EFFECTS OF HYDROTHERMAL MODIFICATION ON THE MECHANICAL PROPERTIES OF RED ALDER (ALNUS RUBRA) NATIVE TO THE PACIFIC NORTHWEST

Abstract

Red alder (Alnus rubra) is a tree species native to the Pacific Northwest and is the most abundant hardwood in the region. Like other tree species native to this region, it is not well suited to exterior use due to poor weathering properties. This research attempts to address these shortcomings by hydrothermally modifying the wood. Hydrothermal modification is a form of wood treatment that uses heat and high-pressure steam to improve the quality of timber. The treatment results in wood that is more resistant to weathering and is less affected by water. The research compared hydrothermally modified Red alder to an untreated control group of the same wood. Previous studies on other species of timber show that a significant shortcoming of hydrothermal treatment is a drop in fracture resistance of the wood. This was similar to Red alder, which had a 38% reduction in its Modulus of Rupture. An analysis of the data using a paired T-test also revealed that the presence of knots in hydrothermally treated wood significantly impacts its mechanical performance. These results lead to a recommendation for using clear wood for hydrothermal modification. Hydrothermal treatment presents an opportunity to create sustainable wood products by increasing resistance to rot and insect damage of existing wood species.

Keywords: Hydrothermal modification, sustainable wood, wood treatment, Red alder.

Introduction

Landscape Architects have had limited choices for sustainable wood products in the Pacific Northwest region (PNW). The Pacific Northwest region refers to the Western North American region of the states of Washington, Oregon, and Idaho. Most trees native to this region, with the notable exception of Western red cedar (Thuja plicata), are not well suited to exterior use due to poor weathering properties, or they are soft and wear rapidly. Western red cedar, a native PNW tree, has a long history of exterior use in construction however, the price premium reflected in its cost makes its use cost-prohibitive for less premium applications. Wood product options for exterior use in the region have shifted from using less competitive local wood species to importing tropical hardwoods and/or chemically treating non-native softwoods to increase resistance to rot and insect damage. More recently, a new generation of treatments including chemical and thermal modification have been used on wood species grown outside of the region (Hill, 2006). Chemical treatment of wood, though relatively well-researched and effective at treating the wood (EPA, 2022), has its share of environmental impact through its production processes and the leaching of chemicals into the environment through their long-term use (Washington State Department of Ecology, 2022). As designers look to extend the longevity of wood products, promote sustainable materials, and protect the local environment, while moving beyond local and federal standards, a shift from chemically treated to thermally treated products could prove beneficial in meeting these goals. Thermal modification is an environmentally friendly process known to effectively improve wood decay resistance; however, it results in a loss of some mechanical properties (Bi, Morrell, Lei, Yan, & Ji, 2022). Hydrothermal treatment, an improvement on the thermal modification process through the addition of steam for more effective heat transfer, improves the modification process and potentially opens more uses for previously underutilized tree species (Ganguly, et al., 2018). Given the overall properties of thermally modified timber (TMT), a potentially good use for TMT products in landscape architecture would be as an exterior decking finish material/wear surface. The absence of locally produced TMT options in the Pacific Northwest market presents an opportunity to utilize existing commercially viable technologies with a history of performance in combination with Pacific Northwest tree species that are a part of the existing regional forest industry to produce wood products with an extended useful life in exterior applications while also improving the local ecology through restorative forest practices (Carey & Cutis, 1996). The research presented in this study explores the effect of hydrothermal modification on the mechanical properties of Red alder (Alnus rubra), the most abundant hardwood in the Pacific Northwest.

Literature Review

Chemical Treatment of Wood

Currently, the prevailing option available for exterior wood construction for most homebuilders nationwide is Southern yellow pine (Dunn, Shupe, & Vlosky, April 2003) and Cedar. The timber products from these trees are extensively used to produce dimensional lumber and plywood products in the United States. For exterior use, wood is pressure treated with Alkaline Copper Quaternary (ACQ), a copper-based wood preservative, to protect it from fungi and insects (EPA, 2022). ACQ replaced Chromated Copper Arsenate (CCA), which contained arsenic, a hazardous chemical and a known carcinogen (Dobson, 2017) (Campbell, Donald, & Simpson, 2005).

In Washington state, Douglas fir, Pseudotsuga menziesii, is the principal wood used for pressure-treated exterior wood applications (Western Wood Products Association, 2022) (Carey & Cutis, 1996) using similar ACQ treatments at rates that vary per the intended use.

ACQ treatment has several shortcomings. First, the treatment results in products that are corrosive to nails, screws, and other metal fasteners (Writer, 2020). Second, ACQ, like other chemical treatment methods, does not completely penetrate the wood grain of timber, resulting in the inner part of the wood remaining untreated (So, Eberhardt, Lebow, & Groom, 2006). Methods to improve chemical penetration include incising the wood's surface which degrades the finished timber's mechanical properties. Third, though ACQ treatment results in 14 times lower emissions than wood plastic composite (WPC) products (Bolin & Smith, 2011), the ACQ production system generates some air pollution in the form of ammonia (NH3), a known greenhouse gas (Chen, 1994). Additionally, the same literature sources indicate high leaching of the active ingredients from ACQ treatment (copper, TKN, TOC) in run-off. Copper, in humans, is essentially non-toxic though it has been associated with dermal sensitivity in high concentrations (Cushing, Lowney, & Holm, 2007). Copper is, however, toxic to salmon and other fish, making ACQ products a barrier to certain certification programs such as Salmon-Safe (BENNETT, 2022). Considering all the points mentioned above, the ethical discussion surrounding the use of ACQ treatment should involve considering various perspectives, including the role of human beings in environmental conservation, how our choices affect the public health of the surrounding community, downstream economic impacts of our choices, and the balance between human activities and the well-being of ecosystems.

