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Thermomechanical Densification of Timber:

Initial Investigations of the Potential of Softwood Timber

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Researchers:
R. Adlam
GHD Pty Ltd
GPO Box 668, Brisbane QLD 4001

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Forest and Wood Products Research and Development Corporation
PO Box 69, World Trade Centre, Victoria 8005
Phone: 03 9614 7544 Fax: 03 9614 6822 Email: info@fwprdc.org.au
Web: www.fwprdc.org.au

Thermomechanical Densification of Timber:

Initial Investigations of the Potential of Softwood Timber

Prepared for the

Forest & Wood Products
Research & Development Corporation

by

R. Adlam

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Executive Summary

Timber manufacturers are being challenged by the increasing quantities of plantation softwoods that are being harvested at a younger age and supplied for processing. The timber, which has higher quantities of juvenile corewood, subsequently has increased warping characteristics and lower mechanical properties that reduce the utility and value of the final timber products.

The aim of this research was to design a thermomechanical densification procedure that could be used as a complete processing method to season structural or semi-structural timber in a time and energy efficient manner and to produce minimum cost final timber products with a high degree of retention of the compressed dimensions and improved mechanical properties.

The optimal thermomechanical densification procedure allows timber cells to redistribute under conditions of high plasticity with minimal internal timber stresses being established. To determine the design parameters for the thermomechanical densification procedure, existing processing techniques such as Compreg, Staypak and press drying were investigated in conjunction with theory on the chemistry, cellular structure, viscoelastic properties and drying responses of timber. The knowledge established in these areas provided the basis for timber temperature response and moisture content variation experiments which provided clear output on the design parameters required for the thermomechanical densification procedure.

The thermomechanical densification procedure was used to process timber samples at 40 mm and 45 mm initial thicknesses to a final nominal thickness of 35 mm, representing 13 % and 22 % densification levels respectively. The retention of compressed dimensions and mechanical properties of the densified timber samples were then compared to the kiln dried control sample timber.

Observation of the timber samples during densification indicated that high moisture content conditions were present during densification due to the large amount of steam and liquid water released by the timber samples during this process. Final densified timber samples did reveal minor discontinuous cracking along the length of the timber.

The final densified timber products were seasoned to within the target moisture content range of 8 to 16 % and achieved residual compression levels after conditioning that were approximately equal to the compression applied to the timber samples, nominally 13 % and 22 %, indicating the effectiveness of the pressing procedure that included a 2 mm over-press.

The mean MOE results were similar between the timber samples densified to 13 %, the timber samples densified to 22 % and the kiln dried control samples, for both the facewise and edgewise testing orientations. Evaluation of results also indicated that timber samples tested facewise produced lower average results compared to samples tested edgewise. This result occurred partially due to the higher number of defects included in the timber samples tested facewise.

Mean MOR results of timber samples tested facewise indicate that the timber densified to the 13 % level is slightly stronger than the kiln dried control samples, whereas the timber densified to the 22 % level is slightly weaker than the kiln dried control samples.

Hardness results show that there is a mean improvement of 23 % and 31 % over the kiln dried control samples for the timber samples densified to the 13 % and 22 % levels respectively.

The thermomechanical densification procedure designed in this research was successful. This was evident through observation of the timber samples being densified and by inspection of the final timber products. Timber samples were seasoned to within the target final moisture content range and achieved a high degree of retention of the compressed dimensions. There was no significant improvement in MOE and MOR in the densified timber samples compared to the kiln dried control samples, however timber hardness was improved at both timber densification levels.

Thermomechanical densification technologies provide potential solutions to timber manufacturers processing increasing quantities of plantation softwoods that are being harvested at a younger age and that are looking to produce final timber products with improved utility and value.

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1. Introduction

Timber manufacturers are being challenged by the increasing quantities of plantation softwoods that are being harvested at a younger age and supplied for processing. The timber, which has higher quantities of juvenile corewood, subsequently has increased warping characteristics and lower mechanical properties, which reduce the utility and value of the final timber product.

There are opportunities to improve the current processing techniques for young plantation softwoods. This research investigates thermomechanical densification as a processing method that can potentially produce rapidly seasoned and densified timber products with improved mechanical properties.

The design of the thermomechanical densification procedure to achieve optimal process and product benefits was identified as being important. Knowledge on the chemistry, cellular structure, viscoelastic properties and drying responses of timber was required to provide a basis for the design of the procedure.

Thermomechanical densification as a manufacturing procedure has potential process and product improvements. Combining a reduction in production costs with final timber products that have improved utility and value would have large scale benefits to timber manufacturers processing the increasing quantities of lesser quality plantation softwood timber, allowing them to produce a timber product with improved competitiveness.

This collaborative research project was completed with the support of project partners, whose financial and in-kind contributions are gratefully acknowledged. Project partners were S & S Timbers of Gympie, the Forest and Wood Products Research and Development Corporation (FWPRDC), the Queensland Forestry Research Institute (QFRI) of the Department of Primary Industries (DPI), and The University of Queensland (UQ).

2. Timber Selection

Plantation softwood is suitable for thermomechanical densification research due to its large-scale use, high potential for property improvement and the suitability of its cellular structure to the densification process.

The current large scale use of plantation softwood and its strong future supply indicates that process and product improvements would have significant long-term financial benefits for the plantation softwood industry. The volume of plantation softwood processed in Queensland is in excess of 1.25 million cubic meters. This current annual processing figure, combined with future supply indicators, strengthen the importance of research outputs as results will have long term relevancy due to the large and sustained supply of plantation softwood timber.

Plantation softwood timber that is being typically harvested a younger age has increased warping characteristics and low mechanical properties associated with the higher proportions of juvenile corewood. These undesirable characteristics provide the opportunity for product improvement of softwood timber currently being manufactured.

Softwood timber is more suited to the thermomechanical densification process when compared to the structure of hardwood timber. The relatively permeable and uniform structure of softwood timber allows moisture movement and densification of the timber cells to occur more evenly throughout the timber.

The timber used in this research was slash pine (*Pinus elliottii*), from the Gympie region in Queensland. Slash pine is plantation grown in the coastal regions of northern New South Wales to Central Queensland and is a medium sized tree attaining a height of 30 to 35 m and a stem diameter of 0.7 m. Branches are usually large and spreading. The sapwood of slash pine is usually pale yellow to yellow and is generally straight grained. Timber density at 12 % moisture content is 625 kg/m^3. The strength group for seasoned slash pine is SD5 and the stress grade ranges from F7 to F17 (Boland et al 1984).

The results and outputs of this research are expected to be relevant for similar plantation softwood timbers. Due to plantation softwood timber species having comparable chemical and cellular structures, it is expected that dimensional stability and mechanical property improvements resulting from this research work involving slash pine would be similarly application to other plantation softwoods.

3. Densification of Timber

Different methods have been developed and patented for the production of densified timber products. Procedures generally involve transverse compression of timber under conditions where the wood is sufficiently plasticised.

3.1 Compreg

Compreg is the product name given to compressed wood products that are manufactured by impregnating solid wood or veneer with a thermosetting resin. The resin used is a fibre penetrating phenol formaldehyde resin. Resin treated timber is compressed under platen temperatures of 150 °C and platen pressures of 6.5 MPa, with the deformation occurring before the thermosetting resin cures. Compressed timber products can be produced with specific gravities of 1.20 to 1.35 (Stamm 1964).

Structural-sized compressed timber is difficult to manufacture using Compreg. This is due to difficulties in achieving full resin penetration into the timber and due to curing of the thermosetting resin adjacent to the high temperature platens, before full densification has occurred. For these reasons, Compreg is mainly used in the manufacture of veneer products. The overall cost of Compreg timber products is high when compared to standard timber.

3.2 Staypak

Staypak compressed timber products are manufactured from untreated timber with platen temperatures above 150 °C and platen pressures of 10 MPa to 18 MPa. The platen pressure is applied to the timber when it has a moisture content of approximately 10 %, producing timber products with specific gravities of 1.30 to 1.35 (Stamm 1964). Platen pressures are maintained as the timber is conditioned, allowing the thermoplastic lignin to cure.

The strength properties of Staypak products are improved when compared to standard timber products, as reported by Stamm (1964). Structural and veneer Staypak timber products can be manufactured using a process which is less material and process intensive than the Compreg process. Manufacturing issues with plantation pine Staypak products stem from the high concentration of water-insoluble extractives present in pines, which retard lignin flow and impede timber compression.

Research on timber processing methods similar to Staypak, has been completed by Tabarsa and Chui (1997). This study investigated the concurrent effects of compression and platen temperature on the properties of white spruce timber. Timber with an initial moisture content of 15 % was processed using platen temperatures of 20, 100, 150 and 200 °C and densification levels of 12, 16, 24 and 32 %, to produce test specimens 210 mm long, 20 mm wide and 12 mm thick. The compression was applied to reach the target densification level within one minute and was maintained for a further four minutes.

Study results indicate that timber stiffness and strength are generally improved with the level of densification. The timber processed at platen temperatures of 20 and 100 °C showed lower levels of stiffness and strength increase in MOE and MOR compared to the timber processed at 150 and 200 °C. Higher levels of compression set were retained in the timber samples after conditioning when the timber was processed at higher temperatures and there was also evidence of reduced cell wall damage.

3.3 Press Drying

Press drying aims to rapidly season green timber between heated platens and is generally a constant pressure operation. The level of pressure applied to the timber has varied in research and industry from low levels to ensure contact between the timber piece and the platens, to higher levels causing low levels of timber densification. Press drying procedures are generally designed to minimise thickness loss of the timber piece.

Studies on the effects of press drying on the reduction of timber warping and mechanical properties have been completed by numerous researchers. In research by Simpson et al (1988), green loblolly pine 50 mm thick and 100 mm wide, was press dried in 90 minutes using platen temperatures of 175 °C and platen pressures of 175 kPa (25 psi) and 345 kPa (50 psi). The resulting timber was reported as being successfully seasoned and free of checking, cell collapse and excessive thickness loss. There was minimal difference in the timber that was restrained in the press after cooling or removed from the press and was unrestrained during cooling. Timber samples dried at 175 kPa produced a statistically significant reduction in warping, a downgrade of 4 % compared to that of kiln dried timber that varied from 18 to 30 %.

In a study on the mechanical properties of press dried timber, green timber 40 mm thick by 100 mm wide and 800 mm long was press dried following the manufacturing procedure used to investigate timber warping properties by Simpson et al (1988). The specific gravity, strength and stiffness increased by 7.0, 12.9 and 19.0 % for timber pressed at 175 kPa. The same properties, specific gravity, strength and stiffness increased by 10.3, 14.7 and 24.0 % for timber pressed at 345 kPa, compared to kiln dried timber (Tang and Simpson 1989).

Timber processing company, A/S Junckers Savvaerk of Copenhagen, utilised press drying to process medium quality beechwood (hardwood) into parquet flooring material. Timber strips 75 mm wide by 30 mm thick and 610 mm long were steamed before being loaded into a press for two hours. The press operated with a platen temperature of 165 °C and a pressure of 1250 kPa. On completion of pressing, the dried timber strips densified by 10 % were conditioned in steel vacuum cylinders to obtain an equalized moisture profile through the timber product. Process advantages reported include increased timber production and reduced energy consumption on a per unit weight basis. Product improvements were evident though an increase in material utilisation by approximately 20 % and improved strength of between 10 to 15 % (Schmidt 1967).

3.4 Thermomechanical Densification

Thermomechanical densification has fundamental differences in aims and objectives compared to Compreg, Staypak and press drying manufacturing methods, which typically apply to discrete parts of the processing procedure and in the case of Compreg, are resource intensive to produce. Thermomechanical densification aims to provide a complete processing method that can be used to season structural or semi-structural timber products with reduced energy consumption costs and provide improved dimensional stability and mechanical properties.

Thermomechanical densification processing methods use high temperature platens to rapidly season and densify timber. Pressure is applied to densify the timber under conditions of maximum plasticity and over a discrete time interval.

