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THE STRUCTURAL BEHAVIOUR OF COMPRESSED WOOD MANUFACTURED USING FAST-GROWN SITKA SPRUCE

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ABSTRACT: An investigation was carried out to examine the potential to manufacture a compressed wood product from fast-grown Sitka spruce, using a process of thermo-mechanical compression to increase its strength and stiffness. The process involves subjecting timber to a thermal load followed by a compressive load to reduce its cross-section, increasing its density and improving its structural performance. In this study, the influence of the manufacturing parameters, specifically, the pressing time and compression ratio, are examined. These parameters have been evaluated based on the microscopic structure and bending strength from three-point bending tests. The results have demonstrated that there is significant potential to manufacture a compressed wood product with improved structural behaviour from fast grown timber.

KEYWORDS: Compressed Wood, Thermo-mechanical Compression, Microscopic study, Bending strength

1 INTRODUCTION

The aim of this research is to investigate the potential to manufacture a modified or compressed wood product from Irish-grown Sitka spruce. This species is the most common species grown in Ireland and is characterised as a fast-grown low-density timber [1,2]. In this study, this species is subjected to a process of thermo-mechanical compression which involves the compression of wood under heat and pressure to form a material of superior performance. The thermo-mechanical compression of wood typically results in increased density, decreased porosity and improved material strength, stiffness, hardness and dimensional stability making it highly suited to demanding applications [3–7]. Some studies on various softwood species have achieved strength and stiffness increases of more than double that of the un-compressed wood counterpart [8,9]. Thermo-mechanical compression of wood is typically carried out in the radial direction, which involves flattening or folding the wood cells without fracture [10]. Typically the tangential direction is avoided as tangential compression can lead to damage and buckling of the latewood annual rings resulting in a zig-zag pattern forming through the cross-section of the densified wood material [11,12].

The degree of compression is often termed the compression ratio (or densification ratio) which refers to the difference between the initial and final thickness of the wood as a percentage of the initial thickness. Equation (1) gives the formula for the compression ratio (*CR*), where t_0 and t_c are the thicknesses (in the compression direction) before and after compression, respectively.

$$CR = \frac{t_0 - t_c}{t_0} \times 100\% \qquad (1)$$

When wood is above the glass transition temperature, radial compression can occur to a certain degree without damaging the wood cells. The temperature required for the thermo-mechanical compression of wood typically ranges between 120 – 160°C [10]. Heating the timber enables the free folding of the cell walls under the compressive action and the lumens or voids of the cells can almost be completely closed. In *Figure 1*, an un-compressed timber specimen is compared to a specimen that has been subjected to the process of thermo-mechanical compression. The specimen has been compressed to a *CR* of approximately 70% under heat and pressure in the radial direction, which significantly increases its density.

Figure 1: *Un-compressed Sitka spruce compared to a similar specimen that has been subjected to thermo-mechanical compression to form Compressed Sitka spruce*

