (foliage, branches, logs) could be utilized to enhance the natural durability of engineered juniper strandboard for use in highly exposed applications. Therefore, the specific research objectives were: (1) to assess the durability of five strandboard panel types against decay fungi in laboratory microcosms measured by weight loss, and (2) to assess possible impacts of juniper oil impregnation on the internal bond properties of the strandboard.

EXPERIMENTAL

Manufacturing

Slabs containing sapwood and heartwood of western juniper were obtained from two different locations in Oregon. Materials were cut to the length 117 mm and submerged in water at 30 °C for 72 h as a plasticization step before cutting strands. Juniper blocks were cut into strands varying in thickness from 0.6 to 0.9 mm using a veneer slicer. Strands were dried in a rotary drier at 50 °C until they reached a moisture content of 4 ± 1%. Southern yellow pine strands were obtained from an OSB mill in Alabama with average dimensions of 0.6 × 25 × 117 mm (thickness × width × length).

Solid wood and a variety of strandboard specimens were milled and are described in Table 1. Seven control/baseline treatments were included to assess the ability of each test fungus to decay untreated southern yellow pine (Pine-W), the inherent decay resistance of natural juniper sapwood (Sap-W) and heartwood (Heart-W), and the inherent decay resistance of each type of untreated strandboard, including southern yellow pine (Pine-S), mixed juniper sapwood and heartwood (Mix-S), juniper sapwood (Sap-S), and juniper heartwood (Heart-S). The final two treatments were assessed to measure the durability of sapwood juniper strandboards impregnated with juniper oil in strands prior to panel pressing (Pre-S) and panels after pressing (Post-S). The Pre-S and Post-S samples were of interest to explore whether juniper oil would be volatilized by the high pressing temperatures.

Impregnation

Impregnation processes were made on both the juniper strands and strandboard. Strands and panels were oven-dried at 103 °C for 24 h, cooled in a desiccator, and weighed. Western juniper oil (High Country Essential Oils, Fort Jones, CA) was diluted to 10% (vol/vol) in 95% ethanol. Specimens were soaked in the dilute oil solution and kept under vacuum (70 kPa) for 30 min. Afterward, the vacuum was released, and the specimens remained submerged in solution for an additional 30 min. Then they were removed and weighed. Strands were oven-dried at 90 °C for 60 min, and strandboard was dried in the hot press at 0.5 MPa and 90 °C for 60 min.

Panels were made using liquid phenol formaldehyde (PF) resin (GP 265C08 with 49% resin solids, Georgia Pacific Chemicals, Atlanta, GA) with 5% resin solids by weight and 0.5% wax added. Resin was sprayed with a spinning disk atomizer (Model EL-4, Coil Manufacturing, Surrey, Canada) at 10,000 rpm. Three panels with an average density 560 kg/m^3 and dimensions 8 × 254 × 254 mm (thickness × width × length) were fabricated in each group. Single layer strandboard panels were formed on wire mesh without any attempt to orient strands. Panels were pressed at 120 °C with 30 seconds of closing, 240 seconds at position, and 40 seconds to vent. Following panel preparation, decay tests were performed similarly for all solid wood samples and panels.

Testing Procedures

Decay test

Ten replicates per treatment were oven-dried at 50 °C for 48 h and weighed to the nearest 0.001 g. Samples were soaked in distilled water until their moisture contents reached 30% to 40%, placed into individual plastic bags, and sterilized by exposure to 2.5 mrad of ionizing gamma radiation from a cobalt 60 source at the Oregon State University Radiation Center (Corvallis, OR). Resistance to fungal decay was assessed according to procedures described in the American Wood Protection Association (AWPA) Standard E10-16 (2020).

Briefly, decay chambers (473 mL French squares) were half-filled with a custom soil blend of 45% sandy loam soil (40% sand, 40% silt, and 20% clay), 42% organic amendments (∼14% each of composted dairy manure, horse manure, and Douglas-fir bark) and ∼13% organic soil building conditioner (Gardner and Bloome®, Carson, CA, USA). Strips of western hemlock (*Tsuga heterophylla* (Raf) Sarg.) for brown rot or red alder (*Alnus rubra* Bong) for white rot test fungi were placed on the soil surface, and the bottles were autoclave sterilized at 121 °C for 100 min. The bottles were inoculated with 5 mm malt agar disks from the actively growing edges of cultures for the two brown rot fungi *Gloeophyllum trabeum* (Pers.: Fr.) Murr. (isolate # Madison 617) and *Rhodonia placenta* (Fr) Niemela, Larss, and Schagel (Isolate No. Mad 698) or the white rot fungus *Trametes versicolor* (L. ex Fr.) Pilát (Isolate # R-105). Inoculated bottles were incubated at 28 °C until test fungi completely covered the feeder strips (~10 days). Sterile test samples were then placed on the surfaces of the feeder strips. The bottles were loosely capped and incubated at 28 °C for 12 or 16 weeks for blocks exposed to brown or white rot fungi, respectively. Non-fungal exposed controls were included to provide a measure of mass losses that occur from block handling.