Current Regional Practice

For appearance-grade exterior architectural applications, non-native wood species and alternate materials dominate the Pacific Northwest market. Historically, western red cedar or redwood was used for decking, siding, and fencing. Due to the limited availability of old-growth timber and the wood's relatively soft material characteristics, the market has shifted toward several alternatives. Alaskan Yellow Cedar is one such alternative that closely compares to red cedar in relation to its natural characteristics. Like red cedar, it has high insect and decay resistance making it one of the 'world's most durable woods (Duffield Timber, 2022). One shortcoming though is that it does tend to slowly darken over time and presents a distinctive silvery-grey appearance if left untreated. Northern White Cedar is another alternative to red cedar. Usually found growing in the northeast region of the United States, these trees tend to be short, growing to a height of 65 feet. They have a high resistance to rot and insect attack and have a straight wood grain and fine texture. This wood species, however, tends to be quite soft and is plagued with numerous knots making it sometimes challenging to work with. Internationally, Siberian Larch is the closest softwood competitor to Red cedar. It is naturally durable and scratch resistant, making it the hardest softwood (Duffield Timber, 2022). It is, however, visually different from red cedar, it presents as golden yellow, and given current sanctions against Russia, its availability and cost vary accordingly. Heat-treated Ayous, also known as African whitewood (Triplochiton scleroxylon), is incredibly durable, stable, and long-lasting, however it is typically priced along the higher end of the market, and like red cedar is more prone to scratches, abrasions, and indentations than other hardwoods (Duffield Timber, 2022). European Oak coming from France, Germany, or England, is stronger, heavier, and tougher than its American equivalents. It is relatively more expensive but is available in longer lengths (Hardwood Area, 2021). In the Northwest, Douglas fir is the most readily available red cedar replacement. It is widely regarded as one of the world's best timber-producing species and yields the highest amount of timber in the Western US, about 34% of all US lumber exports, and over 1 billion board feet (Carey & Cutis, 1996). It is harder than most softwoods and is considerably decay resistance. As noted earlier, it is currently utilized after ACQ treatment. In summary, native PNW trees face stiff competition from other non-native trees. As illustrated above, native species have certain short coming in terms of appearance, rot resistance, scratch resistance, abrasions, indentations, durability etc. Non-native species offer alternatives with improved performance against native species, contributing to the decline of native tree species use in the timber market.

US Lumber Industry

In the United States, the primary construction application for exterior decking wood products is residential repair and remodel (approximately 86%), followed by new home construction (approximately 14%) (Ganguly, Eastin, Crespell, & Gaston, 2010). In line with these metrics, research in 2001 found that approximately 6.5 million decks are constructed in the US annually at a cost of between $1.9 to $3 billion, with an average annual rate of 8.1 percent (Shook, Eastin, & Fleishman, 2001). Additionally, R.E. Taylor & Associates (2002) estimated the current retail value of the residential decking market at about $2.5 billion in 2002. Despite the enormous size of the residential decking market, limited research is available on the current size, and current estimates could be upwards of $8.5 billion.

Thermal Modification

Thermal modification, specifically Hydrothermal treatment, presents a potential alternative to chemical treatment and a way to improve the quality of timber produced by local species.

Thermal modification is a treatment that uses heat to alter the chemical composition of timber. Thermally Modified Timber (TMT) is produced by heating wood up to a temperature range of 180–260 °C. Unlike chemical treatment, thermal modification enhances the wood throughout the grain, not just the outer surface. Hydrothermal treatment is a form of thermal modification under high-pressure steam. The application of steam allows for a more effective heat transfer compared to conventional heat treatment without steam. The resulting wood product from this process is more dimensionally stable, less hygroscopic, more resistant to weathering, and presents an improved color uniformity and stability that is darker (Ganguly, et al., 2018). Previous research on Thermally Modified Spruce Timber confirmed its suitability for outdoor use but pointed to a drop in fracture resistance (Blokland, Adamopoulos, & Ahmed, 2020). Several researchers are working to address the structural shortcomings of TMT wood products. One such paper outlines the use of wax impregnation to improve the thermal modification of wood. This paper found improvements to certain properties already improved by thermal modification, such as water resistance (Humar, et al., 2016). A similar paper explores the concept of densification of wood. Densification, the author stated, results in improved surface hardness (They also note that it might be particularly suitable for flooring products). The author, in particular, noted that the increase in density of the wood from densification is only maintained under moisture conditions when the wood is thermally modified (TM) after densification, potentially linking to a future study that this work can look at to explore this further (Laine, Segerholm, & Walinder, 2016).

Improvement of wood through the addition of several components eventually leads to a subset of wood products referred to as composite wood products. The Beijing Key Laboratory of Wood Science and Engineering has done work on the development of high-performance wood composite materials by wood metallization. Researchers noted that this metallic wood was 5.85 times denser and 3 times and 10 times higher in compression strength and thermal conductivity than unmodified wood (Zhao, et al., 2022)

Ecological, Economic, and Ethical Argument

Shifting back to the ecology of the PNW, some of the tree species indigenous to the region include Douglas fir (*Pseudotsuga menziesii*), Western hemlock (*Tsuga heterophylla*), Ponderosa pine (*Pinus ponderosa*), Western red cedar *(Thuja plicata)*, Sika spruce *(Picea sitchensis)*, Red alder (*Alnus rubra*) among others. The lack of competitiveness of local species becomes especially worrying when you investigate the metrics of commercial forest ownership in the region. In Washington, 47% of forests are working forests used for harvesting (WFPA, 2023). Of these forests, nearly 70% of the timber harvested comes from privately owned forests (WFPA, 2023). The private forests are further split down to about 60% of these classified as being managed by "industrial private forest landowners" the other 40% consists of small family tree farmers and private individuals (WFPA, 2023). Looking at this data, suggests that the private sector plays a key role in forest management. To avoid the economic pressure to replace indigenous trees, along with the plant ecologies and the animal habitats they provide, with other lucrative non-indigenous species of trees, it is vital that we improve the economic viability of our native trees. A utilitarian argument for incentivizing these private owners to maintain indigenous forests is by making these trees and associated products competitive. By creating these competitive products, we can help create economic conditions that enhance societal benefits. These goals align with the basic utilitarian goal of maximizing happiness and well-being for the greatest number of people (Nathanson, 2014).

With the shortcomings of native species and the competition from non-native species listed in section 2.2, it is easy to explain the reduced market share of PNW native species. Hydrothermal modification provides an opportunity to improve some of these shortcomings and add value to these species. Hydrothermal modification is ecofriendly and can also help to reduce the use of chemical treatment that has a significant impact on the environment (section 2.1). The growing timber market provides an economic opportunity to launch products to tap into this demand. In the following chapters this research will give a detailed report on the application of hydrothermal modification to Red alder and the results from testing of the resulting wood products.

Research Methodology

The research method selected for this study was an experimental approach. Red Alder was sourced and grouped into “thermally modified” or “control wood” to determine the efficacy of thermal modification. The thermally modified group was treated, while the control group was not. Once this was done, the two groups were tested using ASTM D198: Standard Test Methods of Static Tests of Lumber in Structural Sizes.