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2 MATERIALS & METHODS

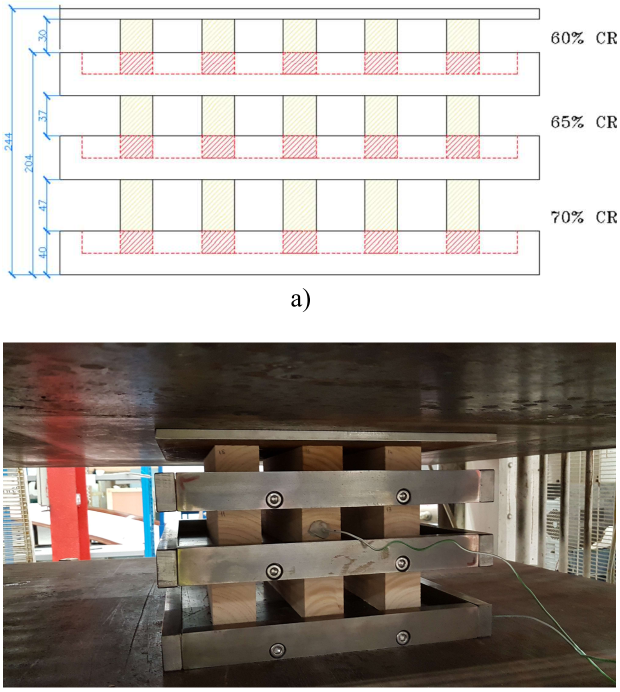
2.1 INTRODUCTION

The timber used in this study is Irish-grown Sitka spruce. This species is the most common species grown in Ireland and due to the climatic conditions in Ireland, this timber is fast grown which typically results in a relatively low-density timber. In structural terms, timber in Ireland is typically graded to a structural grade of C16 grade timber in accordance with EN 338 [13]. This grade of timber is characterised as having a 5th-percentile bending strength of 16 N/mm^2, a mean elastic modulus of 8000 N/mm^2 and a mean density of 370 kg/m^3. It has been shown that there is potential to create an added value product and improve the structural performance of this fast-grown species [8,9] by means of thermo-mechanical compression. In fact, the relatively low density of this timber makes it particularly suitable for the manufacture of densified or compressed wood; however, the success of this technology relies on establishing the optimal processing parameters.

2.2 DENSIFICATION PROCESS

A primary aim of densification of wood to produce compressed wood is to increase the mechanical properties by reducing the pores and voids (lumen) between the cell walls, thus increasing the density and other mechanical properties (e.g., strength, elastic modulus etc.). The typical process of thermo-mechanical compression involves the use of a heated press [3]. The un-compressed specimen is placed between the platens of a heated press and the timber is allowed to reach the desired temperature. The pressure or displacement is then applied, and the timber specimen is held under pressure for the given pressing time. The heat is then turned off and the timber is allowed to cool while under pressure. Once the timber cools below 60 °C approximately, the pressure may be released. This process is termed thermo-mechanical compression. Additionally, timber can be densified by other methods such as impregnating the voids between the cell walls with different materials such as molten metals/sulphur and polymers [14]. This is not considered here.

In this study, the compression of the timber specimens was performed within a specially designed press apparatus as seen in *Figure 2*. The apparatus comprised three stiff steel plates or layers, each 40 mm thick with a 20 mm recess. The plates are stacked, and the timber specimens are placed between the layers of the press apparatus. The plates and timber are then heated to the required temperature and the timber is then compressed until the plates meet each other under a compressive load. The 20 mm recessed groove in each plate means that 20 mm thick compressed wood samples will remain between the plates on complete closure of the press apparatus. The resulting compression ratio (Equation (1)) depends on the initial height of the timber specimens. The elevation view of the press apparatus with the specific clear distances between the plates and the associated compression ratios can be seen in *Figure 2*a. In *Figure 2*b the press apparatus is positioned between the heated platens of the press. Two thermocouples were also used to ensure the correct temperature was achieved. One thermocouple was positioned along the edge of the steel press apparatus and one thermocouple was positioned within a 1.5 mm hole that was drilled into a timber specimen to ensure the timber reached the correct temperature before the application of the compressive pressure. The thermocouple within the timber was removed prior to compression to allow for the complete closure of the press apparatus.



a)

b)

Figure 2: *Compressed wood press apparatus a) Press elevation showing different layer dimensions and associated compression ratios - Timber is in yellow, final densified wood is in red (dimensions in mm), b) press apparatus with timber specimens between the heated platens of the press.*

Once completed, the compressed wood specimens were stored in a sealed container prior to testing to ensure there are no significant fluctuations in the relative humidity of the surrounding environment. This ensures that there is no shape recovery of the compressed behaviour which has been shown to occur with changes in the moisture content of compressed wood.

