MECHANICAL PROPERTIES OF WOOD FOLLOWING MICROWAVE AND RESIN MODIFICATION

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By

Meshack Odera Muga

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Melbourne, Australia.

ABSTRACT

The influence of microwave and resin modification of wood on its density, modulus of elasticity (MOE), modulus of rupture (MOR) and surface hardness is the subject of this thesis. Microwave energy has been used in industrial processing for many years. Microwave energy is an attractive option for wood processing and drying. Recent studies have shown that microwave energy can be used to modify wood by rupturing ray cells to form a large number of cavities in its radial – longitudinal planes resulting in micro voids of various sizes throughout its cross-section. The resultant wood ('Torgvin') is more permeable and more flexible but has a lower density and mechanical properties (MOE, MOR and surface hardness) as compared to the original wood. Further treatment to restore initial density and mechanical properties by addition of resin has resulted in a new timber product 'Vintorg'. Initial trials of Vintorg production employed isocyanate resin. An increase in MOE, an increase in surface hardness and a 100% restoration of MOR of *P. radiata* heartwood was achieved. Despite being a tough adhesive, isocyanate has some drawbacks that may not make it acceptable for the production of Vintorg.

This study therefore focused on melamine formaldehyde (MF) and furfuryl alcohol (FFA) resins as potential substitutes for isocyante resin in the manufacture of Vintorg. The study evaluates Vintorg produced by soaking *P. radiata* and *E. regnans* in these two resins. A factorial design is used to evaluate the effect of wood species, resin type and duration of soaking on resin uptake, resin loss, increase in density of Torgvin, density of Vintorg and mechanical properties of Vintorg.

The results show that wood species and duration of soaking and resin type have significant effects on resin uptake. The increase in the density of Torgvin during the manufacture of Vintorg is found to be influenced by wood species, duration of soaking and resin type. A higher overall increase in the density of Torgvin was obtained in *E. regnans* compared to *P. radiata.* Melamine formaldehyde resin tends to have a greater effect on the increase in the density of *E. regnans* than *P. radiata*. Torgvin samples impregnated with FFA had a greater effect on increasing the density of *P. radiata* than *E. regnans*.

Vintorg in the timber species tested is found to be the same or higher in MOE, much higher in density but lower in MOR than natural wood from the same species, irrespective of wood species, resin type or soaking time. Vintorg produced from *P. radiata* is also higher in surface hardness than natural wood from the same species irrespective of resin type and soaking time.

It is interesting to note that surface hardness of Vintorg is lower in *E. regnans* as compared to natural wood from the same species.

It is also evident that FFA and MF Vintorg are the same or higher in MOE but lower in MOR than isocyanateVintorg from the same species irrespective of wood species tested and. duration of soaking used. The FFA and MF Vintorg from are also the same or higher in surface hardness in the case of P. *radiata* but same or lower in the case of *E. regnans.*

It is concluded that it may be possible to substitute the two resins for isocyanate resin in the production of Vintorg provided that a way is devised to ensure that the MOR of the resultant Vintorg is at least same or higher than that of original wood. It is recommended that further research be carried out to establish a microwave regime for optimal wood permeability and whilst minimizing the reduction in MOR, and that low cost, environmentally friendly resin systems are developed with low viscosity. These resins need to be tough enough to result in Vintorg with characteristics similar to Vintorg produced with isocyanate resin and superior to natural wood in terms of mechanical properties.

Declaration

I hereby declare that this thesis is my original work except where acknowledgement is made in the text to all other material used. The work contained in this thesis has not been previously submitted to any other institution for the award of any degree. I further declare that the thesis is less than 30,000 words exclusive of tables, appendices, bibliography and footnotes.

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CHAPTER 1

1 INTRODUCTION

This thesis is concerned with the influence of microwave and resin modification on some mechanical properties (modulus of elasticity (MOE), modulus of rupture (MOR) and surface hardness) of heartwood of *Eucalyptus regnans* (F. Muell). *Eucalyptus regnans* is an important native commercial hardwood species in Australia, occurring in Victoria and Tasmania. It is a medium density timber suitable for many uses particularly flooring, linings, weatherboards, joinery, furniture, cabinet work, cooperage, veneers and for general construction (Bootle, 1983). *Pinus radiata* (D.Don) is a very important commercial softwood species grown in plantations in many parts of Australia. It produces low to medium density timber used for mouldings, floorings, linings, weather boards, shelving, joinery, turnery, core-stock, match splints, box hooks and plywood manufacture (Bootle, 1983).

Heartwood appears in *P. radiata* at 14 years of growth (Harris 1954, Nicholls and Dadswell, 1965 cited in Hillis (1987)); the most common transformation age is 14-28 years (Carrodus, 1972). In Eucalypts, heartwood normally forms after about five years of growth (Hillis, 1987).

The heartwood of these species is less permeable to liquids than the sapwood and is in fact resistant to preservative treatment (Bootle, 1983). The heartwood of pines being generally two to three times less permeable to wood treatment than sapwood (Erickson, 1970). It is therefore a difficult task treating the heartwood of these species with chemicals as such treatment involves depositing and distributing the chemicals in the microscopically visible void structure or within the cell walls.

Studies have indicated that it is possible to achieve more than 90 % penetration of heartwood of *P.radiata* after microwave conditioning (Vinden & Torgovnikov, 1996). Structural modification of some eucalyptus, including Mountain Ash, using microwave conditioning has also been achieved.

Microwave energy is an attractive option for wood processing and drying as large amounts of microwave energy can be applied and is absorbed by a given amount of wood compared to conventional heating and drying methods. Microwave modification of wood overcomes a number of wood processing problems arising from the variable nature of wood. It does this by making the wood permeable. The increased wood permeability assists conventional drying

processes and facilitates downstream processing of wood with liquids and gases. The improvement in wood permeability by microwave irradiation of timber operates through physical destruction of the ray cells to form a large number of cavities in the radial-longitudinal planes of wood.

The application of intensive microwave energy results in the formation of a new material 'TORGVIN', which has micro-voids throughout its cross-section (Vinden & Torgovnikov, 2000). 'Torgvin' is derived from the inventors' surnames (Torgvikov and Vinden). Torgvin has a high permeability and an increased flexibility but has reduced mechanical properties and lower density as compared to the original wood. The greater permeability allows for further treatment with resin. The application of the resin followed by compression of the wood to its original dimensions and curing of the resin results in an increase in initial density. An increase in mechanical properties such as MOE and surface hardness has also been observed. This new material has been termed 'Vintorg' (also a name coined from the inventors' names (Vinden and Torgovnikov)). The new timber product 'Vintorg' has an appearance of solid wood but with improved performance attributes. Henceforth in this thesis, microwave modified wood will be referred to as Torgvin and if further modified by subsequent resin treatment to restore the original dimensions, as Vintorg.

The technology of Vintorg production (Figure 1-1) has the following main stages: Microwave timber modification, resin application, pre-pressing for removing excess resin, hot pressing for resin curing and cross-section formation, sawing, machining and finishing of the material (Vinden & Torgovnikov, 2000). Substantial economies seem to be possible in the manufacture of Vintorg compared to LVL production as shown in Table 1-1. The process also lends itself to small-scale production. The production costs, including leased capital costs (AU \$/ m^3) are shown in Table 1-1 below.

Table 1-1. Comparison of Vintorg and LVL production costs in A$ (Radiata pine heartwood) (Vinden & Torgovnikov, 2000).

Out put (m^3/ year)	Laminated Veneer Lumber (LVL)	Vintorg (Estimated)
20,000	-	355-366
30,000	669	-
40,000	576	338-349
50,000	484	-
80,000	381	-

These estimates were derived by an independent private sector engineer, experienced in plant costing for LVL particleboard and Oriented strand board (OSB). The costs are based on a green field site and assumptions are made on the basis of projected throughputs, power costs, resin costs and other relevant costs. Vintorg is able to save costs in resin loadings and raw material production.

The initial production of Vintorg employed an isocyanate resin. Vintorg produced using isocyanate resin resulted in an increase in Modulus of Elasticity (MOE) and surface hardness of natural *P. radiata* heartwood of 28.9 % and 10.8 % respectively and a 100 % restoration of MOR (Filcock, 2000). An increase in MOR of 10.6 % was observed in samples pressed to a thinner cross-section than those of the original wood.

Problem statement

The isocyanate resin so far used in Vintorg production has very high bond strength and is a suitable binder for various types of wood composites. However, it is more expensive than the more commonly used resins, has a high viscosity and can only be effectively applied under pressure. Furthermore, isocyanates are considered to be hazardous and may have some carcinogenic effects. The technology needed for the production of Vintorg is given in Figure 1. For the technology to be fully automated and cost effective it would be advantageous for the resin to have a low viscosity in order to be quickly and fully absorbed by the Torgvin preferably utilising a soaking method.

This study focused on furfuryl alcohol (FFA) and melamine formaldehyde (MF) as alternative resins for the manufacture of Vintorg. Both of these resins have lower viscosity and are more environmentally friendly than isocyanate resin. However, it is not certain whether these resins can be substituted for isocyanate and still produces Vintorg that is superior to natural wood even if it is inferior to isocyanate Vintorg. It is also not known how the strength restoration (and possible enhancement) in the production of Vintorg occurs. Nor is the optimal amount of resin and duration of treatment required in the production of Vintorg known, as it is a new material.

1.1 Aim and scope of the study

Recognizing that research in Vintorg production is still in its infancy and that the isocyanate resin so far used in the initial manufacture of Vintorg has some disadvantages, the aims of this study were therefore:

1. To evaluate Vintorg manufactured from heartwood of *E. regnans* and *P. radiata* with furfuryl alcohol (FFA) and or melamine formaldehyde (MF) resins substituted for Isocyanate.

2. To model the relationship between resin uptake and density of Vintorg and the mechanical properties of Vintorg and determine how much of the variability in each of the mechanical properties can be attributable to resin uptake and density of Vintorg.

1.2 Research approach

To achieve these aims, the study was organised in four phases. First a literature review was carried out to establish the present state of knowledge in respect to the main components involved in the manufacture of Vintorg, Chapter 2 reviews current literature related to microwave and resin modification of wood and their influence on wood properties and a review of the properties of the two resins. The second phase of the study, described in Chapter 3 involved a series of experiments to determine the influence of wood species, resin type and duration of soaking on resin uptake by Torgvin and on the increase in density of Torgvin during the manufacture of Vintorg.

This was followed by experiments to evaluate the density and mechanical properties of Vintorg manufactured from the two resins, described in Chapter 4. Finally, the study was concluded with a general discussion of the results and consideration of the implications of the findings for the purposes of industrial application and further research, reported in Chapter 5.

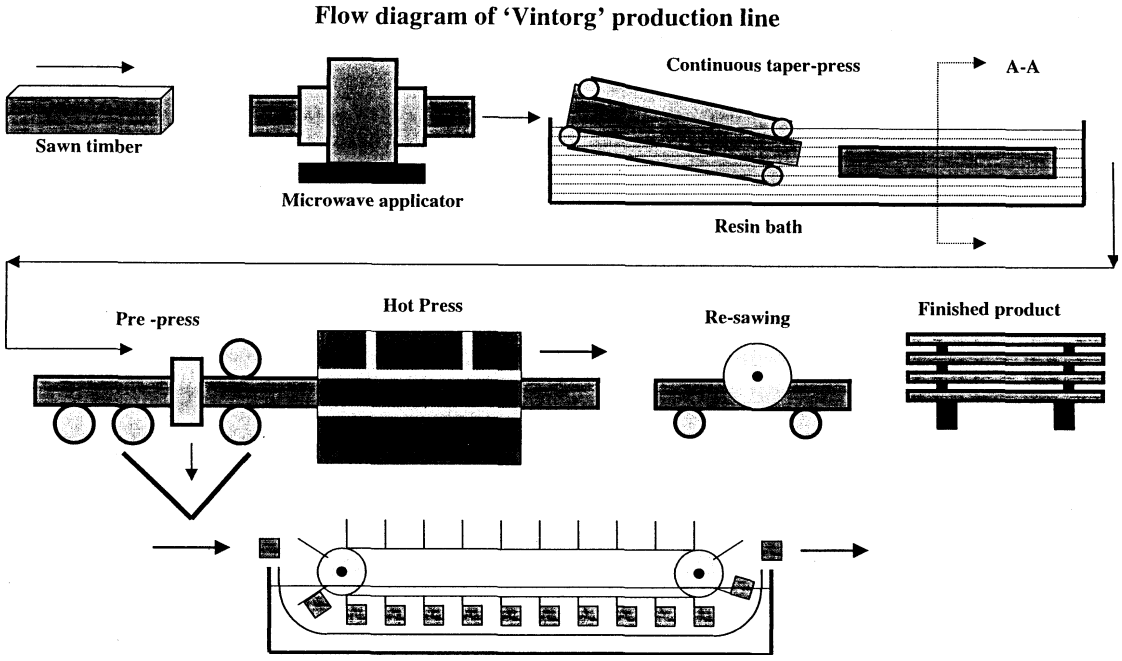


Fig. 1-1. Flow diagram of 'Vintorg' production line (Torgovnikov, 2000).

CHAPTER 2:

2 LITERATURE REVIEW

2.1 MODIFICATION OF WOOD

The modification of wood can be achieved by either physical or chemical means, or a combination of both. Research on modification of wood dates back to early 20th Century. During the period from 1930 to 1960, research was carried out and many attempts were made to alter wood properties by the application of heat, pressure for surface densification, chemical addition to bulk the cell walls, impregnation with polymers, alteration of the chemical composition of wood with γ- and β-radiation, as well as other techniques (Meyer, 1984). Two excellent reviews of these have been published by (Seborg *et al*., 1962)) and (Tarkow, 1966).

Wood has been densified and otherwise modified by impregnating its void structure with a wide range of compounds that can be solidified within the structure. Phenol formaldehyde resins, liquid vinyl impregnants, molten natural resins, waxes, sulfur and even low fusion metals have been used as impregnants (Kollmann *et al*., 1975). These impregnants improved chiefly the compressive strength and the hardness of wood. Treatment of wood with resins followed by densification under heat and pressure has been shown to result in the production of modified wood products with high resistance to decay, good fire retardancy and/or dimensional stability and with increased specific strength properties (Kollmann *et al*., 1975).

Some of the major products of these modifications of wood have been: staybwood (heat stabilised wood), staypak (heat stabilised compressed wood), impreg (phenol-formaldehyde wood composite) and compreg (phenol-formaldehyde compressed wood composite). Laminated compressed wood, marketed as Lignofol and Kunstharzsscichtholz, a resin laminated compressed wood have also been in commercial production (Kollmann *et al*., 1975). These densified materials are used for textile shuttles, bobbins and picker sticks, for mallet heads, for forming jigs and for various tool handles.

More recently, microwave modification of wood has been achieved.

2.2 MICROWAVE MODIFICATION OF WOOD

Microwave energy has been used in industrial processing for many years. The use of microwave frequencies (300MHz to 300GHz) was the result of intensive research on high

definition radar during the Second World War (University of Birmingham, 1940 cited in Meredith, 1998). Further development in the post-war years resulted in microwaves being used especially for domestic heating but also in industry. Modern industrial-microwave-heating systems are used for a diversity of processes in the food industry and in rubber, plastic and chemical industries. Its adoption against competition from more conventional heating methods depends on its special advantages, such as faster throughputs, space and energy savings and quality improvement. The overall efficiency of microwave heating systems is usually very high because of the exceptional efficiency of high-power magnetrons (85% at 900MHz, 80% at 2450MHz) (Meredith, 1998).

Microwave energy is an attractive option for wood processing and drying as large amounts of microwave energy can be absorbed and more energy applied to a given amount of wood compared to conventional heating and drying methods. Microwave heating enhances the rate of evaporation of water from wood and the energy generated is absorbed throughout the wood volume (Metaxas & Meredith, 1983).

Wood is a dielectric material. The dipolar components of its molecules couple electro-statically to the microwave electric field and tend to align themselves with it mechanically (Meredith, 1998). The two positively charged hydrogen ions and double negatively charged single oxygen ion of water molecule rotates and aligns with the electrical field direction. Since the microwave field is alternating, a reversal of the field causes the molecules to realign 180^{o} causing a vibration. The dipoles therefore attempt to realign as the field reverses, and so are in a constant state of mechanical oscillation at the microwave frequency. This process manifests itself as heat (McAlister & Resch, 1971);(Barnes *et al*., 1976), and causes the temperatures inside the wood to rise.

The energy is directly transferred into the material, absorbed by water molecules and changed into heat (Zielonka & Gierlik, 1999). The microwave has the ability to maintain an adequate moisture flow to the evaporating surface and therefore helps in extending the constant drying rate beyond the critical moisture content for wood (Zielonka & Gierlik, 1999).

Some possible areas of microwave application in forest industries include: heating, thermo-mechanical treatment of wood, drying, moisture leveling, and heat sterilisation for biological wood protection. So far microwave energy has been used successfully, albeit on an experimental basis, for drying and leveling of moisture content of various wood products, rapid fixation of CCA preservatives, reduction of formaldehyde emissions and improvement

in wood permeability to various chemicals (Torgovnikov *et al*., 1999; Torgovnikov & Vinden 1997).

2.2.1. Industrial attributes of microwave processing of wood

Microwave modification of wood overcomes a number of wood processing problems arising from the variable permeability of heartwood as compared to sapwood. The increased wood permeability assists drying processes and facilitates treatment of wood with liquids and gases. Microwave treatment of wood can also relax growth stresses in wood resulting in reduction of defects following the drying ((Torgovnikov *et al*., 1999)).

Microwave modification of wood has the potential not only to enhance existing processes but also making possible the development of entirely new processing and product options for wood. Some specific applications have already been identified. These include: rapid preservative treatment of softwoods, the treatment of refractory wood species with preservatives, preservative treatment of hardwood posts and poles, rapid drying of hardwoods and production of new materials such as 'Torgvin' and 'Vintorg' (Vinden & Torgovnikov, 2000).

Some of the potential advantages of microwave energy over conventional methods of heating and conditioning of wood like steaming are: the provision of 'on line' conveyor belt and automated treatment, substantially lower strength losses because of reduced product residence time, lower capital costs for processing round wood and sawn timber, adaptability to small scale as well as large scale production, higher quality product with finer surface checks, and low production costs (Vinden & Torgovnikov, 1996).

2.2.2. Difficulties associated with microwave technology

Current understanding of microwaves is such that it is difficult to achieve uniform energy distribution in drying installations. Equipment required for microwave energy generation and supply to wood is complicated and more expensive than conventional equipment.

2.2.3. Wood permeability following microwave treatment

The application of high intensity microwaves to green or partially green wood results in the generation of high steam pressure and selective rupturing or modification of wood cells (Vinden & Torgovnikov, 1996). The soft ray tissue found in *P. radiata* species is ruptured to provide pathways for liquid movement (Vinden & Torgovnikov, 2000) whilst in hardwoods

the thinner ray tissue leads to the formation of micro-checks at the ray fibre/interface (Vinden & Torgovnikov, 2000) This results in a substantial improvement in permeability in the radial/longitudinal grain direction.

Studies on the effect of microwave treatment on wood permeability have so far concentrated only on wood preservatives (Copper-Chrome-Arsenic solution and creosote) and four wood species namely, Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco, radiata pine (*P. radiata*), Messmate (*Eucalyptus oblique* (L'Herit) and Yellow stringy bark (*E. muelleriana* (Howitt)) (Vinden & Torgovnikov, 2000). Improvement in wood permeability (as indicated by CCA preservative absorption) leads to a significant increase in preservative uptakes (using the Bethel treatment method) for Torgvin compared to unmodified wood. These increases were up to 323% for radiata pine, 533% for Douglas fir, 136% for Messmate and 769.7 % for Yellow stingy bark (Vinden & Torgovnikov, 2000). Soaking of Torgvin (from Messmate) in creosote for 30 minutes resulted in uptakes in the range of 119-220 Lm^{-3} as compared to only 38 Lm^{-3} for the untreated controls, an increase in permeability in the range of 313-580%. The permeability of messmate wood in the radial direction increased by approximately 170-1200 times that of the original untreated sample.

2.2.4. Effect of microwave modification on density and volume of wood

Studies by Vinden and Torgovnikov (Vinden & Torgovnikov, 2000) have indicated that Torgvin has a reduced oven dry wood density and an increased wood volume. The reduction in oven dry density corresponds to an increase in the cross-sectional dimensions of the wood. The extent of the changes varies with species, oven dry density being reduced by up to 15.5% for radiata pine, up to 9.4% for Douglas fir, up to 13.4% for Messmate, and up to 11.1% for Mountain ash. The same workers further reported that the extent of reduction in wood density is also affected by microwave power and conveyor belt (feed) speed.

2.2.5. Effect of microwave modification on mechanical properties of wood

Studies so far carried out on mechanical properties of Torgvin have concentrated on the basic mechanical properties i.e. MOE (modulus of elasticity) and MOR (modulus of rupture). The mechanical properties of wood are reduced in Torgvin. An increase in microwave power leads to a progressive reduction in both MOE and MOR of wood. Studies by Vinden and Torgovnikov (2000) on *P. radiata and E. obliqua* (Messmate) revealed that intensive microwave treatment of wood reduces the MOE in the range of 10-65% (of initial MOE) and MOR in the range of 6-68% (of initial MOR). They further observed that there is a higher

reduction in MOE in the tangential direction than in the radial direction, in both species (Table 2-1). The same trend is also true for MOR in *P. radiata*. However, there is no difference in the reduction in MOR in either direction in the case of Messmate.

Table 2-1 Minimum losses in MOE and MOR associated with microwave treatment to effect changes in wood permeability (Vinden & Torgovnikov, 2000).

Species	Mechanical property			
	Modulus of Elasticity (MOE) GPa		Modulus of Rupture (MOR) MPa	
	Tangential direction	Radial direction	Tangential direction	Radial direction
Radiata pine	26	4	23	6
Messmate	17	12	15	15

2.2.6. Effect of microwave and resin modification on mechanical properties of wood

Microwave modification of wood followed by resin treatment results in a new material Vintorg as mentioned in Chapter 1. The production of Vintorg is a new technology and has not been the focus of in-depth studies. Estimated mechanical properties of Vintorg compared with those of other structural timber products for which Vintorg is a potential substitute are as shown in Table 2-2. According to these estimates, Vintorg material has potential strength properties comparable with LVL and higher than Stress-graded lumber (T30) and Glu-lam (L-40) (Vinden & Torgovnikov, 2000).

Table 2-2. Comparison of allowable stress and practical maximum dimensions of structural lumbers (based on softwoods) (Vinden & Torgovnikov, 2000)

Parameter	Allowable stress (MPa)			Practical maximum dimensions (mm)		
	Bending	Shear	MOE	Length	Thickness	Width
LVL	18	1.7	10,000	Unlimited	75	1200
Stress-graded lumber (T30)	11	1.0	7,000	6,000	150	225
Glu-lam (L-40)	14	1.2	8,400	30,000	150	2000
Vintorg (Estimated)	15-18	1.4-1.7	8,000-10,000	6,500	250	250

The only published study that has reported actual results on the mechanical properties of Vintorg is that of Filcock (2000). She used microwave power of 30 kW (and two regimes of 12 mm/s and 6 mm/s feed speeds) and three pressing regimes (to original dimensions, to a thicker size and to a thinner size) on heartwood samples from *P. radiata* of dimension 28 x 25 x 300 mm. The samples were dipped in isocyanate resin after 15 minutes of heat pre-treatment at 80^{o}C. The resin treated samples were pressed for 10 minutes between plates that had been pre-heated to 150^{o}C and these further placed in an oven at 100^{o}C until the resin was cured. The results of her study summarised in Table 2-3, showed a significant difference between MOE of isocyanate Vintorg pressed to original dimensions (5040 MPa) and that of untreated wood (3910 MPa) and that of Torgvin (2580 MPa) for the second regime (with a feed speed of 6 mms^{-1}). The MOR in this case was the same as that of natural wood (33 MPa) and higher than that of Torgvin. For the first regime (12 mms^{-1} feed speed and pressed to original dimensions), the MOR of the isocyanate Vintorg was only significantly higher than that of the natural wood when pressed to a thinner size than the original size. The MOE was lower than that of the natural wood in all the three pressing regimes in the case of samples subjected to the first microwave regime (12 mms^{-1} feed speed). The surface hardness values for the isocyanate Vintorg pressed to thinner dimension than original wood were significantly higher than those of the natural wood. The second microwave regime increased the surface hardness by 8.1 % and the first regime by 10.8 % for the samples that were pressed to the original dimensions.

Table 2-3. MOR, MOE and surface hardness of isocyanate resin treated solid wood samples with microwave preconditioning and curing while pressing (Filcock, 2000)

Treatment	MOR (MPa)	MOE (MPa)	Hardness (N)
M1 control	20.4	1920	1348
M1 original	36.4	3680	2580
M1 thicker	26.5	3530	1700
M1 thinner	50.7	3870	2698
M2 control	26.0	2570	1599
M2 original	32.8	5040	2517
Unt control	32.9	3910	2329

Note: M1 = microwave conditioning regime 1; M2 = microwave conditioning regime 2; control = isocyantae resin untreated; thicker = pressed to 29 mm; thinner = pressed to 22 mm; original = pressed to 25 mm; unt = not microwave preconditioned**.**

2.3 MODIFICATION OF SOLID WOOD WITH RESINS

Wood is often treated with various chemicals to enhance its properties. Most of the research carried out in the area of chemical modification of wood has concentrated on improving its dimensional stability or its resistance to bio-deteriorating agents. Some studies on the effect of chemical modification on physical and mechanical properties have also been done. Rowell (1996) and (1984) did an extensive review of chemical modification of solid wood and later, a detailed review of the physical and mechanical properties of chemically modified wood (Rowell, 1996). By introducing active functional groups into solid wood, plastic-like cross-linked woods having properties not observed in the original wood could be obtained (Matsuda, 1996). Etherification, esterification and thermoplasticization are the main methods that have been used to chemically modify solid wood. The mechanical properties of the treated wood are affected uniquely by each set of treatment chemicals and process.

2.3.1. Treatment of wood with melamine formaldehyde resin

Melamine formaldehyde (MF) resin is a colourless hot press adhesive used as a sizing and bonding resin in textile, paper, and wood products industries. It was discovered independently and approximately at the same time by the firms Henkel (1935), Ciba (1938,1939,1965), and the former I.G. Farbenindustrie AG (1936) (Kollmann *et al*., 1975) Though slightly less durable than phenol formaldehyde or resorcinol formaldehyde resins it is still considered for structural purposes (Vick, 1999). It is a most attractive adhesive because of: (a) its resistance to moisture in the cured state and requiring shorter press times than those necessary for phenol-formaldehyde (PF) resins; and (b) its unique ability to fulfill the simultaneous role of

impregnating as well as an adhesive agent (Delmonte, 1947, cited in (Kollmann *et al*., 1975). However, it is expensive. When based on 100% resin solids, it is about 3.5 times the price of Urea formaldehyde and 20-25% more expensive than PF resin (Pizzi, 1983). The high cost and higher curing temperature requirements limit its use to a few special applications. Some of these uses include waterproof or even boil-proof plywood, laminated boards, finger joints, laminated decking and high frequency edge gluing where a durable, colorless glue line is required (Rowell, 1984) and (Kollmann *et al*., 1975). It is employed especially where cheaper phenolic resins cannot be used, for example in the production of plywood for boat building with light coloured wood species, where the dark phenolic resin glue layers could shine through the outside veneers.