The data obtained from the test was directly compared using spreadsheets and graphs. In addition, the Modulus of Elasticity, Modulus of Rupture, and Max Load were compared using a paired-sample T-Test. The sample T-Test was set up using R programming on RStudio using the t.test function.

Data Collection & Analysis

Wood Sourcing

Northwest Hardwoods, located in Centralia, Washington, donated the wood used for testing. The donated wood consisted of 24 pieces of 2 in. x 4 in. x 8 ft. samples of Red Alder.

Figure 1: Donated wood from Northwest Hardwoods

The wood was transported from Centralia, Washington, to the University of Washington's School of Environmental and Forest Sciences' Lab in Seattle. Once there, each of these 8 ft. samples was coded and cut into two 4 ft. pieces.

The wood was also visually inspected to note any visual defects in the wood. These observations were in the form of location and size of knots and or cracks on the wood. See Knot Sheet in the Appendix.

Figure 2: Sample of a coded 8 ft. plank of lumber

These resulted in two separate stacks of 24 4 ft. pieces of lumber.

Figure 3: Two separate stacks of 24 4 ft. pieces of lumber

The two stacks were grouped either as;

i. Thermally modified (TMRA)
ii. Or Control (CRA)

Wood Treatment

The stack designated as Thermally modified (TMRA), was sent to Therma Wood Technologies (TWT) in Polson, Lake County, Montana. There the wood underwent the process of thermal modification (covered in the literature review). TWT is a specialized Industrial Thermal wood producer. They focus on modifying several regional tree species, including:

1) Clear Vertical Grain Western Hemlock
2) Small Tight Knot Hemlock
3) Ponderosa Pine
4) Southern Yellow Pine
5) Douglas Fir (TWT, 2023)

Based on their experience, TWT has developed several Kiln schedules for the species of wood they process.

Once the modification was completed, the TMRA, along with the Control wood was sent to Washington State University to undergo Strength Testing.

Wood Testing

At Washington State University, the wood was tested based on ASTM D198: Standard Test Methods of Static Tests of Lumber in Structural Sizes. These standard testing methods are used to evaluate the physical properties of various wood to determine their flexural properties.

The testing employed the flexure method, which is a testing method listed in ASTM D198. For this test, a structural wood member is supported at its ends while a flexure load is either applied in the center or (as in this case) at two points equidistant from the supporting locations (ADMET, 2023). The wood was loaded into the four-point bending test, flexure test, and loaded till failure (breakage).

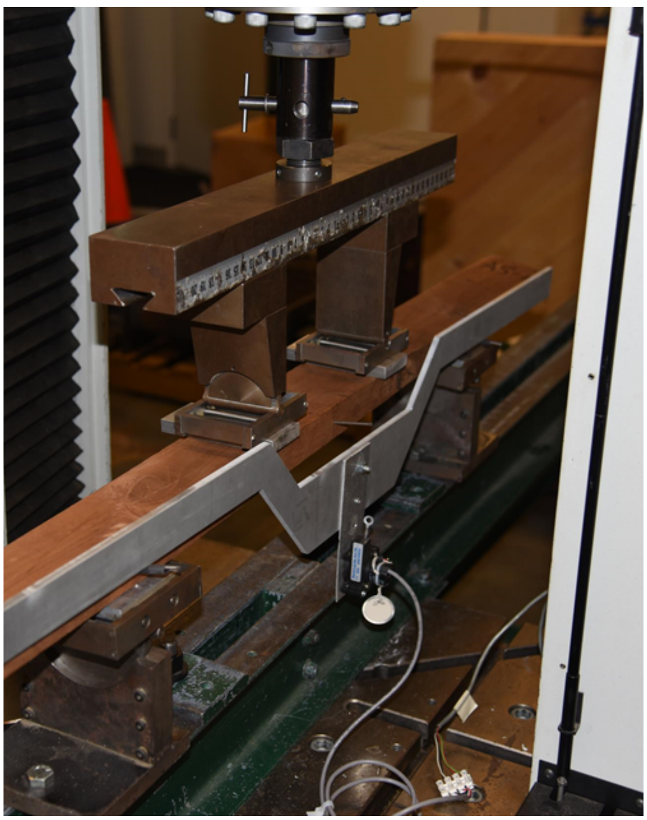

Figure 4: TMRA Undergoing Static Tests

The testing method was applied to both the thermally modified wood and the control wood, and the following data was recorded about each sample.

1) Average Width (in)

2) Average Depth (in)
3) Density (lb. ft 3)
4) Modulus of Rupture (psi)
5) Apparent Modulus of Elasticity (psi)
6) Max. Load (lbf)
7) Moisture Content (MC)
8) Specific Gravity (SG)
9) Failure Type

Results and Discussion

The data obtained from testing was in the form of two tables representing the TMRA and CRA test data.

Specimen no.	Average Width (in)	Average Depth (in)	Density (lb.ft-3)	Modulus of Rupture (psi)	Apparent Modulus of Elasticity (psi)	Max. Load (lbf)	MC	SG	Failure Type
TMRA1	3.328	1.348	27.1	3,210	1,380,000	718.4	15.8%	0.45	tension @ load point
TMRA2	3.341	1.333	30.1	3,640	1,172,000	801.3	11.8%	0.53	tension @ center
TMRA3	3.358	1.305	28.5	1,290	745,000	272.2	12.8%	0.49	knot @ center
TMRA4	3.353	1.340	27.7	6,350	1,462,000	1,415.0	13.6%	0.52	tension @ center
TMRA5	3.346	1.332	28.1	3,140	1,225,000	691.0	12.5%	0.48	knot @ center
TMRA6	3.354	1.334	27.8	2,740	1,109,000	604.8	13.7%	0.46	knot @ center
TMRA7	3.345	1.326	29.5	5,730	1,318,000	1,248.0	15.8%	0.50	tension/knot @ center
TMRA8	3.335	1.302	28.7	7,600	1,776,000	1,591.0	9.4%	0.43	tension @ center
TMRA9	3.304	1.346	29.0	4,280	1,106,000	947.9	10.6%	0.50	tension @ center
TMRA10	3.304	1.329	27.8	5,170	1,780,000	1,117.0	11.3%	0.46	tension @ load point
TMRA11	3.301	1.300	29.6	4,210	1,336,000	869.8	11.6%	0.45	tension @ load point
TMRA12	3.327	1.339	30.1	5,940	1,579,000	1,311.0	10.8%	0.45	tension @ load point
TMRA13	3.327	1.329	28.1	8,400	1,707,000	1,827.0	12.7%	0.46	tension @ center
TMRA14	3.333	1.309	29.9	7,250	1,933,000	1,533.0	11.0%	0.46	tension @ center
TMRA15	3.317	1.267	29.2	2,670	1,990,000	526.7	9.9%	0.44	tension @ load point
TMRA16	3.305	1.310	28.6	6,230	1,662,000	1,310.0	10.9%	0.44	knot @ load point
TMRA17	3.364	1.282	26.2	3,750	1,800,000	767.5	11.1%	0.41	brash @ center
TMRA18	3.331	1.294	27.8	3,990	1,632,000	824.7	10.9%	0.42	tension @ center
TMRA19	3.306	1.318	29.2	8,000	1,598,000	1,702.0	9.0%	0.45	brash@ center
TMRA20	3.341	1.317	26.3	3,700	627,000	794.9	12.3%	0.43	knot @ load point
TMRA21	3.309	1.327	29.6	9,510	1,852,000	2,051.0	11.4%	0.52	tension @ center
TMRA22	3.309	1.343	28.4	3,090	1,413,000	683.8	8.2%	0.47	brash @ center
TMRA23	3.353	1.343	30.2	2,990	1,067,000	670.1	13.6%	0.52	knot @ load point
TMRA24	3.319	1.317	29.5	4,300	1,487,000	915.7	13.4%	0.50	knot @ load point
Average	**3.330**	**1.320**	**28.6**	**4,880**	**1,448,000**	**1,049.7**	**11.8%**	**0.47**	
COV	**0.59%**	**1.58%**	**4.00%**	**43.49%**	**24.64%**	**43.44%**	**16.08%**	**7.23%**	