2.3 MICROSCOPIC STUDY

The microscopic study involved the preparation and optical examination of un-compressed and compressed wood specimens to visually observe the influence of the different processing parameters on the structure of the timber. Excessive compression can adversely affect the compressed wood product, resulting in poor structural performance so damage evaluation is an essential tool in determining the optimal processing parameters.

Specimens of un-compressed and compressed wood with an approximate thickness of 20-40 µm were produced using a rotary microtome. The un-compressed specimens were prepared in the wet condition, which allowed a smooth surface to be achieved, whereas the compressed wood specimens were cut in a dry condition to avoid excessive shape recovery of the cell structure when in contact with water. Furthermore, for this reason, staining agents were not used to improve the quality of the microscopic images. Specimens were then sealed to ensure no significant changes in the moisture content of the specimens before imaging the specimens. In total, ten specimens were chosen for the microscopic study in which one specimen was un-compressed to form a basis for comparison and a further nine specimens with varying degrees of compression, density and pressing time.

2.4 BENDING TEST

Compressed wood specimens measuring 20 x 20 x 300 mm^3 were cut from the compressed material and were then subjected to a three-point bending test to failure in accordance with BS 373 [15]. The specimens were loaded over a test span of 280 mm. Each specimen was loaded at a displacement rate of 2.5 mm/min to ensure failure occurred within 300 ± 120 s. In *Figure 3*, the typical load-displacement behaviour of a compressed wood sample (27a) subjected to three-point bending to failure can be seen. The bending strength was assessed at the maximum load (F_{max}) using Equation (2) where l is the span of the specimen, b is the width and d is the depth of the specimen. The elastic modulus was determined from the slope of the initial straight-line portion of the load-displacement curve. The elastic slope was calculated from the change in load (ΔF) between 10% and 40% of F_{max} and the associated change in displacement (ΔU) as shown in Equation (3).

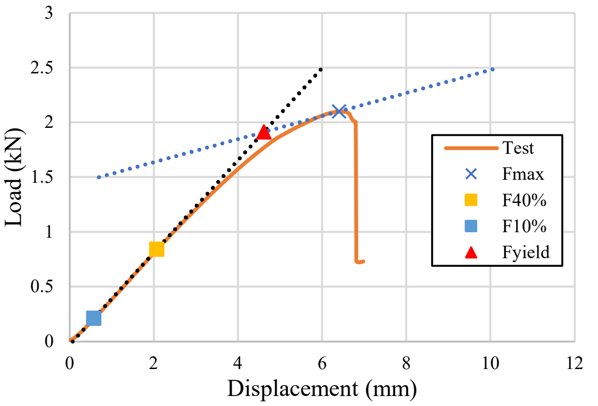
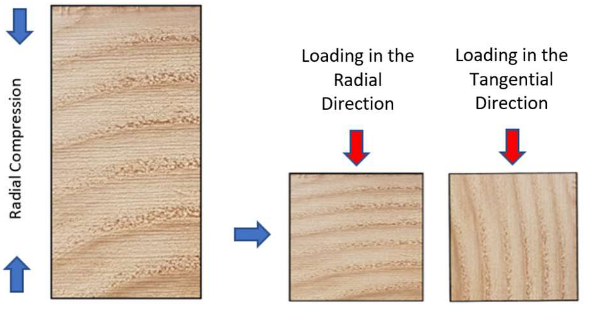


Figure 3: *Load-displacement behaviour of a densified wood specimen (27a) subjected to three-point bending.*

$$f_m = \frac{3 \cdot F_{max} \cdot l}{2 \cdot b \cdot d^2} \qquad (2)$$

$$E_0 = \frac{\Delta F \cdot l^3}{4 \cdot \Delta U \cdot b \cdot d^3} \qquad (3)$$

In addition to studying the manufacturing parameters, the compressed wood specimens were specifically loaded perpendicular to either the radial grain direction or the tangential grain direction to assess if the orientation of the specimen is a significant factor in the structural behaviour. This is important as the specimens have been manufactured by compression of the radial direction only as seen in *Figure 4*. It is important to examine if there is any significant difference in performance due to the orientation under loading as this may affect the potential use of this material in structural applications.



a) b) c)

Figure 4: *Compressed wood, a) specimen subjected to radial compression, b) structural test load in the radial direction, c) structural test load in the tangential direction.*

3 EXPERIMENTAL PROGRAMME

The experimental test programme designed to examine and optimise the processing parameters of compressed Irish Sitka spruce wood can be seen in *Table 1*. The number of specimens subjected to the microscopic study (n_M) and the bending tests (n_B) are presented along with the target *CR* and the pressing times examined.