Properties of melamine formaldehyde resin

Dry melamine resin powders are easily dissolved in cold water. MF resins have good resistance against light. Treatment of wood with formaldehydes is an acetylation process and formylisation occurs as follows (Reactions (1) and (2)):

$$\text{Wood-OH} + \text{HCHO} \rightarrow \text{Wood-O-CH}_2\text{OH} \quad (1)$$

$$\text{Wood-O-CH}_2\text{OH} + \text{Wood-OH} \rightarrow \text{Wood-O-CH}_2\text{-O-Wood} + \text{H}_2\text{O} \quad (2)$$

Tarkow and Stamm first reported this treatment in 1953. Wood moisture content of 4 to 12 % is necessary for good results (Kollmann *et al*., 1975). MF resins can be cured without acid catalyst by heat treatment. Strong acids, such as HCL normally catalyze the reaction, but formylisation with strong acids results in degradation of wood (Rowell, 1996). The hardening reaction takes place at temperatures of up to 150ºC by formation of ether-bridges (Kohler, 1941, 1943 cited in Kollmann, 1975) or at higher temperatures by formation of methylene-bridges (Kollmann *et al*., 1975). Finally, an insoluble and infusible three-dimensional network is formed under the influence of heat or catalysts. This gives a higher thermal stability than cured UF resins.

Open assembly times range from zero to 24 hours. Temperatures in the press range from between 70ºC and 120ºC. The pressure required ranges between 5 and 15 $kpcm^{-2}$ (70 and 210 lbs./sq. inch) and varies with different formulations, wood species and quality of wood surface. The basic pressing time (at 100ºC) is about 3 to 5 min plus 1 min for every millimetre of thickness of the wood material, measured from the innermost glue line.

Formaldehyde treated wood shows high anti-shrinkage efficiency (ASE) of 90% at a weight gain (WG) of 7% (Stamm, 1959). However, mechanical properties of formaldehyde-treated

wood are reduced relative to those of untreated controls (Burmester, 1967)) and ((Rowell, 1984). Toughness and abrasion resistance are greatly reduced (Tarkow & Stamm, 1953), and (Stamm, 1959); crushing strength and bending strength are reduced by up to 50% (Burmester, 1967) in specimens reacted to 4-7% weight percent gain (WPG). The loss in toughness is directly proportional to the gain in dimensional stability as measured in anti-shrink efficiency (ASE). For example, a specimen with a 60% ASE is equal to a 60% loss in toughness (Tarkow & Stamm, 1953) Furthermore, the treatment causes embrittlement of wood, probably attributable to the short, inflexible, cross-linking unit of the O-C-O linkage.

More recently, SO_2 has been found to be a good catalyst for formylisation of wood with only a small decrease in strength (Minato and Yano, 1990 cited in Matsuda, 1996). The most effective among the various formylisation methods for improvement of dimensional stability and retention of strength has been the SO_2- catalysed formylisation with tetraoxane (Minato, Yasuda and Yano, 1990 cited in Matsuda, 1996.)

2.3.2. Treatment of wood with furfuryl alcohol (FFA)

Pure furfural alcohol is a colourless liquid with a pungent smell that darkens rapidly in the presence of air due to autoxidation. It is produced commercially by the catalytic hydrogenation of furfural. Furfuryl alcohol is produced by a partial reduction of furfural, which is derived from pentose (C_5 sugars)-containing plant materials. Currently, agricultural residues including oat hulls, corncobs, rice hulls, straw, sugarcane baggasse, and wood waste are being used in the production of furfuryl alcohol. A summary of the physical properties of furfuryl alcohol is provided in Table 2-4.

Furfural alcohol (FFA) is a chemical with along history of industrial application**.** It is an excellent solvent and as such is used extensively as a selective solvent for lube oil refining and extraction of unsaturated C_4 and C_5 hydrocarbons. It is also widely used in the foundry industry and in the manufacture of anticorrosive paints.

FFA has been used for the preparation of material requiring stability, acid, alkali, and solvent resistance at relatively low costs. Some of the materials that have been manufactured using FFA resin include: laboratory table tops and ceramic sinks, FFA resin cements for bonding corrosion resistant tiles or bricks, tank coatings, brick linings, bonding of glass fibre mats, adhesives in aircraft industries, manufacture of storage battery cases, solvent for cellulose esters, vinyl compounds, many natural gums, phenolic resins, and in general for substances of aromatic character (Schmitt, 1974). It has also been used as antifreeze and corrosion

preventive agent in the aqueous systems of gas meters and internal combustion engines, for the fabrication of glass fiber and other laminates and as binder materials for the manufacture of various carbon and graphite products.

Table 2-4. Physical Properties of Pure Furfuryl Alcohol (Schmitt, 1974)

Property	
Boiling point, ºC (700 mm)	170
Density, 20/4 ºC	1. 1285
Melting point: meta-stable crystalline form, ºC	29
Stable crystalline form, ºC	14.63
Viscosity at 25 ºC, cP	4.62
Surface tension, dynes/cm	~ 38
Solubility in: water	∞
Alcohol	∞
Ether	∞
Specific heat: Liquid at 0 ºC, cal/g/ºC	0.472
Liquid at 25 ºC, cal/g/ºC	0.502

Effect of FFA resin on wood properties

Dimensional stability has been improved by the impregnation and polymerization of FFA into wood with or without a catalyst (Zavarin, 1984).

Chemistry of furfuryl (FFA) alcohol polymerization and resin cure

The chemistry of furfuryl alcohol has been studied by a number of workers (Dunlop & Peters, 1953), (Barr & Wallon, 1971)), (Werwerka *et al*., 1971), (Schmitt, 1974), (Gandini, 1977), (Milkovic et al., 1979) and (McKillip, 1989),(Standen, 1972). Catalysed furfuryl alcohol polymerizes yielding a complex mixture of polyfurfuryl compounds, which eventually condense into a solid product that is chemically inert (Dunlop & Peters, 1953).

FFA polymerises readily in the presence of heat, although, a number of catalysts such as acids and γ-alumina are usually employed to speed up the reaction (Gandini, 1977). The predominant reaction in acid catalysed polymerization of FFA and in resin chain extension is reported to be intermolecular dehydration between the hydroxyl of one molecule and the

active hydrogen in the ring 5 position of another molecule (Gandini, 1977) and (Schmidt, 1974 cited in Milkovic, 1979).

Dehydration can also occur by reaction between methylol groups to yield amethylene ether linkage between furan rings. The occurrence of other reactions has also been established. For example, formaldehyde is evolved, presumably by some thermal decomposition processes (Werwerka *et al*., 1971), (Dunlop & Peters, 1953) and (Werwerka *et al*., 1971). Difurylmethane has also been positively identified in FFA resins (Werwerka *et al*., 1971), (Barr & Wallon, 1971). It is presumed to result from difurfuryl ether degrading. Conley and Metil (1963) cited in Milkovic, 1979 were also able to isolate 1% of levulinic acid from an acid catalysed resin.

Other carbonyl compounds have also been isolated. A carbonyl and hydroxyl containing material was found in an acid catalysed resin (Barr & Wallon, 1971) and the compound 4-furfuryl-2-pentenoic acid-γ-lactone has been positively identified in γ-alumina catalysed polymerization of FFA (Werwerka *et al*., 1971). FFA resins are therefore complex mixtures, and this complexity increases during cross-linking and cure because other types of reactions must take place to increase the effective functionality of FFA above two. Chain extension undoubtedly occurs via the dehydration reactions in the initial stages of cure.

It has been hypothesised that cross-linking takes place through attack at ring positions 3 and 4 by the formaldehyde produced by dehydration reactions (Wewerka, 1969, Boquist *et al*., 1963 cited in Milkovic, 1979). The poly-condensation of 2-furfuryl alcohol is therefore essentially a bi-functional, linear aggregation process, accompanied by the occurrence of side reactions accelerated by acids, oxygen and heat, which introduce occasional branching points and poly-conjugated sequences in the chains. These side reactions give rise to ring cleavage and/or oxidation and structural rearrangements at some repeating units and ultimately to the cross-linking and blackening of the products (Gandini, 1977).

Curing temperature

Acid catalysed reactions of FFA occur in three stages: polymerization of alcohol to resin, initial early resin cure and late cure stages. The thermograms are quite complex and highly dependent upon catalyst type and concentration. In an unsealed differential scanning calorimetry (DSC) pan, a thermogram of the FFA resin catalysed with p-toluenesulfonic acid (PTSA) shows a strong initial exotherm which is abruptly terminated near 100ºC by an endotherm, the latter being followed by a rather complex pattern leading to another

exothermic process at about 140ºC (Milkovic *et al*., 1979). Experiments using the same catalyst but in hermetically sealed pans indicated that the low temperature exotherm (I) peaks at about 80˚C, immediately succeeded by a second exotherm (II), peaking at about 110ºC and that it is not possible for the reaction to return to the baseline due to a third exothermic process (III) which peaks at about 180ºC. It was further noted that if scans were terminated in the valley between II and III, the specimens were hard and brittle, whereas, specimens removed between II and I were no harder than rubber. Milkovic *et al*. (Milkovic *et al*., 1979) found that if temperatures did not exceed 180ºC, no loss of vapour and attendant endothermic effects were apparent with sealed pans.

Copolymerization of Furan and homologues with maleic anhydride

Furan and maleic anhydride form a donor-acceptor complex capable of giving an alternative copolymer when treated with azo-bis-isobutyronitrile in benzene solution (Butler *et al*., 1970 cited in Gandini, 1977). The charge-transfer complex formed between furan and its homologues and maleic anhydride, probably in its excited state (Gaylord *et al*. cited in Gandini, 1977). is the species that polymerizes: the nature of the interactions in the complex being strong enough to overcome the restrictions to radical polymerization exhibited by furan derivatives.

2.3.3. Physical-chemical relationships in resin treatment of wood

A number of important physical-chemical factors that influence treatment of wood with resins may also greatly influence the strength and dimensional properties of the treated wood. These include cohesion and adhesion, temperature, concentration of resin, pH, thermal reactivity of resin, pretreatment of wood, pressing of wood and curing of resin.

Cohesion and adhesion

Cohesion and adhesion are the two main forces, involved in gluing of materials (Kollmann *et al*., 1975). Forces of attraction between atoms or molecules cause cohesion while adhesion is generally the sticking power of adjacent molecules. "In practice, adhesion is effected the by use of liquid adhesives which can adapt to the profile of the surface due to their rheological behaviour" (Kollmann *et al*., 1975 p. 2). Liquid adhesives wet the surfaces to be glued and then form glue joints after having been set or hardened. They wet, flow, and set to a solid during bond formation. There are two types of adhesion, mechanical and specific (McBain, 1932 cited in Kollmann, 1975).

Mechanical adhesion is produced by penetration of the resin into open pores on the surfaces of wood. Capillary forces facilitate the entrance of liquid resin into wood pores. Microscopic investigations have shown that glue penetrates vessels and/or other hollow cells of the wood before it is hardened (Truax, 1929 cited in Kollmann, 1975). This is followed by a three dimensional mechanical branching of the hardened threads or fingers of the glue. However, mechanical effects contribute only a small part to the total joint strength of wood (Voss, 1947 and Brone and Truux, 1926 cited in Kollmann, 1975).

Specific adhesion depends on intermolecular forces (van de Waals' forces) between wood and the resin (Kollmann *et al*., 1975). The main factors that influence specific adhesion are forces of molecular attraction (maximum adhesion) and the ability of molecules of adhesive and adherend to attain molecular nearness (inherent strength of bond) (Reinhart, 1954 cited in Kollmann, 1975). The latter depends on the wetting of the adherend by the adhesive. The total adhesion of glues to wood is therefore dependent on both specific and mechanical adhesion.

Penetration of resins mainly occurs throughout cell ends. The depth of penetration is a function of grain angle. The total adhesion is a function of the nature of the porous surface.

Influence of temperature

The rate of change of surface tension for most liquids is a constant, equal to

$$d\sigma / dT = - K$$

(Where: σ. =surface tension, T = absolute temperature and K= constant).

The use of heat in curing the adhesive and causing it to flow before setting contributes to lowering its surface tension (Delmonte, 1947 cited in Kollmann, 1975). Temperature rise in wood samples varies with wood thickness or cross-section.

Temperature affects the mechanical properties of wood. The values recorded for mechanical properties of wood generally decrease when it is heated and increase when cooled. At constant moisture content and below approximately $150^{o}C$, mechanical properties of wood are approximately linearly related to temperature (Green *et al*., 1999).

Concentration of adhesive

The rate of change in surface tension is dependent on the rate of change in concentration for a solution and is expressed as:

$$d\sigma / dc = -\mu RT/c$$ (Gibbs, 1876 cited in Kollmann, 1975)

(Where: σ= surface tension, dynes/cm, R=gas constant (8.314x 10^{7} erg/ ˚C mole), T= absolute temperature and c= concentration, μ = fluid on the surface in g mole per cm^2.)

Adhesion is therefore improved if its fractions with low molecular weights are used, as they are chemically more active and possess a better penetration capacity. The surface tension of high molecular adhesives can be lowered substantially by addition of some materials. Molecular weight distribution of an adhesive can affect mechanical properties such as tensile strength, elongation, impact strength and elasticity (Kollmann *et al*., 1975).

Influence of pH value on the hardening of adhesive

pH has a significant influence on hardening of glue joints. Strong acids or alkalis reduce the strength of the joint. Materials like wood which are derived from cellulose are especially affected by differences in pH (Delmonte, 1947 cited in Kollmann, 1975).

Thermal reactivity of adhesive

The thermal reactivity of thermosetting adhesive governs the optimal gluing temperature and the pressing time necessary at a given temperature to obtain the curing of the adhesive in the final stage of the chemical process (Mason *et al*., 1993) The thermal reactivity varies with temperature, type and quantity of acid hardener and the presence/absence of an extender. An amount of 2 percent of hardener with 20 percent of extender was found optimal (Mason *et al*., 1993).

Influence of moisture content

The properties of the glue joint can be affected by the properties of the wood adherend. Hardwoods are generally more difficult to glue than softwoods (Kollmann *et al*., 1975). Hardwoods generally have thicker cell walls and less lumen volume, resulting in higher density and reduced permeability. Thus making it difficult for adhesives to penetrate, so important mechanical interlocking of adhesives is limited to one or two cells deep. Furthermore, hardwoods generally have higher amounts of extractives than softwoods. Acidity and polarity of extractives may affect gluability of certain hardwoods species.

Moisture content strongly affects the final strength and durability of joints, development of surface checks in wood, and dimensional stability of the bonded assembly (Vick, 1999). The higher the moisture content, the lower the strength of the glue joint. Many mechanical properties are affected by changes in moisture content of wood below the fiber saturation point, most of them increasing with the decrease in moisture content (Green *et al*., 1999). The

moisture content of wood in bonded products should therefore be targeted to the equilibrium moisture content (EMC) that the product will experience in service.

Pressing of bonded parts

Pressing of the parts of wood to be glued helps to provide a joint of high strength by forcing entrapped air from the joint line, bringing the adhesive into molecular contact with the wood surface, forcing adhesive to penetrate into the wood structure for more effective mechanical interlocking and squeezing the adhesive into a continuous film and holding the assembly in position while the adhesive cures (Vick, 1999).

The amount of pressure that should be applied depends on the density of the wood. For low-density wood, low pressures of about 700 kPa (100 $lbin^{-2}$) are suitable and for higher density woods that are difficult to compress, high pressures of up to 1,700 kPa (247 $lbin^{-2}$) are required (Vick, 1999).

There are two methods of pressing bonded wood: cold pressing and hot pressing. The following conditions should be observed during pressing (Kollmann *et al*., 1975): complete contact of the surfaces to be glued, air and superfluous glue should be expressed at the edge of the joints, a thin line of equal thickness over the whole surface of the joint must be produced and finally the parts to be glued should be kept under some pressure during the major part of the curing. When heat and pressure are simultaneously applied, wood responds to compression more rapidly than when the resin is heated prior to pressing (Stamm & Seborg, 1941).

2.4 Conclusions

Microwave modification of wood can be used to overcome a number of problems in wood processing which arise from the variable nature of wood. Microwave modification therefore has the potential to enhance existing processes and make possible the development of new products from wood. Microwave modification of wood results in Torgvin, which is many times more permeable to liquids than untreated wood from the same species. As well as being less rigid (more flexible), it is of lower density, different dimensions and has lower mechanical properties. Impregnation of Torgvin with resins followed by compression to the original dimensions to produce Vintorg restores the original properties and increases some of them (dimensional stability, surface hardness and modulus of elasticity). The isocyanate resin used to date in the manufacture of Vintorg has some undesirable features (e.g. it may have some carcinogenic effects and it has a high viscosity, more than 200 cps) so that it would be

advantageous if other resins without these draw backs could be used to manufacture Vintorg equal to isocyanate Vintorg.

Two potential substitutes of isocyanate resin in the manufacture of Vintorg seem promising. Melamine formaldehyde resin, though more expensive and less durable than phenol formaldehyde and resorcinol resins, has a number of advantages over these and many other resins. It is unique in the sense that it can fulfill the role of an impregnating agent as well as an adhesive agent. It is also colourless and would be preferred in wood for furniture to phenol formaldehyde. It may only have the drawbacks of requiring high temperatures for curing between 100 and 150^{o}C and acid catalysed reactions of MF resin and wood, possibly resulting in reduction of some strength properties.

Furfuryl alcohol also has properties that would make it an attractive resin for the manufacture of Vintorg. The main advantage would be its low viscosity (2 –4.6 cps) that would allow it to penetrate any cross-section of timber within a short time. It is also produced from renewable natural resources (agricultural wastes) and would therefore be readily available and cheap. It may have the disadvantages of discolouring the wood and causing it to be brittle. The extent of this brittleness, however, is not known.

It is also evident that the properties of Vintorg can be influenced by a number of factors. These include: degree of microwave modification, resin type, method of resin treatment, concentration of adhesive, pH of adhesive or wood, type of catalyst, chemical reactivity of the adhesive, temperature and duration of curing of adhesive, moisture content of wood, amount of pressure and duration of pressing of the bonded wood. A microwave treatment regime of 30 kW and feed speed of 6 mm/s seem to be optimal for *P. radiata*, as it results in an increase in MOE and surface hardness and 100% restoration of MOR (from previous studies). It is also apparent that it is advantageous to apply heat and pressure simultaneously as wood responds to compression more rapidly than when resin is heated prior to pressing. Pressures of between 700 kPa (100lb/in^2) and 1,700 kPa (247 lb/in^2) would be required to press the bonded parts, the exact amount depending on the density of the wood being pressed.

However, it is not known whether it is possible to make Vintorg using other resins with mechanical properties equal to or greater than the unmodified wood and equal to isocyanate Vintorg. Nor is it clear how wood species and resin levels affect the properties of the Vintorg produced. The following study aims to answer these questions.

CHAPTER 3:

3 THE INFLUENCE OF WOOD SPECIES, RESIN TYPE AND DURATION OF SOAKING ON THE MANUFACTURE OF VINTORG

3.1 Introduction

From the literature review, it was evident that there were some significant gaps in the basic data on the effect on mechanical properties of wood following microwave and resin modification to help determine the direction of future research and development in Vintorg production. Consideration of them led to the formulation of the following three hypotheses for testing:

1. Wood species, resin type and duration of soaking have significant effects on the resin uptake by Torgvin and the resulting expected increase in density and mechanical properties of Vintorg.

2. Vintorg manufactured using resins other than isocyanate has density and mechanical properties superior to those of natural wood.

3. It is possible to predict the mechanical properties of Vintorg from resin uptake and density values.

The testing of the hypotheses involved the following investigations:

1. Determination of the effect of wood species, resin type and duration of soaking on uptake of two resins, namely MF or FFA, by Torgvin.

2. Assessment of the effect of wood species, resin type and duration of soaking on the expected increase in density and decrease in cross-sectional area of Torgvin during the manufacture of Vintorg.

3. Evaluation of the wood density and the mechanical properties of Vintorg from *P. radiata* and *E. regnans*.

4. Comparison of the density and mechanical properties of Vintorg manufactured from these two resins to those of natural wood and isocyanate Vintorg.

5. Modeling of the effect of resin uptake and density of Vintorg on mechanical properties of Vintorg.

This chapter deals with the first of the hypotheses: wood species, resin type and duration of soaking have significant effects on the resin uptake by Torgvin and the expected increase in density of Vintorg.

3.1.1 Mechanisms for chemical impregnation of wood

Several methods exist for impregnating solid wood with chemicals. These fall into three categories: sap displacement, capillary absorption and diffusion (dipping and soaking), and pressure methods. Pressure methods are the most effective means of chemical treatment of timber containing sizeable amounts of air. The method has the advantage of considerably reduced treatment times compared to those required by the other methods. However, such treatment requires expensive equipment and the high investment cost in pressure equipment only pays off in large-scale plants. Sap displacement is suitable for highly permeable species with high moisture content. Heartwood is impermeable and generally has too low moisture content for sap displacement to occur through its voids. Capillary absorption and diffusion (soaking) seems to be the simplest and most suitable method of Torgvin treatment in automated Vintorg production (Vinden & Torgovnikov, 2000), although higher viscosity resin solutions may require the application of pressure.

When dip and soak methods are applied to air-dry wood, the solution is taken up by capillary absorption into the void structure from which diffusion occurs into the cell walls. When applied to water saturated wood, the whole process depends on diffusion. A combination of capillary absorption and diffusion results in a superficial to moderately effective treatment of wood depending on the diffusability of the impregnant and underlying permeability of the timber.

Capillary uptake of a solution by dry wood is about 100 times faster in the longitudinal direction as in the transverse direction (Kollmann *et al*., 1975). Permeability of softwoods ranges from 50 to 100 times as great in the fibre direction as across the fibre direction for specimens of the same size that exceed the fibre length (Johnson and Maas, 1930 and Sutherland, Johnson and Maas, 1934 (cited in Stamm, 1964)). Diffusion of a solute into water saturated wood is 10 to 15 times as rapid longitudinally as transversely (Stamm, 1946).

Creating a partial vacuum within the wood in the hot and cold bath treatment method (Kollmann *et al*., 1975) has accelerated capillary absorption in solid wood. More recently, microwave conditioning of Messmate (*E. obliqua*) has been shown to increase its uptake of creosote by 313-580% due to improved permeability (Torgovnikov & Vinden 2000). In

Torgvin production from *P. radiata* the uptake of MF resin was increased by 746% after 20 minutes of soaking treatment (Muga *et al*., 2001).

The treatment of wood by soaking it in the treating liquid, though the simplest of all the treating processes (Stamm, 1946), is very slow. The penetration of the treating liquid in the early stages of treatment is fairly rapid, but the rate of capillary rise falls off more rapidly than would otherwise be expected due to the building up of a backpressure of air within the wood. Heating of dry wood prior to immersing it in the unheated solution can aid the penetration of the solution into the wood, especially in a small specimen of easily treated timber which is short in the fibre direction. When deep penetration of the treating chemical is desired, this method is not recommended. As the production of Vintorg involves heating of the wood by microwave energy and because microwave modification of wood produces micro checks and voids in the wood it has been shown to improve the uptake of preservatives. It could be expected; therefore that microwave treatment will also increase the uptake of resins (as indicated by the amount of resin absorbed) by the soaking method. However, this improved uptake will probably be dependent on wood species, resin type and duration of soaking. It is also not known how the expected increase in the density of Torgvin following resin treatment and pressing would vary with these factors.

The objectives of this phase of the study were:

1. To investigate the effect of wood species and duration of soaking on initial and final resin uptakes by Torgvin and the relative amount of resin loss during the manufacture of Vintorg with FFA and MF resins.
2. To investigate the effect of wood species, resin type and duration of soaking on resin uptake and loss during the manufacture of Vintorg.
3. To assess the effect of wood species, resin type and duration of soaking on the expected increase in density and decrease in the cross-sectional area of Torgvin during the manufacture of Vintorg.

3.2 MATERIALS AND METHODS

3.2.1. Materials

Pinus radiata

Six butt logs from *P. radiata* trees grown at Langi Kal Kal Prison, Beaufort, Victoria, were selected from the Ballarat Timber Processors log yard. The trees were appromixametely 100 years old at the time of felling. Two 90 x 90 x 6000mm quarter-sawn heartwood square sections (labeled A and B) were obtained from each log. The logs were sawn ensuring that as little as possible and preferably none of the pith material was included in the piece of timber. The 6000mm pieces of timber were crosscut into two equal lengths of 3000mm. Each 3000mm timber piece was labeled in such a way that it was possible to identify a piece of timber with a particular log and its position in the log (top (T) or bottom (B)). The timber pieces were block stacked, wrapped in plastic sheets and transported to the microwave plant at the School of Forestry, Creswick.

Eucalyptus regnans

A 5400mm long butt log from a 1939 *E. regnans* regrowth tree from Erica, Central Victoria, was obtained from the Timber Training Centre at Creswick. The log was crosscut into two equal length logs and each sawn into 90x 90 x 2700mm heartwood square sections. As little as possible or none of the pith material was included in the piece of timber. Each 2700mm timber piece was labeled in such a way that it was possible to identify pieces of timber from the top or bottom section of the log. The timber was transported to the microwave facility at School of Forestry, Creswick.

Resins

Furfuryl Alcohol (FFA)

Furfuryl alcohol (98%) was supplied by Sigma Aldrich. Maleic acid (5%) and water (3%) were added to the furfuryl alcohol to give a final resin forming system comprising of 90% furfuryl alcohol, 5% maleic acid and 5% water. The maleic acid was to act as a catalyst in the polymerization reaction.