There has not been a large volume of research conducted on the thermomechanical densification manufacturing method. Consequently information on critical processing characteristics such as platen temperature, platen pressure, densification time interval and the total time required to season a given timber piece, is difficult to obtain. However, information from press drying can be related to the thermomechanical densification process.

Restraint of the timber piece is required after the timber has been densified, during the conditioning process. This is due to the thermo-plastic nature of the lignin in the timber which endeavours to recover to its original form after the application of stress and whilst still at high temperature.

Potential advantages of thermomechanical densification compared to the other alternative drying techniques discussed in this section include the processing benefits of rapid drying and lower energy consumption rate, as has been reported in studies on the press drying process. Potential product improvements include a high degree of retention of the compressed dimension, stiffness, bending strength and hardness properties.

4. Objectives and Justification

4.1 Objectives

This research work aimed to improve the level of understanding of the thermomechanical densification process and to produce improved densified timber products. These aims were achieved through the following objectives:

1. Investigation of timber temperature response and moisture content variation characteristics during the densification procedure to provide the parameters for design of a thermomechanical densification procedure.
2. Production of timber samples using the designed thermomechanical densification procedure to process initially 40 mm and 45 mm thick timber to a nominal final thickness of 35 mm, representing 13 % and 22 % nominal compression levels respectively. Use of the restraint press for the timber samples in the conditioning period after densification.
3. Evaluation of dimensional and mechanical properties of densified and kiln dried timber samples. Full-length timber samples were tested for stiffness about the axis perpendicular to the platen contact face, or in an edgewise orientation. Half-length timber samples were tested for stiffness about the axis parallel to the platen contact face, or in a facewise orientation. Timber strength was measured on the half-length timber samples about the axis parallel to the platen contact face, or in a facewise orientation. Hardness measurements were taken on the faces that contacted the platens.
4. Comparison of densified timber and kiln dried timber property results to give an evaluation of the effectiveness of the densification procedure.

4.2 Justification

There is an opportunity to utilize alternative drying techniques for processing the increasing quantities of plantation pine that is being harvested at a younger age. Potential benefits of thermomechanical densification include those associated with a rapid and efficient seasoning method, and the ability to improve the utility and value of the final timber products.

The increased warping characteristics of plantation softwood timber are due to increased proportions of juvenile corewood and the associated large fibril angles of this juvenile wood, which causes a high degree of longitudinal shrinkage. Warping is a consequence of differential longitudinal shrinkage and has the effect of reducing the utility and value of the timber products.

Slash pine was chosen for the investigation due to its strong future supply, the economic significance of property improvement and due to the suitability of softwood for densification.

Several methods of manufacturing thermomechanically densified timber were investigated. These methods were generally not suited to producing low cost, structural sized timber pieces. Press drying generally aims to rapidly season timber products with a high degree of retention of compressed dimension and is optimised by reducing the amount of densification and corresponding loss of saleable timber.

Moisture movement paths and heat transfer mechanisms involved in traditional kiln drying and press drying procedures were investigated to provide a background for an effective thermomechanical densification procedure. Experimental work was required to provide information on the optimal time to densify the timber and the total time to season the timber.

The thermomechanical densification procedure used in this research aimed to provide an efficient processing method of producing timber products with a high degree of retention of compressed dimension and to benefit from the increased density through improved mechanical properties such as bending strength, stiffness and hardness

The resulting dimensional and mechanical properties of the densified timber were assessed and compared to the kiln dried control timber samples. All timber samples were from young plantation softwood timber without specific matching of the juvenile corewood present in the samples.

4.3 Industry Benefits

The large quantity of plantation softwood processed annually indicates that process efficiencies and product improvements potentially associated with thermomechanical densification manufacturing methods are financially significant.

Similar to those benefits reported by press drying research, timber processing efficiencies including significantly reduced drying times and improved energy consumption rates are expected for the thermomechanical densification manufacturing process.

Timber manufacturers are processing increasing quantities of plantation softwood timber that is being harvested at a younger age and has escalating warping characteristics and lower strength properties. Traditional processing methods result in a percentage of the processed timber being lost to shavings due to the planing of warped timber pieces. The thermomechanical densification procedure uses this material, which would normally be lost to shavings, as some portion of the timber that is densified. The value of the loss in material, above that lost in traditional kiln dried timber processing, is offset against the product improvements of the final timber product.

Timber product improvement due to thermomechanical densification would increase the application and value of existing and future timber processed. Improved timber properties would increase recovery rates, yield from juvenile and lower grade timber and may cause classification improvements when the timber is graded. Impact and hardness property improvements could result in plantation pine being used in higher valued markets such as for flooring.

5. Timber Temperature Response and Moisture Content Variation Experiment

Densification of a timber piece optimally occurs when the timber is highly plasticised, which occurs under high temperature and high moisture content conditions. To provide quantitative information on the interaction of timber temperature and moisture content over the thermomechanical densification procedure, a series of temperature and moisture contents were completed.

The temperature experiments were designed to provide temperature response information over the timber cross section throughout the thermomechanical densification procedure. Moisture content experiments were designed to provide total timber moisture content variation information over the thermomechanical densification procedure.

The outcomes of these experiments were used to provide parameters for the design of the thermomechanical densification procedure.

5.1 Equipment

- Thermomechanical press
- K-type thermocouples: temperature range of -50 to 260 °C
- Digital temperature meter with two channel input
- Beam balance

5.2 Procedure

5.2.1 Timber Temperature Response Experiment

The following procedure was used to obtain temperature data throughout the thermomechanical densification process.

1. Timber samples were graded and sawn from green timber lengths.
2. Holes were drilled in the end face of the timber samples to the maximum depth of the drill bit.
3. The end face was coated in grease to inhibit moisture exiting from the end.
4. Thermocouples that had their ends coated in silicon gel (heat sink) were inserted to the limit of the drilled holes.
5. Two thermocouples were connected to the temperature meter, refer Figure 1.
6. The timber piece was loaded into the preheated press and the press was closed to provide contact pressure between the platen and the timber piece.
7. Temperature readings were taken at set time intervals, rotating between the colour coded thermocouples.

8. When the temperature experiment was complete, the thermocouples were removed from the timber piece and a docking saw was used to cut the timber at the maximum depth of the drilled holes.
9. The exact location of the drilled holes, corresponding to the position of the thermocouples, were measured and recorded

Four temperature experiments were conducted using the procedure outlined above. Experiment 1 was a low temperature trial using an average platen temperature of 75 °C and contact platen pressure. Experiments 2 and 3 were high temperature trials using an average platen temperature of 155 °C and contact platen pressure. Four thermocouples were located close to the surface of the timber piece for Experiment 2 and six thermocouples were distributed over the timber section for Experiment 3. Experiment 4 used six thermocouples distributed over the section where the average platen temperature was 155 °C and platen pressure was used to densify the originally 40 mm thick timber to 35 mm thick.

Figure 1. Digital Temperature Meter and Thermocouples.

5.2.2 Moisture Content Variation Experiment

The following procedure was used to obtain moisture content data throughout the thermomechanical drying process.

1. Timber samples were graded and sawn from green timber lengths.
2. Two timber samples were cut from the green timber piece immediately. The sample lengths of approximately 5 mm and 150 mm were labelled and wrapped in plastic to limit moisture loss.
3. The remaining timber sample length was loaded into the preheated press and the press was closed to provide the required platen contact pressure.
4. The timber piece was removed from the press after 15 minutes and an end section of 200 mm was discarded, to limit end-drying effects, prior to samples being taken. Samples approximately 5 mm and 150 mm long samples were cut from the timber piece and were then labelled and wrapped in plastic.
5. This process of taking timber samples was repeated at 15 minute intervals for the 90 minute drying period.

6. The wet weights of the timber samples taken throughout the drying procedure were determined using a beam balance.
7. The dry weights of the timber samples were determined using an iterative process of microwave drying and weighing. Microwave drying was used to remove some moisture from the timber pieces before the samples were stored in a silicon vessel to cool and were then weighed. This process was repeated until the weight of the timber sample converged to the final dry weight of the timber piece.

In cases where the moisture content measurements from the 5 mm samples were uncharacteristic, another sample was cut from the 150 mm sample and processed according to the procedure outlined above.

5.3 Results

In the results and discussion sections, the experiments on timber temperature response and moisture content variation are simply referred to as temperature and moisture content experiments or trials, respectively.

5.3.1 Timber Temperature Response Experiment

A temperature trial, Experiment 1, was conducted using an average platen temperature of 75 °C and pressure to ensure contact between the platen and the timber, without significantly densifying the timber. The experiment results are shown in Figure 12 and Figure 13.

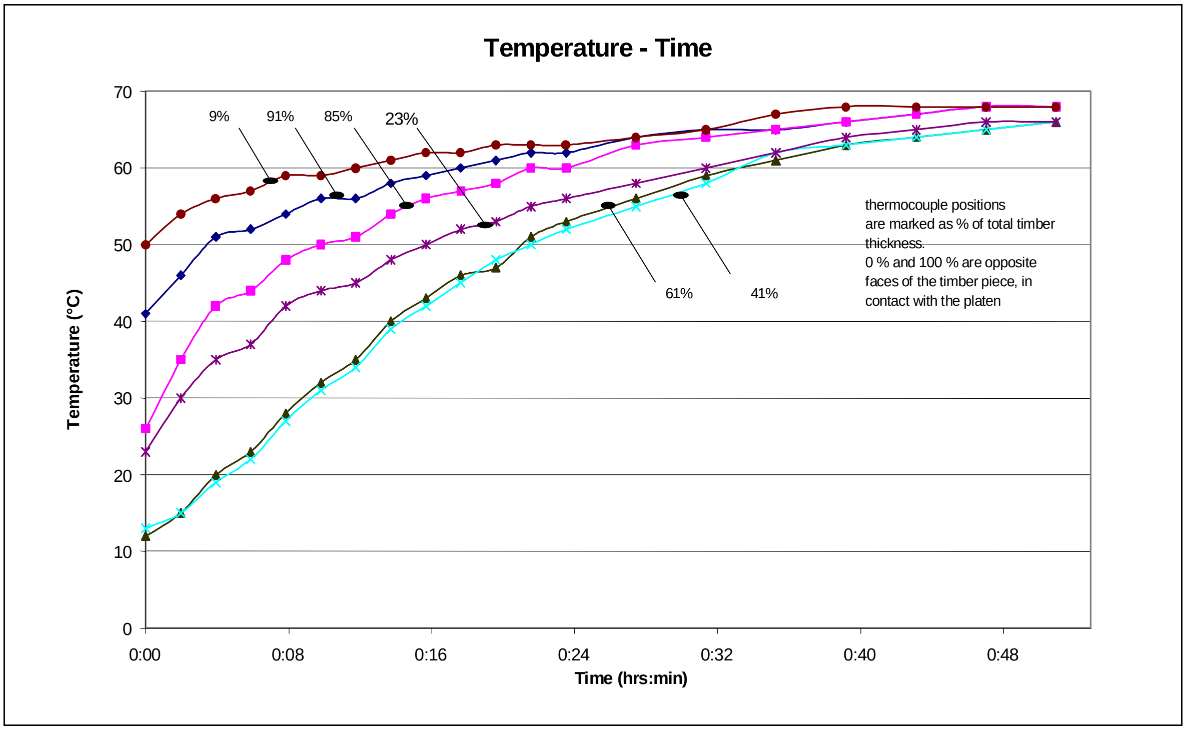

Figure 2. Timber temperature response during the Experiment 1 pressing procedure at different distances from the platen contact face.

The outer regions of the timber increase in temperature rapidly and experience a high rate of heat transfer initially, indicated by the steep temperature gradient in Figure 12. Towards the centre of the timber, illustrated by the 41 and 61 % timber thickness levels, the rate of heat transfer is initially less than that experienced by the outer timber and consequently the temperature rises less rapidly. The entire timber section approached the platen temperature after a heating period of approximately 40 minutes.