Table 1: Thermally Modified Group Test Results

The data recorded above was from the Thermally modified (TMRA) wood.

Specimen no.	Average Width (in)	Average Depth (in)	Density (lb.ft-3)	Modulus of Rupture (psi)	Apparent Modulus of Elasticity (psi)	Max. Load (lbf)	MC	SG	Failure Type
CRA-1	3.365	1.329	29.6	7390	1,438,000	1,658	15.4%	0.46	brash @ load point
CRA-2	3.382	1.355	31.9	8,060	1,529,000	1,854	16.0%	0.50	tension @ center
CRA-3	3.348	1.330	30.5	8,070	1,305,000	1,769	14.4%	0.47	tension @ center
CRA-4	3.356	1.357	29.3	9,600	1,530,000	2,197	14.7%	0.48	tension @ load point
CRA-5	3.413	1.334	30.6	7,070	1,304,000	1,589	15.9%	0.47	tension @ load point
CRA-6	3.378	1.314	30.6	6,510	1,528,000	1,406	14.7%	0.47	brash @ center
CRA-7	3.398	1.340	32.9	7,090	1,344,000	1,601	16.3%	0.50	tension/brash @ center
CRA-8	3.393	1.351	30.9	7,790	1,436,000	1,786	16.5%	0.48	brash knot @ load point
CRA-9	3.364	1.335	32.7	8,530	1,662,000	1,895	15.4%	0.49	brash @ center
CRA-10	3.347	1.338	31.2	10,100	1,502,000	2,241	13.9%	0.48	tension @ load point
CRA-11	3.379	1.330	31.7	7,520	1,560,000	1,665	17.1%	0.50	tension @ load point
CRA-12	3.411	1.342	31.8	6,180	1,251,000	1,405	17.3%	0.49	brash @ center
CRA-13	3.368	1.352	30.7	9,750	1,540,000	2,222	15.1%	0.49	tension @ center
CRA-14	3.340	1.339	32.0	8,140	1,505,000	1,805	14.5%	0.50	tension @ center
CRA-15	3.363	1.327	31.6	7,940	1,387,000	1,742	14.5%	0.50	tension @ load point
CRA-16	3.368	1.331	31.6	9,470	1,628,000	2,094	13.9%	0.47	tension @ center
CRA-17	3.370	1.340	29.1	6,210	1,240,000	1,392	15.6%	0.45	tension @ center
CRA-18	3.423	1.330	30.6	8,530	1,398,000	1,914	17.6%	0.46	brash @ center
CRA-19	3.421	1.336	32.3	7,360	1,627,000	1,663	16.5%	0.50	brash/knot @ load point
CRA-20	3.359	1.332	29.5	7,350	1,002,000	1,623	16.5%	0.45	tension @ center
CRA-21	3.386	1.345	32.9	7,110	1,578,000	1,614	19.1%	0.52	tension @ center
CRA-22	3.353	1.361	30.6	8,320	1,310,000	1,914	15.3%	0.50	tension @ load point
CRA-23	3.361	1.344	32.2	6,260	1,201,000	1,407	14.6%	0.49	knot @ load point
CRA-24	3.358	1.330	32.8	9,980	1,426,000	2,195	14.4%	0.53	tension @ center
Average	**3.375**	**1.338**	**31.2**	**7,930**	**1,426,000**	**1,777**	**15.6%**	**0.49**	
COV	**0.70%**	**0.82%**	**3.69%**	**14.97%**	**11.16%**	**15.03%**	**8.25%**	**4.20%**	

Table 2: Control Group Test Results

The data recorded above was from the Control (CRA) wood.

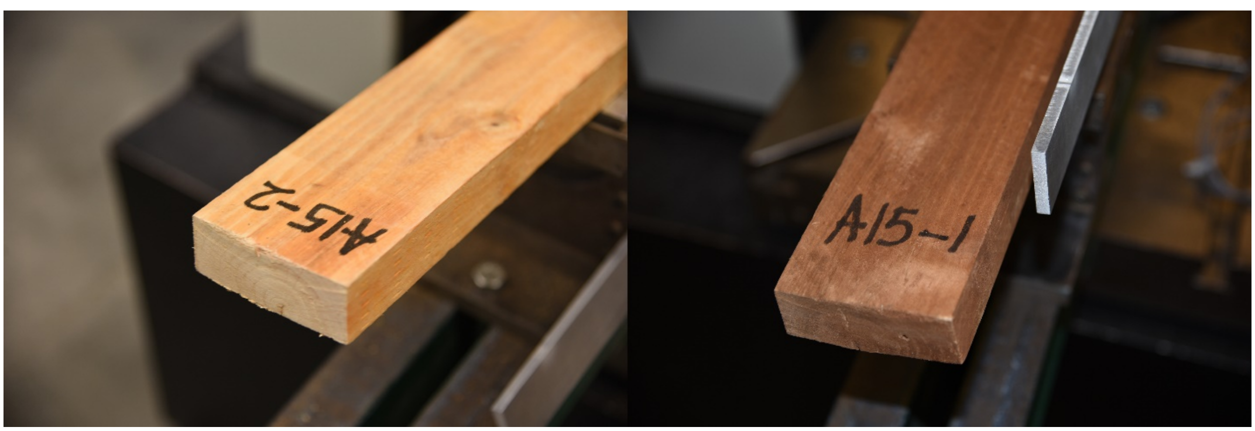

Figure 5: CRA Sample vs TMRA Sample

Each parameter represents the wood's mechanical properties with the Modulus of rupture (MOR), Apparent Modulus of Elasticity (MOE), and Max load representing the main mechanical properties tested. By comparing the results from the thermally modified wood to the control group, several inferences were deduced and are discussed in the coming paragraphs. The comparison was based on two factors:

I. Differences within the same tree stands (DST):

This is the difference obtained by first grouping both the TMRA and CRA from the same tree stand (i.e., TMRA1 and CRA1) averages across all the sample groups.