Melamine formaldehyde

Melamine formaldehyde (MF) resin (Sylvic 8007) was supplied by Orica Chemical Company. Preliminary trials with this resin revealed that the viscosity was not low enough to result in sufficient penetration of the Torgvin by the soaking method. It was therefore necessary to add ethylene glycol (to reduce viscosity) and the surfactant Fentak -25 (to reduce surface tension) of the MF resin. The MF resin used in the studies therefore comprised of MF (93%), Ethylene glycol (5%) and Fentak F- 25 (2%). The amounts of ethylene glycol (5 %) and the surfactant,

Fentak –25 (2 %), used in the MF resin forming system were suggested by the manufacturers of these chemicals and confirmed by preliminary trials**.**

3.2.2. Methods

Experimental design

A two factorial design with four treatments (duration of soaking) and 10 replications was used for each resin in the determination of the effect of wood species and duration of soaking on resin uptake by Torgvin during the manufacture of Vintorg. The durations of soaking in FFA were 1, 5, 10 and 20 minutes while that for MF were 5, 20, 60 and 90 minutes. The shorter range in the duration of soaking of wood in FFA as compared to that of MF was due to the difference in the viscosity of the two resins, 2 cps and 50-75 cps respectively. For the determination of the effect of wood species, resin type and duration of soaking on resin uptake and increase in the density of Torgvin during the manufacture of Vintorg, samples soaked in either resin for 5 and 20 minutes were used. The design was a three factor (wood species, resin type and duration of soaking) and 10 replications. The frequency distributions of the density of the Torgvin samples from each species used in the study are illustrated in Figures 3-4 and 3-5.

Preparation and selection of samples

Microwave modification (Torgvin preparation)

Torgvin was prepared in a 60 kW microwave facility at the University of Melbourne, Creswick. Microwave power of 30 kW (for *P. radiata*) and 39.2 kW (For *E. regnans*) and a feed speed of 6.2 mms^{-2} were used for each treatment.

Before microwave modification of timber, a clear piece of timber 450 mm in length was cut off from the ends of each 90 x 90 x 3000 mm *P.radiata* square sections and used for the preparation of the control specimen (Figure 3-1). The remaining 2550 mm long pieces of *P. radiata* timber were converted to Torgvin. In the case of *E. regnans* six of the 2700 x 90 x 90 mm sections (3 from the bottom and 3 from top portions of the log) were then converted to Torgvin. Two pieces from each section of the *E. regnans* log were randomly selected and used to provide the specimen for the untreated controls.

Selection of samples

Pinus radiata

Twenty four of the microwave treated 90 x 90 x 2230mm *Pinus radiata* square sections from the six logs (4 square sections per log BA, BB (from bottom part of the square sections A and B), TA and TB from top part of the square sections) were cross-cut into 3 end-matched clear specimens of 90 x 90 x 450mm each, giving a total of six specimens from each of the original 90 x 90 x 6000mm square sections. The sampling positions of the six specimens and the controls from each section are as shown in Figure 3-1. Six treatments were randomly allocated to the six numbers by casting lots (randomly picking folded papers with numbers corresponding to the position of sampling of the specimen). The six treatments to which the six wood samples from each of the six logs were randomly assigned are as shown below.

All the specimens bearing the same numbers were used in a particular treatment. Sampling and labeling were done in such a way that it was possible to identify the position of sampling, the section and the log where it came from. The 90 x 90 x 410mm samples allocated to treatments 3,5 and 6 were further cut into four specimens each of 43 x 43 x 410mm and these assigned to four sub-treatments 1, 2, 3 and 4 as shown in Figure 3-2. The numbering was done with the position of the pith (as indicated by growth rings) as the reference point.

1. Control – untreated Torgvin

2. Soaking treatment – Preliminary trials

3. Soaking treatment – FFA resin (T1-1 min, T5-5 min, T10-10 min and T20-20 min)

4. Soaking treatment – spare samples

5. Soaking treatment – MF (T5-5 min, T20-20 min, T60-60 min and T90-90 min)

6. Pressure treatment – isocyanate resin

Section A

BA	BA1	BA2	BA3	TA	TA4	TA5	TA6

Section B

BB6	BB5	BB4	BB	TB3	TB2	TB1	TB

Fig. 3-1. The sampling positions of the 90 x 90 x 450mm *P. radiata* Torgvin sections and controls.

1	2	2	4	4	3	3	1
3	4	1	3	2	1	4	2

Fig. 3-2. The numbering and selection of the specimen for the four treatments from the 90 x 90 x 410mm Torgvin from *P. radiata* and *E. regnans.*

Eucalyptus regnans

The six microwave treated 90 x 90 x 2700mm *E. regnans* square sections (3 from top and 3 from bottom part of the log) were cross-cut into six end-matched clear specimens of 90 x 90 x 450mm each and labeled A, B, C giving a total of six end matched samples for each of the original 90 x 90 x 2700mm sections (Figure 3-3). The sampling position of the specimens for the 3 treatments from each section was as shown in Figure 3-3. The 90 x 90 x 450mm samples were further cut into specimens of 43 x 43 x 450mm. These were labeled 1, 2, 3 and 4. The numbers 1, 2, 3 and 4 were alternately put as shown in Figure 3-2. Specimens were randomly allocated to the various treatments (1, 2, 3, 4) by casting lots (randomly picking folded papers with numbers corresponding to the position of sampling of the specimen).

A	C	B	A	C	B

B	A	C	B	A	C

C	B	A	C	B	A

Fig. 3-3. The sampling position of the specimen for the 3 treatments (A, B, C) from each 90 x 90 x 2700 mm *E. regnans* Torgvin square section.

The three treatments to which the specimen were randomly assigned were:

A. 43 x 43 x 410mm – soaking in furfuryl alcohol (T1-1 min, T5-5 min, T10-10 min and T-20 min soaking pressed to 35mm and cured at 130˚C).

B. 43 x 43 x 410mm – soaking in melamine formaldehyde (T5-5 min, T20-20 min, T60-60 min, T90-90 min soaking, pressed to 35mm and cured at 130˚C).

C. 43 x 43 x 410mm – Pressure treatment (Isocyanate pressed to 35mm and cured at 130˚C).

Soaking of wood samples

The wood specimens were weighed and then end sealed with silicon glue to prevent longitudinal penetration of the resin through the transverse direction. The samples were pre-heated in a Baioni hot press at 120ºC (for one hour) without pressure. The samples were weighed before and after soaking.

Before each treatment, the moisture content and nominal density of the samples were determined. A 20mm section was cut at the end of each untreated sample for the determination of the moisture content. The mass of each specimen was measured by weighing on an electronic balance before and after drying at 105ºC. The cross-sectional dimensions (width and thickness) of each specimen before soaking in resin were measured at the middle position of each specimen by a digital caliper. The moisture content and density were computed as shown in Appendix 1. The frequency distributions of the density of the Torgvin samples from each species used in the study are illustrated in Figures 3-4 and 3-5.

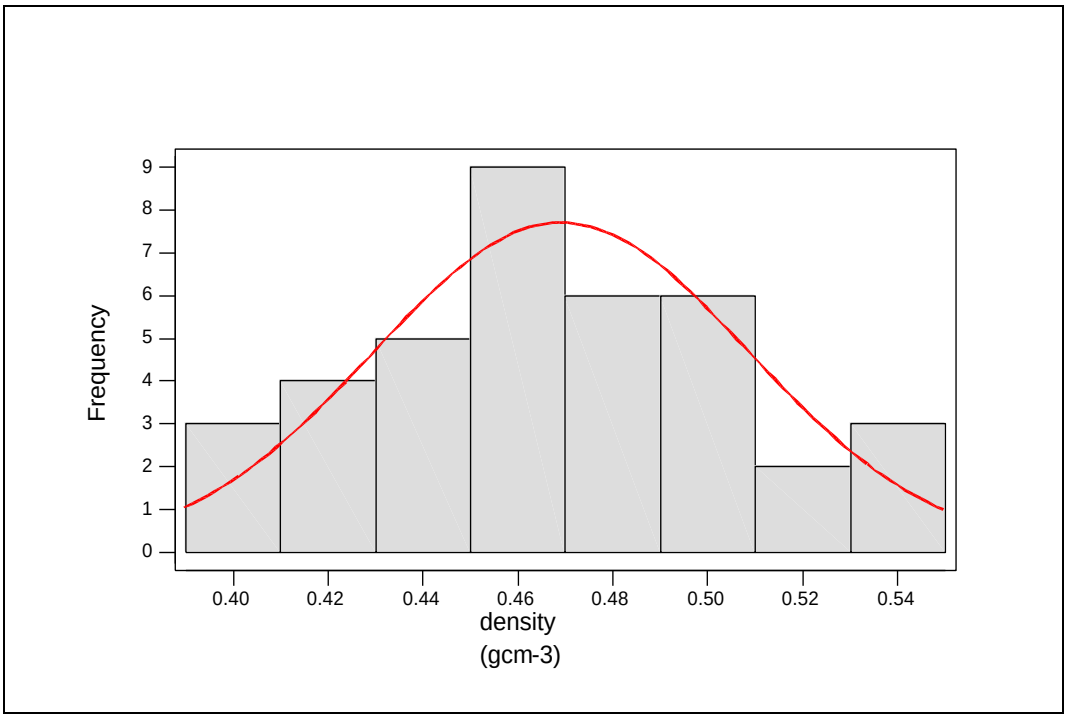


Fig. 3-4. Frequency distribution of the density of *P. radiata* Torgvin samples used in the study.

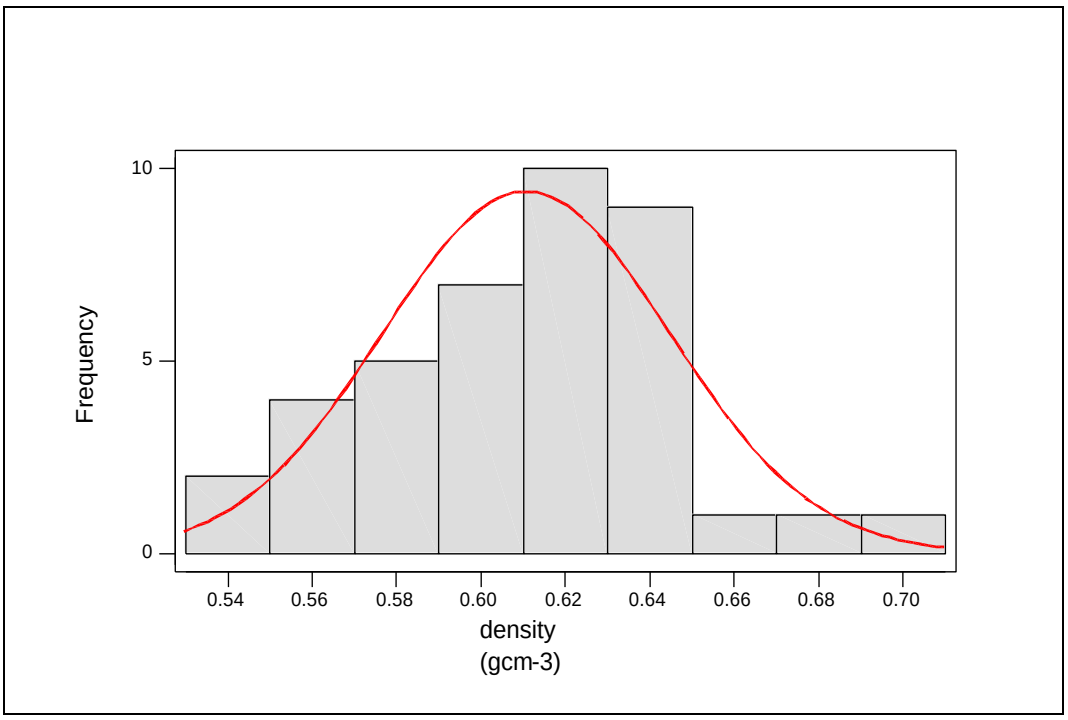


Fig. 3-5. Frequency distribution of the density of *E. regnans* Torgvin samples used in the study.

Pressing of treated wood samples and curing of resin

After treatment with resin, the sample stood for five minutes to allow excess resin to drip out. The samples were wiped with paper towel and then reweighed. The treated samples were placed in oven bags and pressed on the radial face using a hydraulic press (a Baioni press) (Figure A2-1, Appendix 2) at 130 ºC for 2 ½ hours. The extent of pressing was controlled by the use of spacers (35mm thick hardwood timber placed within the press). The press was set at full vertical and horizontal pressures of 1467 kPa and 1333 kPa respectively. The final cross-sections of Vintorg after pressing and curing of the resin were measured at the mid position of each sample using digital calipers.

Computations of resin uptake after soaking treatment.

Maximum possible absorption of resin

For each sample, the maximum possible absorption in kg L^{-1} (McQuire, 1975) was also determined:

$$F = 1000-(d_w\,(g + 66.7)/100) \qquad (3\text{-}1)$$

The maximum resin uptake in (kg m^{-3}) was computed from the above formula thus:

$$Fr = F \times d_r$$

Where

F = maximum possible absorption of water (Lm^{-3})

F_r = maximum resin uptake in ($kg\ m^{-3}$)

g = moisture content (%) of Torgvin

d_w = density of wood in Vintorg ($kg\ m^{-3}$)= M_1 / V_t

dr = density of resin ($kg\ L^{-1}$)

The density of each resin ($kg\ L^{-1}$) was determined by weighing 100 mL of the resin in a volumetric flask d_r = mass of resin (g)/ volume of resin (mL)

Initial resin uptake before pressing (U_1)

$$U_1 = (M_2-M_1) / V_t \quad (3\text{-}2)$$

Where:

U_1 = initial resin uptake ($kg\ m^{-3}$)

V_t = Volume of Vintorg (m^3)

M_2 = mass of resin treated Torgvin (kg)

M_1 = mass of untreated Torgvin (kg)

Final resin uptake after pressing of resin treated Torgvin and curing of resin (U_2)

$$U_2= (M_3-M_1) / V_t \quad (3\text{-}2\ b)$$

Where:

U_2 = resin uptake after pressing of resin treated Torgvin and curing of resin ($kg\ m^{-3}$)

V_t = Volume of Vintorg (m^3)

M_3 = Mass of Vintorg (kg)

M_1 = Mass of untreated Torgvin (kg)

Saturation of Torgvin with resin (%) = $100xU_1/F_r$ (3-3 a)

Saturation of Vintorg with resin (%) = $100 \times U_2/F_r$ (3-3 b)

Amount of resin lost during the manufacture of Vintorg = (U_1-U_2) (3-4)

Data analysis

Microsoft excel was used to organise the data and Minitab Statistical package 13 was used for analysis of variance (ANOVA), paired–t tests, 2-sample t-test, determination of Pearson's correlation coefficient's and regression analysis between variables.

Normality test

To establish that the samples for each species were obtained from a population with normally distributed population, standardized residuals were obtained using the general linear model and plotted against the group variables. The test for normality was done using Ryan-Joiner test (Gordon, 2000). The test for constant variance for the factors being compared was also carried out using the Minitab package.

Analysis of variance (ANOVA)

A two way ANOVA was used in analysing the 2 x 4 factorial design experiments and a three way ANOVA for the 2^3 factorial design experiments.

The model that was assumed in the two-way analysis of variance was:

$$X_{ijk} = \mu + \alpha_i + \beta_i + \gamma_{ij} + e_{ijk}$$

Where X_{ijk} denotes the k^{th} observation using level i of factor A (species)

and level j of factor B (treatment) μ denotes the overall mean,

α_i denotes the main effect of the i^{th} level of factor A,

β_i denotes the main effects of factor B,

γ_{ij} denotes the interaction between the i^{th} level of factor A and the j^{th} level of factor B and the e_{ijk}s, the random errors are assumed to be independent and normally distributed N $(0,\sigma^2)$, (Gordon, 2000).

The model that was assumed in the three ways ANOVA was that:

$$Y_{ijk} = \mu + \alpha_i + \beta_i + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_i k + (\beta\gamma)_{ik} + (\alpha\beta\gamma)_{ijk} + e_{ijkl}$$

Where:

μ denotes the parametric mean of the population;

α_i, β_i and γ_k are the fixed treatment effects for the i^{th}, j^{th} and k^{th} groups of treatments A, B, C, respectively; $(\alpha\beta)_{ij} + (\alpha\gamma)_{ik}$ and $(\beta\gamma)_{ik}$ are first-order interaction effects in the subgroups represented by the indicated combinations of the i^{th} group of factor A, j^{th} the group of factor B and k^{th} group of factor C; $(\alpha\beta\gamma)_{ijk}$ is the second order interaction effect in the sub group representing the, i^{th}, j^{th} and k^{th} groups of factors A, B and C, respectively; e_{ijkl} is the error term of the l^{th} item in subgroup ijk (Sokal & Rohlf, 1995).

One-way analysis of variance was used to establish the variation among treatments for each individual wood species. The model in the analysis assumed that:

$$X_{ij} = \mu + \alpha_i + \beta_j + e_{ij}$$

Where X_{ij} denotes the measurement from each block (each sample) and treatment (duration of soaking), μ denotes the overall mean,

α_i denotes the effect of the i^{th} block,

β_j denotes the effects of the j^{th} treatment,

and the e_{ij}s, the random errors, are assumed to be normally distributed, N $(0,\sigma^2)$ (Gordon, 2000).

Multiple comparisons

Multiple comparisons between treatments in cases where there were significant differences among the treatments, for a particular species, were done by determining the least significant difference (LSD) for the treatment means. Tukey's method was used.

t-test

Paired t-test was used for analysis of the paired comparison designs and 2-sample t-test was used to compare samples from independent populations.

Correlation and regression

Pearson's correlation coefficient and regression equations were used to establish the relationships between various variables. The strength of a correlation was classified as follows:

Table 3-1. The strength of a correlation (Fowler *et al.*, 1998)

Value of coefficient r (positive or negative)	Meaning
0.00 to 0.19	A very weak correlation
0.20 to 0.39	A weak correlation
0.40 to 0.69	A modest correlation
0.70 to 0.89	A strong correlation
0.90 to 1.00	A very strong correlation

3.3 RESULTS

3.3.1. Effect of wood species and duration of soaking on resin uptake and loss during the manufacture of Vintorg

Furfuryl alcohol (FFA) resin

The data on maximum possible, initial and final FFA resin uptakes by microwave modified wood (Torgvin) after soaking treatment, percentage saturation of Torgvin and Vintorg with the FFA resin and the relative amount of FFA resin lost during pressing of treated Torgvin and curing of the resin, for the four treatments (duration of soaking) for both *P. radiata* and *E. regnans* are summarised in Table A-1 (Appendix 4). The results from a two way ANOVA are summarised in Table 3-2.

Maximum possible resin uptake

The mean maximum possible FFA resin uptake values for *P. radiata* were generally higher than those for *E. regnans* (Figure 3-6). This could be mainly attributed to higher moisture content in the *E. regnans* samples and lower density of *P. radiata* samples. The slight differences in the values of the maximum possible resin uptake among the samples used in the four treatments (T1-1min, T5-5min, T10-10 min and T20-20 min) for each species is due to the slight differences in their moisture content and wood density.

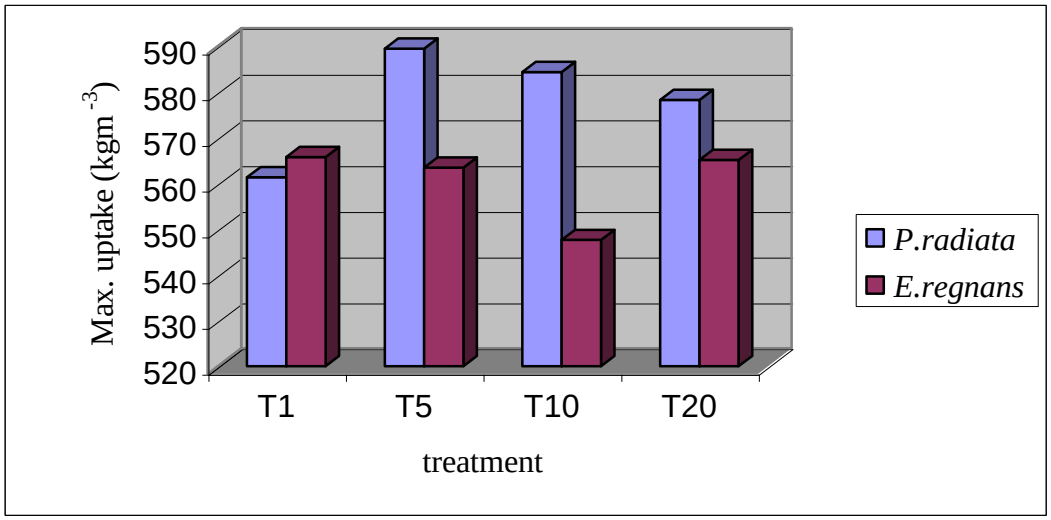


Fig. 3-6. Mean maximum possible FFA resin uptake for Torgvin from *P. radiata* and *E. regnans.*

Initial and final resin uptakes

Wood species and duration of soaking had an extremely significant ($P<0.001$) effect on initial and final FFA resin uptakes (Table 3-2). The result of multiple comparisons using Turkey's test (Table 3-3) indicated that the mean value of the initial resin uptake for the samples soaked for one minute was significantly lower than those for the other duration of treatment. No other significant differences between the treatments were observed. It was also evident that samples soaked in the FFA resin for 1 and 5 minutes had mean final uptake values lower than those soaked for 10 and 20 minutes. There was no evidence of any difference in the final resin uptake between samples soaked for 1 and 5 minutes and between those soaked for 10 and 20 minutes.

Significant interactions between wood species and duration of soaking in their effect on final resin uptake ($P<0.05$) during the manufacture of Vintorg were found. However, there was no evidence of any significant ($P=0.54$) interaction between wood species and duration of soaking on their effect on the initial FFA resin uptake. The interaction plot (using the mean values) for species and duration on their effect on the final resin uptake is as shown in Figure 3-7.

Amount of resin loss during the manufacture of Vintorg

Wood species and duration of soaking had very significant effects on amount of resin loss (Table 3-2). The amount of FFA resin lost from *P. radiata* during the manufacture of Vintorg is significant compared to that from *E. regnans* (Table 3-2). Significant interactions between wood species and duration of soaking in their effect on the relative amount of resin lost during the manufacture of Vintorg were observed (Figure 3-8). Results of multiple comparisons (Table 3-3) indicated differences in amount of resin loss were significant only between the samples soaked for 1 and 5 minutes.

Table 3-2. Two way ANOVA for wood species and duration of soaking on FFA resin uptake and loss during the manufacturing of Vintorg.

Model	Variable	Degree of freedom	P-value
Initial resin uptake~species * duration	species	F 1,72	0.000 s
	duration	F 3,72	0.000 s
	interaction	F 3,72	0.543 n.s
Initial resin uptake~species + duration	species	F 1,75	0.000 s
	duration	F 3,75	0.000 s
Final resin uptake~species * duration	species	F 1,72	0.000 s
	duration	F 3,72	0.000 s
	interaction	F 3,72	0.015 s
Final resin uptake~species +duration	species	F 1,75	0.000 s
	duration	F 3,75	0.000 s
Amount of resin lost~species * duration	species	F 1,72	0.000 s
	duration	F 3,72	0.005 s
	interaction	F 3,72	0.008 s
Amount of resin lost~species +duration	species	F 1,75	0.000 s
	duration	F 3,75	0.010 s

Note: s- indicates significant results at 0.05 level; n.s – non-significant results at the same level.

Table 3-3. Tukey's pair-wise comparisons for FFA resin uptakes and loss between various treatments during the manufacturing of Vintorg.

Treatment pairs	Statistical significance of difference for pairs of treatment[1]		
	Initial resin uptake	Final resin uptake	Amount of resin lost
5-1	**	n.s	**
10-1	***	***	n.s
20-1	***	***	n.s
10-5	n.s	**	n.s
20-5	n.s	**	n.s
20-10	n.s	n.s	n.s

[1] Key: n.s- not significant, *- significant (95 % level), **- very significant (99 % level) and *- extremely significant (99.9 % level) (Gordon, 2000).**

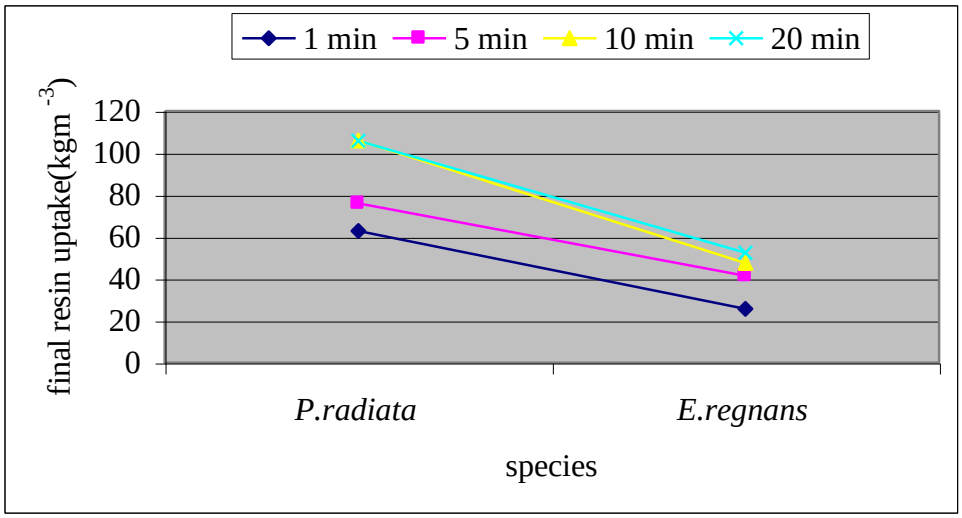


Fig. 3-7. The interaction plot for species and duration of soaking on their effect on the mean final FFA resin uptake.

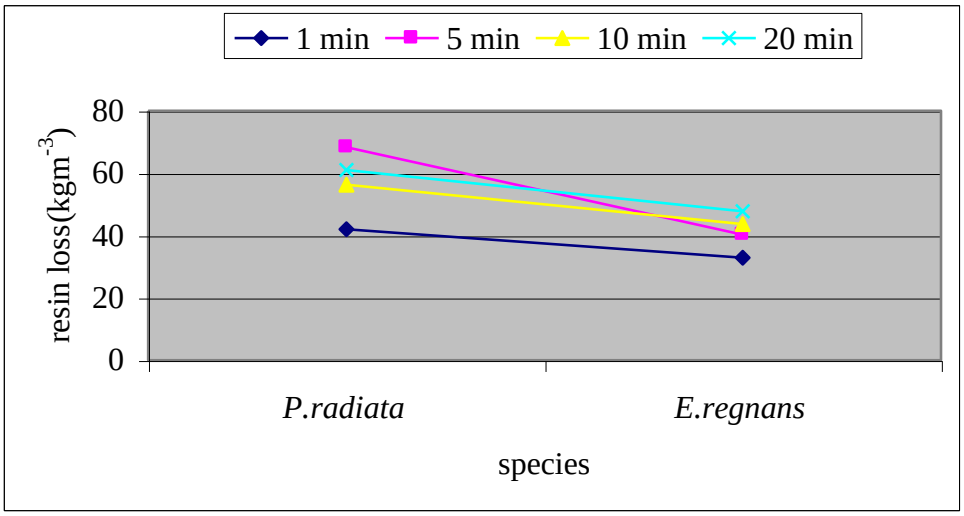


Fig. 3-8. The interaction plot for species and duration of soaking on their effect on the mean FFA resin loss.