Table 1: *Test Programme*

Test	n_M	n_B	Target *CR* (%)	Pressing time (min)
Microscopic/Bending	1	12	0	0
Microscopic/Bending	3	16	60	30, 60, 90
Microscopic/Bending	3	17	65	30, 60, 90
Microscopic/Bending	3	14	70	30, 60, 90

4 RESULTS

4.1 INTRODUCTION

During the manufacturing process of the compressed wood specimens, it was found that there was a range of *CR* values produced and the production of a specific *CR* was difficult. Due to the variation in results, the compressed wood specimens were divided into three groups, namely *CR*s between 56-64% (n=16), 64-67% (n=17) and 67-72% (n=14) when examining the bending test results. Furthermore, a high *CR* does not always indicate high density, which is often shown to be positively related to bending strength and elastic modulus and for that reason, the results are also examined in low-, medium- and high-density groups. The low-density group ranged from 732-915 kg/m^3 (n=15). The medium-density group ranged 916-1000 kg/m^3 (n=16) and the high-density group ranged from 1001-1211 kg/m^3 (n=16).

4.2 MICROSCOPIC STUDY RESULTS

The result of the microscopic study allows for the extent of compression to be visually assessed and compared to the uncompressed specimen of Irish Sitka spruce.

In *Figure 5*, a microscopic image typical of un-compressed softwood timber can be seen. The microscopic image shows the formation of the cell wall structure of this softwood Sitka spruce timber. It is the voids or lumens that are reduced as the cell walls fold during the process of thermo-mechanical compression.

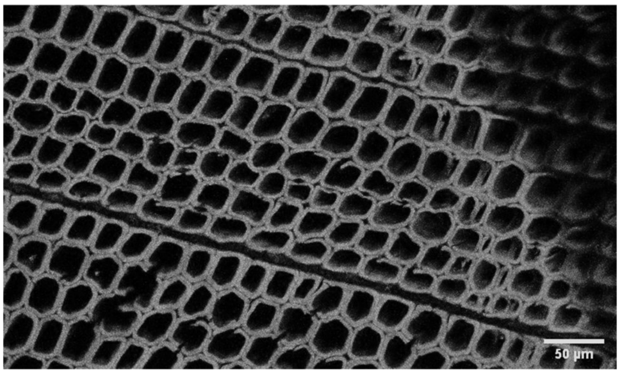


Figure 5: Microscopic image of the uncompressed specimen of Irish Sitka spruce

In Figure 6, a specimen with a *CR* of 65.8% is presented where the scale indicates 50 μm distance. It can be seen that the voids have been reduced and the material has been subjected to significant deformation with limited scope for further compression. The reduction of these voids results in a significant increase in density. Under close inspection, there appears to be free folding of the cell walls for the given temperature and pressing time with no significant signs of damage to the cell wall.

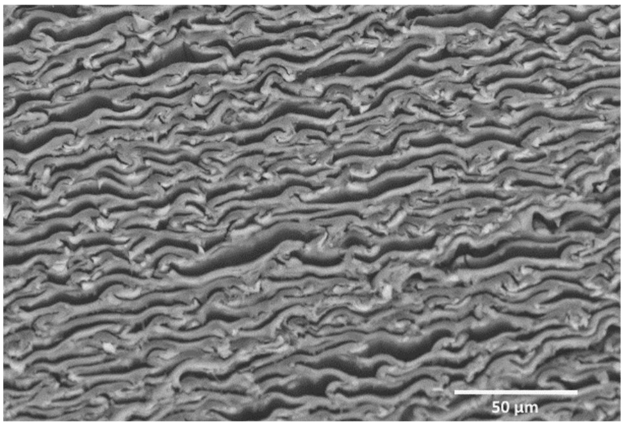


Figure 6. Microscopic image of Specimen 6 which has a *CR* of 65.8% (Scale 50 μm).

