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DENSIFICATION OF NEW ZEALAND-GROWN REDWOOD FOR IMPROVED MECHANICAL PROPERTIES

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ABSTRACT: Redwood (*Sequoia sempervirens*) has attractive, naturally durable timber, and is an emerging plantation species in New Zealand. Redwood has low density timber, and correspondingly low stiffness and surface hardness. Thermomechanical densification was used to increase the density of either one wood surface or the bulk of the wood, with the aim of improving the mechanical properties to make it suitable for a wide range of end uses. Both densification processes created a density peak >900kg/m^3 1-3mm below the wood surface. Both densification processes significantly increased the surface hardness of the wood. A thermal modification post-treatment substantially reduced the set-recovery (thickness swelling) of the densified wood, which has previously not been demonstrated for this species. The combination of increased hardness, and reduced set-recovery show promise for commercial applications for this product.

KEYWORDS: densification, hardness, *Sequoia sempervirens*, stiffness, thermal modification

1 – INTRODUCTION

Decreasing availability of timber from old-growth forests, combined with growing awareness of the environmental harm caused by deforestation, has increased interest in products made from plantation wood species as sustainable alternatives to high-performing old growth wood species. In order to match the performance of existing wood products, wood modifications are increasingly being used as a means of enhancing the properties of plantation-grown timbers [1].

Native to the West Coast of North America, redwood (*Sequoia sempervirens* (D.Don) Endl.) is being cultivated in increasing quantities in plantations across New Zealand [2]. It is intended as an alternative to imported Western Red Cedar (*Thuja plicata* Donn ex D.Don), for use as cladding and window joinery. Redwood produces durable timber [3], but its low density (~350kg/m^3 [4]) results in low strength and stiffness. This limitation restricts its use in areas prone to mechanical surface damage (e.g. flooring, decking) or structural applications such as wide spans between joists in a wooden decks. Densification is a promising method for improving the surface hardness and mechanical properties of redwood, making it suitable for a wider range of applications.

Thermomechanical densification involves heating wood and compressing it to flatten the wood fibres, creating a dense layer. This dense region can be produced either as a thin surface layer, or distributed throughout the entire thickness of the wood [5]. Surface densification typically involves lower levels of compression to increase the surface hardness without unduly reducing the sample thickness. Bulk densification involves compressing wood to a much greater degree, resulting in compression and hardening throughout the entire thickness of wood. Both densification processes can be applied to a wide range of wood species, including both softwoods and hardwoods [6, 7]. One challenge with the densification process is that, without a suitable post-treatment, the wood may swell and regain a proportion of its original dimensions when exposed liquid water [5]. Previous work densifying redwood found high levels of set-recovery following water soaking of surface densified wood, with 21-86% of the original uncompressed thickness being regained following water soaking [8]. Several post-treatment methods have been explored in previous studies, including thermal modification [9], to reduce the irreversible swelling and to improve other wood properties. Thermal modification involves heating the wood to high temperatures in the absence of oxygen [10], increasing the dimensional stability by reducing wood shrinkage and swelling caused

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by changes in moisture content. Additionally, thermal modification can improve the durability of wood when performed at a sufficiently high temperatures.

Surface hardness is an important property for understanding densified timber structure. However, existing hardness tests, e.g., Brinell, Janka, are designed for homogenous materials, whereas densified wood exhibits a sandwich-like structure with differing properties in the surface layer compared to the core. This density gradient through the thickness affects the apparent hardness properties of the material [11]. So, care has to be taken to choose a suitable hardness test that effectively characterises the surface properties of the material and takes into account factors such as elastic recovery. Additionally, the elastic recovery can be substantial in wood, leading to a much greater depth of indenter penetration compared to the residual indentation depth. Previous work on densified poplar and Douglas-fir [12] investigated a range of methods for measuring hardness. Researchers subsequently adopted one of these methods, which involves holding the indenter at maximum load for a short time period and using the maximum indentation depth to calculate the hardness [13]. This method has also been used here.