<u>Comparisons of initial and final resin uptakes for each species</u>

Paired t-tests showed ($P<0.001$) significant differences in the initial and the final FFA resin uptakes for each of the four treatments for each species (Table 3-4).

Consequently, the percentage saturation of Torgvin with FFA resin was higher than that for Vintorg with either species. The values for percentage saturation of Torgvin and Vintorg were observed to be higher in *P. radiata* than in E. *regnans* (Figure 3-9).

Table 3-4. Paired t-test results of the mean difference in the initial and final FFA resin uptakes for *P. radiata and E. regnans*.

Variable	*P. radiata*					*E. regnans*				
	Mean	Mean S.D	SE Mean	T-value	P-value	Mean	Mean S.D	SE Mean	T-value	P-value
Initial resin	142.4	41.5	6.6	-	-	83.2	19.8	3.1	-	-
Final resin	84.5	30.8	4.9	-	-	49.6	16.2	2.6	-	-
Difference (loss)	57.9	22.7	3.6	16.2	0.000	33.6	10.6	1.7	20.4	0.000

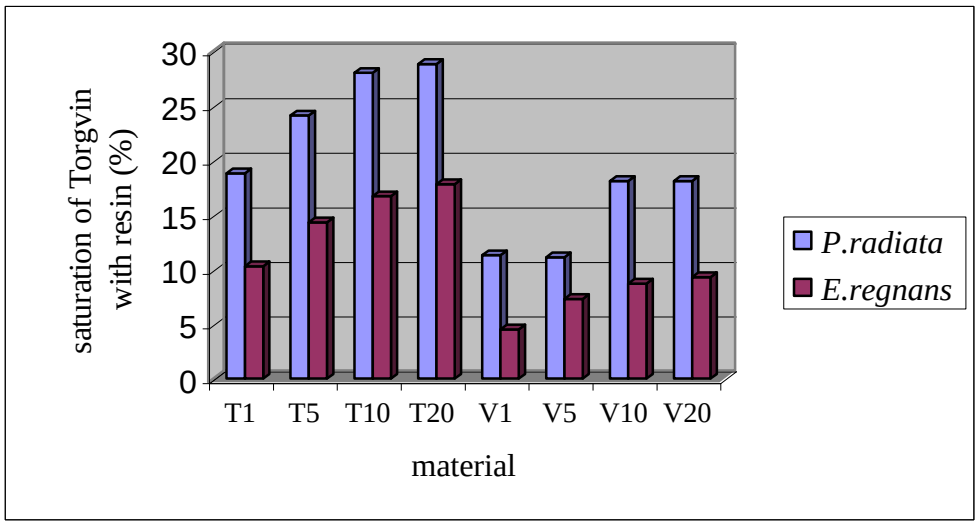


Fig. 3-9. Percentage saturation of Torgvin (T) and Vintorg (V) with FFA resin.

There was a general tendency for resin uptake to increase with duration of soaking for both species as shown in Figures 3-10 and 3-11.

Comparisons of resin uptakes among treatments in *P. radiata*

Tukey's comparisons among the four treatments (Table 3-5) revealed that the initial resin uptake after 1 minute of soaking was not significantly lower than that after 5 minutes ($P=0.07$) but significantly lower than the initial resin uptakes after 10 and 20 minutes ($P< 0.01$). The comparisons on the final resin uptakes indicated significantly high ($P \leq 0.001$) uptake values after 10 and 20 minutes as compared to the values after 1 and 5 minutes. There was no significant ($P=0.99$) difference in the values of the final FFA resin uptake after 1 and 5 minutes of soaking.

Comparisons of the amount of resin loss among treatments in *P. radiata*

Turkey's comparisons among the four treatments (Table 3-5) revealed a significant difference ($P<0.01$) in amount of resin lost during the manufacture of Vintorg only between the resin loss from the samples treated in FFA resin for 1 (42.0 kgm^{-3}) and 5 (76.0 kgm^{-3}) minutes.

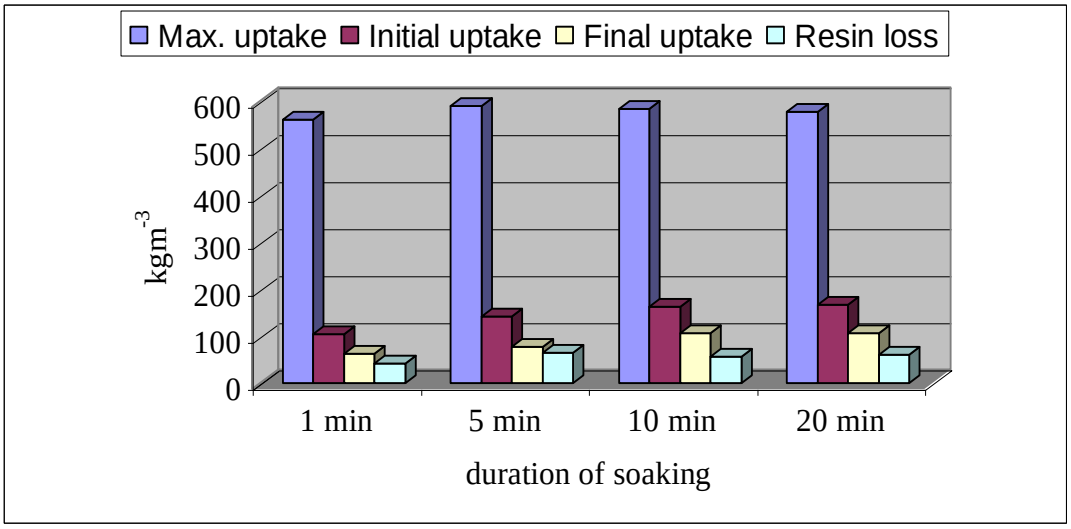


Fig. 3-10. Variation of FFA resin uptake and loss with duration of soaking for *P. radiata*.

Comparisons of resin uptake among treatments in *E. regnans*.

Tukey's comparisons for the four treatments (Table 3-5) revealed that the values for the initial and final FFA resin uptakes after 5, 10 and 20 minutes of soaking were extremely significantly higher ($P<0.001$) than those after 1 minute of soaking. The initial FFA resin uptake after 20 minutes of soaking was also observed to be significantly higher ($P<0.01$) than that after 5 minutes of soaking. The comparisons between the rest of the treatment pairs showed no evidence of any significant differences.

Comparisons of the amount of resin lost among treatments in *E. regnans*.

The comparisons between the treatment pairs (Table 3-5) showed no evidence of any significant differences in the amount of resin loss between all the pairs except for the samples that were soaked for 20 minutes and 1 minute in FFA resin (Figure 3-11). The relative amount of FFA resin loss from the samples treated for 20 minutes were significantly higher ($P< 0.05$) than that from samples treated for 1 minute.

Table 3-5. Tukey's pair wise comparisons for the mean FFA resin uptakes and loss between various treatments during the manufacturing of Vintorg.

Treatment pairs	Statistical significance of difference for pairs of treatment for each species[2]					
	P. radiata			*E. regnans*		
	Initial resin uptake	Final resin uptake	Amount of resin lost	Initial resin uptake	Final resin uptake	Amount of resin lost
5-1	*	n.s	n.s	***	***	n.s
10-1	**	***	n.s	***	***	n.s
20-1	**	***	n.s	***	***	*
10-5	n.s	***	n.s	n.s	n.s	n.s
20-5	n.s	***	n.s	**	n.s	n.s
20-10	n.s	n.s	n.s	n.s	n.s	n.s

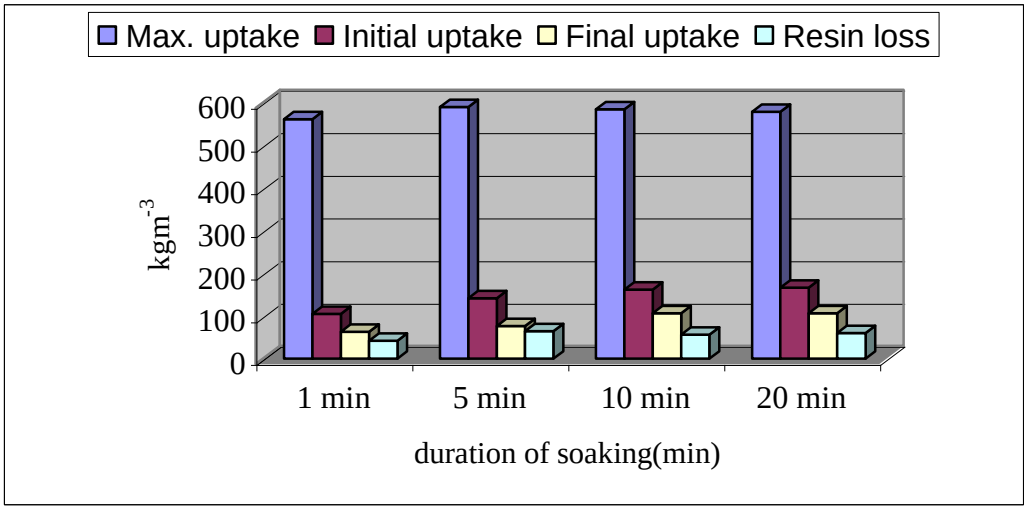


Fig. 3-11. Variation of FFA resin uptake and loss with duration of soaking for *E. regnans.*

Melamine formaldehyde (MF)

The data on maximum possible, initial and final MF resin uptakes by Torgvin after soaking treatment, percentage saturation of Torgvin and Vintorg with the MF resin for both *P. radiata* and *E. regnans* are summarised in Table A-2 (Appendix 3).

[2] Key: n.s- not significant, *- significant (95 % level), **- very significant (99 % level) and *- extremely significant (99.9 % level) Ibid.**

Maximum possible resin uptake

The mean maximum possible MF resin uptakes for the two species were about the same for *E. regnans* and *P. radiata* (Figure 3-12). This is due to similar moisture content of these samples (Appendix 4, Table A-2).

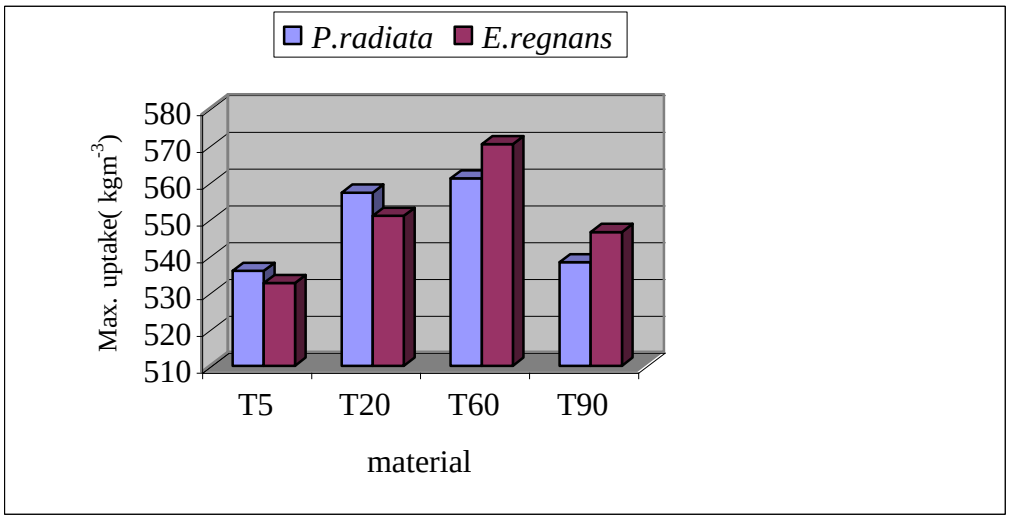


Fig. 3-12. Mean maximum possible MF resin uptake by Torgvin (T) from *P. radiata* and *E. regnans*.

Initial and final MF resin uptakes

Results of a two way ANOVA for the effect of wood species and duration of soaking on MF resin uptake and loss by Torgvin during the manufacturing of Vintorg are indicated in Table 3-6. There was evidence of a significant effect of wood species ($P<0.05$) and significant effect ($P<0.001$) of duration of soaking on the initial MF resin uptake. Significant interactions ($P=0.001$) between wood species and duration of soaking on their effect on initial resin uptake were observed. The interaction plots are shown in Figure 3-13. *E.regnans* generally had higher mean values for the initial MF resin in all the treatments except for the samples soaked in MF resin for 20 minutes (Figure 3-13).

There was also a significant effect of duration of soaking on the final MF resin uptake (Table 3-6). However, wood species did not have any significant effect on the final MF resin uptake ($P=0.18$). The final MF resin uptakes for the two species were about the same, though the values for *P. radiata* were slightly higher than those for *E. regnans* (Figure 3-14). However, there was no evidence of any interactions between wood species and duration of soaking on their effect on final resin uptake. The results of multiple comparisons between treatments using Tukey's test are summarised in Table 3-7. There was evidence of significant differences

in the MF resin uptakes in all pairs of treatment comparisons except between the samples soaked for 5 and 20, and 60 and 90 minutes.

Amount of MF resin lost during the manufacture of Vintorg.

Wood species and duration of soaking had significant (P<0.001) effects on the amount of MF resin loss during the manufacture of Vintorg. The mean amount of MF resin lost from *E. regnans* (81.1 kgm^{-3}) during the manufacture of Vintorg was significantly (P<0.001) higher than that from *P. radiata* (59.1 kgm^{-3}) (Table 3-6). Tukey's pair wise comparisons (Table 3-7) indicated that the mean amount of resin loss from samples soaked for 5 minutes was (P<0.001) significantly higher than for all the other treatments. The interaction plots for species and duration on their effect on the mean MF resin loss are shown in Figure 3-15**.**

Table 3-6. Two way ANOVA for the effect of wood species and duration of soaking on MF resin uptake and loss by Torgvin during the manufacturing of Vintorg.

Model	Variable	Degree of freedom	P-value
Initial resin uptake~species * duration	species	$F_{1,72}$	0.045 s
	duration	$F_{3,72}$	0.045 s
	interaction	$F_{3,72}$	0.000 s
Initial resin uptake~species + duration	species	$F_{1,75}$	0.051 n.s
	duration	$F_{3,75}$	0.000 s
Final resin uptake~species * duration	species	$F_{1,72}$	0.179 n.s
	duration	$F_{3,72}$	0.000 s
	interaction	$F_{3,72}$	0.496 n.s
Final resin uptake~pecies +duration	species	$F_{1,75}$	0.177 n.s
	duration	$F_{3,75}$	0.000 s
Amount of resin lost~species * duration	species	$F_{1,72}$	0.000 s
	duration	$F_{3,72}$	0.000 s
	interaction	$F_{3,72}$	0.143 n.s
Amount of resin lost~species +duration	species	$F_{1,75}$	0.000 s
	duration	$F_{3,75}$	0.000 s

Table 3-7. Tukey's pair wise comparisons for the mean initial and final MF resin uptakes and amount of resin lost between various treatments during the manufacturing of Vintorg.

Treatment pairs	Statistical significance of difference for pairs of treatment for each species[3]		
	Initial resin uptake	Final resin uptake	Amount of resin lost
20-5	n.s	n.s	n.s
60-5	***	*	***
90-5	***	***	***
60-20	**	*	***
90-20	***	***	n.s
90-60	n.s	n.s	n.s

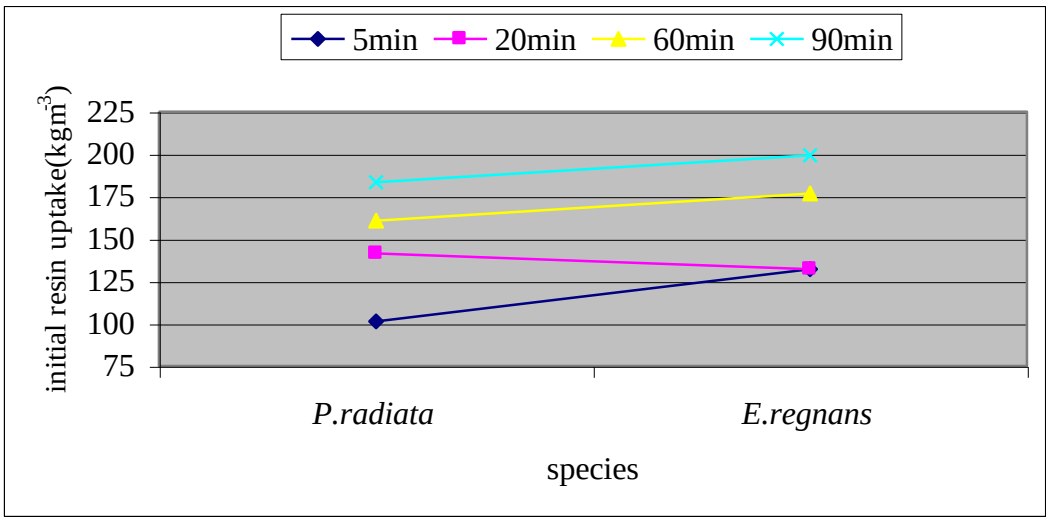


Fig. 3-13. Interaction plot for species and duration on their effect on the mean initial MF resin uptake.

[3] **Key: n.s- not significant, *- significant (95 % level), **- very significant (99 % level) and ***- extremely significant (99.9 % level) Ibid.**

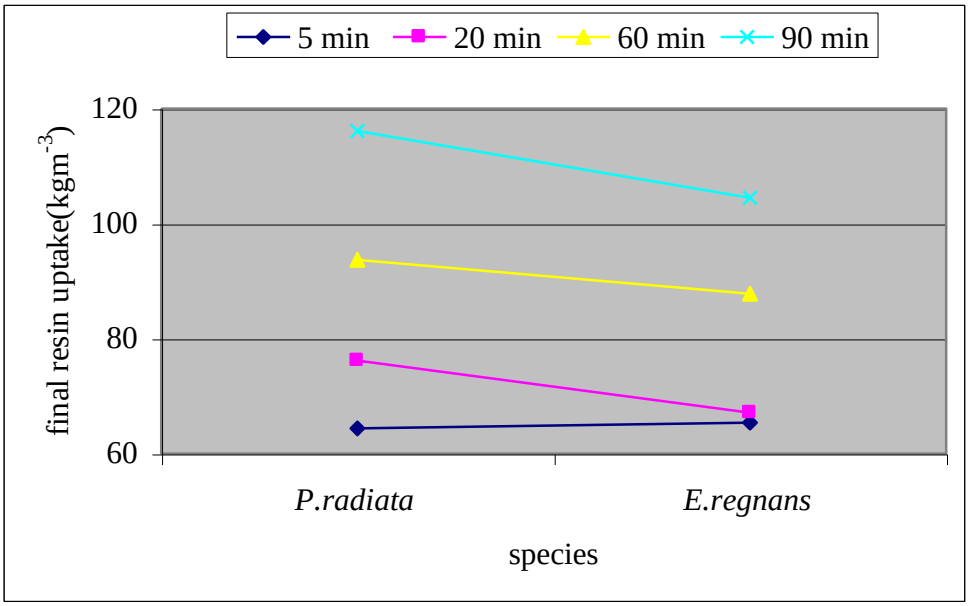


Fig. 3-14. Interaction plot for species and duration on their effect on the mean final MF resin uptake.

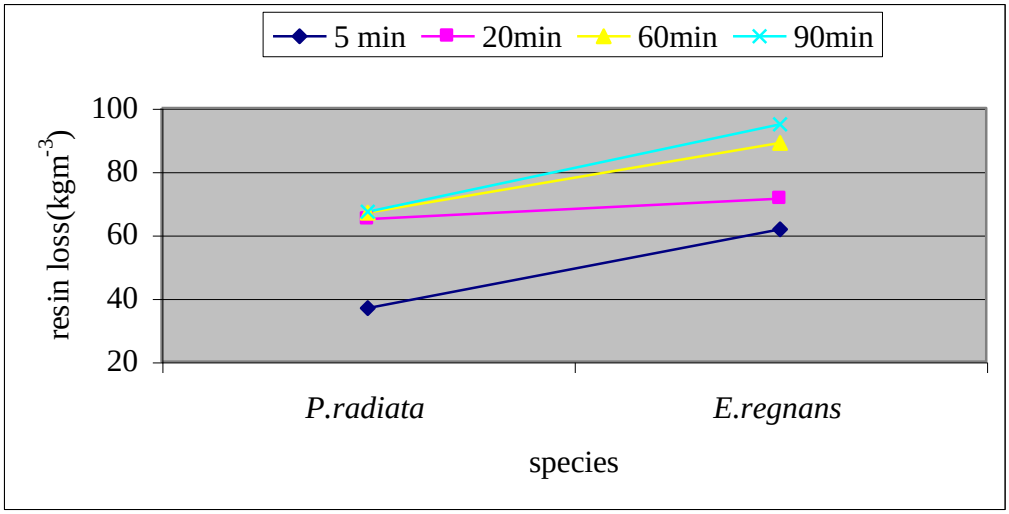


Fig. 3-15. Interaction plots for species and duration on their effect on the mean MF resin loss.

Comparisons of resin uptakes among treatments for each species

Paired t-tests showed (P<0.001) significant differences between the initial and the final MF resin uptakes for each of the four treatments for each species (Table 3-8). The mean values for percentage saturation of Torgvin and Vintorg with MF resin were generally higher in *P. radiata* than in *E. regnans* (Figure 3-16).

Table 3-8. Paired t-test results for the mean difference in the initial and final MF resin uptakes for *P. radiata* and *E. regnans*.

Variable	*P. radiata*					*E. regnans*				
	Mean	S.D.	SE Mean	T-value	P-value	Mean	S.D.	SE Mean	T-value	P-value
Initial resin (kgm^{-3})	146.7	39.9	6.3	-	-	161.0	45.6	7.2	-	-
Final resin (kgm^{-3})	87.6	27.9	4.4	-	-	79.9	33.4	5.3	-	-
Difference (resin loss kgm^{-3})	59.1	17.4	2.8	21.5	0.000	81.1	26.1	4.4	18.3	0.000

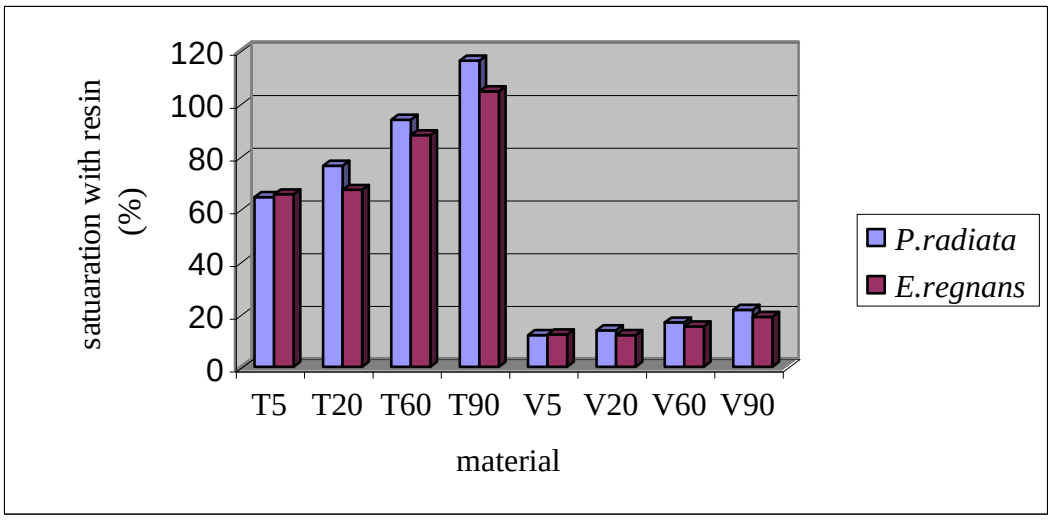


Fig. 3-16. Percentage saturation of Torgvin (T) and Vintorg (V) with MF resin.

<u>Comparisons of the MF resin uptakes in *P. radiata*</u>.

The resin uptake in *P. radiata* increased with duration of soaking (Figure 3-17).

Tukey's pair wise comparisons (Table 3-9) indicated that the initial MF resin uptakes by *P.radiata* Torgvin after 5 minutes of soaking were significantly lower (P<0.001) than those after 60 and 90 minutes of soaking and significantly lower (P<0.05) than that after 20 minutes

of soaking. There was also evidence that the initial resin uptake after 20 minutes was significantly lower (P<0.05) than that after 90 minutes of soaking. There was no evidence of any other significant differences in the other pair wise comparisons in the initial resin uptakes between the treatments. The final MF resin uptake after soaking treatment for 5 minutes was significantly lower (P<0.001) than that after 90 minutes and significantly lower (P=0.03) than that after 60 minutes of soaking. There was no evidence of any other significant differences in the final MF resin uptakes between the other pairs.

Comparisons of MF resin loss among treatments in *P. radiata*.

The amount of MF resin loss during the manufacture of Vintorg increased with duration of soaking to a maximum after 60 minutes of soaking and then remained the same as shown in Figure 3-17.

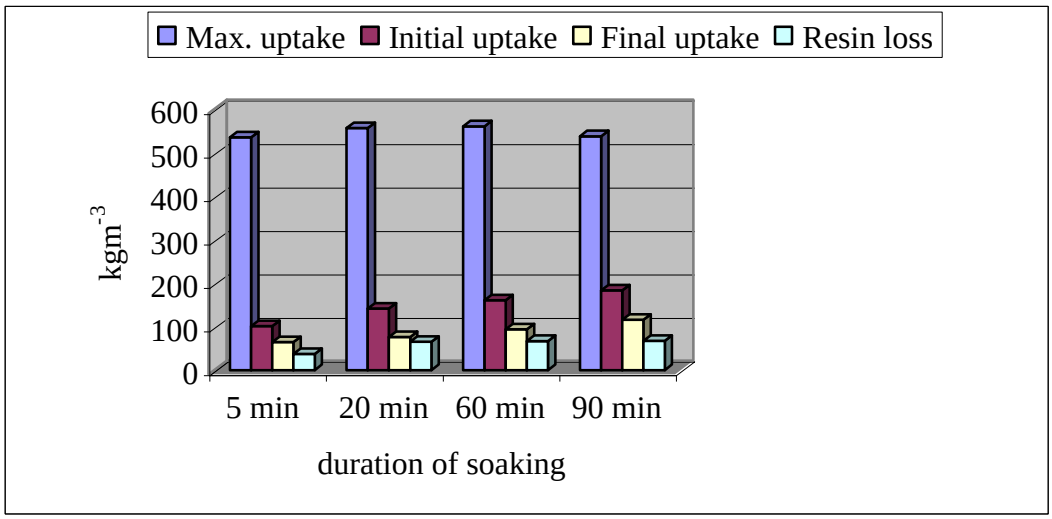


Fig. 3-17. Variation of MF resin uptake and loss with duration of soaking for *P. radiata* during the manufacture of Vintorg.