At the end of the incubation period, samples were removed, scraped clean of adhering mycelium, and weighed to determine moisture content at harvest. The samples were then oven-dried at 50 °C for 72 h and reweighed to determine mass loss. The difference between initial and final oven-dry weight was used as a measure of the decay resistance of each material. The degree of resistance to fungal attack was assessed using the scale described in ASTM D2017-05 (2014), where 0 to 10% weight loss is considered highly resistant to decay, 11 to 24% weight loss is resistant, 25 to

44% is moderately resistant, and >45% is slightly or non-resistant.

Table 1. Specimens for Testing Resistance to Brown and White Rot Fungi

Sample Type	Treatment Description	Sample Dimensions	Identifier
Natural wood	Southern yellow pine	19 mm^3	Pine-W
	Juniper sapwood	19 mm^3	Sap-W
	Juniper heartwood	19 mm^3	Heart-W
Strandboard	Southern yellow pine	19 x 19 x 9 mm	Pine-S
	Juniper (sap/heart mixed)	19 x 19 x 9 mm	Mix-S
	Juniper sapwood	19 x 19 x 12 mm	Sap-S
	Juniper heartwood	19 x 19 x 12 mm	Heart-S
	Pre impregnated sapwood strands	19 x 19 x 9 mm	Pre-S
	Post Impregnated sapwood panel	19 x 19 x 9 mm	Post-S

Mechanical properties

Internal bond strength (IB) was measured on an Instron 5582 universal testing machine with a 100 kN load cell (Waltham, MA, USA) for ten strandboard specimens with dimensions 50 × 50 mm following ASTM D1037-12 (2020).

Statistical Analysis

The data were processed in STATISTICA 10 software (StatSoft Inc., Tulsa, OK, USA) and evaluated using a one-factor analysis of variance (ANOVA) and Tukey's honest significance test (HSD test) to explore differences in weight loss and internal bond strength.

RESULTS AND DISCUSSION

Weight percent gain (WPG) of strands and strandboards treated with the essential oil diluted in the ethanol was 147.2% and 59.3% for strands and strandboards after soaking. Final WPG of the essential oil was 3.1% and 3.3% for strands and strandboards after drying, respectively.

Southern yellow pine strandboards exposed to *R. placenta* experienced average weight losses of 40.8% and weight losses for juniper strandboards were about 2.5%. Based on these results, the former were moderately resistant to decay, and the latter were highly resistant, according to the guidelines in the ASTM D2017-05 (2014). The heartwood of juniper contains cedrol, widdrol, and other sesquiterpene alcohol compounds that show strong termiticidal and antifungal properties (Orejuela 1995; Craig *et al*. 2004; Mun and Prewitt 2011). The presence of biocidal terpenes in the wood, along with other properties, such as high lignin content, were likely major contributors to the high decay resistance of juniper strandboards.

Wood samples exposed to *G. trabeum* showed higher weight losses in comparison to the other fungi. Pine-W and Sap-W showed comparable weight losses of about 44%, which is also comparable with the results of Miyamoto *et al*. (2019), where southern pine wood lost 42.6% of its mass exposed to *G. trabeum*. The highest weight loss, 64.3%, was seen in the southern yellow pine strandboards, which is about 21 times higher than weight loss on the heartwood strandboards, in line with previous observations for similar materials (Wan *et al*. 2007). All of the juniper strandboards had significantly lower weight loss for *G. trabeum* than the southern yellow pine strandboards.

Weight loss for *T. versicolor* on the Pine-W was 26.2% and on juniper heartwood (Heart-W) was 0.2%, which is comparable with the results of Miyamoto *et al*. (2019), 32.2% and 1.2% for pine and juniper respectively. Juniper heartwood strandboards exposed to *T. versicolor* showed an average weight loss of 1.1%, which was the lowest value for strandboards. Other strandboards made from juniper and pine had statistically similar results, with higher average values for impregnated specimens (Pre-S, Post-S). Wan *et al*. (2007) reported strandboards with surface layers of the eastern white-cedar and aspen core layer showed weight losses of about 18.5% under *T. versicolor*, which is slightly lower than results here.