2 – PROJECT DESCRIPTION

Redwood boards were densified using two densification processes (surface and bulk densification), then, thermally modified to reduce set-recovery (irreversible thickness swelling following contact with water). Mechanical properties and surface hardness were measured before and after thermal modification, in addition to swelling when samples were soaked in water.

3 – EXPERIMENTAL SETUP

Two 3 m-long redwood logs were harvested from Whakarewarewa Forest near Rotorua in the Central North Island of New Zealand. The logs were cut from trees approximately 100 years old and were cut from 18.5 m up the tree. The logs were live-sawn into nominal 100×50 mm boards with a Lucas 10-30 swing-blade portable sawmill. The sawing pattern was chosen to produce a combination of quarter-sawn and flat-sawn boards. The boards were air-dried in an open shed for 3 months from August to November (late winter to mid-spring). Once the boards had dried to a moisture content of 12-15% MC, they were moved into an enclosed laboratory for several weeks to complete the drying process (EMC conditions in the laboratory are generally around 11% MC). The boards were initially intended to be steamed to recover cell collapse once after drying to 20-30% MC; however, no collapse was observed, making this step unnecessary.

From the dried redwood boards, eight flat-sawn and 8 quarter-sawn boards were selected for densification. Three clear sections, each 390 mm long, were cut from each board, assigned to two densification processes or left as undensified controls. The sections were then machined to their final dimensions as follows:

- Bulk densification: 40×100 mm
- Surface densification: 25×100 mm
- Undensified controls: 20×100mm

To meet the requirements for downstream mechanical testing, the final specimen thickness needed to be 20 mm for all specimens, irrespective of the densification process.

Following machining, a 40 mm long section was cut from each board to determine moisture content and basic density using the water displacement method. This left a 350 mm long board for densification.

Boards were densified individually using a Pinette PEI LAB 800PA laboratory hot press. Since the press lacks a built-in cooling system for the platens, removable platens with water-cooling capability were placed between the wood samples and the press platens (Figure 1). Once the press had compressed the sample to the desired final thickness, the platen heating was turned off, and the sample was cooled to ~30 °C using the inserted cooling platens. A thermocouple, placed between the removable platens and the board's surface, was used to monitor wood surface temperature.

Hot press conditions (Table 1) were chosen to replicate those achievable on the continuous densification press at Luleå University of Technology in Skellefteå, Sweden [14]. Since the press was operated at a controlled closing speed, the closing force was not controlled but was recorded for each run. The range of maximum closing force values is shown in Table 1

Table 1: Hot press treatment conditions

	Bulk Densification	**Surface Densification**
Top Platen Temperature (°C)	150	50
Bottom Platen Temperature (°C)	150	150
Initial board thickness (mm)	40	25
Final Press gap (mm)*	18	18
Densification ratio	0.55	0.28
Closing speed (μm/s)	360	180
Final Platen temperature (°C)	30	30
Maximum Press closing force (kN)	164 to 272	120 to 202

* The target final board thickness was 20 mm, so, a smaller press gap was chosen to account for the spring-back.

Figure 1. The employed hot press including removable cooling platens and the thermocouple for measuring board temperature. .

Board dimensions (width, length and thickness) were measured before and after densification. The measured values were used to determine spring-back (recovery of board thickness immediately after pressing) and width expansion values:

$$Spring - back = \left(\frac{t_d - t_t}{t_o - t_t}\right) \times 100 \qquad [\%]$$

where:
t_o is the initial (uncompressed) thickness of the sample
t_d is the thickness after densification
t_t is the target thickness (press gap)

$$Width\ Expansion = \left(\frac{w_o - w_d}{w_o}\right) \times 100 \qquad [\%]$$

where:
W_o is the original width of the sample
W_d is the width after densification

3.1 Density Profiling

One-dimensional density profiles were measured using a Grecon DAX600 densitometer on 50×50 mm blocks cut from each densified specimen. Density profiles were analysed according to the method described in [15]. The measured metrics are shown in Figure 2. Briefly, PD is the peak, i.e., maximum density, PDi is the depth below the surface of PD and DTh is the thickness of the densified zone, where the density is >80% of PD.