II. And the Average difference (AD):

It was obtained by comparing the average values at the base of each table group.

Dimensional Change

Dimensional Change refers to the average width and depth of the samples. After the modification, it was noted that the wood dimensions slightly decreased. The AD width was 3.375” in the CRA sample and 3.330” in the TMRA sample. The exact noticeable change is observed in the AD depth, where the CRA was 1.338” and the TMRA was 1.32”. The AD change represents a reduction of 1.35% in width and 1.35% in depth. This was like the DST that had a reduction by 1.34% in width and 1.35% in depth. The change is relatively small but consistently represented across all the tested samples.

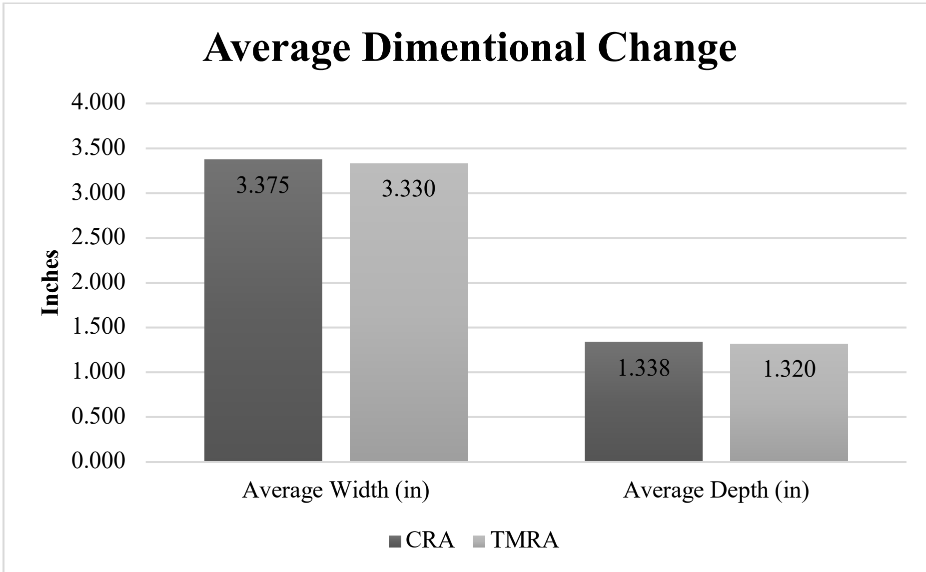

Figure 6: Graph of the AD Dimensional Change

Density and Specific Gravity

Density, which is defined as the mass of an object in a unit volume, is also slightly reduced across all the samples. The AD density of the CRA samples was 31.2 lb./ft^3 vs. 28.6 lb./ft^3 in TMRA, an 8.4% reduction which was like the 8.39% observed in the DST comparison.

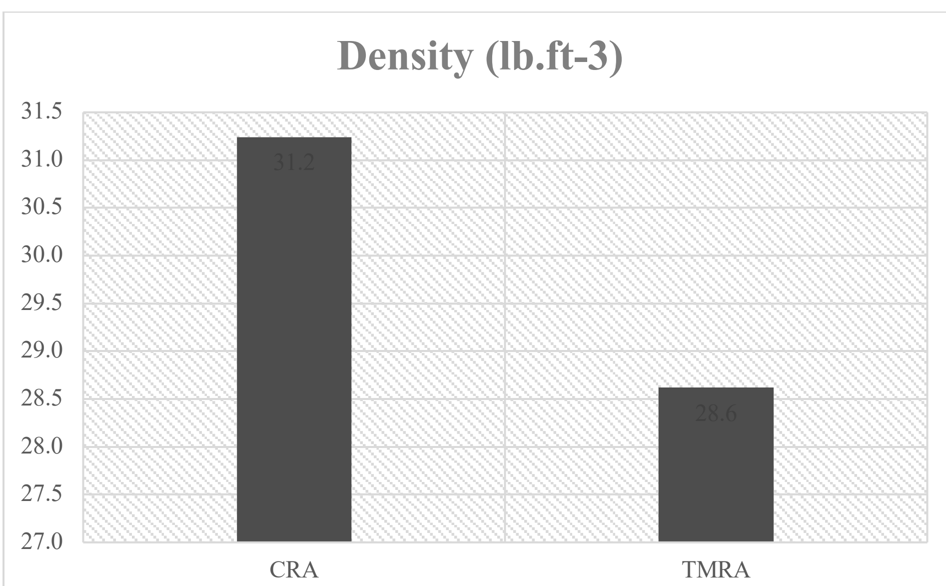

Figure 7: Graph of the AD Density Change

Specific Gravity (SG) relates the density of the wood to that of water. SG also reduced slightly from 0.49 in CRA to 0.47 in TRMA, a 3.36% change in the AD figure which was like the 3.36% in DST.

Moisture Content (MC)

Moisture content or water content is the amount of water contained in a material. This also reduced by nature of the drying effect of the treatment. The AD MC of the CRA samples was 15.6% vs. 11.8% in TMRA, a 24.27% reduction which was like the 23.65% observed in the DST comparison.

Modulus of Elasticity (MOE)

Modulus of Elasticity, also referred to as elastic modulus, quantifies the woods' resistance to non-permanent, or elastic, deformation. The change in this mechanical property between the TMRA and the CRA was negligible with 1,426,000 psi and 1,448,000 psi, respectively, which was a -1.54% change in the AD comparison vs a -1.51% in the DST.