Table 3-9. Tukey's comparisons for the mean initial and final MF resin uptakes and amount of resin lost between various treatments during the manufacturing of Vintorg.

Treatment pairs	Statistical significance of difference for pairs of treatment for each species[4]					
	P. radiata			*E. regnans*		
	Initial uptake	Final uptake	resin loss	Initial uptake	Final uptake	resin loss
20-5	*	n.s	***	n.s	n.s	n.s
60-5	***	*	***	**	n.s	**
90-5	***	***	***	***	***	***
60-20	n.s	n.s	n.s	n.s	n.s	n.s

[4] **Key: n.s- not significant, *- significant (95 % level), **- very significant (99 % level) and ***- extremely significant (99.9 % level) Ibid.**

90-20	*	**	n.s	***	***	n.s
90-60	n.s	n.s	n.s	*	n.s	n.s

The Tukey's pair wise comparisons are shown in Table 3-9. The relative amount of MF resin lost from the samples soaked in the resin for 5 minutes was significantly (P<0.001) lower than that for all the other treatments. There was no evidence of any significant differences in the amount of resin loss from the *P. radiata* samples soaked in MF resin for 20, 60 and 90 minutes.

Comparisons of the MF resin uptakes in *E. regnans*.

There was also a general tendency for MF resin uptake to increase with duration of soaking in *E. regnans* Torgvin (Figure 3-18). The Tukey's pair wise comparisons are summarised in Table 3-9. The initial MF resin uptake after 90 minutes of soaking was significantly higher than after 5 (P<0.001), 20 (P=0.001) and 60 (P<0.05) minutes of soaking The initial resin uptake after 60 minutes of soaking was significantly higher than that after 5 minutes of soaking (P<0.01) and about the same as that after 20 minutes of soaking (P=0.09). The final MF resin uptake after 90 minutes of soaking was significantly higher than those after 5 and 20 minutes of soaking (P≤0.001) and not significantly higher than that after 60 minutes of soaking (P=0.08). The final MF resin uptake after 60 minutes of soaking was just slightly higher than that after 20 minutes (P=0.06). There was no evidence of any significant differences between the values of the final MF resin uptake after 5 minutes of soaking with those after 20 (P=0.7) and 60 (P= 0.22) minutes of soaking.

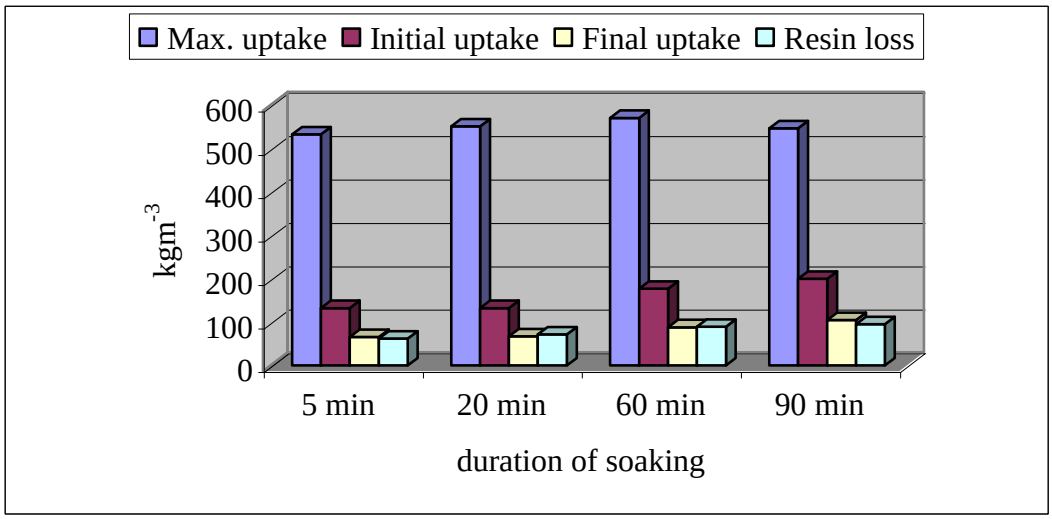


Fig. 3-18. Variation in MF resin uptake and loss for *E. regnans* during the manufacture of Vintorg.

Comparisons of MF resin loss among treatments in *E. regnans*.

The amount of MF resin loss during the manufacture of Vintorg had a tendency to increase with duration of soaking (Figure 3-18).

Tukey's comparisons are summarised in Table 3-9. The relative MF resin loss after 5 minutes of soaking was significantly lower than after 60 ($P<0.01$) and 90 ($P<0.001$) minutes of soaking. There was no evidence of any other significant differences between any of the other pair wise comparisons

3.3.2. Effect of wood species, resin type and duration of soaking on the resin uptake and loss during the manufacture of Vintorg.

The result of three-way analysis of variance using the general linear model is summarised in Table 3-10. There was evidence of significant ($P<0.001$) effect of wood species and duration of soaking on initial resin uptake and final resin uptake. *P. radiata* had higher mean values of initial and final resin uptakes than *E. regnans* respectively (Table 3-11). Torgvin samples soaked for 20 minutes had higher mean values of initial and final resin uptakes than those soaked for 5 minutes respectively. However, there was no evidence of any significant effect of resin type on initial ($P=0.10$) and final ($P= 0.83$) resin uptakes for duration of soaking between 5 and 20 minutes.

Significant interactions of wood species and resin type, wood species and duration of soaking, wood species, resin type and duration of soaking on initial resin uptake were observed (Figure 3-19). There was no evidence of any significant interaction between resin type and duration of soaking in their effect of initial resin uptake. In the case of the final resin uptake, only species and duration of soaking exhibited a significant interaction in this variable.

There was also evidence of significant effects of wood species ($P<0.05$) and resin type ($P=0.01$) on amount of resin loss during the manufacture of Vintorg. However, there was no evidence of any significant effect of duration of soaking on the amount of resin loss. Significant interactions of wood species and resin type, resin type and duration of soaking and wood species, resin type and duration of soaking on their effect on the amount of resin loss were observed (Figure 3-20) However, there was no interaction of species and duration of soaking alone on their effect on the amount of resin loss.

Table 3-10. Three ways ANOVA for wood species, resin type and duration of soaking on resin uptake and loss during the manufacturing of Vintorg.

Model	Variable	Degree of freedom	P-value
Initial resin uptake~species* resin type* duration	species	F 1,72	0.000 s
	resin type	F 1,72	0.100 n.s
	duration	F 1,72	0.000 s
	Species*resin type	F 1,72	0.000 s
	Species*duration	F 1,72	0.000 s
	Resin type *duration	F 1,72	0.650 n.s
	interaction	F 1,72	0.000 s
Initial resin uptake~species + resin type +duration	species	F 1,76	0.000 s
	resin type	F 1,76	0.184 n.s
	duration	F 1,76	0.007 s
Final resin uptake~species* resin type* duration	species	F 1,72	0.000 s
	resin type	F 1,72	0.830 n.s
	duration	F 1,72	0.000 s
	Species*resin type	F 1,72	0.100 n.s
	Species*duration	F 1,72	0.000 s
	Resin type*duration	F 1,72	0.060 n.s
	interaction	F 1,72	0.440 n.s
Final resin uptake~species + resin type +duration	species	F 1,76	0.000 s
	resin type	F 1,76	0.855 n.s
	duration	F 1,76	0.001 s
Amount of resin lost~species* resin type* duration	species	F 1,72	0.040 s
	resin type	F 1,72	0.010 s
	duration	F 1,72	0.160
	Species*resin type	F 1,72	0.000 s
	Species*duration	F 1,72	0.900 n.s
	Resin type *duration	F 1,72	0.010 s
	interaction	F 1,72	0.000 s
Amount of resin lost~species + resin type +duration	species	F 1,76	0.065 n.s
	resin type	F 1,76	0.282 n.s
	duration	F 1,76	0.047 s

Note: s- indicates significant results at 0.05 level; n.s – non-significant results at the same level.

Table 3-11. The mean resin uptake and loss during the manufacture of Vintorg.

Response	Duration of soaking (min)	*P. radiata*	*E. regnans*
Initial resin uptake (kgm^{-3})	5	121.6	110.5
	20	161.0	113.5
Final resin uptake (kgm^{-3})	5	65.1	53.5
	20	98.7	59.3
Amount of resin lost (kgm^{-3})	5	56.5	49.2
	20	60.2	54.1

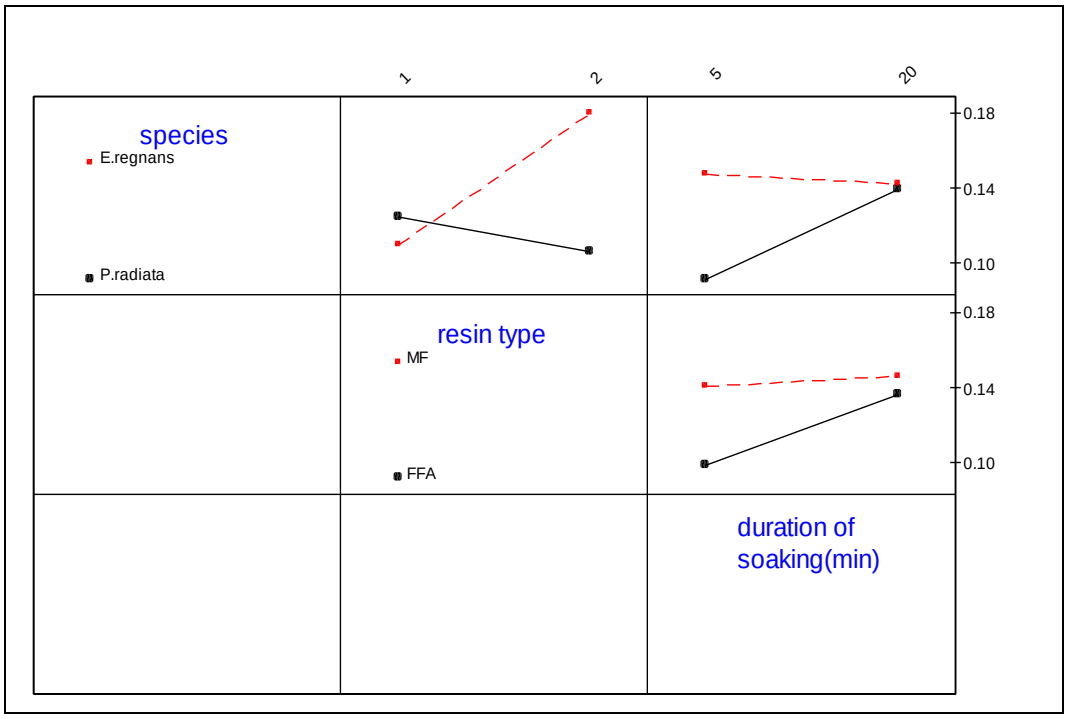


Fig. 3-19. Interaction plot for species, resin type and duration of soaking on their effect on the initial resin uptake.

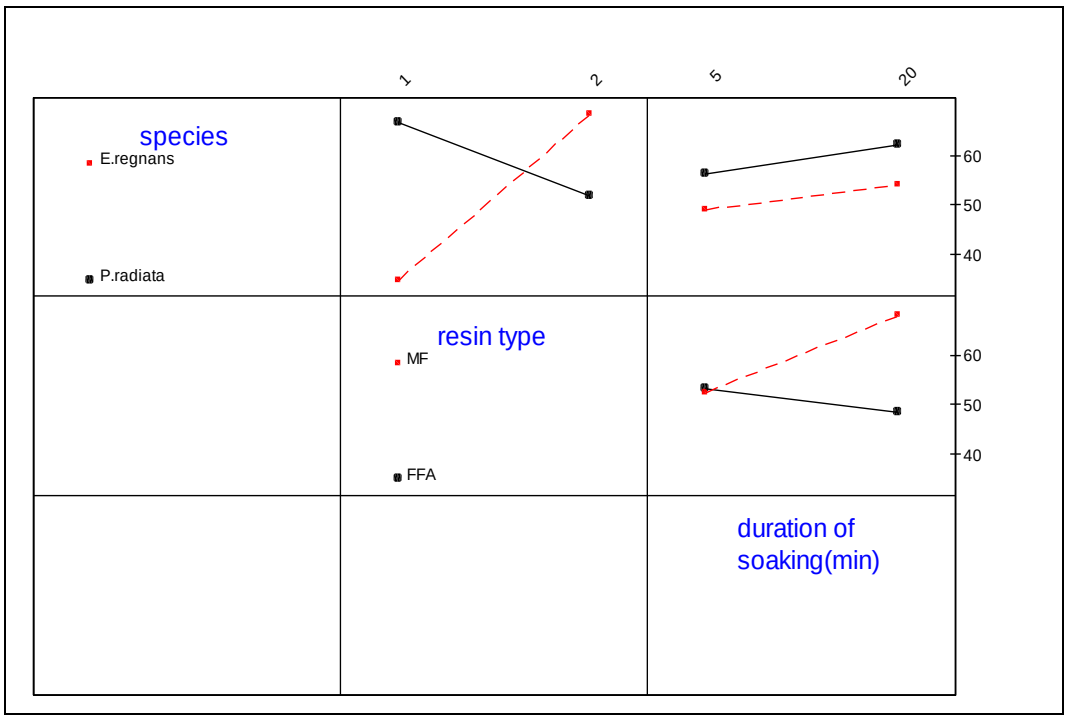


Fig. 3-20. Interaction plot for species, resin type and duration of soaking on their effect on the resin loss.

3.3.3. Effect of wood species, resin type and duration of soaking on the increase in density and decrease in the cross-sectional area of Torgvin during the manufacture of Vintorg.

Increase in density

A three way analysis of variance on the effect of wood species, resin type and duration of soaking on the increase in wood density of Torgvin (Table 3-12), for the samples treated for 5 and 20 minutes revealed highly significant effects ($P \leq 0.01$) for wood species, resin type and duration of treatment.

The mean increase in density of Torgvin from *E. regnans* treated with MF resin was higher than that in *P. radiata* Torgvin treated with the same resin (Table 3-13). The mean increase in the density of Torgvin treated with FFA resin for 5 minutes was the same for the two species tested. However, the increase in density for Torgvin samples from *P. radiata* following treatment with FFA for 20 minutes was slightly higher than that of *E. regnans*. Melamine formaldehyde resin had a higher effect on the mean increase in density of the Torgvin samples than furfuryl alcohol. Torgvin samples soaked for 20 minutes in either resin had a higher mean increase in density than those soaked for only 5 minutes except in the case of the Torgvin from *P. radiata* treated with MF resin where there was no difference in the increase in density.

Table 3-12. Three ways ANOVA for effect of wood species, resin type and duration of soaking on increase in density of Torgvin during the manufacturing of Vintorg.

Model	Variable	Degree of freedom	P-value
Increase in density~species* resin type* duration	species	$F_{1,72}$	0.000 s
	resin type	$F_{1,72}$	0.010 s
	duration	$F_{1,72}$	0.000 s
	species*resin type	$F_{1,72}$	0.000 s
	species*duration	$F_{1,72}$	0.000 s
	resin type *duration	$F_{1,72}$	0.060 n.s
	interaction	$F_{1,72}$	0.740 n.s
Increase in density ~species + resin type +duration	species	$F_{1,76}$	0.006 s
	resin type	$F_{1,76}$	0.184 n.s
	duration	$F_{1,76}$	0.045 s

Note: s- indicates significant results at 0.05 level; n.s – non-significant results at the same level.

Significant interactions between wood species and resin type and between wood species and duration of soaking on their effect on the increase in the density of Torgvin were observed (Figure 3-21). However, there was no evidence of any interactions of resin type and duration of soaking and wood species, resin type and duration of soaking on their effect of the increase in the density of Torgvin.

Table 3-13. The mean increase in density of Torgvin during the manufacture of Vintorg.

Resin type	Duration of soaking (min)	Mean increase in density			
		P. radiata		*E. regnans*	
		Mean (gcm^{-3})	%	Mean (gcm^{-3})	%
FFA	5	0.10	24.7	0.10	17.2
	20	0.16	34.2	0.12	21.1
MF	5	0.09	19.9	0.20	33.2
	20	0.09	22.7	0.17	30.5

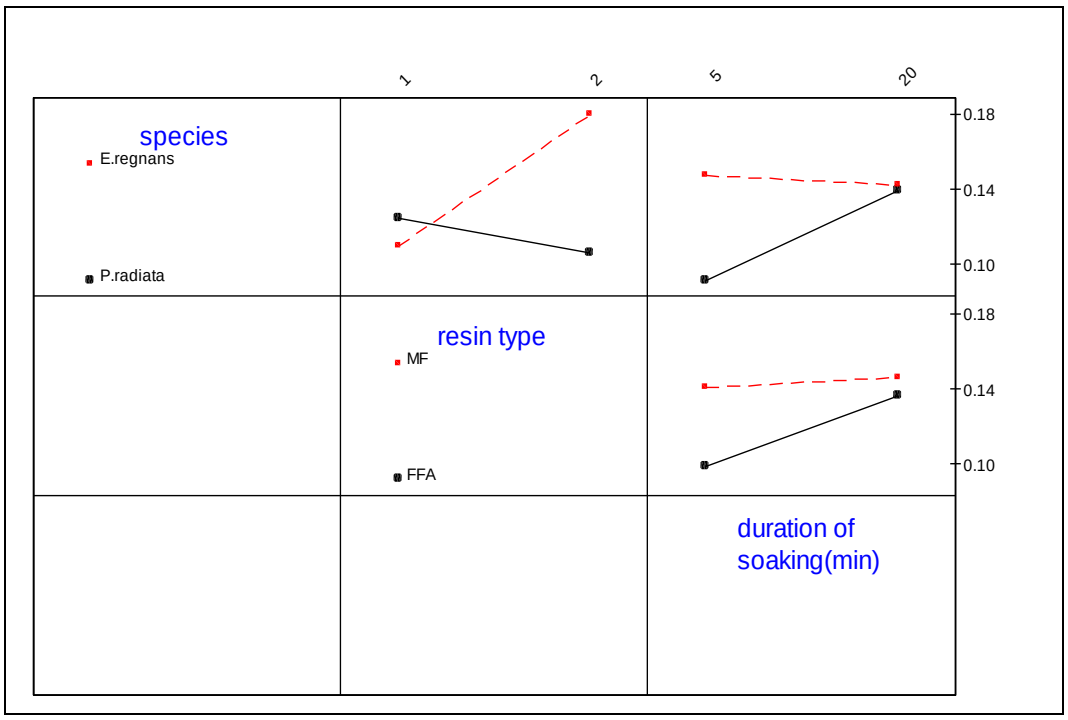


Fig. 3-21. Interaction plot for species, resin type and duration of soaking on increase in density of Torgvin during the manufacture of Vintorg.

<u>Decrease in cross-sectional area of Torgvin during the manufacture of Vintorg</u>.

The mean decrease in cross-sectional area of Torgvin during the manufacture of Vintorg was affected significantly by wood species ($P<0.001$) and resin type ($P<0.01$) (Table 3-14). There was no evidence of any significant effect of duration of soaking on the mean decrease in cross-sectional area of Vintorg. The mean decrease in cross-sectional area of *E. regnans* samples during the manufacture of Vintorg with MF resin was significantly higher than that in *P. radiata* samples (Table 3-15). However, the decrease in cross-sectional area of Torgvin during the manufacture of Vintorg with FFA resin was only higher than that for *P. radiata* for samples soaked in this resin for 5 minutes. The mean cross-sectional areas of Torgvin from either species treated with FFA resin were reduced by about the same margin after pressing and curing of the resin (Table 3-15). However, a higher reduction in the cross-sectional area of *E. regnans* Torgvin (17 %) than that in *P.radiata* Torgvin (6-7 %) was observed in samples treated with the MF resin.

There was evidence of significant interactions of wood species and resin type on their effect on the mean decrease in the cross-sectional area of Torgvin during the manufacture of Vintorg (Figure 3-22). There were no other significant interactions of the factors.

Table 3-14. Three ways ANOVA for wood species, resin type and duration of soaking on decrease in cross-sectional area (C.A.) of Torgvin during the manufacturing of Vintorg.

Model	Variable	Degree of freedom	P-value
Decrease in C.A. ~species* resin type* duration	species	$F_{1,72}$	0.000 s
	resin type	$F_{1,72}$	0.010 s
	duration	$F_{1,72}$	0.360 n.s
	species*resin type	$F_{1,72}$	0.000 s
	species*duration	$F_{1,72}$	0.390 n.s
	resin type *duration	$F_{1,72}$	0.660 n.s
	interaction	$F_{1,72}$	0.830 n.s
Decrease in C.A. ~species + resin type + duration	species	$F_{1,76}$	0.000 s
	resin type	$F_{1,76}$	0.004 s
	duration	$F_{1,76}$	0.422 n.s

Note: s- indicates significant results at 0.05 level; n.s – non-significant results at the same level.

Table 3-15. The mean decrease in cross-sectional area of Torgvin during the manufacture of Vintorg.

Resin type	Duration of soaking (min)	decrease in cross-sectional area of Torgvin			
		P. radiata		*E. regnans*	
		Mean (mm^2)	%	Mean (mm^2)	%
FFA	5	149.1	8.4	157.1	8.9
	20	183.3	10.5	173.0	9.5
MF	5	126.5	6.0	327.3	17.2
	20	102.8	6.9	311.7	16.6

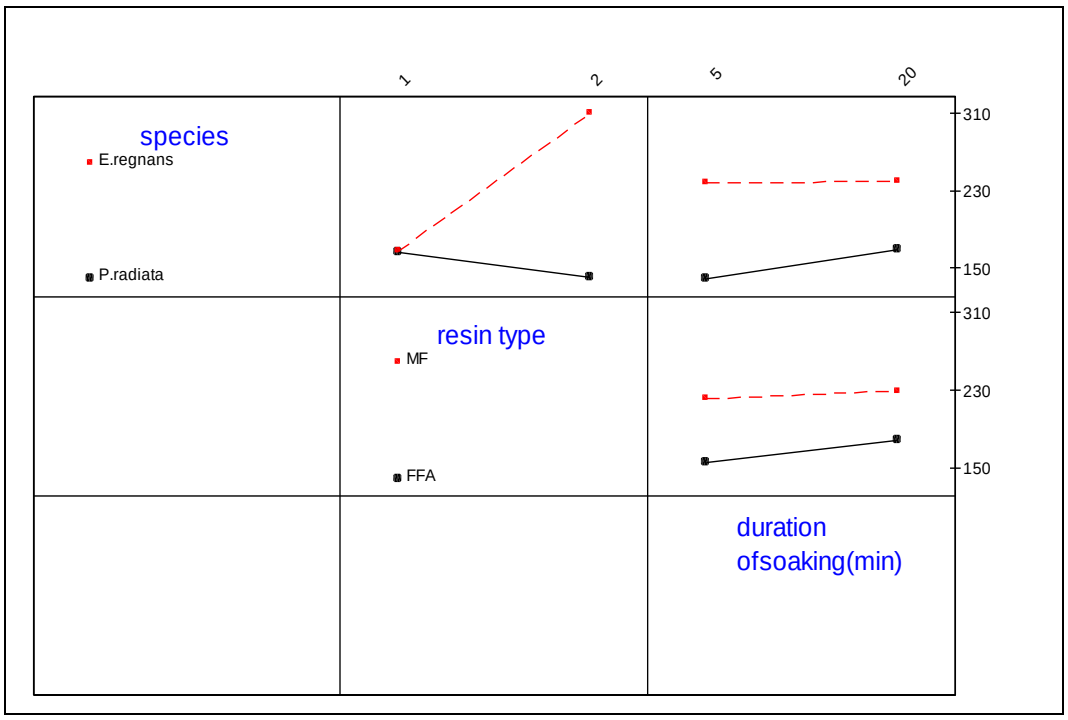


Fig. 3-22. Interaction plot for species, resin type and duration of soaking on decrease in the cross-sectional area of Torgvin during the manufacture of Vintorg.

3.3.4. Correlations for resin uptake and density of Torgvin and Vintorg.

The Pearson's correlation coefficients are as indicated in Table 3-16. Density of Vintorg had a significant ($P \leq 0.05$) but weak correlation with initial uptake of either resin for each species and the final uptake of FFA resin for *P. radiata*. A significant ($P < 0.05$) and a modest correlation with the final uptake of MF resin for each species and FFA resin for *E. regnans* were observed. Density of Vintorg manufactured from *P. radiata* using either resin was significantly ($P < 0.001$) modestly correlated ($r = 0.65$ and 0.68 for FFA and MF resins respectively) with the density of Torgvin. No correlation was observed in the case of *E. regnans* samples.

Table 3-16. Pearson's correlation coefficients (r) for resin uptake and density of Torgvin and Vintorg.

Pairs of variables	*P. radiata*				*E. regnans*			
	FFA resin		MF resin		FFA resin		MF resin	
	r	P-value	r	P-value	r	P-value	r	P-value
Final vs initial resin uptake	0.84	0.000*	0.93	0.000*	0.78	0.000*	0.78	0.000*
Density of Torgvin vs. initial resin uptake	-0.17	0.293	-0.36	0.028*	-0.59	0.000*	-0.63	0.000*
Density of Torgvin vs. final resin uptake	-0.28	0.080	-0.28	0.086	-0.51	0.001*	-0.50	0.001*
Density of Vintorg vs. Initial resin uptake	0.36	0.022*	0.32	0.054	0.34	0.03*	0.40	0.011*
Density of Vintorg vs. Final resin uptake	0.35	0.026*	0.45	0.005*	0.48	0.002*	0.51	0.001*
Density of Vintorg vs. density of Torgvin	0.65	0.000*	0.68	0.000*	0.04	0.818	-0.04	0.825

NOTE-* INDICATES SIGNIFICANT CORELATIONS AT 0.05 LEVEL

3.4 DISCUSSION

The results demonstrate that wood species and duration of soaking have significant effects on the resin uptake and loss during the manufacture of Vintorg. *P. radiata* Vintorg appeared to have a higher saturation with resin than *E . regnans* Vintorg, more so in the case of FFA resin. This could be possibly due to a higher porosity of *P . radiata* resulting from the lower density and more so in the case of FFA resin because of lower moisture content of the *P. radiata* samples than *E. regnans* and the lower viscosity of FFA resin than MF resin. Moisture causes swelling in wood and this results in a decrese in the size of the effective openings. The increase of resin uptake with duration of soaking is due to an increase in diffusion of the resins with time. It appears that the insignificant increases in resin uptake after 10 and 20 minutes of soaking for FFA and MF resins could be presumably due to the fact that wood comes to a high percent of swelling equilibrium in a few minutes and takes much longer to come to a complete equilibrium (Kollmann *et al*., 1975).