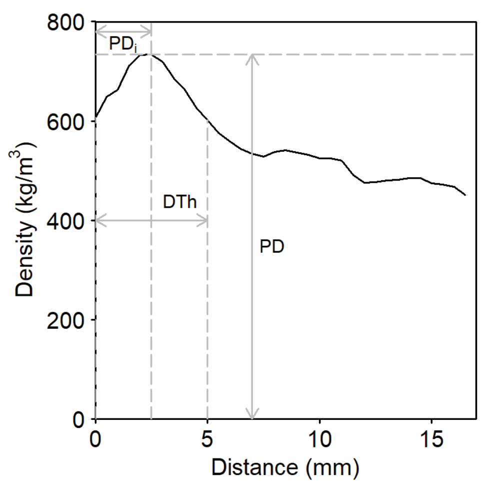

Figure 2. Characterisation of density profiles according to [15]

3.2 Set-Recovery

Each board (2× densification schedules, plus undensified controls) was ripped in half lengthwise. One half was retained for property testing and the second half was thermally modified at 200 °C for 2 hours prior to testing. The thermal modification was performed in the Scion laboratory-scale kiln, with steam introduced to exclude oxygen, but only after the wood temperature exceeded 170 °C, to minimise the risk of liquid water contacting the wood samples and causing swelling.

For both the thermally modified, and unmodified boards, property testing specimens were cut as follows:

- A 20×20mm strip was cut the length of the board for small clears testing.

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- From the remaining board section, a 30 mm long biscuit was cut for set-recovery measurements.

Set recovery was determined as follows:

1. Three points were marked across the specimen width.
2. The specimens were oven-dried, and their thickness was measured at each marked point.
3. The specimens were then soaked in water for 24 hours, after which their thickness was measured, then, oven-dried and their thickness was measured again.

The above process was repeated four times to give five water-soak/oven-dry cycles (finishing with an oven-dry step).

Set-recovery (SR) value is calculated from:

$$SR_{WS} = \left(\frac{t_{wOD} - t_{OD}}{t_o - t_{OD}}\right) \times 100 \qquad [\%]$$

where:
t_o is the initial uncompressed thickness.
t_{OD} is the oven dried thickness following densification.
t_{wOD} is the oven dried thickness following water soaking.

3.3 Mechanical Testing And Hardness Assessment

Small clear specimens were placed in a controlled climate room (20 °C, 65% RH) to equilibrate prior to testing. The bending test was performed according to the method reported in [16]. The densified specimens were randomised so that the uppermost face, i.e., densified face, was pointing up or down during the bending test.

A modified Brinell hardness test was performed, based on the method of Rautkari et al. [13]. An 11.28 mm sphere was pressed with a 1 kN force into the uppermost face, i.e., densified face, of the sample and the force was held constant for 25 s.

The Brinell hardness is calculated by:

$$BHN = \frac{F}{\pi D h} \qquad [\mathrm{kN/mm^2}]$$

where:
F is the applied force (kN)
D is the diameter of the ball (mm)
h is the maximum depth of the indentation (mm)