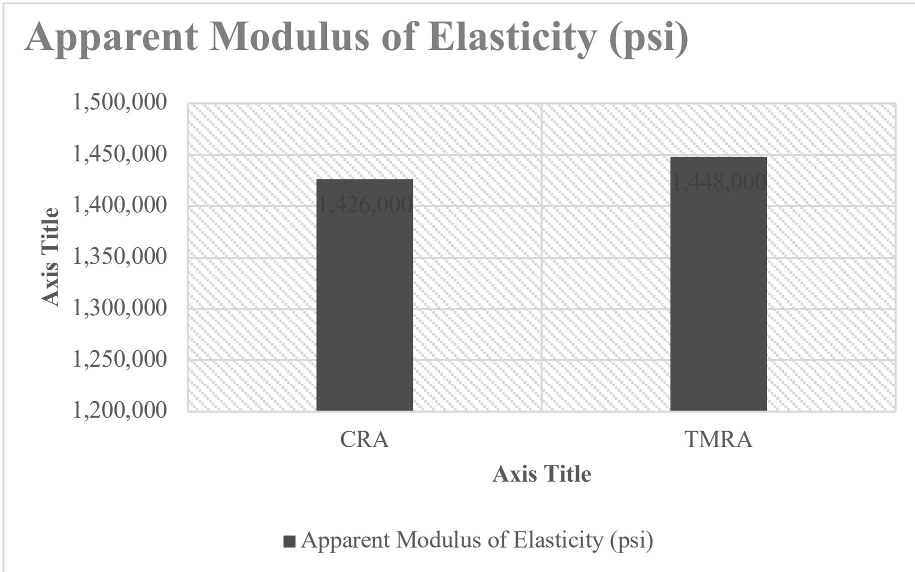

Figure 8: Graph of the AD MOE Change

Modulus of Rupture (MOR)

Modulus of Rupture, also known as flexural strength, bend strength, or fracture strength, is defined as the final strength related to the failure of the beams by the flexibility equal to the moment of bending in the fracture divided by part of the beam section (Ashby, 2011). The MOR represents the highest stress experienced in the wood at the point of failure. As noted in the previously covered literature, this mechanical parameter has the most significant reduction and is the main disadvantage of the Hydrothermal modification process. Based on the AD comparison, the CRA had a MOR of 7930 psi and 4880 in the TMRA, a 38% difference. Based on the DST comparison, the difference saw a 37.85% reduction in strength.

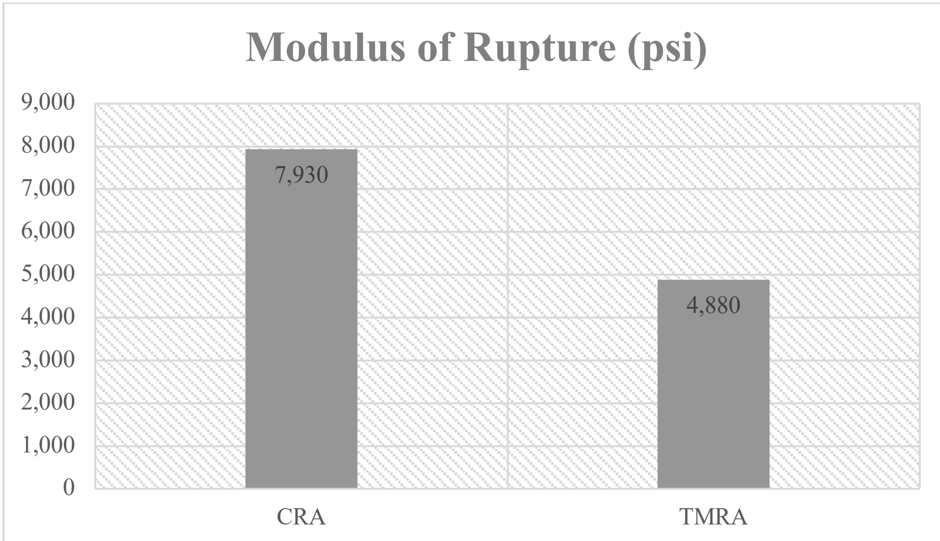

Figure 9: Graph of the AD MOR Change

Max Load

The Max Load is also known as the load bearing or hardness of the wood. Based on the AD comparison, the CRA had a Max Load of 1,777 lbf and 1,049.7 lbf in the TMRA, a 40.93% difference. Based on the DST comparison, the difference saw a 40.93% reduction in strength.

Failure Type

The test data also recorded the various modes in which the wood failed while under the mechanical test. As earlier noted, the wood was subjected to a four-point bending test and the failure was recorded whether it was either a knot, tension, or brash and whether it occurred at the load point or center. Knots are wood imperfections; hence these failures are analyzed separately.

T-Test

A T-test is an important analytical tool that helps to compare two data groups: specifically, the CRA and the TMRA data groups in our use case. Using a T-test, one can compare the means of two data sets to see whether their means are similar or whether their differences are statistically significant.

To execute the T-test, the research utilized R, a programming language used to perform statistical computing. This code was written using the integrated development environment (IDE) RStudio. The analysis was limited to the main mechanical parameters that influence the wood's performance as a construction material, i.e.

i. Modulus of Elasticity
ii. Modulus of Rupture
iii. Max Load

The data for each of these properties was compared directly according to whether they were in the control group (CRA) or the modified group (TMRA). The data was also compared based on the failure type, a key parameter recorded in the research data. The failure was grouped as either a knot failure or 'other' failure.

The data output was synthesized into a .CVS file (found in the appendix) and loaded into the code. The results from the analysis were:

a. Box plot graphs: The middle line showing the mean, and the length of the plot showing variation in the data.
b. Analysis of variance (ANOVA) Tables: Used to determine whether the mean of the variables is equal. The P-value specifically is used to determine whether the difference in mean is statistically significant. If the p-value is less than .05, we can conclude that the difference between the mean is statistically significant. Otherwise, a P-value that is less than 0.05 indicates that the mean is not statistically significant.