On examination of the remaining microscopic results, one specimen from each of the low-, medium- and high-density groups, and one specimen from each of the pressing times of 30, 60 and 90 minutes were imaged and examined. Under close inspection, it was clear that all specimens were subjected to considerable compression and the majority of specimens appear to result in free folding of the cell walls for the given temperature and pressing times with no significant signs of damage to the cell wall.

One exception to this relates to Specimen 7 where there is arguably some recurring damage within some cell walls which can be seen in Figure 7. Specimen 7 is characterised as having relatively large cell wall thickness and there appears to be some damage within the cell wall after being subjected to thermo-mechanical compression. This specimen had a relatively high density prior to thermo-mechanical compression and also produced one of the highest densities of all the compressed specimens post-compression (1180 kg/m^3).

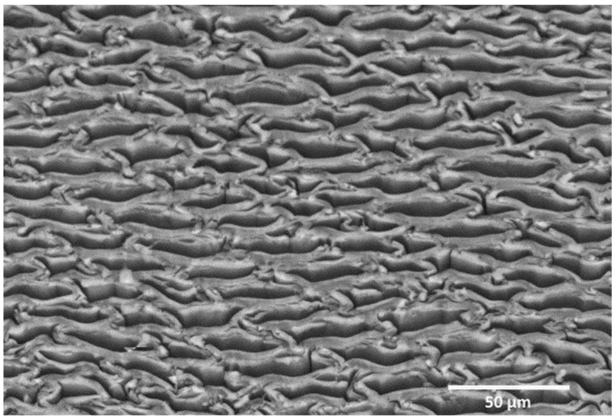


Figure 7: Microscopic image of Specimen 7 which has a *CR* of 68.4% (Scale 50 μm).

The results indicate that the pressing time has no significant influence on the free folding of the cell structure of Irish Sitka spruce during the thermo-mechanical process presented, but the density and, potentially, the initial density prior to compression does appear to be influential. High initial density was shown to potentially lead to excessive damage to the cell structure.

4.3 BENDING TEST RESULTS

The structural behaviour of the compressed Sitka spruce is assessed by means of a bending test. An example of a specimen loaded to failure can be seen in *Figure 8*. The load-displacement behaviour of all specimens tested to failure can be seen in *Figure 9*. The uncompressed specimens are represented in black in *Figure 9*. The compressed wood specimens loaded in the radial direction are represented in orange and the specimens loaded in the tangential direction are represented in blue. The typical load-displacement behaviour can be characterised as linear elastic to brittle failure with some specimens demonstrating some plastic behaviour. The elastic modulus and the bending strength are the main structural characteristics presented.

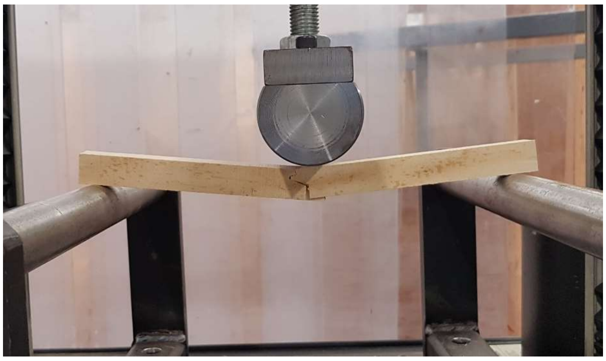


***Figure 8**: Bending test set-up and specimen subjected to bending failure.*

The results shown in *Figure 9* demonstrated that significant improvements in bending strength and stiffness can be achieved through the process of thermo-mechanical compression to increase the density of Irish

Sitka spruce. It can be seen in *Figure 10* that there is a positive trend of increased bending strength with increased *CR*. The highest bending strength values have been produced by the specimens subjected to the highest *CR* range.