4 – RESULTS

Spring-back was minimal (average <10%) following densification and was not significantly different between the two densification processes or sawing orientations, so the data is not shown here. Due to the low spring-back levels, the boards' final thickness was very close to the press gap of 18 mm. Only the flat-sawn bulk densified boards had a significantly higher final thickness of 18.9 mm. Width expansion was considerably higher in the bulk-densified boards compared to the surface densification (average 8.5% *vs* 3.1% for surface densification). For each densification process, width expansion was higher in the quarter-sawn boards, although this difference was not significant for the surface densified boards. For the bulk densified boards, width expansion averaged 5.5% and 11.5% for flat-sawn boards and quarter-sawn boards, respectively. It is not surprising that this resulted in significantly higher levels of width expansion, given the much larger degree of compression for the bulk densified boards. The quarter-sawn boards appear to have deformed sideways during densification, possibly due to the stronger latewood cells buckling sideways under load toward the weaker earlywood, rather than being compressed. In contrast, the flat-sawn boards did not show any sideways buckling, but it is likely that most of the deformation occurred in the earlywood, with the latewood cells remaining largely uncompressed. Overall, these results suggest that flat-sawn redwood boards are more suitable for densification than quarter-sawn boards.

4.1 Density Profiling

Table 3 shows the results of the characterisation of the one-dimensional density profiles. Within each densification process, no significant differences were seen between the two sawing orientations, so the results from each sawing orientation have been combined for simplicity. As expected, the bulk-densified boards exhibited a significantly higher peak density compared to the surface-densified boards. The depth of the peak density was greater in the quarter-sawn boards, but this was only significant for the surface densification process. This result contrasts with findings from *Eucalyptus nitens* [17], where the peak density was closer to the surface in quarter-sawn boards. The sideways buckling of the quarter-sawn redwood boards likely results in a more complex pattern of wood deformation and compression within the earlywood rings, causing the cells to be compressed through a greater proportion of the wood's thickness. The depth of the densified zone was narrower for the surface-densified boards, but this difference was not always significant.

Table 3. Density profile of samples treated by each densification process

Densification process	Peak Density PD (kg/m³)	Depth of Peak Density PDi (mm)	Thickness of densified layer DTh (mm)
Bulk Densified	1039[a]	1.87[a]	3.42[a]
Surface Densified	921[b]	2.01[a]	2.46[b]

Superscript letters indicate groups that are not significantly different (95% confidence level)

4.2 Thermal Modification

The process of thermal modification must be performed very carefully to prevent the densified wood from coming into contact with liquid water or excessive steam, as both can cause irreversibly swelling [13]. During the heat-up phase of the modification, the kiln atmosphere's humidity was kept low to minimise the amount of steam required. A constant stream of steam was introduced only after the wood temperature exceeded above 170 °C. Typically in industrial processes, water sprays are used to cool the stack following thermal modification. Here the use of water sprays was minimised, and the boards were allowed to cool gradually. Despite these precautions, liquid water was found on the surface of some boards following thermal modification. The bulk-densified samples exhibited a significant thickness increase following densification, swelling from an average of 18.5 mm to 21.5 mm. In contrast, the surface densified samples did not show a significant change in thickness. Since the thermal modification process requires steam to exclude oxygen from the kiln atmosphere, and water sprays are used to cool and recondition the wood, achieving a balance between using sufficient steam and water for a high-quality result and avoiding excessive amounts that cause wood swelling is challenging. Future work could explore thermal modification with even lower levels of steam and water to determine if the swelling of the bulk-densified wood can be prevented.

4.3 Set-Recovery

The set-recovery test results before and after thermal modification is shown in Table 5. No significant differences in set-recovery were observed between the two sawing orientations, so the results have been aggregated for simplicity. Before thermal modification, both bulk- and surface-densified boards showed very high levels of set-recovery, with an average of 70-80% of the board thickness lost during compression being regained following water soaking. This is consistent with findings in other studies, e.g. [8,18]. Following thermal modification, set-recovery reduced to just over 10%, with no significant difference between the two densification processes. While this represents a substantial reduction, it still amounts to significant swelling, i.e., approximately 2.3 mm and 0.7 mm for bulk- and surface-densified boards, respectively, which may not be acceptable in service. Additional measures, such as applying impermeable surface coatings or employing more intensive levels of thermal modification, may effectively prevent significant swelling. However, further research would be required to examine these approaches.