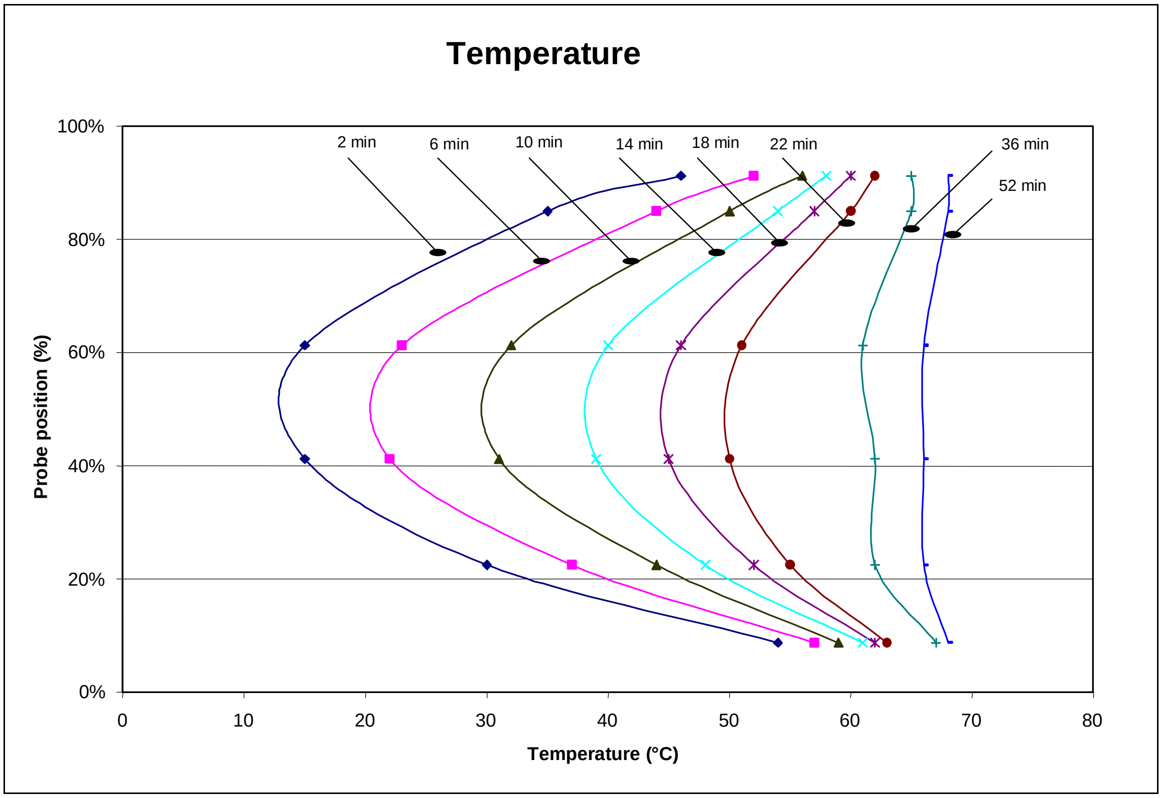

Figure 3. Timber temperature response through the timber cross section at discrete time intervals during the Experiment 1 press procedure.

The temperature profiles graph indicates the temperature distribution through the timber section at discrete time intervals. Initially the timber temperature adjacent to the platen rises rapidly and the inner timber experiences a temperature lag. As the platen drying process continues, the outer timber approaches the platen temperature at a decreased rate whilst the inner timber rises in temperature, which decreases the temperature lag in the timber section. Heat transfer in this process is by conduction and is driven by temperature gradient.

A high temperature trial, Experiment 2, was completed using an average platen temperature of 155 °C and platen contact pressure. Four probes adjacent to the timber surface were used to monitor the temperature behaviour of the timber and the results are shown in Figure 14.

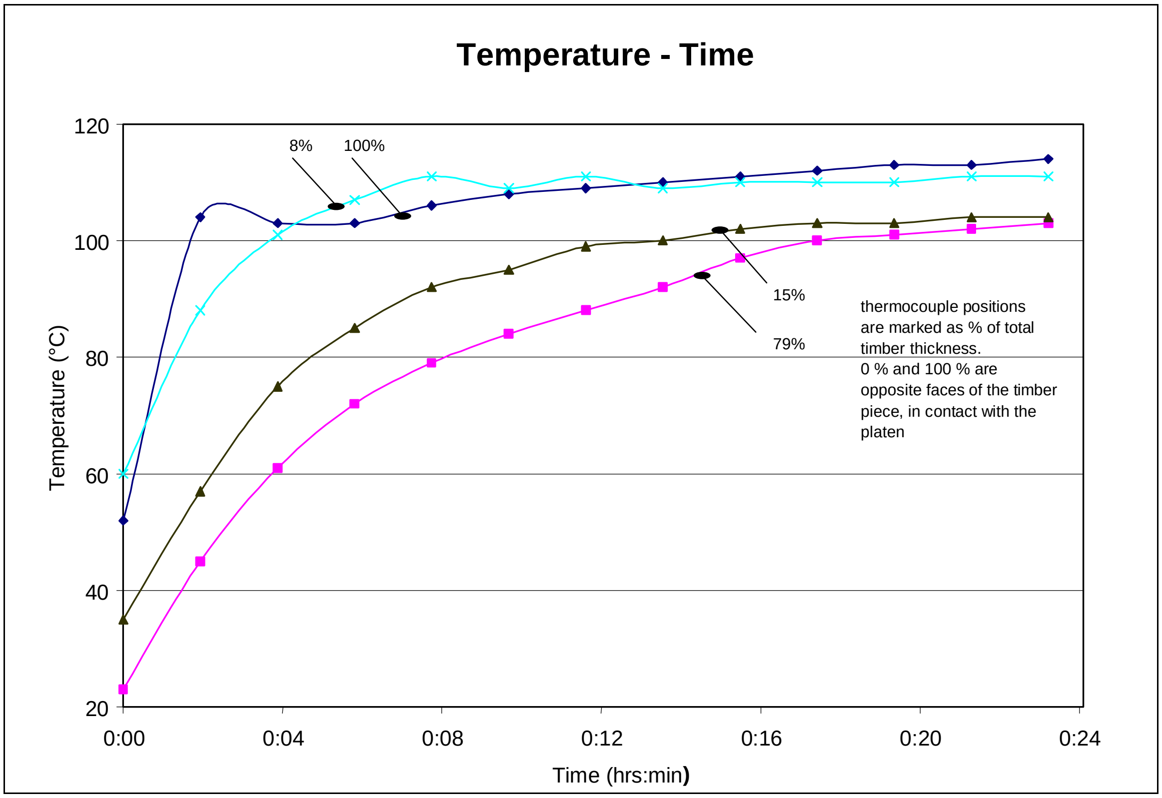

Figure 4. Timber temperature response during the Experiment 2 pressing procedure at different distances from the platen contact face.

The timber adjacent to the platens increased in temperature rapidly, indicating a high rate of conductive heat transfer. However, the timber temperature did not continue to rise towards the platen temperature at a decreasing rate, as occurred in the low temperature trial. The timber adjacent to the platen reached a temperature just above water boiling point, 100 °C, where it remained relatively constant for an extended period of time.

The temperature response of the outer timber region that is not directly adjacent to the platens, represented by the 15 and 79 % thickness levels, is similar to the behaviour illustrated by the low temperature trial. The exception being that instead of the timber temperature tending towards the platen temperature, the timber approaches a temperature marginally above water boiling point where it remains relatively constant.

The temperature profiles graph was not considered in this trial due to the four probes being located close to the timber surface and therefore not providing a representative temperature distribution over the entire timber section.

A high temperature trial, Experiment 3, was conducted using six temperature probes and similar pressing conditions as for Experiment 2. The results are shown in Figure 15 and Figure 16.

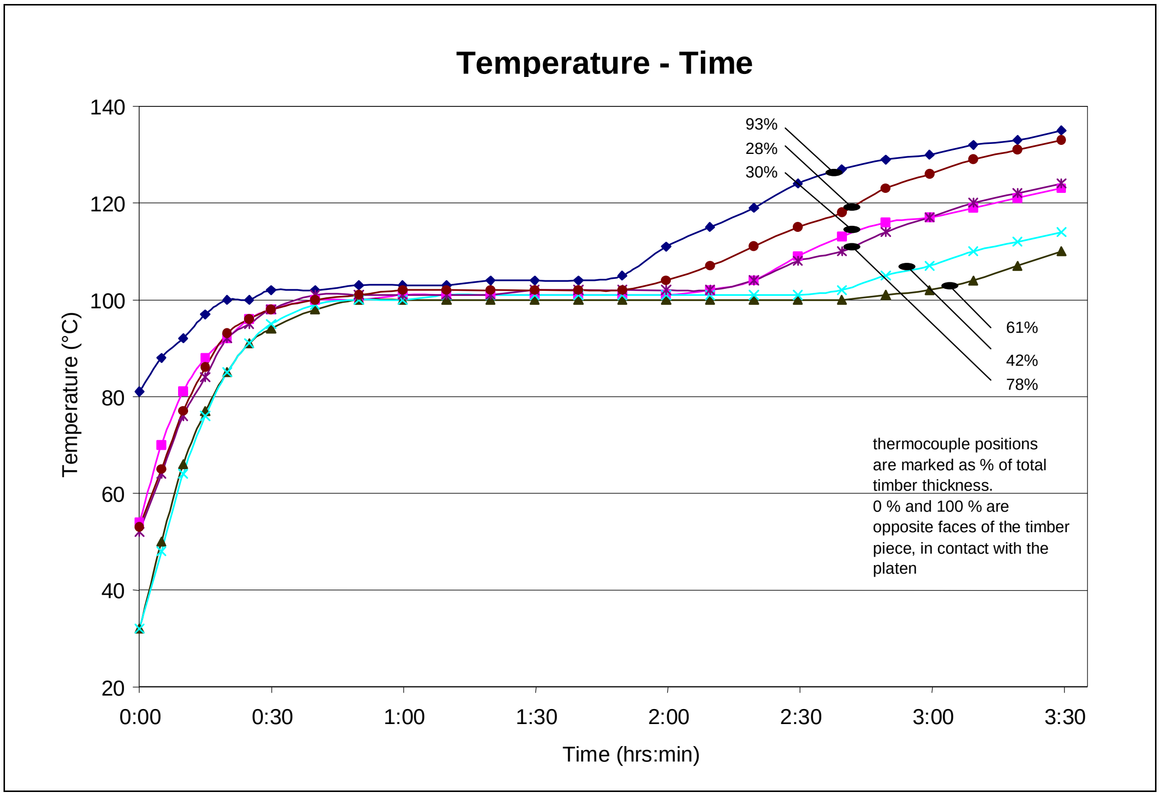

Figure 5. Timber temperature response during the Experiment 3 pressing procedure at different distances from the platen contact face.

The temperature through the timber piece rose rapidly to approximately water boiling point, where it remained relatively constant for an extended period of time. The entire timber section reached 100 °C within 40 minutes, with the 93 % thickness level reaching 100 °C within 20 minutes. The temperature remained at approximately water boiling point for a further 80 minutes before increasing in temperature again, at the 120 minute (2:00, on graph) mark. Timber adjacent to the platens increased in temperature first and was followed by the internal timber.