The apparently lower values for the final resin uptake and percentage saturation of Vintorg with FFA resin in each case could have been due to losses resulting from evaporation of water and other volatile components of the resins during the pressing of treated Torgvin and curing of the resin.

The insignificant differences in the uptake of the two resins by Torgvin after same duration of soaking despite the differences in the viscosity could possibly be attributed to the formation of checks as a result of microwave modification.

The greater decrease in the cross-sectional area of *E. regnans* relative to that for *P. radiata* during the manufacture of Vintorg can be attributed to a higher degree of pressing of the resin treated *E. regnans* as compared to resin treated *P. radiata,* and could perhaps be due to a higher plasticising effect of the resins (MF more especially) on *E. regnans* than *P. radiata*. The type of adhesive used has been reported to determine the plasticity (deformation) of the wood (Kollmann *et al*., 1975).

As density is computed as mass/volume, the reduction in the density of Torgvin and the increase in the density of Vintorg are simply the mathematical results of microwave treatments for Torgvin, which reduces mass and increases volume and Vintorg by resin treatment and pressing which increases mass and reduces volume back to the original volume. The higher effect of MF resin on the increase in density of Torgvin than FFA resin is possibly due to its higher density.

The strong correlation between the initial and final resin uptake indicate that it is possible to estimate the final amount of resin in Vintorg if the values of the initial resin uptake are known.

3.5 CONCLUSIONS

- Resin uptake by Torgvin and the resulting increase in its density are influenced by wood species and duration of soaking irrespective of resin type.
- Wood species and resin type have a significant influence on the amount of resin lost during the manufacture of Vintorg irrespective of duration of soaking.
- Melamine formaldehyde resin has a greater effect on the increase in the density of the Torgvin samples in *E. regnans* than P. *radiata* while FFA resin has a greater effect on the increase in density in *P. radiata* than *E. regnans.*

CHAPTER 4:

4 EVALUATION OF DENSITY AND MECHANICAL PROPERTIES OF VINTORG

4.1 Introduction

Mechanical properties of wood refer to its resistance to imposed loads or forces. These properties include: (1) resistance to deformations and distortions (elastic properties), (2) failure–related (strength) properties, and other performance properties. The most common measure of elastic properties is the modulus of elasticity (MOE). The main mechanical properties measured and represented as 'strength properties' for design include modulus of rupture (MOR) in bending; maximum stress in compression parallel to grain, compressive stress perpendicular to grain, and shear strength parallel to grain (Green *et al*., 1999). Additional strength properties measured include maximum load in bending, impact bending strength, tensile strength perpendicular to grain, and hardness.

The mechanical properties of wood are most important when wood and wood products are used for structural building applications. Structural uses of wood and wood products include floor joists and rafters in wood-frame housing, power line transmission poles, plywood roof sheathing and sub-flooring and glue laminated beams in commercial buildings (Haygreen & Bowyer, 1989).

A number of natural characteristics of wood can affect its mechanical properties. These include specific gravity, knots, slope of the grain, annual ring orientation, reaction wood, juvenile wood compression failures, pitch pockets, bird peck, and extractives (Green *et al*., 1999); (Bootle, 1983). Intrinsic mechanical properties are therefore measured on clear straight–grained wood. However, these natural defects must be taken into account in assessing actual properties or estimating the actual performance of wood products. The strength properties of wood and wood products can also be influenced by a number of environmental factors. These include moisture content, duration of loading, temperature and exposure to chemicals.

Treatment of wood with resins followed by densification under heat and pressure

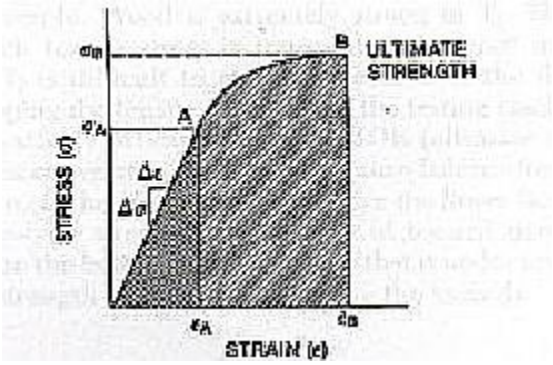
can result in the production of modified wood products with increased specific strength properties (Kollmann *et al*., 1975).

Treatment of wood with various impregnants e.g. phenol formaldehyde resins, liquid vinyl impregnants, molten natural resins, waxes, sulfur and even low fusion metals has been reported to improve the compressive strength and the hardness of wood (Kollmann *et al*., 1975). Solidified impregnants alone have been found to increase the hardness of wood much more than they increase its specific gravity. The only strength properties adversely affected by the combined resin treatment and compression are the Izod impact strength and toughness (Kollmann *et al*., 1975). This is attributable to the hardening and stiffening effect of the treating resin within the cell walls of wood.

When wood is exposed to environmental agents of deterioration, such as chemical treatments or elevated temperatures, each mechanical property reacts differently. In most cases, ultimate strength properties are reduced where elastic properties show little or no effect (Winandy & Rowell, 1984).

Wood modified with microwave energy (Torgvin) has reduced mechanical properties (Torgovnikov & Vinden 2000). Impregnation of Torgvin with isocyanate resin followed by compression to the original dimensions and curing restores the original mechanical properties. A considerable increase in MOE and surface hardness has been achieved and 100% restoration in MOR has been observed as mentioned in chapters 1 and 2 of this thesis. The isocyanate resin, however, has some disadvantages (as mentioned in chapter 1), but the extent of restoration of the density and mechanical properties of the original wood following treatment of Torgvin with resins other than isocyanate is not known. Nor is the effect of wood species and resin levels on the extent of the restoration of these properties known. The purpose of this phase of the study was therefore to evaluate the density and mechanical properties of the FFA and MF Vintorg produced in the previous phase of the study.

The study focused on nominal density and three mechanical properties of Vintorg: MOE, MOR and surface hardness. The MOE quantifies a material's resistance to deformation under load). MOE corresponds to the slope of linear part of the stress-strain relationship from zero to the proportional limit (Figure 4-1). MOR measures the ultimate bending strength of a material (Figure 4-1, point B). It thus describes the load required to cause a wood beam to fail and can be thought of as the ultimate resistance that can be expected from a wood beam or member exposed to bending type stress (Winandy and Rowell, 1984). Surface hardness is the force required to indent wood with a steel ball or the hemispherical end of a steel rod of 11.28 mm (Mack, 1979).



Key: A, proportional limit; B, ultimate strength; σ_B MOR and $\Delta\sigma/\Delta\epsilon$ (from origin to A), MOE.

Fig 4-1. Example of the relationship between a typical stress-strain diagram and some mechanical properties (Winandy and Rowell, 1984).

The objectives of this phase of the of the study were therefore:

1. To investigate the effect of resin type and duration of soaking on density and some key mechanical properties of Vintorg from *E. regnans* and *P. radiata*.

2. To compare the mechanical properties of FFA and MF Vintorg with those of Torgvin, natural wood and isocyanate Vintorg.

3. To establish the correlation between the density of Torgvin, density of Vintorg and resin uptake with the mechanical properties of Vintorg from each species.

4. To model the effect of resin uptake and density of Vintorg on its mechanical properties and determine the most suitable model(s) for the estimation of the mechanical properties.

4.2 Materials and methods

Small clear specimens of Vintorg were used to determine the MOE, MOR and surface hardness. The control samples used for the comparisons were obtained as outlined in chapter 3. The isocyanate Vintorg was produced as described in Appendix 3. The specimen sizes and test procedures used were based on methods used in Australia, described by Mack (1979) except that a span length of 300mm instead of 280mm was used for bending strength due to some limitations on the available jig. The tests were carried out on a Hounsfield 10 K strength-testing machine with a maximum bearable load cell force of 10 KN (Figure A-2, Appendix 2). The strength-testing machine was a grade A machine as per NATA certification. All tests were continued until it was clear that a maximum load had been reached. Prior to testing, the mass and dimensions of each specimen were recorded for the computation of density and the various strength properties. After testing, the moisture content of each specimen was determined by the oven drying method. The density and moisture content were determined as shown in Appendix 1.

4.2.1. Specimen selection and testing

Static bending (3) point loading.

Two small clear specimen measuring 20 x 20 x 340mm were obtained from the 43 x 43 x 410mm Vintorg samples and used in the bending tests. The loading rate was 1mm s^{-1}.

Computation of the mechanical properties

Strength and other properties were calculated from test data as follows:

Modulus of rupture = $3\ PL/2bd^2$

Modulus of elasticity = $P`L^3/4\Delta bd^3$ or $EL^3/4bd^3$

Where: b = width of specimen

D = thickness of specimen

L = loading span and span deflectometer

P` = LOAD AT LIMIT OF PROPORTIONALITY

P = maximum load

Surface hardness

The determination of the surface hardness of Vintorg was done on the 20 x 20 x 340 mm specimen after the bending tests on both radial and tangential faces. Two readings for each face were obtained. A rate of loading of 6.5mm min^{-1} as per British Standards (BS 373) was used (Lavers, 1969).

Computation of surface hardness

The mean for the radial and tangential surface hardness values was computed to represent the overall surface hardness of the sample.

4.3 Results

4.3.1. Effect of type and amount of resin in Vintorg on its mechanical properties.

The means of the mechanical properties of Vintorg for the four different soaking periods in either resin for each species are illustrated in Figures 4-2 to 4-4. The means, standard deviations and coefficient of variations of the mechanical properties and density of Vintorg are summarised in Appendix 4. Results of analysis of variance (ANOVA) for the effect of duration of soaking in either resin on mechanical properties for each species and for the effect of resin type on the mechanical properties of each species are also shown in Tables 4-1.

A one way analysis of variance for the effect of duration of soaking on the mechanical properties of Vintorg from each species revealed that there was no significant effect of duration of soaking of the Torgvin from each species with either resin on any of the mechanical properties of the Vintorg produced, (Table 4-1) except for the surface hardness of *E. regnans* treated with FFA resin.

The MOE of FFA and MF Vintorg samples from *P. radiata* tended to increase gradually with duration of soaking in either resin while the MOE of the Vintorg samples from *E. regnans* had a tendency to increase to a maximum value after 5 minutes of soaking in FFA resin and after 20 minutes of soaking in MF resin and then gradually decreased with increase in duration of soaking in either resin (Figure 4-2). MOR of Vintorg tended to decrease with duration of soaking of *E. regnans* in FFA resin but increased with duration of soaking in the same resin in the case of *P. radiata* (Figure 4-3). A similar trend was observed for *P. radiata* samples treated with MF resin for 20, 60 and 90 minutes. There was no clear trend in MOR of Vintorg

of *E. regnans* samples with duration of soaking in MF resin. There was a general tendency for surface hardness of Vintorg to increase with duration of soaking of Torgvin in either resin for each species (Figure 4-4).

Table 4-1. Analysis of Variance for duration of soaking and resin type on the mechanical properties of Vintorg.

Model	Variable	*P. radiata*		*E. regnans*	
		Degree of freedom	P-value	Degree of freedom	P-value
MOE~duration-FFA	duration	$F_{3,33}$	0.983 n.s	$F_{3,39}$	0.325 n.s
MOR~duration-FFA	duration	$F_{3,33}$	0.704 n.s	$F_{3,39}$	0.721 n.s
Surface hardness~duration-FFA	duration	$F_{3,33}$	0.990 n.s	$F_{3,39}$	0.006 s
MOE~duration$_{MF}$	duration	$F_{3,37}$	0.461 n.s	$F_{3,39}$	0.662 n.s
MOR~duration$_{MF}$	duration	$F_{3,37}$	0.290 n.s	$F_{3,39}$	0.196 n.s
Surface hardness~duration-MF	duration	$F_{3,37}$	0.214 n.s	$F_{3,39}$	0.071 n.s
MOE~duration*resin type	duration	$F_{1,34}$	0.968 n.s	$F_{1,37}$	0.059 n.s
	resin type	$F_{1,34}$	0.067 n.s	$F_{1,37}$	0.310 n.s
	interaction	$F_{1,34}$	0.630 n.s	$F_{1,37}$	0.297 n.s
MOR~duration*resin type	duration	$F_{1,34}$	0.808 n.s	$F_{1,37}$	0.043 s
	resin type	$F_{1,34}$	0.059 n.s	$F_{1,37}$	0.284 n.s
	interaction	$F_{1,34}$	0.234 n.s	$F_{1,37}$	0.494 n.s
Surface hardness~duration*resin type	duration	$F_{1,34}$	0.716 n.s	$F_{1,37}$	0.031 s
	resin type	$F_{1,34}$	0.874 n.s	$F_{1,37}$	0.000 s
	interaction	$F_{1,34}$	0.909 n.s	$F_{1,37}$	0.646 n.s
MOE~duration + resin type	duration	$F_{1,36}$	0.989 n.s	$F_{1,37}$	0.009 s
	resin type	$F_{1,36}$	0.048 s	$F_{1,37}$	0.360 n.s
MOR~duration + resin type	duration	$F_{1,36}$	0.595 n.s	$F_{1,37}$	0.012 s
	resin type	$F_{1,36}$	0.063 n.s	$F_{1,37}$	0.191 n.s
Surface hardness~duration + resin type	Duration	$F_{1,36}$	0.641 n.s	$F_{1,37}$	0.013 s
	resin type	$F_{1,36}$	0.268 n.s	$F_{1,37}$	0.000 s

Note-s indicates significance at 0.05 level; n.s –not significant

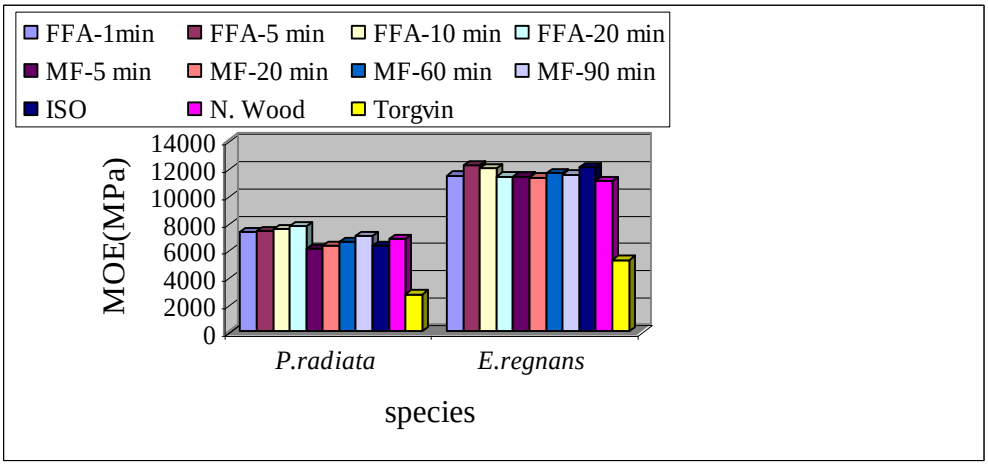


Fig. 4-2. Comparison of MOE (MPa) of Vintorg with that of the controls.

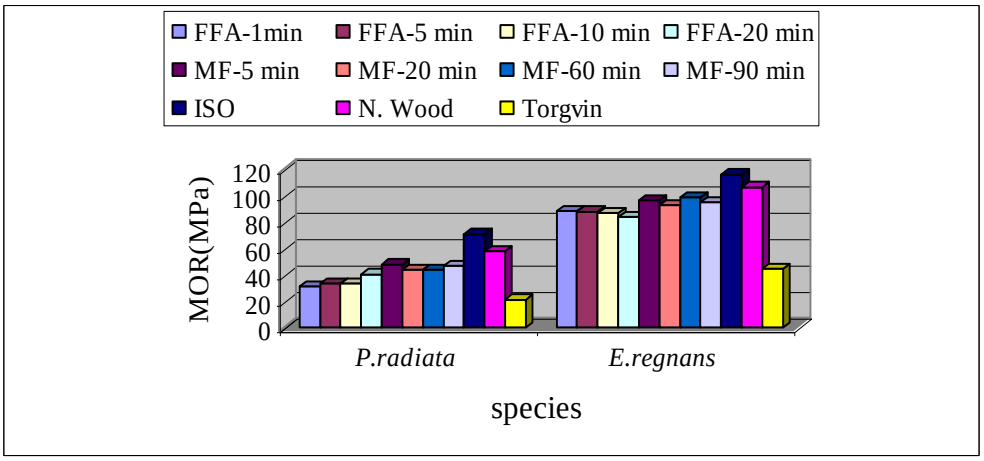


Fig. 4-3. Comparison of MOR (MPa) of Vintorg with those of the controls.

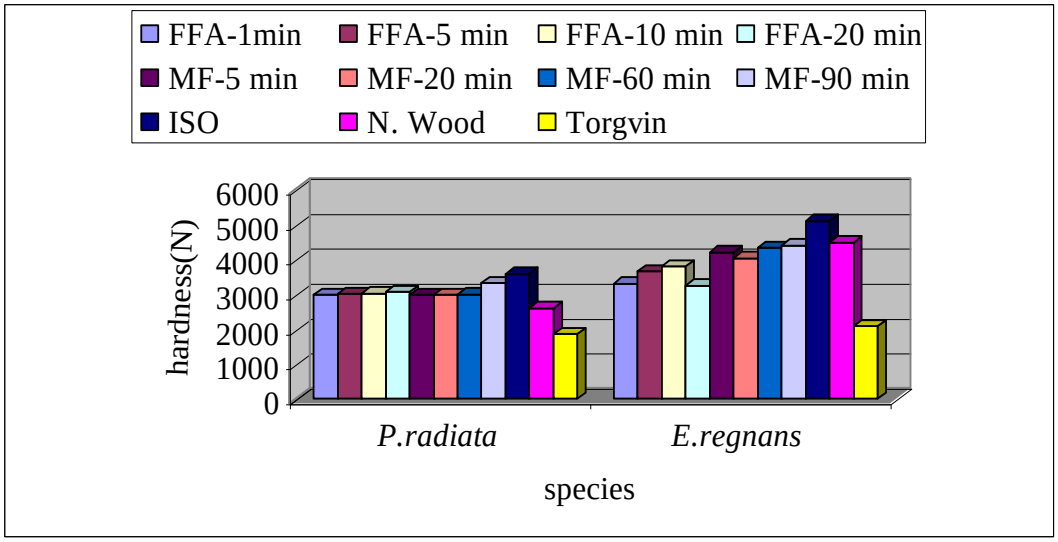


Fig. 4-4. Comparison of surface hardness of Vintorg with those of the controls.

An analysis of variance for the effect of duration of soaking (5 and 20 minutes) and resin type on the mechanical properties of Vintorg (Table 4-1), revealed that there was a significant effect of duration of soaking on the MOE ($P<0.05$) for *P. radiata* Vintorg and all the three mechanical properties in the case of *E. regnans* Vintorg. Resin type had a significant effect ($P<0.001$) on the surface hardness *of E. regnans* only. This could have been due to the significant effect ($P<0.05$) of resin type on the density of *E. regnans* (Table 4-10). There was also no evidence of any interactions of duration of soaking and resin type in their effect on the mechanical properties of either species (Table 4-1).

4.3.2. Comparison with the controls

The results of the statistical comparisons of the mechanical properties of Vintorg and the controls are summarized in Tables 4-2 and 4-3. The comparisons of the means of the mechanical properties of Vintorg and those of the controls are illustrated in Figures 4-2 to 4-4. The reduction in the mechanical properties of natural wood due to microwave modification is as shown in Table 4-4. The ranges in the mechanical properties of Vintorg and those of the controls are as indicated in Table 4-5. The percentage variations in the mechanical properties of Vintorg as compared to natural wood for each species are as shown in Table 4-6.

Comparison of Vintorg with the Torgvin controls

The MOE, MOR and surface hardness values for all the FFA and MF Vintorg samples produced were significantly ($P<0.05$) higher than those for Torgvin control samples as illustrated in Table 4-2 and Figures 4-2 to 4-4. The ranges in the MOE for the Torgvin samples were 1163 to 3583 MPa for *P. radiata* and 2568 to 12385 MPa for *E. regnans* (Table 4-5).

Table 4-2. Comparison of the mechanical properties of Torgvin control samples with Vintorg and natural wood.

Species	Mechanical property	Statistical significance of difference		
		FFA Vintorg	MF Vintorg	Natural wood
P. radiata	MOE	s	s	s
	MOR	s	s	s
	Hardness	s	s	s
E. regnans	MOE	s	s	s
	MOR	s	s	s
	Hardness	s	s	s

Note: s- indicates significance at 0.001 level.

Table 4-3: Comparison of the mechanical properties of MF Vintorg with those natural wood controls.

Species	Mechanical property	Statistical significance of difference in the mechanical properties							
		FFAVintorg and natural wood				MF Vintorg and natural wood			
		1 min	5 min	10 min	20 min	5 min	20 min	60 min	90 min
P. radiata	MOE (MPa)	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s
	MOR (MPa)	s	s	s	s	s	s	s	s
	Hardness (N)	n.s	s	s	s	s	s	s	s
E. regnans	MOE (MPa)	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s
	MOR (MPa)	s	s	s	s	s	s	s	s
	Hardness (N)	s	s	s	s	s	s	n.s	n.s

Note: s –indicates significant differences at 0.05 level and n.s- non-significant differences at the same level.

The ranges in MOR of Torgvin were 8.1 to 27.0 MPa for *P. radiata* and 33.1 to 87.6 MPa for *E. regnans*. The surface hardness for Torgvin ranged from 1688.5 and 2073.3 N for *P. radiata* and 1265 to 4587 N for *E. regnans.*

Comparison of Vintorg with the natural wood controls.

Modulus of Elasticity (MOE)

Treatment of natural wood by microwave energy resulted in a reduction in the MOE in the range of 65-73.7 % for *P. radiata* and 11.7 to 72.4 % for *E. regnans* (Table 4-4). There was no evidence of any significant difference in the MOE of Vintorg and those of the natural wood controls (Table 4-6). The range in the MOE of MF Vintorg samples was 3775 to 11474 MPa for *P. radiata* and 8977 to 14544 MPa for *E. regnans* (Table 4-5). In the case of FFA Vintorg, the range was 4640 to 11623 MPa for *P. radiata* and 6769 to 15965 MPa for *E. regnans.* The ranges for the natural wood controls were 4428 to 10531 MPa for *P. radiata* and 9305 to 14018 MPa for *E. regnans* (Table 4-5).

Table 4-4. Range in Percentage reduction in mechanical properties of wood due to microwave modification.

Species	Reduction in Mechanical property (%)		
	MOE	MOR	Surface Hardness
P. radiata	66-73.7	71-74	9.8-59.3
E. regnans	11.7-72.4	28.2-65.3	3.8-224

Treatment of Torgvin with MF resin resulted in a restoration of MOE to 41.4 % of the original one up to an increase of 159 % for *P. radiata* and 64.0 % up to an increase of 56.3 % in *E. regnans* (Table 4-6). *P. radiata* samples treated for 90 minutes and 60 minutes in MF resin had the highest and lowest ranges in percentage increase in MOR respectively. *E. regnans* samples treated for 5 minutes and 20 minutes in the same resin had the highest and lowest ranges in percentage increase in MOR respectively. FFA treatment resulted in a restoration of MOE of 44.1 % of the original one up to an increase of 162.5 % for *P. radiata* and a restoration of the initial MOE of 48.3 % to an increase of 71.6 % for *E. regnans. P. radiata* samples treated for 20 minutes and 10 minutes in FFA resin had the highest and lowest ranges in percentage increase in MOE respectively. *E. regnans* samples treated for 5 minutes and 1 minute in the same resin had the highest and lowest ranges in percentage increase in MOE respectively.

Modulus of rupture (MOR)

Treatment of natural wood by microwave energy resulted in a reduction in the MOR in the range of 71-74 % for *P. radiata* and 28.2 to 65.3 % for *E. regnans* (Table 4-4). MOR values for all Vintorg samples were significantly lower than those for the natural wood controls (Table 4-3). The range in MOR of MF Vintorg was 26.9 to 84.1 MPa for *P. radiata* and 63.2 to 111.9 MPa for *E. regnans* (Table 4-5). In the case of FFA Vintorg the range was 12.5 to 63.1 MPa for *P. radiata* and 49.5 to 123.2 MPa for *E. regnans.* The range for the natural wood controls was 31.2 to 92.7 MPa for *P. radiata* and 95.4 to 121.8 MPa for *E. regnans*. After treatment of Torgvin with MF resin, the original MOR was restored by 29 % up to an increase of 169.6 % for *P. radiata* and a restoration of 51.8 % up to a slight increase of 17.4 % for *E. regnans* (Table 4-6). *P. radiata* samples treated for 5 minutes and 60 minutes in MF resin had the highest and lowest ranges in percentage increase in MOR respectively.

Table 4-5. The range for mechanical properties and density of Vintorg as compared to the controls.

Spp	Property	Range									
		MF Vintorg				FFA Vintorg			Controls		
		5 min	20 min	60 min	90 min	1 min	5 min	10 min	20 min	N	T
P.r	MOE (MPa)	3775-10531	4149-9378	4214-7456	4360-11474	6034-11397	4766-11623	4802-9516	4640-10609	4428-10531	1163-3583
	MOR (MPa)	29.9-84.1	26.9-68.9	31.1-54.2	33.6-83.2	24.0-58.8	15.6-58.9	12.5-54.7	17.5-63.1	31.2-92.7-	8.1-27.0
	S.H (N)	1985-3589	2681-3267	2571-3695	2683-3987	2638-4065	1808-3915	2457-3867	2405-3547	1855-3302	1689-2073
	Density (gcm-3)	0.56-0.60	0.51-0.69	0.50-0.68	0.54-0.67	0.49-0.66	0.52-0.60	0.32-0.70	0.54-0.67	0.42-0.64	0.40-0.55
E.r	MOE (MPa)	9281-14544	9306-12987	9873-13794	8977-12954	9232-13947	6769-15965	8042-14252	8785-14593	9305-14018	2568-12385
	MOR (MPa)	81-110	63.2-98.8	81-112	71-103	58.2-111	59.5-108.5	50.3-118.7	49.5-123	95.4-122	33.1-87.6
	S.H. (N)	3865-4655	3762-4159	3813-4968	3874-5262	1750-4800	2836-4071	2220-3930	2508-3772	4098-4759	1265-4587
	Density (gcm-3)	0.68-0.81	0.66-0.79	0.69-0.78	0.67-0.77	0.70-0.79	0.70-0.81	0.65-0.90	0.72-0.88	0.63-0.70	0.53-0.69-

Note: *P.r* = *P. radiata*, *E.r* = *E. regnans*, N = natural wood, T = Torgvin and S.H. = surface hardness.