Modulus of Elasticity

After running the T-test analysis on the data from the MOE, several box graphs were developed based on the data and are displayed below:

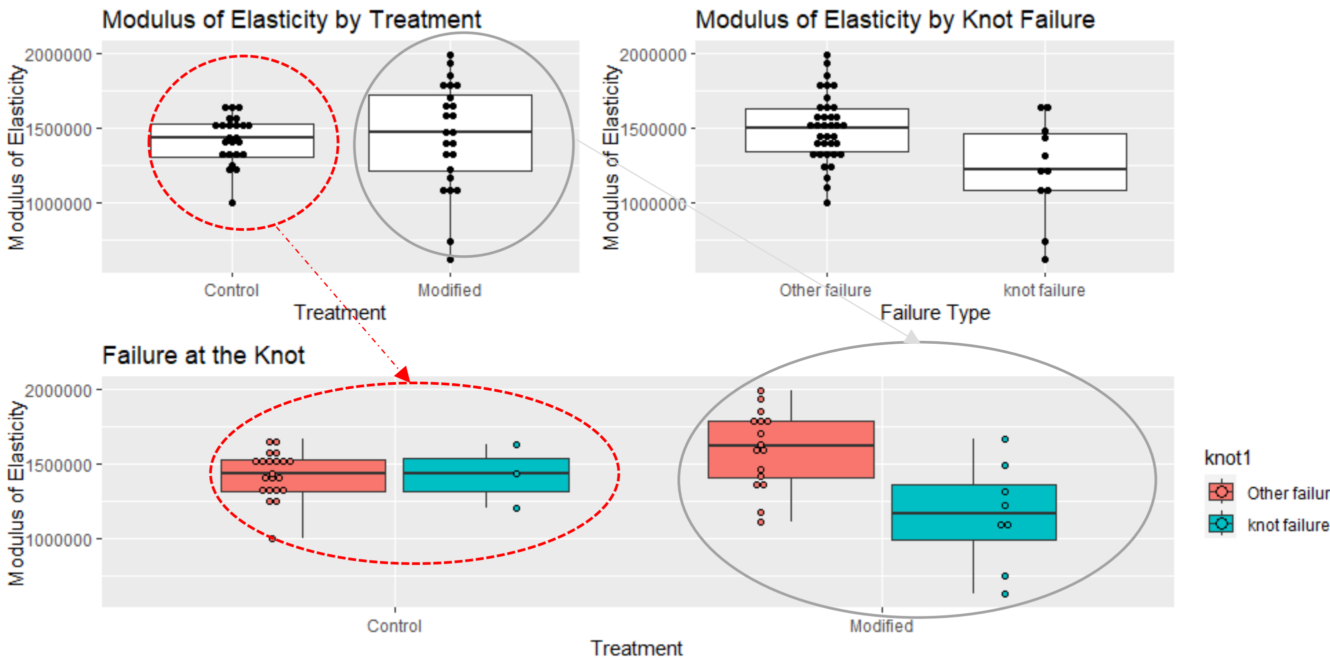

Figure 10: Box Plot Graph of MOE

The first graph (treatment) shows a box plot of the MOE results for the control (CRA) and the modified (TMRA). The closeness of the middle line in each plot, representing the mean, indicates that the mean MOE in both the CRA and TMRA is very similar. The P value of the Treatment graph in the ANOVA table (0.7511) also shows that the mean is likely to be statistically similar. However, looking at the length of the modified results box plot indicates that there is a large degree of variability in the MOE of the TMRA.

		Df	**Sum Sq**	**Mean Sq**	**F value**	**P value (Pr(>F))**

1.	**Treatment**	1	5.742e+09	5.742e+09	0.102	0.7511
2.	**Failure Type**	1	7.000e+11	7.000e+11	12.420	0.0010 **
3.	**Treatment and Failure Type**	1	3.315e+11	3.315e+11	5.882	0.0195 *
	Residuals	44	2.480e+12	5.636e+10		

Table 3: ANOVA Table of MOE analysis

When sorting the data and plotting it in terms of knot failure and other failure, we see that the wood with knot failure has a mean that is statistically different from the other failure (P value = 0.0010**).

The third chart combines the two previous charts by grouping both the Control and Modified MOE based on the failure type. In the control (CRA), the mean MOE is likely to be similar whether the wood experienced knot failure or other failure. However, the modified wood (TMRA) had different means based on the failure type, with knot failure having a significantly less mean and the other failure having a similar mean to the control wood. **This indicates that the CRA and TMRA are likely to have similar MOE values, in the absence of knot failure.**

Modulus of Rupture

Similarly, the T-test analysis on the data from the MOR was developed and is displayed below:

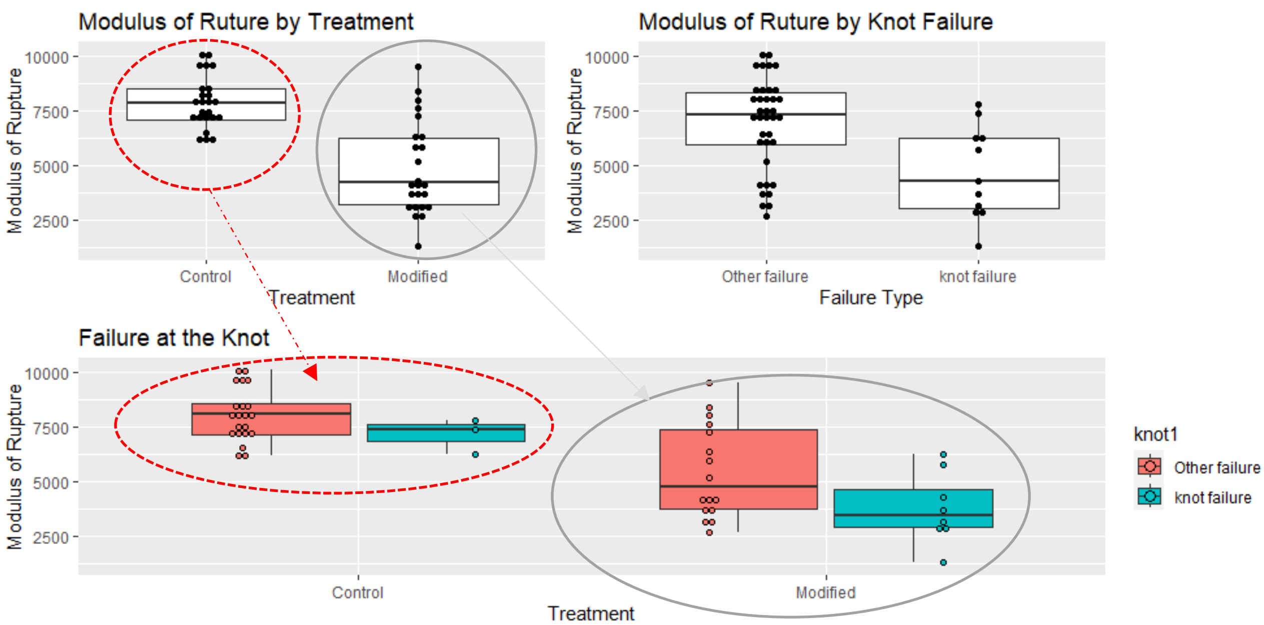

Figure 11: Box Plot Graph of MOR

The first graph (treatment) shows a box plot of the MOR results for the control (CRA) and the modified (TMRA).