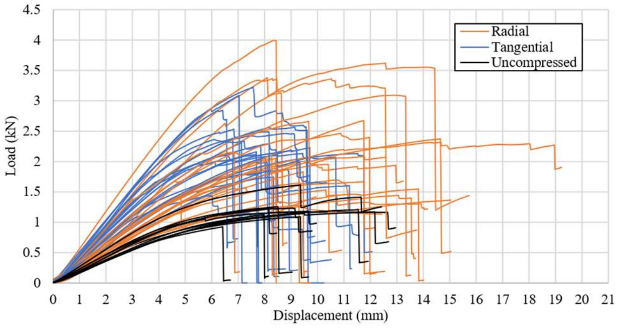


Figure 9: *Load-displacement behaviour of all specimens: Uncompressed specimens are presented in black, specimens loaded in the radial direction are presented in orange and specimens loaded in the tangential direction are presented in blue.*

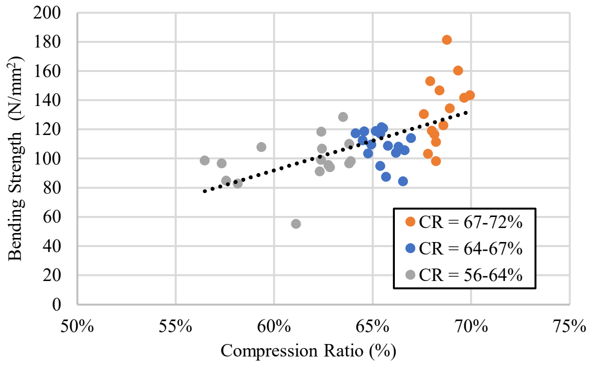
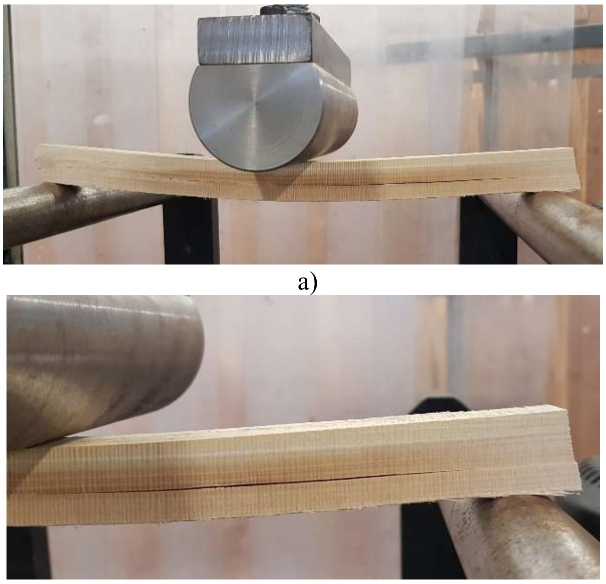


Figure 10: *Bending strength of densified timber compared to the compression ratio.*

When compared to the un-compressed Sitka spruce, which had a mean bending strength of 59.8 N/mm^2 (*n* =12), there is a mean increase in bending strength of 63.4%, 81.5% and 122% for the compressed wood timber with a *CR*=56-64%, *CR*=64-67% and *CR*=67-72%, respectively. When examining the improvement in stiffness and comparing it to the un-compressed Sitka spruce, which had an elastic modulus of 7119 N/mm^2, there is a mean increase of 43.4%, 77.8% and 97.7% for the compressed wood timber with the *CR*=56-64%, *CR*=64-67% and *CR*=67-72%, respectively.