Table 5. Set-recovery test results for samples before and after thermal modification obtained for each densification process.

Densification process	Post-treatment	Set-recovery (%)
Bulk Densified	Unmodified	79.1[a]
Bulk Densified	Thermally modified	11.0[b]
Surface Densified	Unmodified	73.9[a]
Surface Densified	Thermally modified	10.6[b]

Superscript letters indicate groups that are not significantly different (95% confidence level)

4.4 Hardness

Brinell hardness values for the boards, both before and after thermal modification are shown in Figure 3. Both surface and bulk densification significantly increased surface hardness compared to the undensified controls. These results are similar to those seen in [13] for surface densified Scots pine, although both the undensified and surface densified Scots pine had slightly higher hardness values. Prior to thermal modification, bulk-densified boards exhibited higher surface hardness than surface-densified boards. However, following thermal modification, the surface hardness decreased significantly for both densification processes. This reduction was more pronounced for the bulk-densified boards, resulting in their hardness being comparable to that of the surface-densified boards. This contrasts with the results in [13] for Scots pine, where the surface hardness was essentially unchanged following thermal modification.

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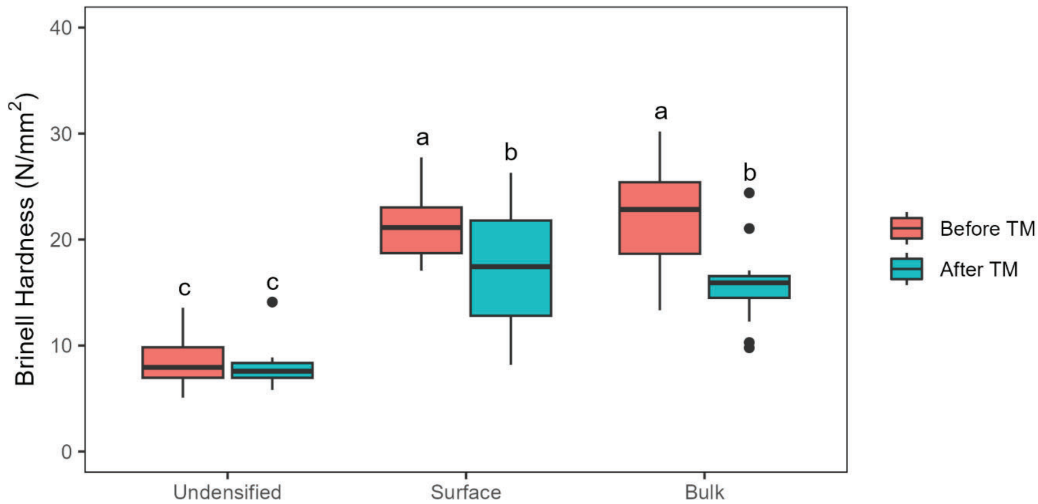

Figure 3. Modified Brinell Hardness for each densification process, both before and after thermal modification (TM). Letters indicate statistical significance groupings (95% confidence level).

4.5 MECHANICAL PROPERTIES

The modulus of elasticity (MOE) for each densification process is shown in Figure 4. The MOE for undensified redwood, which has relatively low stiffness (average 5 GPa), did not change significantly following thermal modification. Both surface and bulk densification increased the MOE. For the bulk-densified boards, the MOE reduced substantially after thermal modification and was significantly lower than that of the surface-densified, thermally modified samples. Thermal modification does not typically reduce stiffness, suggesting an additional factor that may be contributing to this outcome. Following thermal modification, the bulk-densified boards showed a significant increase in thickness. Since MOE is proportional to the cube of the specimen depth (i.e., board thickness), even a small increase in thickness could result in a substantial decrease in MOE. Future work should focus on reducing the likelihood of densified samples swelling during the thermal modification process by further minimising contact with liquid water. Surface densification did not substantially increase MOE, but the low average stiffness (7 GPa) makes it unlikely to be suitable for structural applications. Future work should explore increasing the compression ratio of surface-densified boards to determine if this can enhance the MOE.