		Df	Sum Sq	Mean Sq	F value	P value (Pr(>F))
1.	**Treatment**	1	6349038	6349038	49.292	1.07e-08 ***
2.	**Failure Type**	1	703770	703770	5.464	0.024 *
3.	**Treatment and Failure Type**	1	52961	52961	0.411	0.525
	Residuals	44	5667356	128804		

Table 4 ANOVA Table of MOR analysis

The MOR from the Control is significantly different from the modified wood (P Value = 1.07e-08 ***). In the second graph (Failure Type), it is noted that there is a difference between knot failure and other failure types, with the knot failure being significantly lower (P Value = 0.024 *). However, when looking at the length of the box plots, the range of data is similar.

In the third chart combining the two previous, **the failure type does not affect the overall difference between the Control and the Modified wood (P Value = 0.525).**

Max Load

Lastly, the T-test analysis on the data from the Max Load was developed and is displayed below:

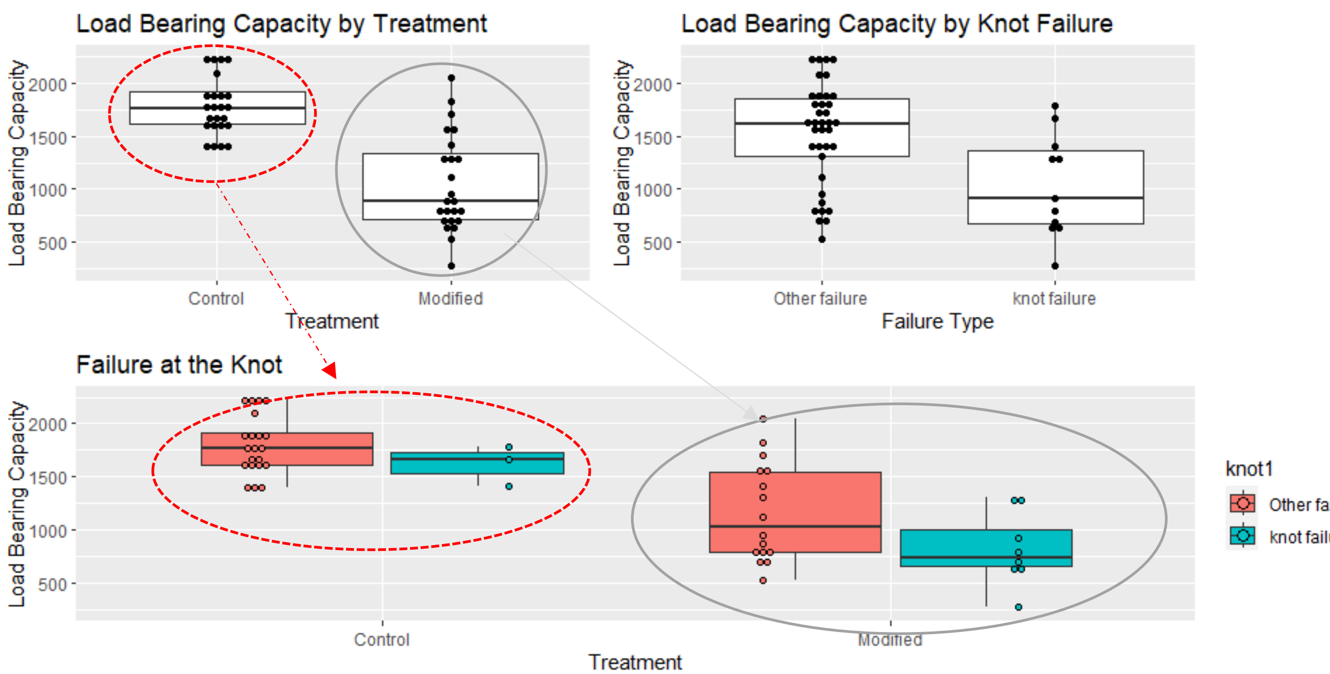

Figure 12: Box Plot Graph of Max Load

The first graph (treatment) shows a box plot of the Max Load results for the control (CRA) and the modified (TMRA).

		Df	Sum Sq	Mean Sq	F value	Pr(>F)
1.	**Treatment**	1	111477552	111477552	41.269	8.02e-08 ***
2.	**Failure Type**	1	16105219	16105219	5.962	0.0187 *
3.	**Treatment and Failure Type**	1	1040590	1040590	0.385	0.5380
	Residuals	44	118854937	2701249		

Table 5: ANOVA Table of Max Load analysis

The Max Load from the Control is significantly different from the modified wood (P Value = 8.02e-08 ***). In the second graph (Failure Type), it is noted that there is a difference between knot failure and other failure types, with the knot failure being significantly lower (P Value = 0.0187 *). However, when looking at the length of the box plots, the range of data is similar.

In the third chart combining the two previous, **the failure type does not affect the overall difference between the Control and the Modified wood (P Value = 0.5380).**

Conclusion

Hydrothermal treatment significantly affected the physical and mechanical properties of the tested Red alder. On a surface level, thermally modified wood had a darker color throughout the wood grain compared to the control samples. Based on the drying nature of the modification, the TMRA had a slight reduction in its dimensional properties (width and depth), Density, Moisture Content, and Specific Gravity, mostly attributed to the moisture loss and cellular changes. On a deeper mechanical level, Modulus of Elasticity, Modulus of Rupture, and Max Load were affected by the treatment. An initial review of the data showed that the MOR and the ML properties were reduced significantly from the hydrothermal treatment, while the MOE was largely unaffected and even slightly better. After a deeper analysis of the data using a paired T-test, it was apparent that the failure points and, specifically, knot failure may impact the mechanical properties of the wood. For MOR and ML, the wood shows an insignificant reduction in strength based on the presence of knots in both the TMRA and the CRA. However, for MOE, both the TMRA and the CRA have a similar mean value when looking at other failure points, but this is significantly lower when factoring in Knot failure, specifically in TMRA. From this data, we can infer that for thermal modification applications, an emphasis on clear wood use is essential to optimize for mechanical performance.

In terms of cost, hydrothermal testing was not as expensive as initially hypothesized, the largest challenge in terms of direct cost was transporting the wood to Montana for the thermal modification processing. Local options for modifying the wood would greatly increase the accessibility of the wood for further application.

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