Impregnation of strands with juniper oil before and after pressing resulted in variable performance among the different decay fungi. The addition of oil appeared to be more effective at inhibiting the growth of brown rot fungi than white rot fungi, as shown by the mass losses near the uninoculated control for oil impregnated panels for *Rhodonia placenta*. The white rot fungus *Trametes versicolor* caused greater weight loss on impregnated panels than juniper sapwood alone. White rot fungi differ from brown rot fungi in that they produce lignin-degrading peroxidases which utilize a non-specific free radical mechanism to oxidize a wide variety of structural moieties in lignin (Kues 2015). This non-specificity enables white rot fungi to chemically modify a variety of xenobiotic compounds, including plant-based terpenes (Lee *et al*. 2015). This ability may have led to the higher mass losses for impregnated panels for *Trametes versicolor* than the brown rot species.

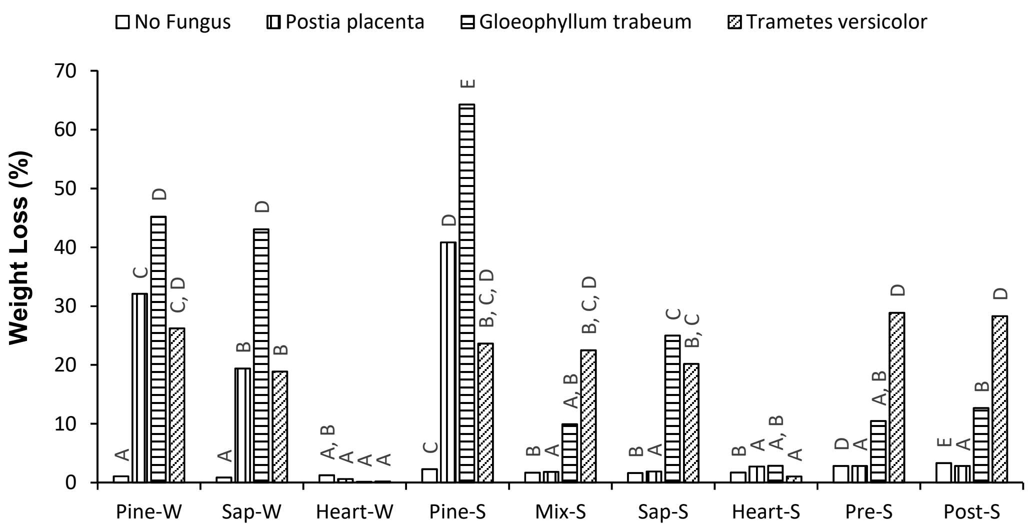

Fig. 1. Weight loss of the wood and strandboard exposed to the different fungi after 12 or 16 weeks for blocks exposed to brown or white rot fungi, respectively

The average internal bond strength values for strandboards are shown in Table 2. The previously reported average internal bond strength for strandboard (624 kg/m^3), with surface layer of eastern white-cedar and aspen core layer (2.4% powdered PF), was 0.36 MPa (Wan *et al*. 2007), which is slightly lower than the IB of the pine (Pine-S) in this research. Pre-impregnation of the strands before manufacturing of the panels compared to post-impregnation resulted in a significant ($p<0.05$) decrease of the IB from an average value of 0.70 to 0.50 MPa. Internal bond strength of Pre-S strandboard was not significantly different than Pine-S strandboard. Internal bond strength for post-impregnated panels (Post-S) was greater than the results for pine (Pine-S). The other strandboards made from juniper strands reached significantly higher IB in comparison to the pine strandboard. In all cases, the juniper strandboards had equal or greater internal bond strength than the pine strandboard.

Table 2. Average Values of Internal Bond Strength of Strandboard at 20 °C and 65% RH

Types of Strandboard	Internal Bond (MPa)
Pine-S	0.42 (0.14) A
Mix-S	0.60 (0.14) B, C
Sap-S	0.90 (0.12) E
Heart-S	0.85 (0.14) D, E
Pre-S	0.50 (0.12) A, B
Post-S	0.70 (0.12) C, D
Means with the same letter in column do not differ statistically by the Tukey's test (α = 0.05). Numbers in parentheses represent standard deviation	

CONCLUSIONS

1. Juniper heartwood has long been recognized as highly durable. Results from this research indicate that strandboard made from juniper heartwood is also highly decay resistant. There appears to be very good potential for manufacturing juniper OSB, especially from heartwood, as a highly decay resistant product. Further, with respect to bond integrity, the findings indicate that impregnating juniper strands with juniper oil prior to pressing results in a significant reduction in internal bond strength compared to panels impregnated after pressing. However, the resulting average IB values for panels made from pre-impregnated strands are similar to those for southern yellow pine panels. Also, juniper strandboard manufactured from non-impregnated strands showed significantly higher internal bond values than pine.
2. One limitation of the research is that the amount of the sapwood in the manufacturing of the strandboards with mixed heartwood and sapwood was not measured. It seems that this is also very important and it can be a next step for better utilization of the juniper wood.

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