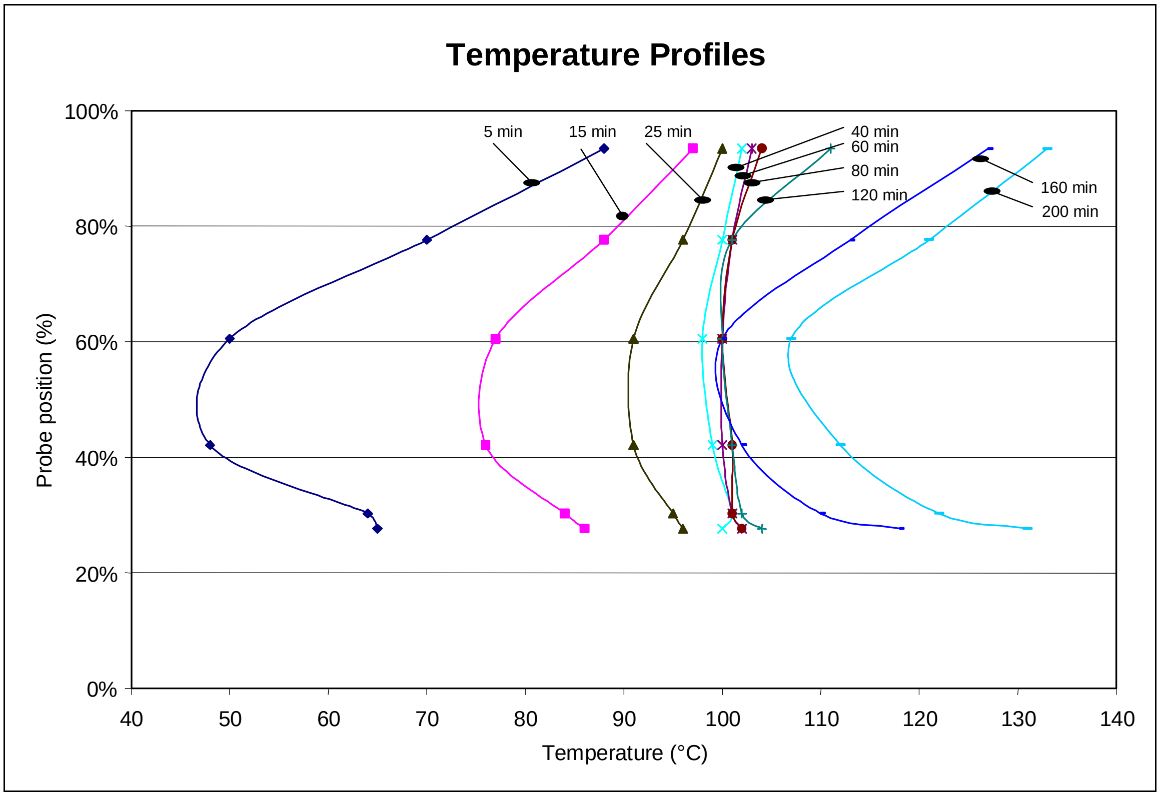

Figure 6. Timber temperature response through the timber cross section at discrete time intervals during the Experiment 3 press procedure.

The temperature profiles indicate that the timber temperature adjacent to the platens rapidly increases whilst the inner timber experiences a temperature lag. As the drying process continues the temperature lag reduces, forming a constant temperature distribution through the timber section at approximately water boiling point, 100 °C. After the period where the entire timber section remains at a relatively constant temperature of 100 °C, the timber temperature rises again. The timber adjacent to the platen increases towards the platen temperature with the inner timber temperature increasing, but again experiencing a temperature lag.

A high temperature trial, Experiment 4, was undertaken using similar press conditions to Experiments 2 and 3, with the addition of pressure applied to densify the timber from 40 mm to 35 mm, representing a 14 % level of densification. The temperature results are shown in Figure 17 and Figure 18.

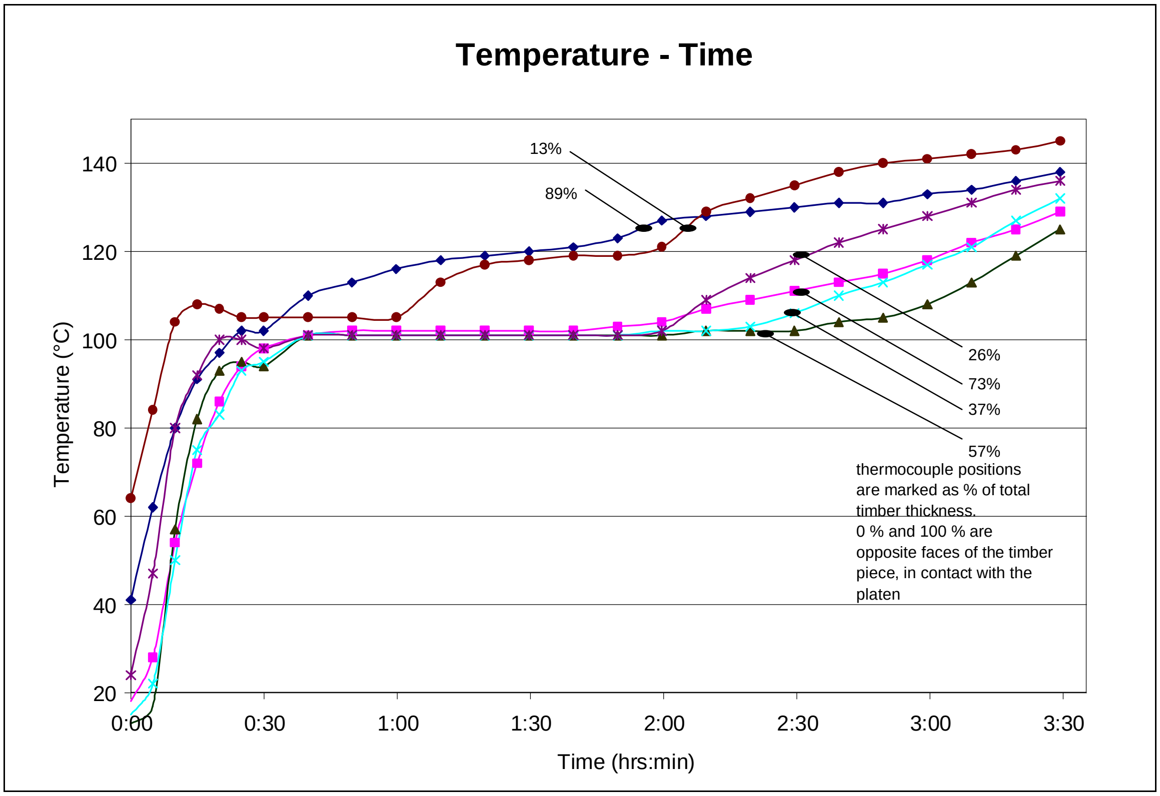

Figure 7. Timber temperature response during the Experiment 4 pressing procedure at different distances from the platen contact face.

The temperature through the timber section increased to approximately water boiling point within 40 minutes, similar to the trial that used contact platen pressure only. Once water boiling point was reached, the timber adjacent to the platens continued to increase in temperature at a reduced rate. The inner 60 % of the timber section remained at temperatures of approximately 100 °C for a further 80 minutes, before beginning to increase towards the platen temperature at the 120 minute mark, similar to the temperature response shown in Experiment 3.

The magnitude and distribution of timber temperatures in the densified and contact pressure temperature trials were comparable upon completion of the 3½ hr trials. Although the timber adjacent to the platens continued to rise above 100 °C during the densified timber temperature experiment, the temperatures at the end of the trial period were only slightly higher than those observed for the contact pressure case.

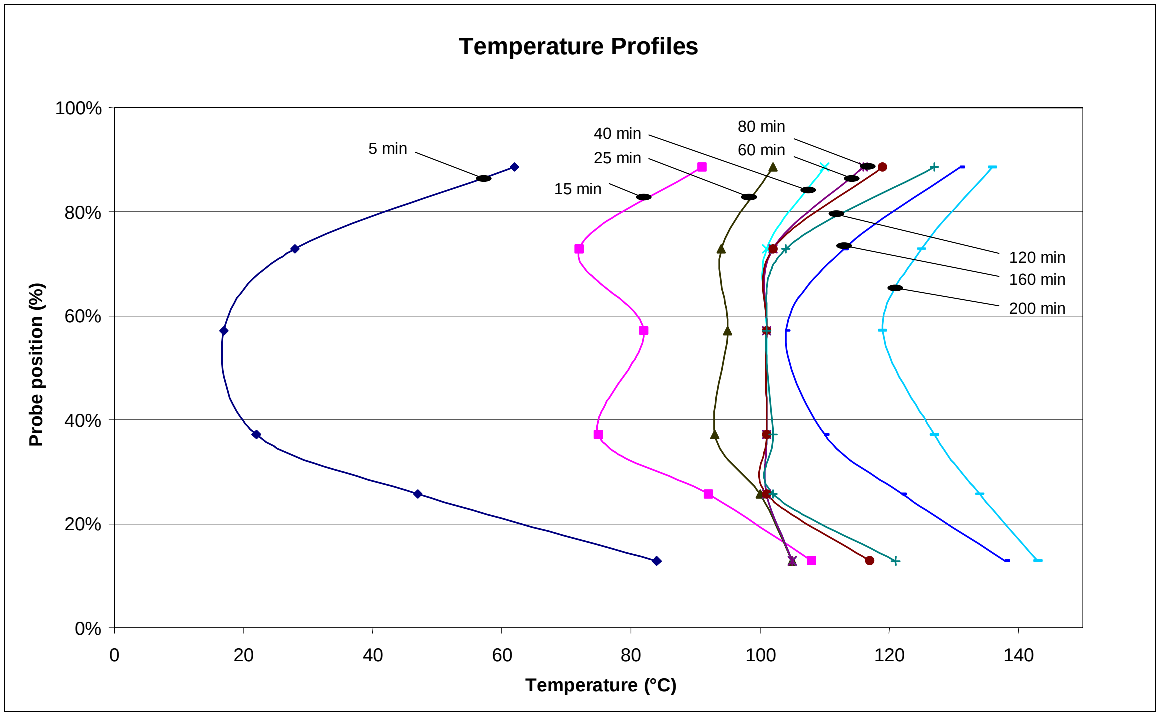

Figure 8. Timber temperature response through the timber cross section at discrete time intervals during the Experiment 4 press procedure.

The temperature profiles are similar to those observed for the high temperature trial using platen contact pressure, Experiment 3. Temperature values at approximately the centre of the timber section are higher than the surrounding timber at the 15 and 25 minute time intervals.

5.3.2 Moisture Content Variation Experiment

Two moisture content experiments were conducted following the procedure outlined in section 5.2.2. The results produced from each trial were similar and the average moisture content variation with press time is shown in Figure 9.

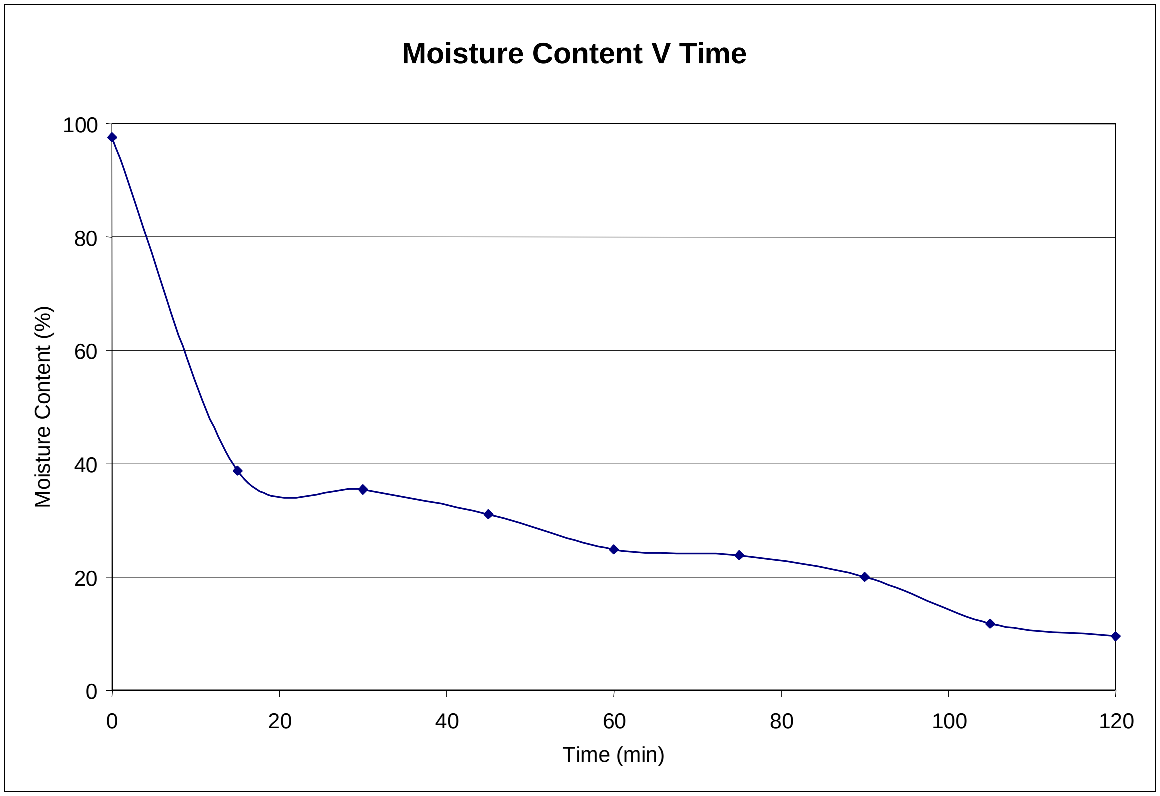

Figure 9. Variation of timber moisture content through a typical pressing procedure.