E. regnans samples treated for 20 minutes and 5 minutes in MF resin had the highest and lowest ranges in percentage increase in MOR respectively.

With FFA resin treatment, the restoration relative to the original MOR was 13.5 up to an increase of 102.2 % for *P. radiata* and for *E. regnans* a restoration of 48.3 % to 28.9 % increase in MOR. *P. radiata* samples treated for 20 minutes and 10 minutes in FFA resin had the highest and lowest ranges in percentage increase in MOR respectively. *E. regnans* samples treated for 20 minutes and 5 minutes in the same resin had the highest and lowest ranges in percentage increase in MOR respectively.

Surface hardness

The range in surface hardness of MF Vintorg was 1985 to 3987 N and that for FFA Vintorg was 1808 to 4065 N for *P. radiata* (Table 4-5). The range for the natural wood controls from

Table 4-6. The range in percentage increase in the mechanical properties of FFA and MF Vintorg as compared to the natural wood controls.

Species	Property	Range in increase in mechanical properties (%)							
		FFA Vintorg				MF Vintorg			
		1 min	5 min	10 min	20 min	5 min	20 min	60 min	90 min
P. r	MOE (MPa)	-42.7-157.4	-54.7-162.5	-54.4-114.9	-55.9-139.6	-64.2-137.8	-60.6-111.8	-60.6-68.4	-58.6-159.1
	MOR (MPa)	-74.1-88.5	-83.2-88.8	-86.5-75.3	-81.1-102.2	-67.7-169.6	-71.0-120.8	-66.5-73.7	-63.8-166.7
	SH (N)	-20.1-119.1	-45.2-111.1	-25.2-108.5	-27.2-91.2	-39.9-8.7	44.5-77.2	-22.1-99.2	-18.7-114.9
E. r	MOE (MPa)	-34.1 49.9	-51.7-71.6	-42.6-53.2	-37.3-56.9	-33.8-56.3	-33.9-39.6	-48.2-29.6-	-36.0-39.2
	MOR (MPa)	-52.3-16.4	-51.2-13.7	-58.8-24.4	-59.4-28.9	-33.6-15.3	-48.2-3.6	-33.6-17.4	-41.8-8.0
	SH (N)	-63.2-17.1	-40.4--0.7	-53.4--4.1	-47.3--8.0	-18.8-13.6	-20.9-1.5	-19.9-21.2	-18.6-28.4

Note: *P.r* = *P. radiata*, *E.r* = *E. regnans* and S.H. = surface hardness.

P. radiata was 1855 to 3302 N. For *E.regnans*, the range in surface hardness of MF Vintorg was 3762 to 5262 N and that for FFA Vintorg was 1750 to 4800 N (Table 4-5). The range for the natural wood controls from *E. regnans* was 4098 to 4759 N. This indicates that microwave modification of natural wood resulted in decrease its surface hardness in the range of 9.8 to 59.3 % for *P. radiata* and 3.8 to 224 % for *E. regnans* (Table 4-4). The surface hardness values of MF and FFA Vintorg from *P. radiata* were all significantly ($P<0.05$) higher than those of the natural wood controls except for that of the FFA Vintorg samples treated for 1 minute (Table 4-3 and Figure 4-4).

Treatment of Torgvin with MF resin resulted in a restoration of surface hardness of 60.1 % up to an increase of 114.9 % in the case of *P. radiata* (Table 4-6). The highest and lowest ranges for *P.radiata* being for samples treated for 90 minutes and 20 minutes in MF resin, respectively. FFA treatment caused a restoration of the initial surface hardness of 54.8 % up to an increase of 119.1 % for *P. radiata.* The highest and lowest ranges being for samples treated for 5 and 20 minutes in FFA resin, respectively.

The values for the surface hardness of MF and FFA Vintorg from *E. regnans* were all significantly lower ($P<0.05$) than those of the natural wood controls except for those of the MF Vintorg samples treated for 60 and 90 minutes whose values were not significantly different from those of the natural wood controls (Table 4-3).

Treatment of Torgvin with MF resin resulted in an increase in the surface hardness of *E. regnans* ranging from a restoration of 79.1 % up to an increase of 28.4 % relating to the initial value (Table 4-6). The highest and lowest ranges being for samples treated for 90 and 20 minutes, respectively, in MF resin. With FFA treatment, the effect on surface hardness ranged from a restoration of 36.8 % up to an increase of 17.1 %. The highest and lowest ranges being for samples treated for 1 and 20 minutes, respectively, in FFA resin.

Comparison of the mechanical properties of FFA and MF Vintorg with isocyanate (ISO) Vintorg.

The comparisons of means of the mechanical properties of FFA, MF and ISO Vintorgs are as shown in Figures 4-2 to 4-4. The statistical comparisons of the same properties are as shown in Table 4-7. The mean MOE values of ISO Vintorg were not significantly different from those of FFA and MF Vintorgs for each species, except for *P. radiata* samples soaked in FFA resin for 20 minutes. The mean MOR values for ISO Vintorg were significantly ($P<0.05$) higher than those of FFA and MF Vintorg, for each species.

In the case of surface hardness, ISO Vintorg had higher mean values than all FFA and MF Vintorg from *E. regnans* and *P. radiata* samples (Figure 4-4). However, significant differences in surface hardness were only found between ISO Vintorg and all MF Vintorg from *E. regnans* and Vintorg produced by soaking *P. radiata* in FFA resin for 20 minutes (Table 4-7).

Table 4-7. Statistical significance of difference in the mechanical properties of FFA and MF Vintorg as compared to ISO Vintorg.[5]

Resin type	Duration of soaking (min)	Statistical significance of difference for each wood property							
		P. radiata				*E. regnans*			
		MOE (MPa)	MOR (MPa)	S H (N)	Density (gcm^{-3})	MOE (MPa)	MOR (MPa)	S H (N)	Density (gcm^{-3})
FFA	1	n.s	s	n.s	n.s	n.s	s	s	s
	5	n.s	s	n.s	n.s	n.s	s	s	n.s
	10	n.s	s	n.s	n.s	n.s	s	s	s
	20	s	s	s	s	n.s	s	s	n.s
MF	5	n.s	s	n.s	n.s	n.s	s	s	n.s
	20	n.s	s	n.s	n.s	n.s	s	s	n.s
	60	n.s	s	n.s	n.s	n.s	s	s	n.s
	90	n.s	s	n.s	n.s	n.s	s	s	n.s

Note: SH= Surface hardness.

4.3.3. Effect of resin type and duration of soaking and on the density of Vintorg.

A one way analysis of variance for the effect of duration of soaking on density of Vintorg for each species treated with either resin (Table 4-8) revealed that duration of soaking did not have any significant effect on the density of Vintorg from each species treated with either resin. However, the effect of resin type on density of Vintorg was significant. Effect of resin type and duration of soaking on the density of Vintorg.

Table 4-8. Analysis of variance for the effect of duration of soaking and resin type on density of Vintorg.

Model	Variable	*P. radiata*		*E. regnans*	
		D.F.	P-value	D.F.	P-value
Density~duration$_{FFA}$	duration	$F_{3,37}$	0.426 n.s	$F_{3,39}$	0.377 n.s
Density~duration$_{MF}$	duration	$F_{3,36}$	0.580 n.s	$F_{3,40}$	0.830 n.s
Density~Duration * resin type	duration	$F_{1,36}$	0.176 n.s	$F_{1,37}$	0.103 n.s
	Resin type	$F_{1,36}$	0.275 n.s	$F_{1,37}$	0.038 s
	interaction	$F_{1,36}$	0.182 n.s	$F_{1,37}$	0.403 n.s
Density ~duration + resin type	duration	$F_{1,36}$	0.192 n.s	$F_{1,37}$	0.100 n.s
	Resin type	$F_{1,36}$	0.266 n.s	$F_{1,37}$	0.033 s

[5] **Note: s- indicates significant results at 0.05 level; n.s – non-significant results at the same level.**

Note: D.F. = degree of freedom, s-indicates significant results at 0.05 level and n.s – non significant results at the same level.

Comparison of density of Vintorg with those of the controls

The significance of the differences between the density of Vintorg and those of the controls is summarized in Table 4-9 and the means compared in Figure 4-5. The nominal density of Vintorg produced with either FFA or MF resin was significantly ($P< 0.05$) higher than that of Torgvin from the same species (Table 4-9). The density of Vintorg was also higher than that for natural wood from the same species, except for Vintorg from *P. radiata* samples soaked in FFA resin for 5 and 20 minutes, that had slightly lower values (Figure 4-5).

Treatment of Torgvin with MF resin resulted in a restoration of the original density to 79.7 % up to an increase of 64.3 % for *P. radiata* and a restoration of 94.3 % up to an increase of 28.6 % in the case of *E. regnans*. Treatment of Torgvin with FFA resin resulted in a restoration of the original density of 50.0 % up to an increase of 66.7 % for *P. radiata* and a restoration of the initial density of 92.6 % up to an increase of 42.9 % for *E. regnans*. The ranges in the percentage increases in the density of Vintorg relating to natural wood controls are indicated in Table 4-10.

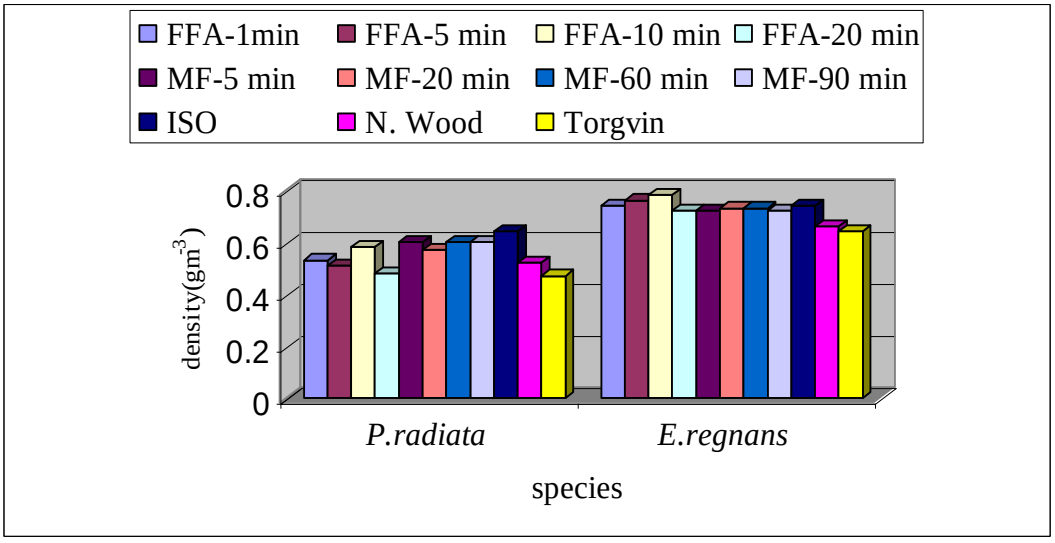


Fig. 4-5. Comparison of density of Vintorg relating to the controls.

Table 4-9: Statistical significance of the difference between the density of Vintorg and the controls.

Resin type	Duration of soaking (min)	Statistical significance of difference			
		P. radiata		*E. regnans*	
		Natural wood	Torgvin	Natural wood	Torgvin
FFA	1	n.s	s	s	s
FFA	5	n.s	s	s	s
FFA	10	n.s	s	s	s
FFA	20	s	s	s	s
MF	5	s	s	s	s
MF	20	n.s	s	s	s
MF	60	s	s	s	s
MF	90	s	s	s	s

Note: s-indicates significant differences at 0.05 level and n.s- non significant differences at the same level.

Table 4-10. The ranges in percentage increase in the density of FFA and MF Vintorg as related to natural wood controls.

Species	Range in increase in Density (%)							
	FFA Vintorg				MF Vintorg			
	1 min	5 min	10 min	20 min	5 min	20 min	60 min	90 min
P. radiata	-23.4-57.1	-18.8-42.9	-50.0-66.7	-15.6-59.5	-12.5-42.9	-20.3-64.3	-21.9-61.9	-15.6-59.5
E. regnans	0.0-25.4	0.0-28.6	-7.4-42.9	2.9-39.7	-2.9-28.6	-5.7-25.4	-1.4-23.8	-4.3-22.2

4.3.4. Pearson's correlation coefficients for some Vintorg variables.

Pearson's correlation coefficients of variation between some Vintorg variables are shown in Table 4-11. MOE of Vintorg from *P. radiata* had significant ($P<0.05$) and modest correlation with the final uptake of FFA resin (-0.43). No other significant correlation was observed between MOE of Vintorg and resin uptake. A modest and significant correlation ($P<0.05$, $r = 0.4$) between MOE of Vintorg and density of Torgvin was observed only in *P. radiata* samples treated with MF resin. However, there was a significant ($P<0.05$) but weak correlation between the MOE of Vintorg and density of Vintorg for each species treated with either resin except for *E. regnans* samples treated with FFA resin, which had a modest and significant ($P<0.001$) correlation ($r = 0.57$) between these two variables.

There was no evidence of any significant correlation between MOR and resin uptake for either species. MOR of MF Vintorg from *P. radiata* showed a significant ($P<0.001$) and

modest correlation (r = 0.57) with the density of Torgvin. No other correlation between MOR of Vintorg and Torgvin was observed. However, MOR of Vintorg had significant ($P<0.05$) correlation with the density of Vintorg in all cases. Weak correlation with the density of Vintorg was exhibited in all the cases except for the density of FFA Vintorg from *P. radiata*, which had a modest and negative correlation (r = -0.49). MOR and MOE of Vintorg had a significant ($P<0.001$) and strong correlation ($r>0.8$) in all cases.

The surface hardness of Vintorg had no correlation with resin uptake. Significant correlation between surface hardness of Vintorg and density of Torgvin was observed only in the Vintorg manufactured from *P. radiata* wood. The correlation of surface hardness of FFA resin treated samples with the density of Torgvin was weak (r = 0.36) while that for MF resin treated samples was modest (r = 0.54). Significant correlation between the surface hardness of Vintorg and density of Vintorg was observed only in the MF Vintorg from each species.

The correlation between surface hardness and density of MF Vintorg was modest in *P. radiata* (r = 0.63) and weak in *E. regnans* (r = 0.34). Significant correlation between surface hardness of Vintorg and MOE of Vintorg was observed only in MF Vintorg from *P. radiata* and FFA Vintorg from *E. regnans*, the former correlation being a modest one (r = 0.69) and the latter a weak one (r = 0.34). The surface hardness of Vintorg had a significant ($P<0.05$) correlation with MOR of Vintorg in all cases except for the FFA Vintorg samples from *P.radiata*. The correlation between surface hardness and MOR of MF Vintorg from *E. regnans* was weak (r = 0.34), while the correlations between surface hardness and MOR of FFA Vintorg from *E. regnans* and MF Vintorg from *P. radiata* were modest (r = 0.45 and 0.66, respectively).

Table 4-11. Pearson's correlation coefficients (r) for some Vintorg variables from *P. radiata* and *E. regnans.*

Pairs of variables	*P. radiata*				*E. regnans*			
	FFA resin		MF resin		FFA resin		MF resin	
	r	P-value	r	P-value	r	P-value	r	P-value
MOE of Vintorg vs. final resin uptake	-0.43	0.01*	-0.00	>0.9	-0.28	0.09	-0.02	>0.9
MOE of Vintorg vs. Density of Torgvin	-0.20	0.25	0.4	0.01*	-0.15	0.37	-0.18	0.28
MOE of Vintorg vs. Density of Vintorg	-0.39	0.03*	0.33	0.04*	0.57	0.00*	0.33	0.04*
MOR of Vintorg vs. final resin uptake	-0.28	0.15	-0.11	0.51	-0.28	0.13	0.10	0.56
MOR of Vintorg vs. Density of Torgvin	-0.34	0.08	0.54	0.00*	0.24	0.19	-0.16	0.32
MOR of Vintorg vs. Density of Vintorg	-0.49	0.01*	0.39	0.02*	0.38	0.00*	0.36	0.02*
MOR of Vintorg vs. MOE of Vintorg	0.81	0.00*	0.90	0.00*	0.83	0.00*	0.81	0.00*
Hardness of Vintorg vs. final resin uptake	-0.07	0.72	0.19	0.26	0.11	0.50	0.001	>0.9
Hardness of Vintorg vs. Density of Torgvin	0.36	0.04*	0.54	0.00*	-0.06*	0.73	0.19	0.25
Hardness of Vintorg vs. Density of Vintorg	0.30	0.09	0.63	0.00*	-0.01*	>0.9	0.34	0.04*
Hardness of Vintorg vs. MOE of Vintorg	-0.30	0.10	0.69	0.00*	0.33	0.04*	0.23	0.15
Hardness of Vintorg vs. MOR of Vintorg	-0.28	0.16	0.66	0.00*	0.45	0.01*	0.34	0.03*

* Indicates significant results at 0.05 level. P-values indicate how the r-values are different from 0.

4.3.5. Modeling of the relationships between mechanical properties of Vintorg and resin uptake.

The coefficients of determination and p-values of regression plots for mechanical properties of Vintorg and final resin uptake are reported in Table 4-12.

Each of the three mechanical properties of MF Vintorg generally tended to have a cubic relationship with the final resin uptake. However, significant regressions were observed only between MOE of Vintorg and final MF resin uptake for both species.

In the case of FFA Vintorg, each of the mechanical properties of *E. regnans* Vintorg and surface hardness of *P. radiata* Vintorg generally tended to have a cubic relationship with the final FFA resin uptake. None of these regressions were significant. However, MOE and MOR of FFA Vintorg from *P. radiata* each had a significant linear relationship with resin uptake.

4.3.6. Modeling of the relationships between mechanical properties and density of Vintorg.

The coefficients of determination and p-values of these regressions are as shown in Table 4-12. Significant relationships (P≤0.05) with density of Vintorg were observed only with MOE of FFA Vintorg and MOR of MF Vintorg for each species and surface hardness for MF Vintorg for *P. radiata*. MOE of FFA Vintorg and MF Vintorg from *E. regnans*, MOR of MF Vintorg from *E. regnans* and surface hardness of MF Vintorg from either species each had a significant cubic relationship with the density of Vintorg. The regression plots for these significant relationships are illustrated in Figures 4-6 to 4-18.

Table 4-12. Coefficient of determinations (C.D.) and p-values for equations for predicting mechanical properties of Vintorg based on regression analysis.

Response	Predictor	Model	*P. radiata*				*E. regnans*			
			FFA resin		MF resin		FFA resin		MF resin	
			C.D. (%)	P-value	C.D (%)	P-value	C.D. (%)	P-value	C.D. (%)	P-value
MOE	Final resin uptake	linear	15.7	0.01*	0.0	>0.9	5.2	0.09	0.0	>0.9
		cubic	11.8	0.09	2.5	0.28	5.3	0.18	3.2	0.25
MOR	Final resin uptake	linear	12.8	0.02*	0.0	0.51	4.6	0.13	0.0	0.56
		cubic	7.7	0.16	6.9	0.15	6.3	0.19	0.3	0.39
Hardness	Final resin uptake	linear	0.0	0.46	1.0	0.26	0.0	0.50	0.0	>0.9
		cubic	0.0	0.85	11.9	0.07	0.0	0.58	0.0	>0.9
MOE	Density of Vintorg	linear	11.4	0.03*	4.7	0.10	8.6	0.03*	24.3	0.00*
		cubic	9.8	0.11	0.0	0.42	34.3	0.00*	21.6	0.01*
MOR	Density of Vintorg	linear	8.6	0.05*	10.4	0.03*	0.4	0.28	16.8	0.01*
		cubic	2.1	0.32	6.5	0.16	9.2	0.13	13.8	0.04*
Hardness	Density of Vintorg	linear	0.0	0.48	16.8	0.01*	0.0	0.90	5.9	0.07
		cubic	2.1	0.72	15.9	0.04*	2.6	0.28	13.3	0.04*
MOR	MOE	linear	70.1	0.00*	79.5	0.00*	66.9	0.00	65.1	0.00*

Note: * indicates significant regressions at 0.05 level.

There was a significant linear regression for any of the mechanical properties of Vintorg and density of Vintorg for each species treated with either resin except for the MOR of FFA Vintorg from *E. regnans.* Surface hardness had a cubic regression with resin uptake. However, a significant regression was only observed between the surface hardness of MF Vintorg and resin uptake for *E. regnans*.

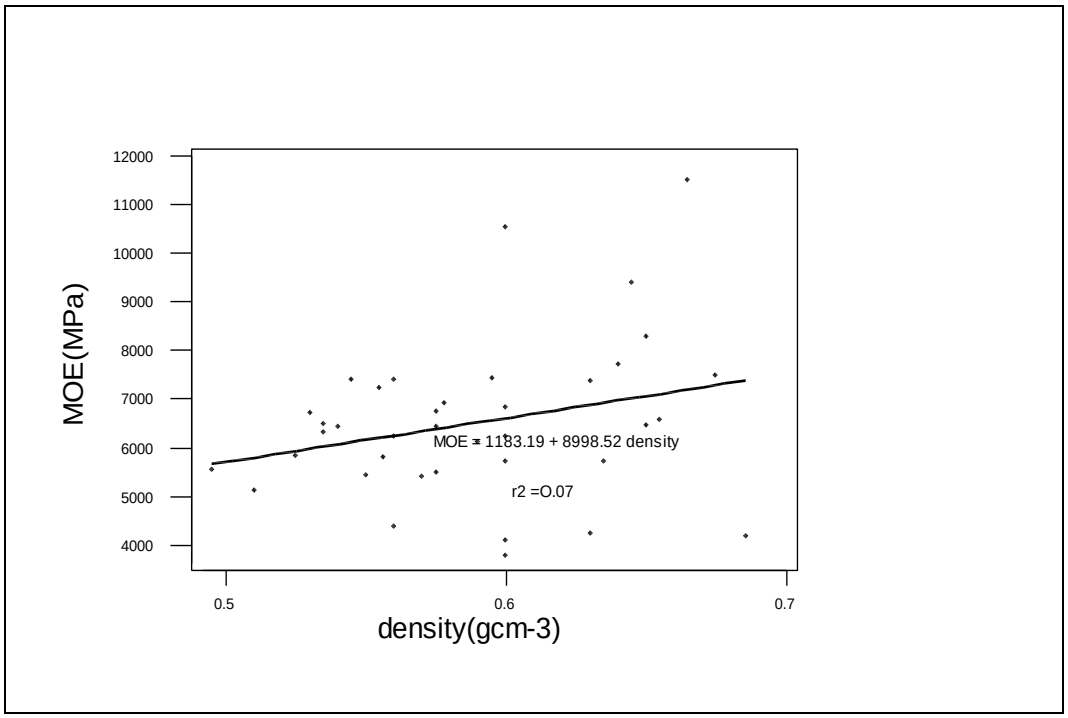


Fig 4-6. Regression plot for MOE and density of MF Vintorg for *P.radiata.*

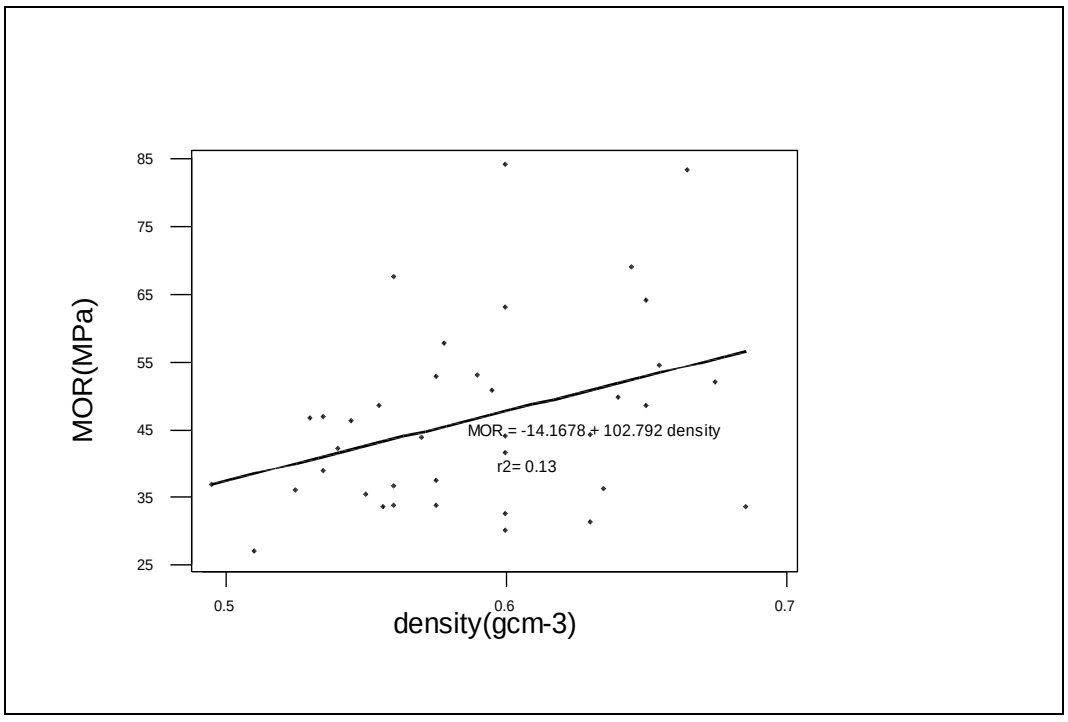


Fig 4-7. Regression plot for MOR and density of MF Vintorg for *P.radiata.*

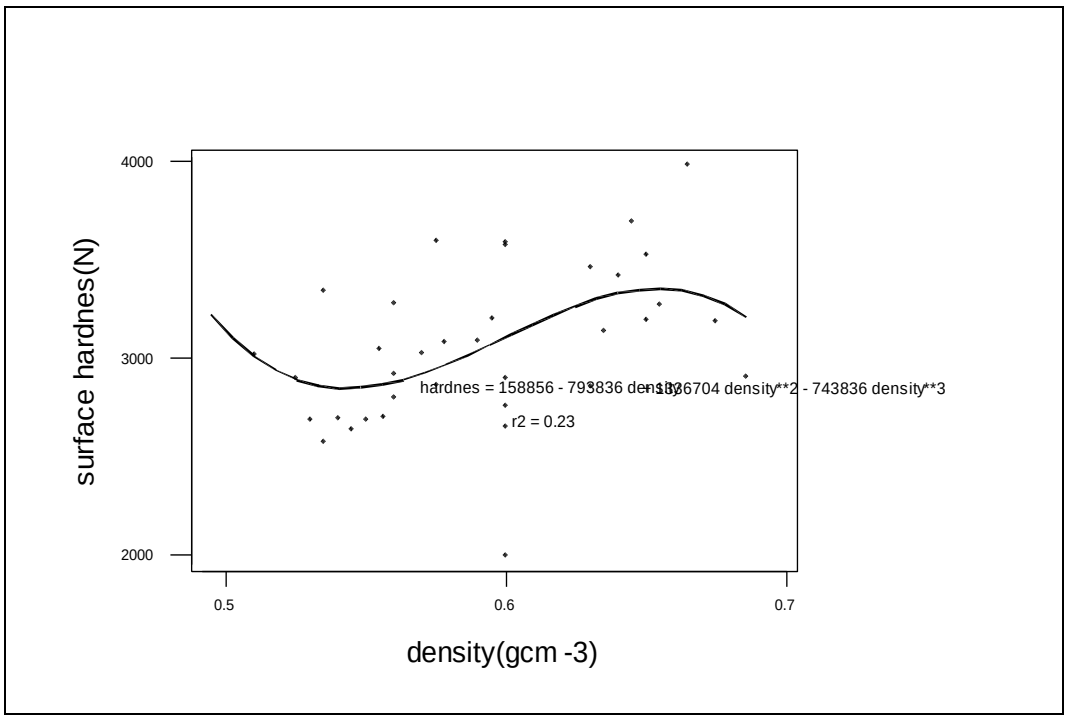


Fig. 4-8. Regression plot for surface hardness and density of MF Vintorg for *P.radiata.*