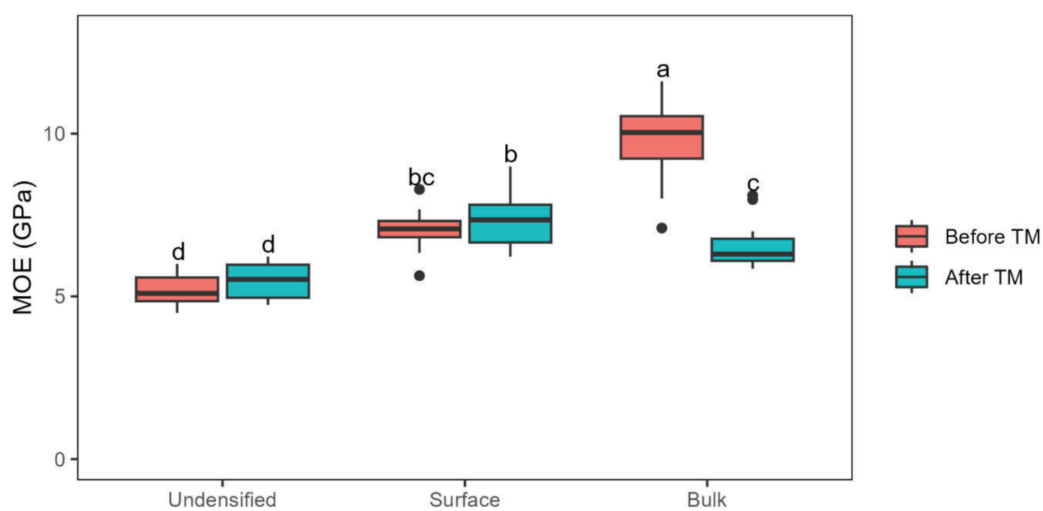

Figure 4. Modulus of elasticity (MOE) for each densification process, both before and after thermal modification (TM). Letters indicate statistical significance groupings (95% confidence level).

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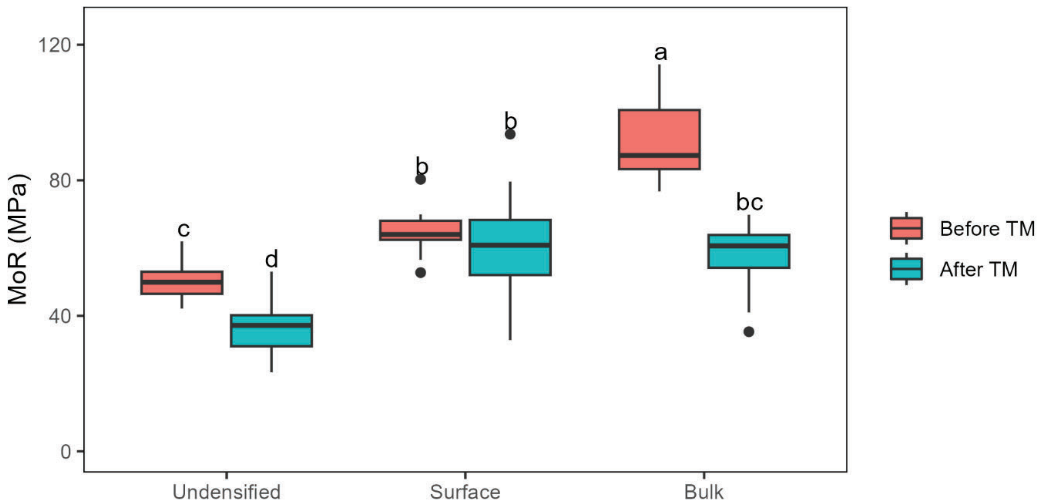

Figure 5. Modulus of rupture (MOR) for each densification process, both before and after thermal modification (TM). Letters indicate statistical significance groupings (95% confidence level).