Platen drying caused the rapid reduction in moisture content of the timber piece. The moisture content was reduced from its initial value of 100 % to 40 % within 15 minutes of platen drying. Moisture reduction then occurred at a lesser rate, taking a further 90 minutes to reduce the moisture content from 40 % to the target moisture content range of 8 to 16 %.

5.4 Discussion

5.4.1 Timber Temperature Response

The temperature of the timber adjacent to the platens increased towards the platen temperature during the low temperature trial. The temperature response was different for the high temperature trial, with the timber temperature being maintained at approximately water boiling point for around 80 minutes. This temperature behaviour is a characteristic observed in both kiln and press drying. A stable temperature of 100 °C in the timber adjacent to the platens and throughout the timber section is an important observation because it indicates that moisture flow is still prevalent near the surface of the timber piece.

After the time period where the temperature was maintained at 100 °C, the temperature of the timber began to rise again. This corresponds to a period where the moisture content in the samples has reduced to a level where the timber is no longer cooled by evaporation. The temperature at the outside of the section increases towards the platen temperature before the interior of the timber begins to increase towards the platen temperature.

It was intended that in each of the temperature profile experiments that the data were gathered over the section at an approximately equal spacing. However, the temperature profile graph for

Experiment 3 is lacking information between the 0 and 28 % thickness levels. This occurred due to the holes being drilled at an angle resulting in two probes being closely spaced at the 28 and 30 % thickness levels.

The temperature response of timber adjacent to the platens was different between the trial where the timber was densified and where only contact pressure was applied. Temperature in the densified timber trial continued to rise above 100 °C instead of forming a plateau region as occurred in the contact pressure trial. This may have been caused due to pressure being applied early in the experiment which crushed the cells closed and inhibited the free movement of moisture. Lack of free moisture movement hampers the cooling evaporation effect and timber temperatures exceeding 100 °C can occur. Similar distributions of temperature occurred upon completion of pressing for the two pressing procedures.

The existence of a higher temperature reading at the centre of the timber for the temperature profile in Experiment 4 is thought to be due to an anomaly and not a function of the pressure applied to timber.

5.4.2 Moisture Content Variation

The moisture content characteristics of platen dying was investigated to further understand the plasticity conditions of timber in the thermomechanical densification process and to determine the drying time required.

The temperature and moisture content characteristics of platen dried timber are related.

Through the first 15 minutes of drying, the moisture content decreased from 100 to 40 %. The temperature experiments indicate that there was high heat transfer through the timber in this period with the temperature approaching 100 °C adjacent to the platens and 70 °C at the centre of the timber section at the 15 minute mark.

The moisture content further reduced at a relatively constant rate from 40 % at the 15 minute mark, to 10 % at the 120 minute mark. The temperature at the centre of the piece increased to form a relatively constant temperature distribution of 100 °C over the timber section until the 120 minute mark.

The timber piece was essentially dried at the 120 minute mark, having a moisture content of approximately 10 %. Timber adjacent to the platens increase in temperature around the 120 minute time, with the interior timber increasing in temperature as the timber continues to dry.

5.4.3 Thermomechanical Densification Procedure Design Outcomes

The timber temperature response and moisture content variation experiments provided information on the variation of these characteristics throughout the thermomechanical densification procedure.

As platen drying occurred, the temperature of the timber increases rapidly and the moisture content of the timber section reduces rapidly. Conditions of high plasticity occur when the lignin is softened, which occurs ideally at temperatures exceeding 80 °C in saturated moisture conditions. It was considered desirable to have the entire section of timber heated to temperatures above 80 °C so that material softening and redistribution could occur through the entire timber piece. In order to maximise the amount of moisture in the timber piece when densification occurs, platen pressure should be applied as soon as the inner section of the timber reached 80 °C. The temperature reached 80 °C at the centre of the timber section in 25 minutes and the corresponding total moisture content was approximately 40 %.

Densification of the timber should occur with the application of platen pressure at the 25 minute mark and be completed in reasonably short time period to make use of the maximum moisture contents. The time period over which the densification occurs was chosen to be 10 minutes, allowing the plastic softening and redistribution of wood components but without continuing until low moisture content conditions. The temperature distribution remains relatively constant at 100 °C for a relatively long period of time, where the moisture content reduces from 40 to 10 %.

Temperatures throughout the timber piece start to increase from around 100 °C towards the platen temperature, once the timber is sufficiently dry. The press dried timber reaches the target moisture content of 8 to 16 % after approximately 120 minutes (2 hrs), indicating the total time required for the thermomechanical densification process.

6. Densified Timber Production and Property Evaluation

The parameters for design of the thermomechanical densification procedure were established through the temperature response and moisture content variation experiments. The procedure used to produce the densified timber is outlined in this section.

The thermomechanical densification procedure was used to process timber samples at 40 mm and 45 mm initial thicknesses to a nominal final thickness of 35 mm, representing 13 % and 22 % densification levels respectively. The degree of retention of compressed dimension and the mechanical properties of the densified timber samples were then compared to the kiln dried control sample timber.

It was expected that densified timber products would have a high degree of retention of compressed dimension and improved mechanical property results, when compared to kiln dried control sample timber. Property improvements were expected to proportionally increase with the level of densification, whilst timber hardness was the property considered to undergo the largest percentage increase.

6.1 Timber Samples

The sample sizes selected were chosen to provide results for analysis and discussion. A sample size of 12 at 1240 mm long was selected for testing timber stiffness about the axis perpendicular to the compressed timber faces (edgewise). For assessment of stiffness and strength about the axis parallel to the compressed timber faces (facewise), the 1240 mm samples were halved, producing 24 samples at 620 mm long. The large numbers of samples required by the timber testing code were not provided in this research due to material restrictions, as well as production and testing time constraints.

The densified timber samples were selected immediately after the green timber was sawn. The control sample set was selected from kiln dried timber. All timber samples were clear graded as best as possible to avoid defects such as knots and wane.

6.2 Equipment

Densified Timber Production

- Timber docking saw
- Panel planer
- Thermomechanical press, Figure 10.
- Restraint press

Figure 10. Thermomechanical Densification Press.

The thermomechanical press used in this research was purpose built. The platens are square hollow section steel members filled with heating oil. Platen temperature is controlled by four electric thermostat oil heaters. Platen pressure applied to the timber piece is controlled by an air-over-oil compressor and four hydraulic rams mounted on the bottom platen.

Testing

» Resistance moisture meter

» Vernier callipers

» Deflection dial gauge

» Amsler Universal Testing Machine, Figure 11

Figure 11. Amsler Universal Testing Machine at DPI Timber Testing Station in Salisbury (Brisbane) used for mechanical testing.

6.3 Procedure

6.3.1 Densified Timber Production:

1. The timber lengths were planed to the correct initial thickness using a panel planer.
2. Timber lengths were loaded into the thermomechanical press with an average platen temperature of 175 °C.
3. Platen pressure was applied at the 25th minute to densify the timber to a final nominal thickness of 35 mm within a 10 minute period.
4. The timber with initial thicknesses of 40 and 45 mm, representing 13 and 22 % nominal compression levels, remained in the press for 120 minutes (2 hrs) and 150 minutes (2½ hrs), respectively.
5. After the densification process, the timber lengths were held in a restraint press whilst conditioning of the timber sample occurred.
6. A length of 100 mm was docked and discarded from the ends of each timber piece to remove any effects due to end drying.
7. Timber lengths of 1240 mm were cut using a docking saw and were labelled as being two samples 620 mm long.

6.3.2 Testing Procedure:

1. Dimensions and moisture contents of the timber samples were assessed after conditioning and prior to testing.
2. The full-length (1240 mm) timber samples were tested for stiffness about the axis perpendicular to the platen contact face, or in an edgewise orientation.
3. The full-length (1240 mm) timber samples were docked into half-length (620 mm) timber samples.
4. The half-length (620 mm) timber samples were tested for stiffness and strength about the axis parallel to the platen contact face, or in a facewise orientation.
5. Janka hardness was assessed on the platen contact faces of the half-length (620 mm) timber samples.

6.4 Observations

6.4.1 Densified Timber Production

Moisture was observed to exit the timber samples throughout the densification process.

During the preheat stage, where only contact platen pressure was applied to the timber, steam exited from the corners of the timber pieces which were in contact with the platens and from the ends of the timber. Platen pressure applied to the initially 40 mm thick timber caused steam to exit along the entire free faces of the timber and for liquid moisture to be expelled from the ends. Similar moisture characteristics were observed during densification of the initially 45 mm thick timber, with liquid moisture accompanying the steam that exited along the free faces of the timber and liquid moisture was expelled from the ends of the timber section at an increased rate.

Additional observations during the densification of the 45 mm thick timber included water and steam bubbling which occurred in some regions along the timber faces where moisture exited more readily, an audible whistling sound accompanying the release of steam during densification of some samples, and the steam bursts which accompanied the release of platen pressure upon completion of the pressing operation.

The full-length (1240 mm) densified timber sample sets A and B are shown below in Figure 12 and Figure 13. The thermomechanical densification procedure was applied to 12 full-length in the A and B sample sets, as pictured below.

Figure 12. A Series: 40 mm initial thickness timber representing 13 % nominal densification.

Figure 13. B Series: 45 mm initial thickness timber representing 22 % nominal densification.

The densification process changed the appearance of the timber. Darkening and staining of the timber occurred due to the high platen temperatures and expelled timber resins being baked on to the timber piece during the pressing operation. The bottom of the timber sample was significantly more stained than the top due to the collection of resins on the bottom platen which coated the bottom face of the timber samples.

The densification of timber caused the lateral expansion of the timber piece. Timber samples experiencing the 22 % nominal compression level laterally expanded more than the timber compressed to the 13 % nominal compression level.

The densified timber experienced some surface cracking which varied with the level of densification. Minor and discontinuous cracking occurred on the timber faces in contact with the platens for timber compressed to the 13 % level. Cracking was more prevalent in the timber compressed to 22 %, although the cracks were still minor and discontinuous. The surface of the timber compressed to 22 % was noticeably smoother than the timber compressed to 13 %.

6.4.2 Testing

Assessments of dimensional properties, moisture content, stiffness on the full-length timber pieces and Janka hardness values were conducted in accordance with the procedure outlined in section 6.3.2 and occurred without abnormal observations.

However, it was observed that a number of full-length timber samples that included defects which were outside the middle third of the timber piece, the high stress zone in a four point bending test, produced half-length timber samples that included defects within the middle third of the timber piece.

When these half-length timber samples where tested for stiffness and strength they were found to be extremely flexible and ruptured at low loading. These test result were removed from the data set, relating to the number of data points on the graphs of MOE and MOR ranging from a maximum of 24 to a minimum of 22.

The experimental procedure intended that clear graded timber samples be used to minimise the impact of defects on the results.

6.5 Results

6.5.1 Experimental Procedure

The experimental procedure used for the production of the densified timber sets, provided a timber response that was consistent with the objectives. Observation showed that the timber was relatively easily compressed when pressure was applied to the timber pieces at the appropriate time. This resulted in the compression limit being reached within the 10 minute time period, ensuring the timber pieces maintained a high moisture content and therefore allowed for maximum timber cell redistribution through high plasticity. A successful experimental procedure for the production of densified timber will produce timber products with improved mechanical properties and minimal cracking.

6.5.2 Moisture Content

The moisture contents of densified and kiln dried timber samples are shown in Figure 24.