Failure of the compressed wood specimens was shown to occur in one of two modes. The primary mode of failure was bending failure, occurring along the outermost tensile fibre, however, a small number of specimens failed through longitudinal shear failure which occurred along an annual growth ring of the specimen. An example of shear failure behaviour can be seen in *Figure 11*. When examining the failure mode of all specimens, the majority of specimens failed through bending failure. Only 4 specimens out of 59 specimens tested failed through shear failure. It was found that all of the specimens that failed due to shear failure, at relatively low loads, are associated with the high-density group which ranged from 1001-1211 kg/m^3 (*n*=16).



a)

b)

Figure 11*: Failure mode: a) shear failure of the specimen along annual growth ring, b) close up view of shear failure.*

This would indicate that excessive densification negatively affects structural performance. Specimens with a final density in excess of 1000 kg/m^3 seemed to be susceptible to this kind of failure. This would indicate that a maximum compression ratio could be specified for timber specimens with a high initial density which would still achieve significant improvements in structural performance.

As part of the experimental programme, it was important to focus on the influence of the pressing time and its effect on the structural performance of the compressed wood specimens. The pressing time is examined to establish the duration of time required to reliably produce compressed wood. Reducing the pressing time has a significant time- and energy-saving and should be optimised when manufacturing this material. Based on the experimental findings, it was decided to analyse the pressing times based on the low- medium- and high-density groups. In *Figure 12*, the mean bending strength is assessed and the influence of density and the pressing time is also presented. The mean values are presented in *Table 2*.

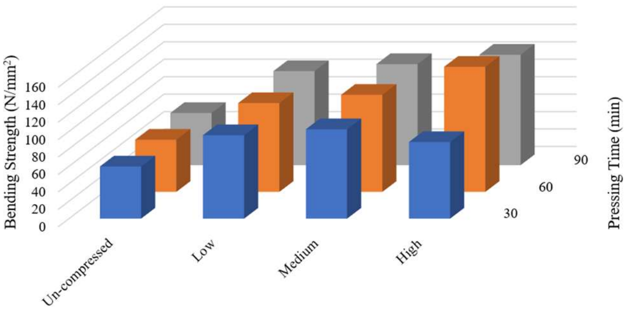


Figure 12: *Bending strength and the influence of density and pressing time.*

It can be seen that for all density groups and all pressing times, there is an improvement in mean bending strength when compared to the un-compressed group (59.8 N/mm^2). For specimens manufactured with a pressing time of 30 minutes, it was found that the high-density group had the lowest mean bending strength. When compared to the un-compressed group, percentage increases in mean bending strength of 60%, 71% and 47% were observed for the low- medium- and high-density groups, respectively. This result was contrary to the trends observed from pressings times of 60 minutes and 90 minutes which resulted in increasing mean strength with increasing density. Overall, the 60 minute pressing time and the high-density group produced the greatest percentage increase in mean bending strength of 140%. For the low- and medium-density groups, there is a trend of increasing strength with increasing pressing time.

***Table 2**: Bending strength and the influence of density and pressing time.*

Group	Pressing Time (min)		
	30	60	90
Un-compressed	59.8	59.8	59.8
Low	95.6 (60.0%)	101.8 (70.3%)	107.8 (80.3%)
Medium	102.5 (71.4%)	111.3 (86.2%)	115.8 (93.6%)
High	87.8 (46.9%)	143.4 (139.9%)	126.5 (111.7%)

In *Figure 13*, the mean elastic modulus is assessed, and the influence of density and the pressing time is also presented. The mean values are also presented in *Table 3*. It was shown that for all density groups and pressing times, there was an improvement in the mean elastic modulus when compared to the un-compressed group (7119 N/mm^2). When examining the low-density group, there was no obvious trend with similar improvements in elastic modulus being observed for all pressing times examined. When examining the specimens subjected to the 30 minute pressing time, it was shown that the performance reduced with increasing density. The best performing combination was the 60 minute pressing time and the high-density group which resulted in a percentage increase in elastic modulus of 105% when compared to the un-compressed group.