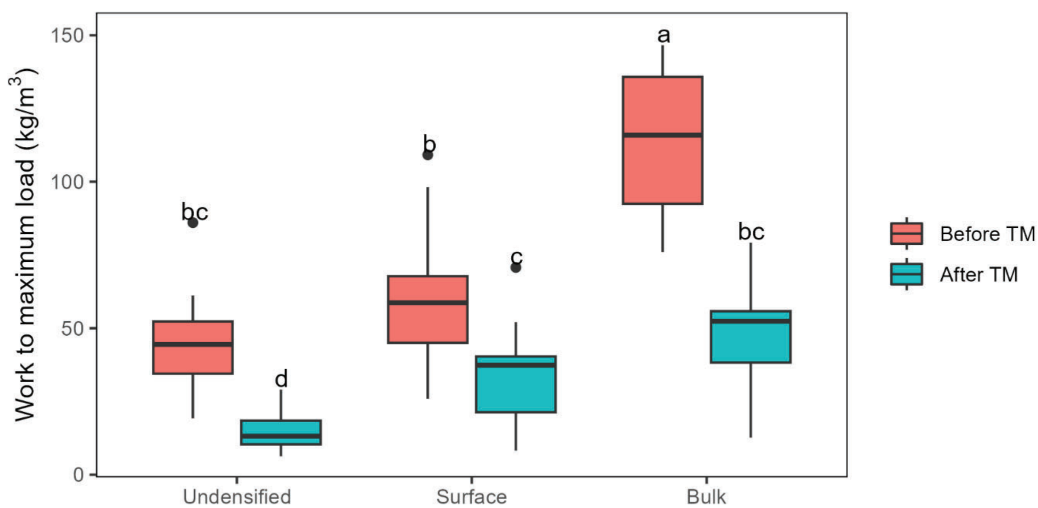

Figure 6. Work to maximum load for each densification process, both before and after thermal modification (TM). Letters indicate statistical significance groupings (95% confidence level).

Figure 5 shows the modulus of rupture (MOR) results for each densification process, both before and after thermal modification. Surface densification significantly increased the MOR, while bulk densification resulted in an even greater increase. The undensified controls showed a significant reduction in MOR following thermal modification, consistent with the property changes seen in other species after thermal modification. For the surface-densified samples, the average MOR decreased slightly but it was not significant. In contrast, the MOR of the bulk-densified samples decreased substantially after thermal modification, bringing it to a level that was not significantly different from that of the surface-densified samples.

Work to maximum load represents the total energy absorbed by a sample before it breaks, with lower values indicating brittleness. The work to maximum load for each densification process is shown in Figure 6. On average, work to maximum load increased with a greater degree of compression, although the obtained values for the surface-densified samples were not significantly higher than those of the undensified controls. As expected, both densification processes showed a significant decrease in work values following thermal modification, closer to that of the undensified wood. This suggests that while the thermal modification increases the brittleness of densified wood, it does not make it more brittle than the wood was prior to densification.

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6 – CONCLUSION

Both surface and bulk densification processes produced a dense layer close to the wood surface, significantly enhancing the surface hardness and mechanical properties. Thermal modification substantially reduced the set-recovery of the densified wood but also led to reductions in the mechanical properties. The bulk-densified samples showed greater reductions in mechanical properties, resulting in properties similar to those of the surface-densified samples, with an average MOE of around 7 GPa. While this represents a significant improvement over unmodified redwood, it is unlikely to be sufficient to enable new structural applications for densified timber. Future work should focus on increasing the MOE of surface-modified samples or maintaining the mechanical properties of bulk densified boards following thermal modification. Although thermal modification effectively reduced set-recovery, the remaining level (11%) is still high enough to cause unacceptable irreversible swelling if the wood becomes wet. Additional measures are necessary to further reduce set-recovery and improve the wood's performance in service.

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