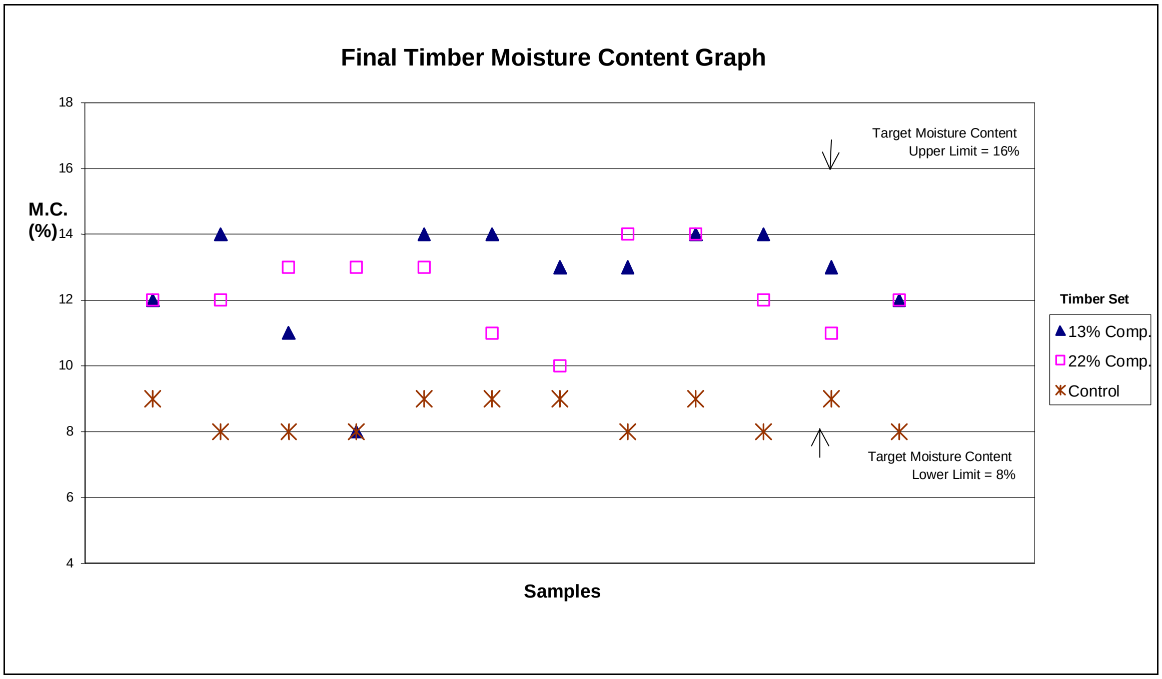

Figure 14. Final timber moisture content of timber samples.

All timber sample moisture contents were within the target seasoned timber moisture content range of 8 to 16 %. Kiln dried timber samples had consistently low moisture contents with a mean and median moisture content of 9 %. The mean and median moisture contents were 13 % and 12 % for the timber samples compressed to the 13 % and 22 % levels respectively. These moisture content results indicate that the thermomechanical densification procedure can season green timber successfully.

6.5.3 Degree of Retention of Compressed Dimension

All timber samples were visually inspected for warping and their physical sizes were evaluated. Warping was not evident in either the densified or kiln dried timber, however the small sample lengths make a characteristic assessment difficult.

The degree of retention of compressed dimension results provide a description of the timbers' response during and after the thermomechanical densification process. The compression of timber describes the percentage change from the initial timber thickness to the compressed timber thickness. The nominal final thickness of the compressed timber is 35 mm, which represents 13 % and 22 % compression for the initially 40 mm and 45 mm thick timber. The actual final thickness of the compressed timber is 33 mm, which includes an additional 2 mm of compression that allows for inherent springback in the timber. The levels of compression when compared to a final thickness of 33 mm are 18 % and 27 % for the initially 40 mm and 45 mm thick timber. Unless specifically stated, the compression levels considered will be the nominal compression levels of 13 % and 22 % that relate to the nominal final timber product size of 35 mm. Degree of retention of compressed dimension results, compression set and springback, are compared to the nominal compression of the samples, as shown in Figure 15 and Figure 16.

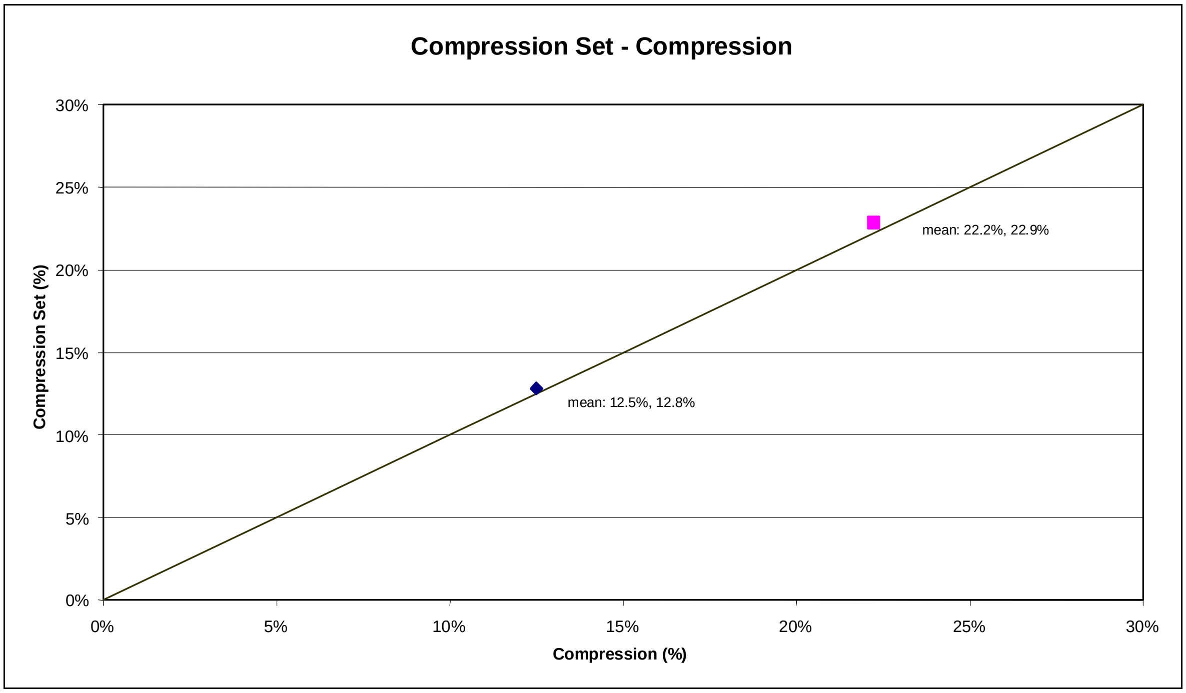

Figure 15. Compression set, or compression retained by the timber sample, compared to the total compression applied over the pressing procedure.

The mean compression set values were 12.8 % and 22.9 % for the timber samples which had 12.5 % and 22.2 % levels of compression applied, respectively. These mean compression set values are approximately equal to the nominal compression applied to the timber samples, indicating that the nominal over-press of 2 mm was effective in providing a mean residual compression level in the timber after conditioning that was similar to the nominal compression applied.

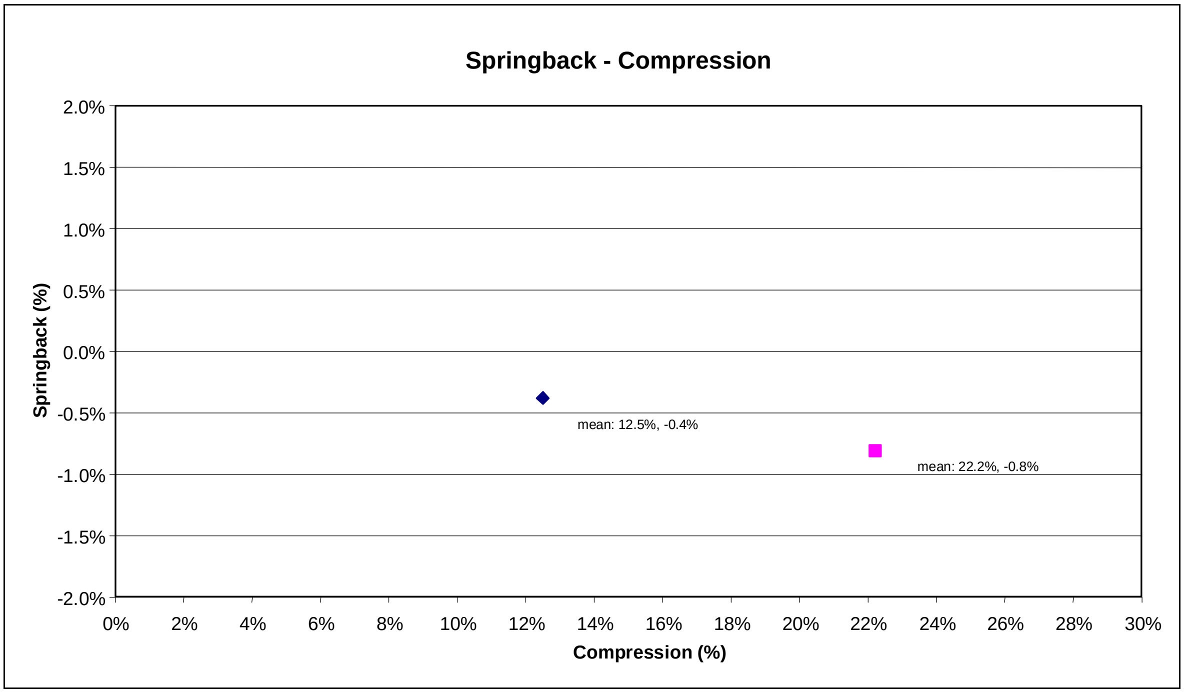

Figure 16. Springback, or the recovery of the timber sample, compared to the total compression applied over the pressing procedure.

The mean springback results are –0.4 % and –0.8 % for timber sample sets densified to the 12.5 % (nominally 13%) and 22.2 % (nominally 22%), compression levels respectively. Although the results are approximately zero, which would mean that there has been no recovery of thickness through the conditioning process, the negative value indicates that compression retained by the timber sample is slightly larger than the compression applied. This is also shown by the compression set values being slightly higher than the compression values in Figure 25. These results indicate that the timber samples maintained some additional thickness reduction after the reconditioning process due to the over-press of 2 mm used in the pressing procedure.

6.5.4 Mechanical Properties

Stiffness

The modulus of elasticity results for the full-length (1240 mm) long timber samples, tested about the axis perpendicular to the timber platen contact face, or edgewise orientation, are compared to the compression set of the timber samples, as shown in Figure 17.