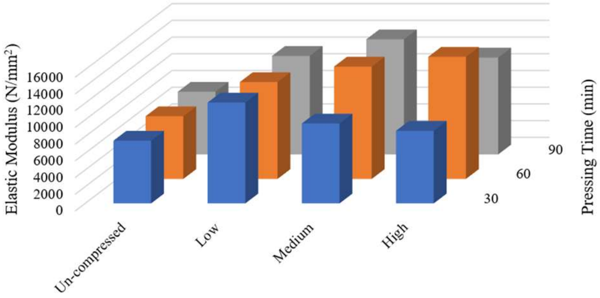


***Figure 13:** Elastic modulus and the influence of density and pressing time.*

***Table 3:** Elastic modulus and the influence of density and pressing time.*

Group	Pressing Time (min)		
	30	60	90
Un-compressed	7119	7119	7119
Low	12070 (69.6%)	11592 (62.8%)	11791 (65.6%)
Medium	9564 (34.5%)	13442 (88.8%)	13771 (93.5%)
High	8691 (22.1%)	14614 (105.3%)	11593 (62.9%)

As can be seen in *Table 3*, the high-density group performs relatively poorly for pressing times of 30 minutes and 90 minutes. This would indicate that the production of high-density compressed material (greater than 1000 kg/m^3) appears to cause some damage to the material during the manufacture as was observed in the microscopic study.

5 CONCLUSIONS

The results have shown that there is a significant potential to utilise Sitka spruce in the manufacture of compressed wood. The specimens examined comprise un-compressed timber and timber compressed to *CR* of 56.4%-68.6%. The microscopic examination has focused on examining the resulting cell structure after compression to determine suitable processing parameters that result in free folding of the cell structure without causing excessive damage to the cell wall.

The results have shown that the pressing time has no significant influence, but the density and, potentially, the initial density prior to compression does appear to be influential. There were no clear trends associated with the *CR* and it was observed that density might be a better indicator of the potential to compress timber without causing excessive damage. As a result, the specimens were grouped into low- medium- and high-density groups. There appeared to be a greater potential for damage in the high-density groups. The high-density groups were characterised as having high initial density prior to compression. Essentially, the higher the initial density, the greater the damage that was observed within the cell wall. This indicates that lower density material can be compressed to a greater degree without causing excessive damage to the cell wall. Conversely, higher density material may be compressed, but to a lower *CR* to ensure no damage occurs.

This would indicate that specimens should be batched prior to thermo-mechanical compression based on their initial density and a maximum *CR* should be established based on the initial density of the material.

The results of the structural examination by bending test indicate that the strength and stiffness of compressed Irish Sitka spruce generally increase with increasing *CR*. Increases in mean bending strength of 63.4%, 81.5% and 122% were found for the compressed wood specimens with a *CR*=56-64%, *CR*=64-67% and *CR*=67-72%, respectively when compared to the un-compressed specimens. There was also found to be an increased chance of shear failure in the case where excessive compression may have occurred. When examined in low-, medium- and high-density groups, timber compressed to a density above 1000 kg/m^3 result in an increased likelihood of failure due to shear. The results indicate that it is best to batch specimens based on the initial density of the un-compressed material to produce the most reliable product after thermo-mechanical compression. It is recommended to target the medium density range (916-1000 kg/m^3) which produced compressed wood that performs well in terms of bending strength and elastic modulus when compared to the un-compressed specimens and did not appear to result in excessive damage during manufacturing which makes it susceptible to shear failure. While the pressing time did not affect the bending strength, it seemed to have a greater effect on the elastic modulus of the compressed wood material. The 30 minute pressing time did not perform well in terms of elastic modulus and a minimum time of 60 minutes is recommended for future production.

The optimised parameters recommended for further production is the medium density range at a temperature of 120 °C subjected to pressure for a total pressing time of 60 minutes.

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