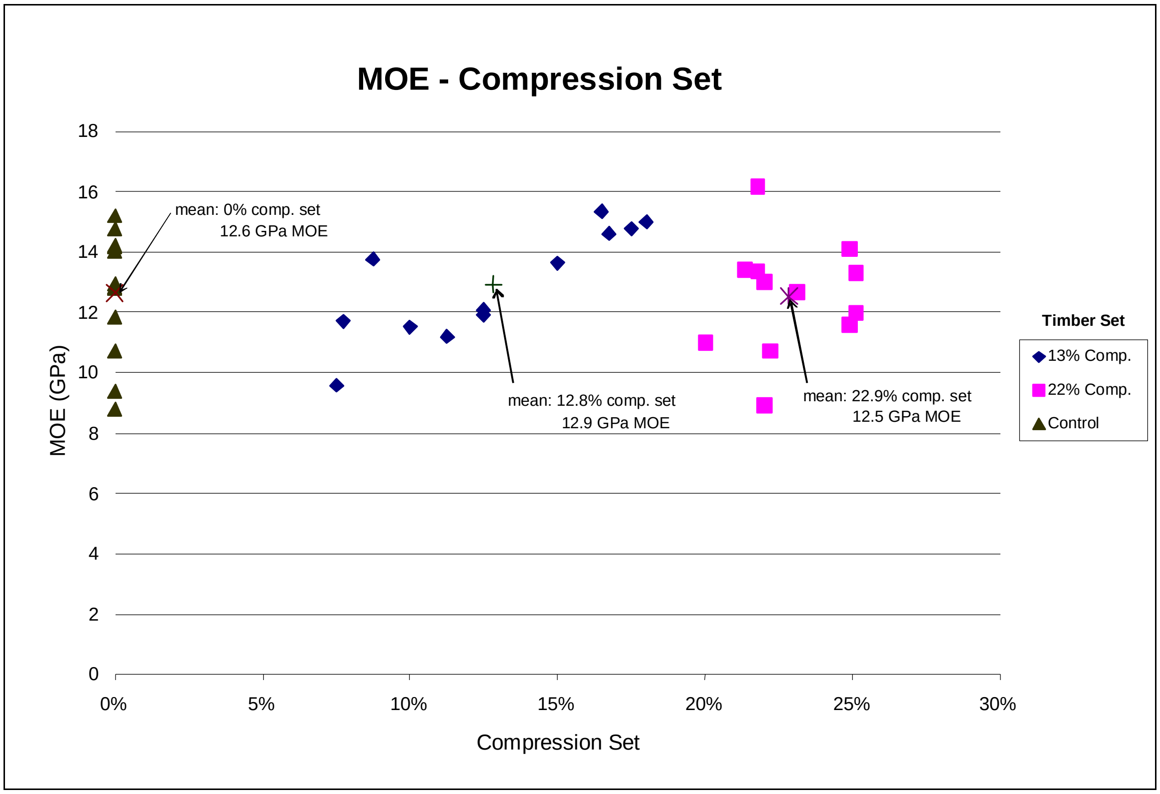

Figure 17. MOE of the 1240 mm long timber samples tested edgewise compared to the compression set of the timber sample.

The mean MOE values for the full-length timber samples tested edgewise are indicated on the graph for each sample set by a line marker. These MOE values are 12.9 GPa, 12.5 GPa and 12.6 GPa for the timber compressed to the 13 % and 22 % levels, and the kiln dried timber respectively. Mean results are similar between the densified sample sets and the kiln dried timber.

The modulus of elasticity results for the half-length (620 mm) timber samples, which were tested about the axis parallel to the platen contact timber face, or facewise, are shown in Figure 18 compared to the compression set of the timber samples.

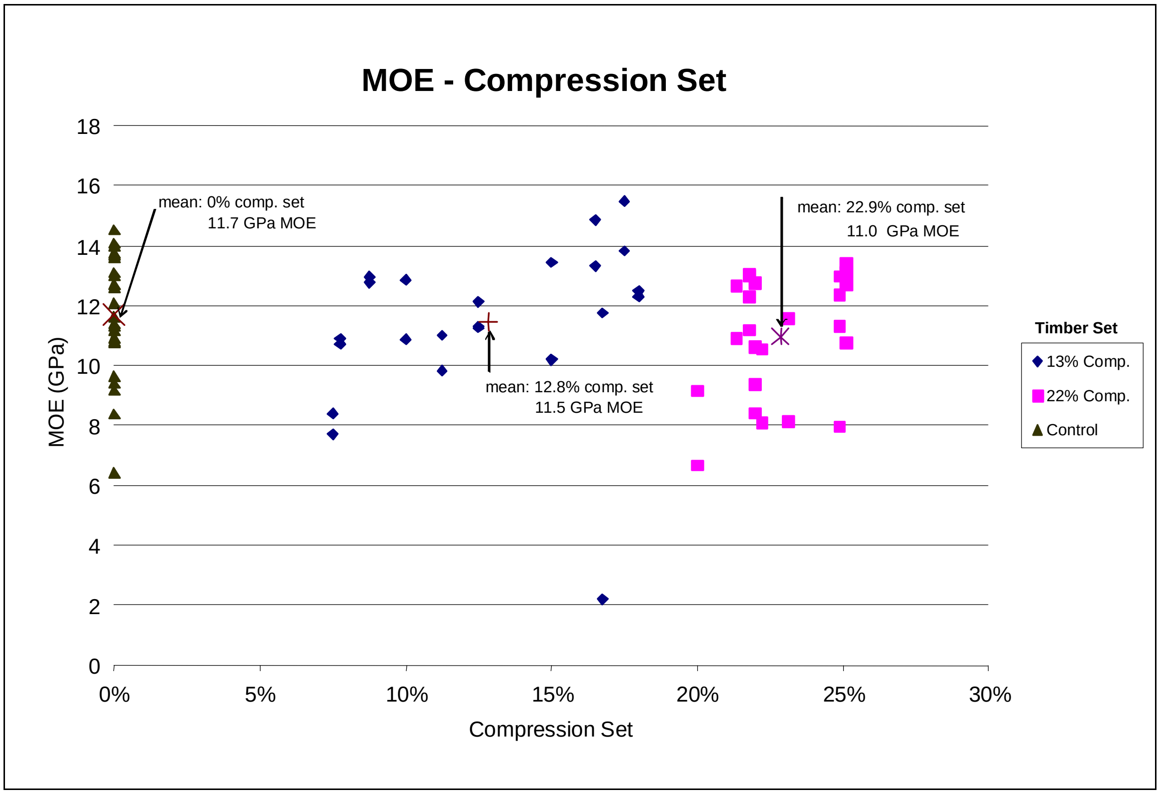

Figure 18. MOE of the 620 mm long timber samples tested facewise compared to compression set, or the compression retained by the timber sample.

The mean MOE values are indicated on the graph for each sample set by a line marker. These MOE values are 11.5 GPa, 11.0 GPa and 11.7 GPa for the timber compressed to the 13 % and 22 % levels, and the kiln dried timber respectively. Mean results of the densified timber sets are slightly lower than for the kiln dried control sample set.

The MOE results are higher for the full-length (1240 mm) timber samples tested edgewise compared to the half-length (620 mm) timber samples tested facewise. The mean MOE value comparison is 12.9 GPa to 11.5 GPa, 12.5 GPa to 11.0 GPa and 12.6 GPa to 11.7 GPa for the timber compressed to the 13 % and 22 % levels, and the kiln dried timber respectively.

Strength

The modulus of rupture results for the 620 mm long timber samples tested about the axis parallel to the compressed timber face (facewise), are shown in Figure 19 compared to the compression set of the timber samples.

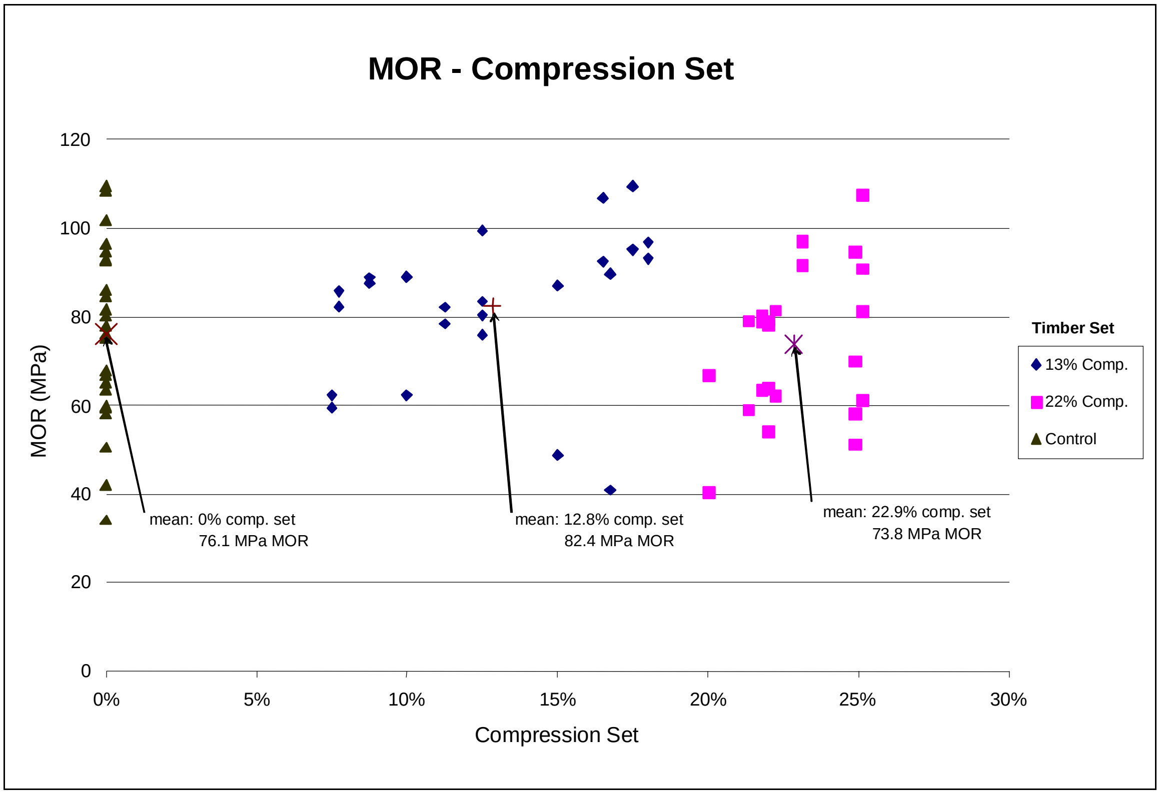

Figure 19. MOR of 620 mm long timber samples tested facewise compared to compression set, or the compression retained by the timber sample.

The mean MOR values are indicated on the graph for each sample set by a line marker. These MOR values are 82.4 MPa, 73.8 MPa and 76.1 MPa for the timber compressed to the 13 % and 22 % levels, and the kiln dried timber respectively. The mean values are reasonably similar, with the timber compressed to 13 % being slightly above the control sample mean, and the timber compressed to 22 % being slightly below the control sample mean. Both results being within 10 % of the mean MOR value of the kiln dried timber.

The median MOR values are 85.8 / 87.1 MPa, 78.2 / 78.0 MPa and 76.2 / 78.1 MPa for the timber compressed to the 13 % and 22 % levels, and the kiln dried timber respectively. The median values are higher than the mean values for each data set for the densified timber sample sets, indicating that low test results have influenced the mean values significantly. Low outlying data values are shown on the graph.

Hardness

The Janka hardness was measured on the compressed face of the 620 mm samples and are shown in Figure 20 in relation to the compression set of the timber samples.

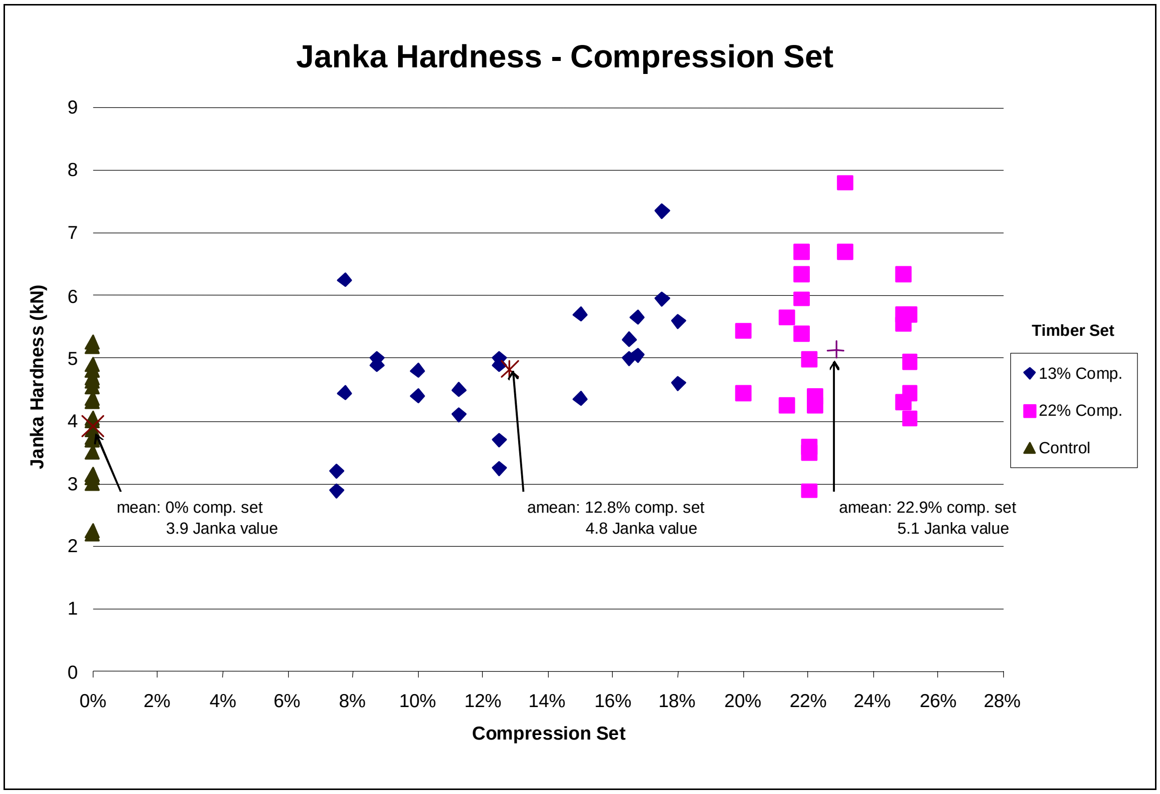

Figure 20. Janka hardness for timber samples tested on the timber face in contact with the platen compared to compression set, or the compression retained by the timber sample.

The mean Janka hardness values are indicated on the graph for each sample set by a line marker. These hardness values are 4.8 kN, 5.1 kN and 3.9 kN for the timber compressed to the 13 % and 22 % levels, and the kiln dried timber respectively. These mean values correspond to a 23 % and 27 % increase in hardness over the kiln dried timber samples, for the 13 % and 22 % compressed timber samples.

6.5.5 Timber Defect Considerations

The sample sets used in this research were relatively small, consequently, an unequal distribution of defects would cause large variations in the results observed. Observations showed that the full-length (1240 mm) timber pieces were relatively defect free within the middle third of the timber pieces, which is the high stress zone under a four point bending test. The half-length (620 mm) timber pieces, however, did contain defects within the middle third of the timber piece, which being the high stress zone, significantly affects stiffness and strength measures. This occurred even though attention was paid to clear grade the timber pieces.

The MOE data values for the half-length timber samples were sorted to exclude timber pieces with defects in the high stress region. There were seven, twelve and five data values removed from the data sets corresponding to the 13 % compressed timber, 22 % compressed timber and kiln dried timber samples, respectively.

Mean MOE values for the samples tested edgewise increased from 11.5 to 12.4 MPa (8 %) and 11.0 to 11.5 MPa (5 %) for the timber sample sets densified to the 13 % and 22 % levels respectively. The mean MOE value for the kiln dried sample set increased from 11.7 to 12.1 MPa

(3 %). Both the densified timber sets had a mean MOE value within 5 % of the kiln dried set mean MOE value, with a slightly higher value recorded for the 13 % compressed timber and a slightly lower value recorded for the 22 % compressed timber.

The sorted MOE mean values for the half-length samples tested facewise are more consistent with the mean values for the full-length samples (tested edgewise). The mean MOE values are 12.4 and 12.9 MPa for the 13 % compressed timber, 11.5 and 12.5 MPa for the 22 % compressed timber, and 12.1 and 12.6 MPa for the kiln dried timber, at the 620 mm and 1240 mm lengths respectively. The MOE mean values for the 22 % compressed timber are notably different, which is partly due to low outlying data decreasing the mean value for the 620 mm long timber set.

The information presented in this section provides result information that is less heavily influenced by defects in the timber. The results show that mean MOE values for the 620 mm timber lengths increased across all sample sets, and that the timber compressed to 13 % and the kiln dried timber had similar mean MOE values when tested facewise and edgewise. The mean MOE results for the timber densified by 22 % was lower when tested facewise than compared to the edgewise timber test results partially due to a low outlying data skewing the mean result values.

6.6 Discussion

The timber temperature response and moisture content variation experiments indicated the thermomechanical densification parameters for the production of compressed timber pieces as outlined in the procedure.

Observation of timber samples throughout the densification process and of the final timber product, provided evidence that the thermomechanical densification procedure designed and utilised in this research was effective. This was observed through the relatively low pressures needed to compress the timber and the excess of moisture that was expelled during the compression, indicating that favourable temperature and moisture conditions were present for the densification process.

The thermomechanical densification manufacturing procedure successfully produced seasoned timber products with a high degree of retention of compressed dimension. Recovery of the timber samples being virtually equal to nil, meaning that the compression retained by the timber samples was equal to the compression applied, indicated the effectiveness of the 2 mm over press used and that the restraint press used through the conditioning period was effective. The resulting timber products had a darkened and stained appearance with some discontinuous surface cracking on the timber faces that were in contact with the platens. The surface of the timber pieces that were in contact with the platens became smooth.

The stiffness results of the timber samples tested facewise and edgewise were approximately equal to the kiln dried timber stiffness results. Strength results showed that the timber compressed to the nominal 13 % level were marginally stronger than the timber compressed to the nominal 22 % compression level which were marginally weaker than the kiln dried timber. The hardness results which showed improvements of over 20 % for both compression sets is perhaps more representative of the stiffness and strength gain achievable by compressed clear graded timber.

The strength properties of a timber piece are several orders of magnitude more sensitive to natural timber defects like knots, juvenile wood and sloping grain, than they are to the inherent properties of the clear wood. Comparison of timber strength properties between different manufacturing methods requires the matching of clear and timber samples with defect, with a very large number of samples used. The hardness testing may give the best indication of general strength gain because it was taken in clear areas of the timber pieces.

7. Conclusions

Thermomechanical densification has aims and objectives that are fundamentally different to those of Compreg, Staypak and press drying manufacturing methods, which typically apply to discrete parts of the processing procedure and can be resource intensive to utilise. The aim of thermomechanical densification is to provide a complete processing method used to season structural or semi-structural timber products in a time and energy efficient manner, producing minimum cost final timber products with a high degree of retention of the compressed dimension and improved mechanical properties.

The optimal thermomechanical densification procedure allows timber cells to redistribute under conditions of high plasticity with minimal internal timber stresses being established. To determine the design parameters for the thermomechanical densification procedure, existing processing techniques such as Compreg, Staypak and press drying were investigated in conjunction with theory on the chemistry, cellular structure, viscoelastic properties and drying responses of timber. The knowledge established in these areas provided the basis for timber temperature response and moisture content variation experiments. These experiments provided clear output on the design parameters required for the thermomechanical densification procedure.

The design parameters for the thermomechanical densification procedure were applied to produce timber samples densified to two different levels, which were then evaluated and compared to kiln dried timber samples. Timber samples to be densified were loaded into the thermomechanical densification press where the platens, operating at an average temperature of 175 °C, were brought into contact with the timber pieces to allow conductive heat transfer. Compression of the timber pieces commenced at the 25 minute mark for the initially 40 mm and 45 mm thick timber pieces and was applied to densify the timber to a final nominal thickness of 35 mm, representing 13 % and 22 % levels of densification respectively. The compression was applied over a 10 minute period where high moisture conditions were present and the samples were retained in the press for 120 minutes (2 hrs) and 150 minutes (2½ hrs), for the initially 40 mm and 45 mm thick timber respectively, to produce seasoned timber pieces.

The seasoned timber samples, still at a high temperature, were transferred from the thermomechanical press to a restraint press for the duration of the conditioning period. This process assisted the residual compression of the timber pieces.

Observation of the timber samples during densification indicated that high moisture content conditions were present during densification due to the large amount of steam and liquid water released by the timber samples during this process. Final densified timber samples did reveal minor discontinuous cracking along the length of the timber.

The final densified timber products were seasoned to within the moisture range of 8 to 16 % and were visually straight, however warping was difficult to assess due to the small sample lengths used in this research. It is expected, however, that reduced warping benefits reported from the press drying process would be applicable to the thermomechanical densification manufacturing method. The densified timber samples achieved residual compression levels that were approximately equal to the compression applied to the timber samples, nominally 13 % and 22 %, indicating the effectiveness of the pressing procedure that included a 2 mm over-press.

The mean MOE results were similar between the densified timber samples and the kiln dried control samples when the timber was tested edgewise and facewise. Results indicated that facewise tests produced lower average results compared to the edgewise tests. This result was partially due to the inclusion of a higher number of defects in the samples used for the facewise tests. Modified data sets that were sorted to exclude timber with defects, yielded mean facewise test results similar to the mean edgewise test results for the timber compressed to the 13 % level and the kiln dried timber. The mean MOE value for the facewise test was still noticeably smaller than the edgewise test value for the timber compressed to the 22 % compression level, which was due to low outlying data significantly affecting the mean facewise test result.

Mean MOR results of timber samples tested facewise indicate that the timber densified to the 13 % level is slightly stronger than the kiln dried control samples, whereas the timber densified to the 22 % level is slightly weaker than the kiln dried control samples.

Hardness results show that there is a mean improvement of 23 % and 31 % over the kiln dried control samples for the timber samples densified to the 13 % and 22 % levels respectively.

The strength properties of a timber piece are several orders of magnitude more sensitive to natural timber defects like knots, juvenile wood and sloping grain, than they are to the inherent properties of the clear wood. Comparison of timber strength properties between different manufacturing methods requires the matching of clear timber samples and a very large number of samples used.

The improvement in timber hardness is an important indicator on the viability of the thermomechanical densification process for two reasons. This first reason is that it indicates that potential property improvements exist which could significantly add value to timber and increase its value in specific markets such as for domestic and commercial flooring. The second reason is that the hardness measurements are taken in areas of the densified timber sample that are not influenced by natural timber defects, which is in contrast to stiffness and strength measurements that are sensitive to natural defects. This indicates that there are potential stiffness and strength improvements that were potentially not realised in this research.

The thermomechanical densification procedure designed in this research was successful. This was evident through observation of the timber samples being densified and by inspection of the final timber products. Timber samples were seasoned to within the target final moisture content range and maintained a high degree of retention of compressed dimension. There was no significant improvement in MOE and MOR in the densified timber samples compared to the kiln dried control samples. There was a resultant increase in timber hardness for samples at both densification levels, however the cracking and discolouration of the timber pieces would need to be further investigated before the benefit of the hardness increase could be realised in industry. Thermomechanical densification may be an effective manufacturing method for young plantation softwoods, producing seasoned timber with improved mechanical properties.

8. Future Research

Future research in the area of thermomechanical densification of timber is an exciting prospect, with a multitude of key topics in both the processing and product improvement areas offering rewards for researchers.

The small sample sizes used in this experiment meant that the full cache of benefits available from this research were not realised. Observation during the densification procedure showed that the timber was densified under conditions of maximum plasticity and produced high quality timber products. Evaluation of densified timber mechanical properties was difficult however, due to the small sample sizes used and the naturally large variation of timber properties. Future research using the thermomechanical densification procedure designed in this investigation should use larger sample sizes and an improved sampling method. The sampling method would be in accordance with standard practices and would include timber samples cut from lengths at random and distributed to different sample sets

A future research topic, which opens up a range of areas for investigation, is altering the method of applying heat and pressure to the timber. An example of this would be changing from fixed heated platens to multiple heated rollers set-up in a process line.

Academic and product improvement interest in this different processing method is the changes to internal stress fields that occur within the timber as part of the densification procedure. Using fixed platens to compress the timber inhibits the small degree of lateral expansion at the platen contact face, which the rest of the bulk section undergoes as part of the densification process. This induces a complex stress field within the timber including transverse tension at the timber faces that is evident through longitudinal cracking in the final product. The use of multiple rollers to compress the timber may impart less transverse forces on the timber during production and provide a final timber product that has minimal cracking and further improved mechanical properties.

Process improvement interest is due to the change from a batch to a continuous processing method. This would combine existing energy efficiency benefits inherent to the densification procedure with a potential decrease in the labour content required to produce a final timber product. Study of this from a production and financial viewpoint would provide an indication of the potential viability of thermomechanical densification to the timber manufacturing industry.

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