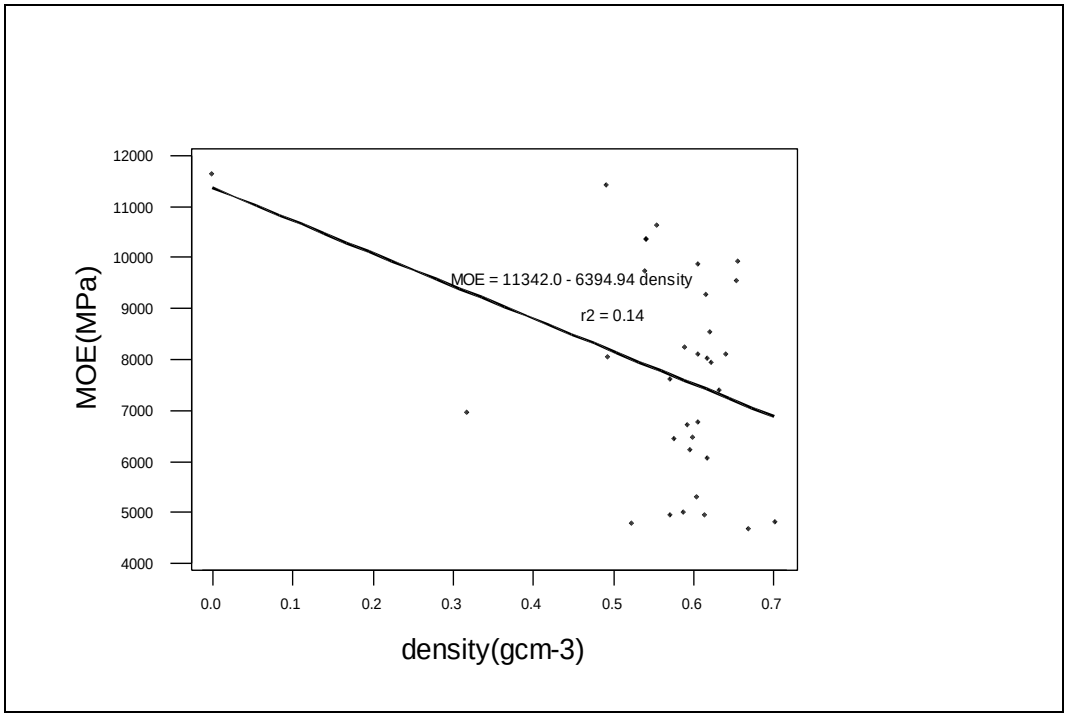


Fig. 4-9. Regression plot for MOE and density of FFA Vintorg for *P.radiata.*

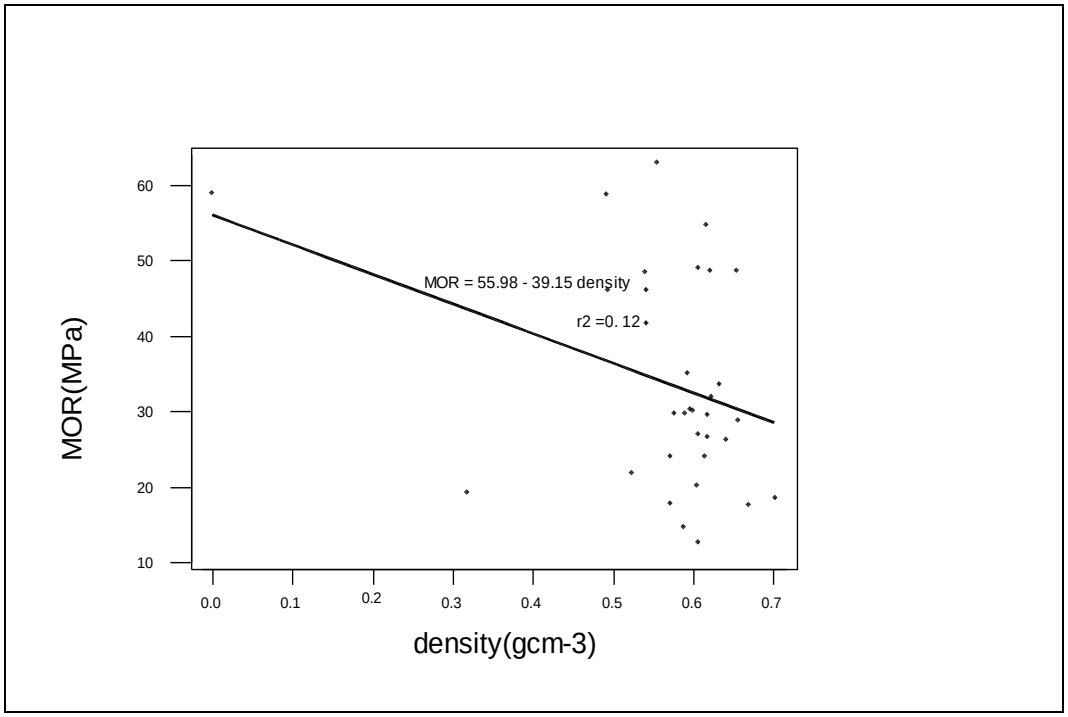


Fig. 4-10. Regression plot for MOR and density of FFA Vintorg for *P.radiata.*

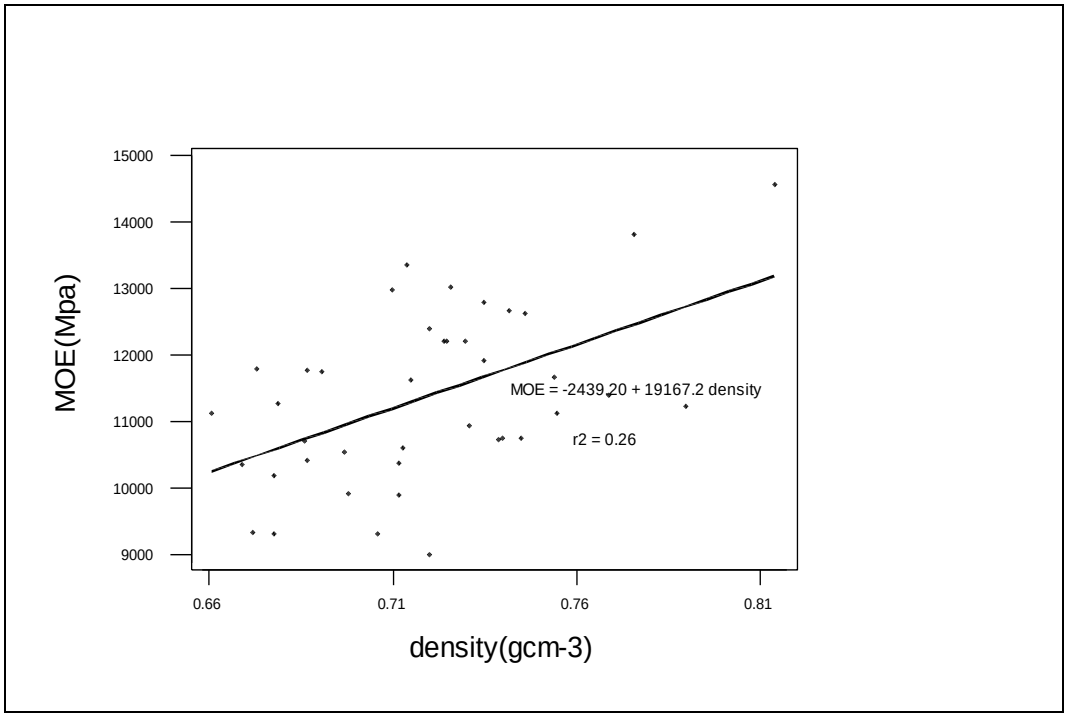


Fig. 4- 11. Regression plot for MOE and density of MF Vintorg for *E. regnans*.

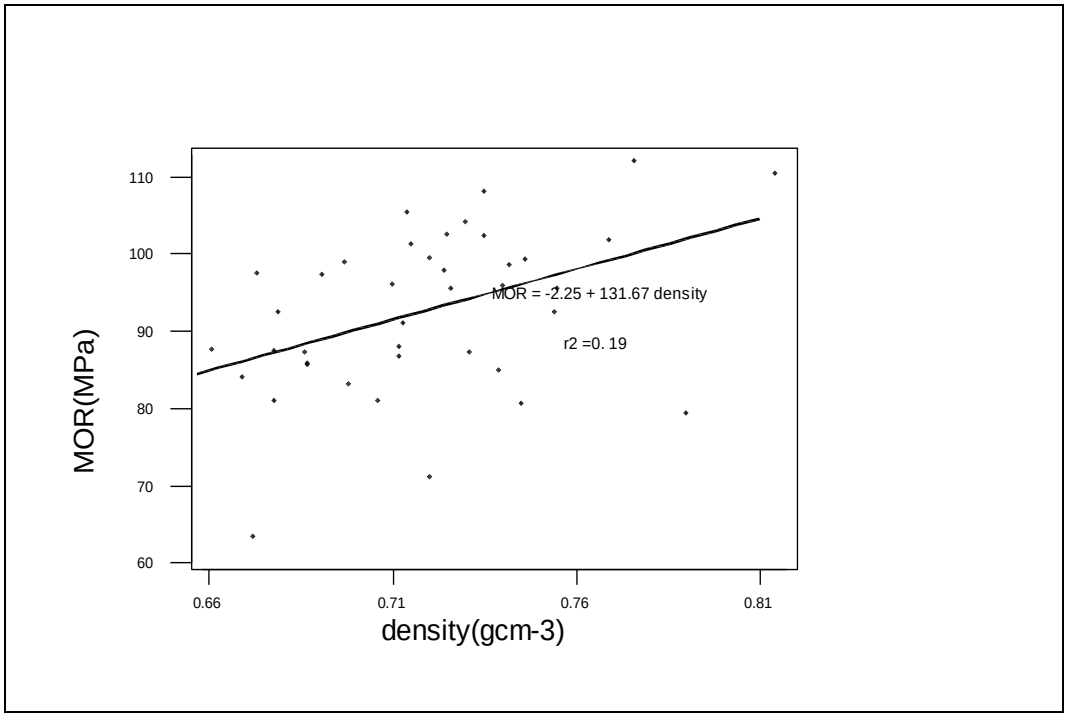


Fig. 4- 12. Regression plot for MOR and density of MF Vintorg for *E. regnans.*

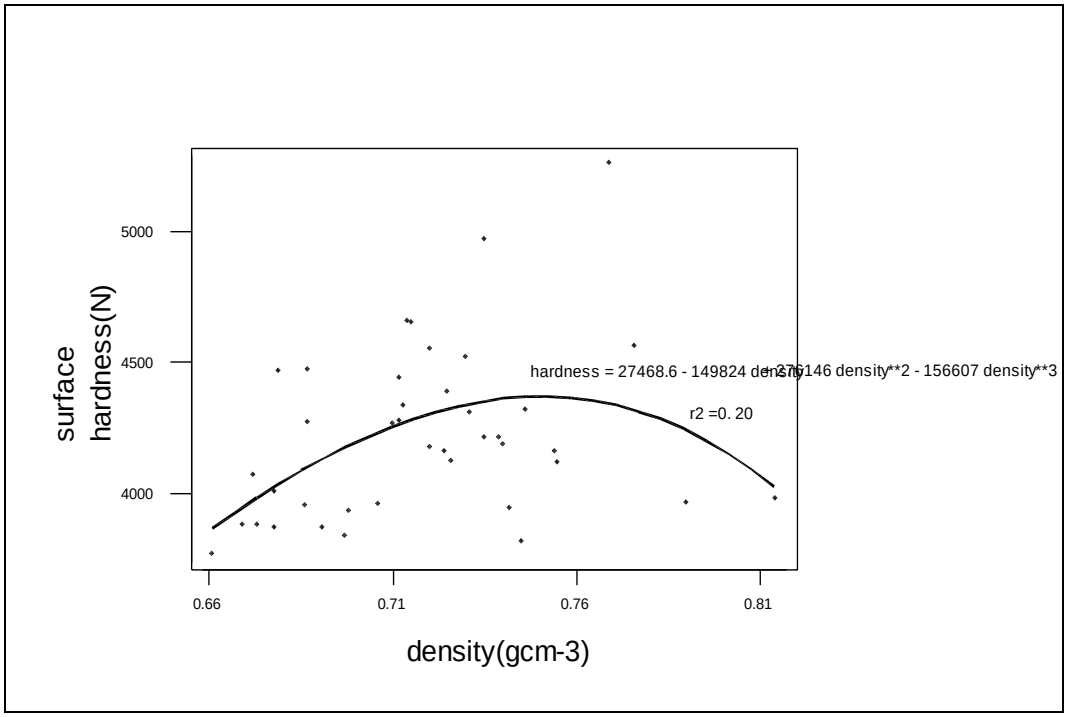


Fig. 4-13. Regression plot for surface hardness and density of MF Vintorg for *E. regnans.*

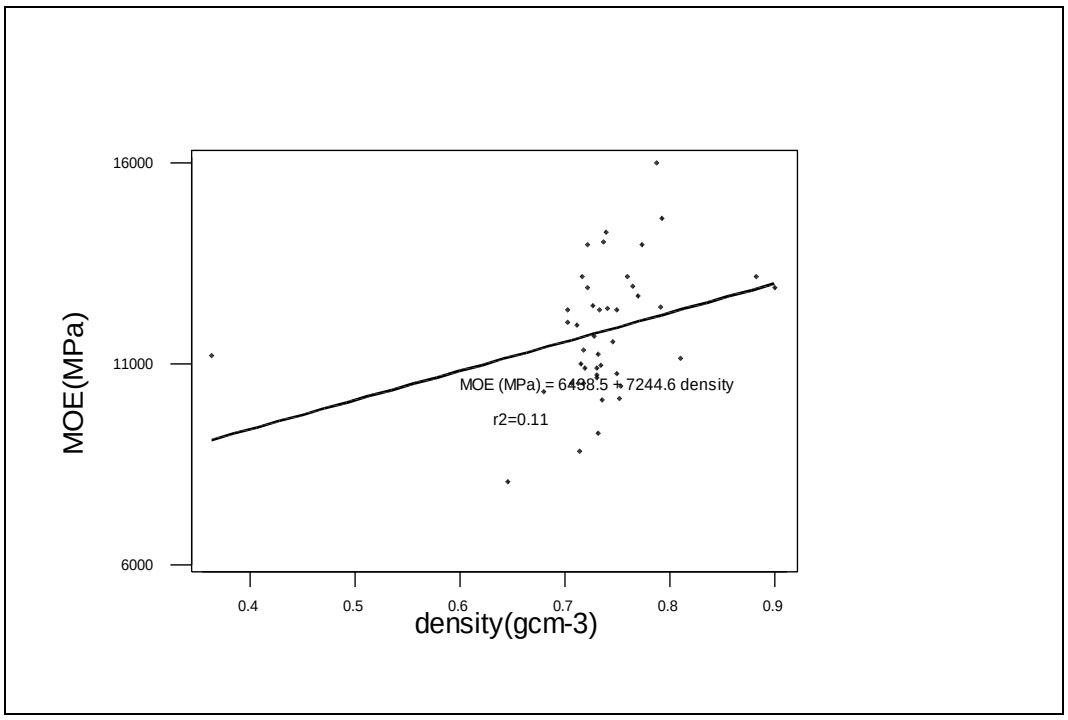


Fig. 4-14. Regression plot for MOE and density of FFA Vintorg for *E. regnans.*

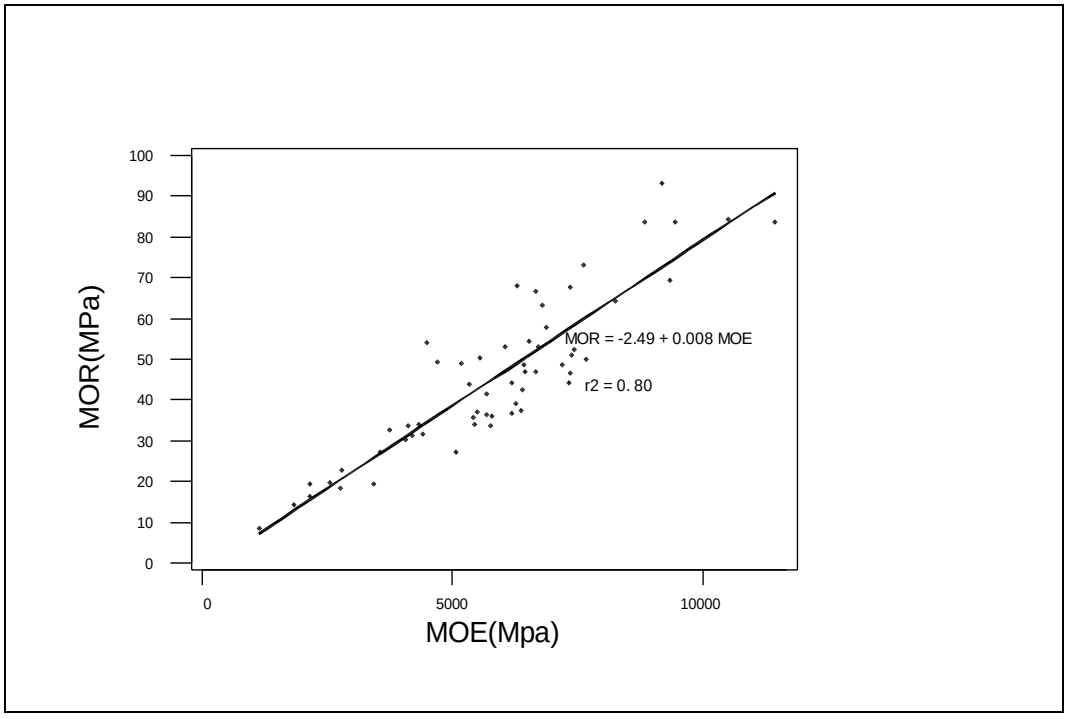


Fig. 4-15. Regression plot for MOR and MOE for MF Vintorg from *P. radiata.*

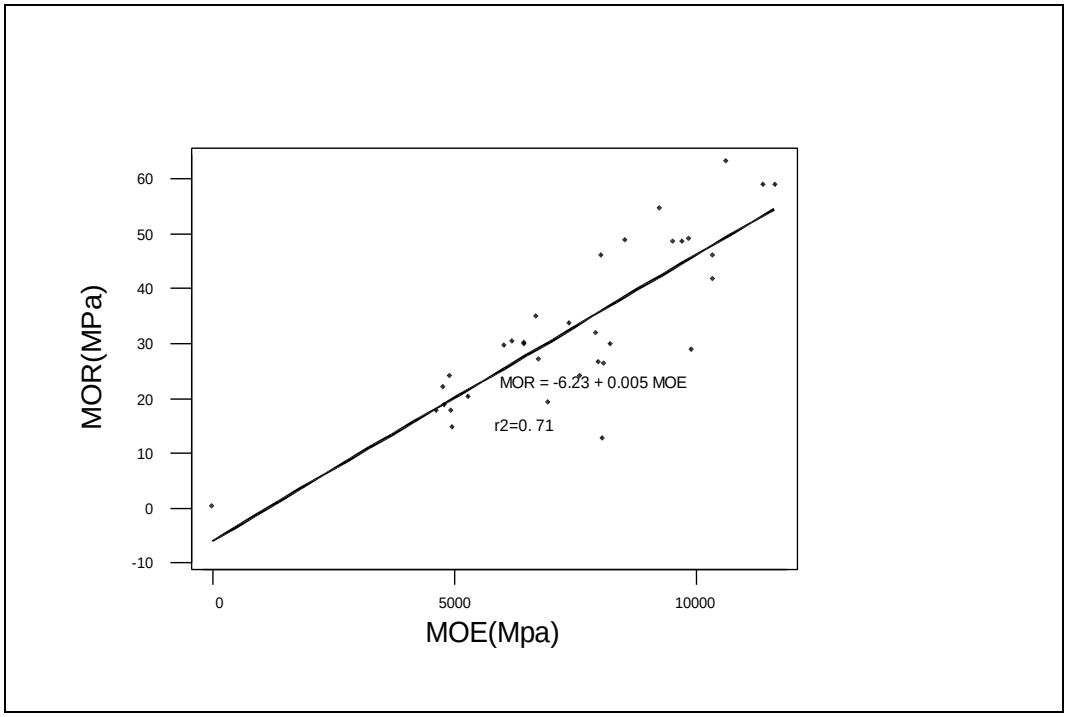


Fig. 4-16. Regression plot for MOR and MOE for FFA Vintorg from *P. radiata*.

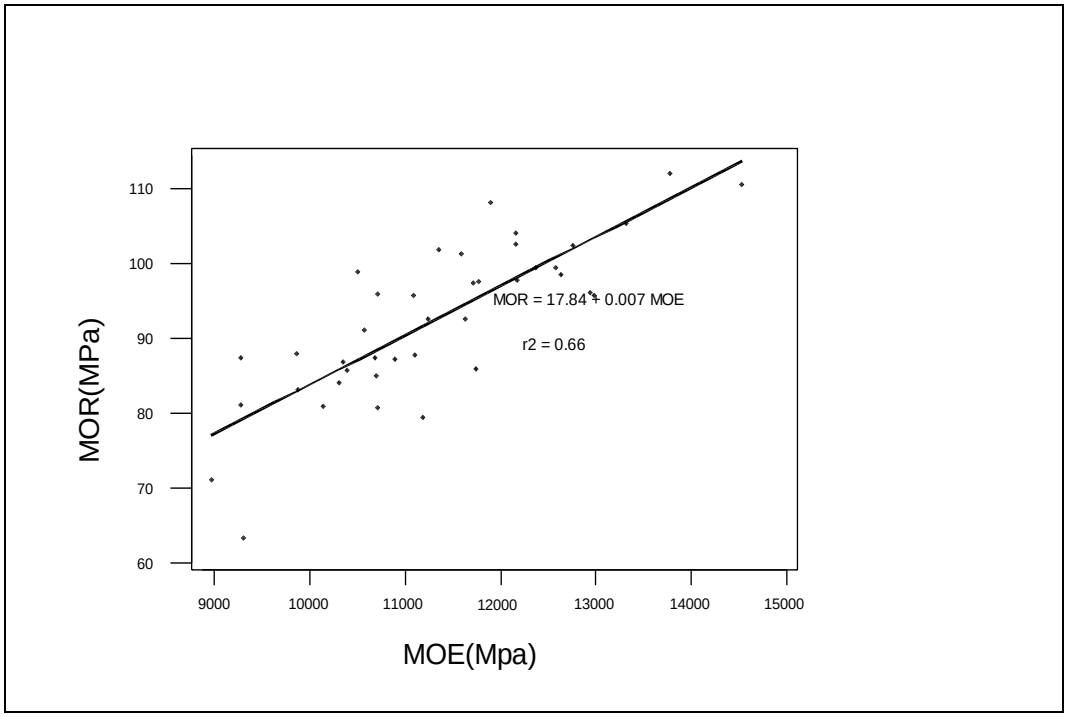


Fig.4-17. Regression plot for MOR and MOE for MF Vintorg from *E. regnans*.

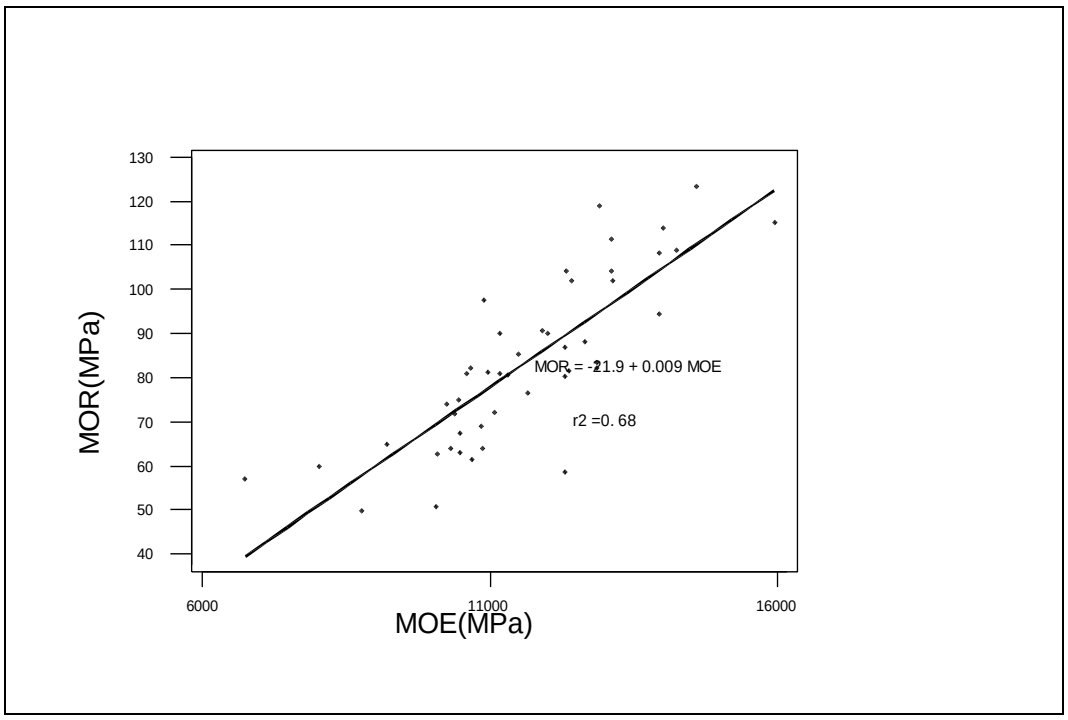


Fig. 4-18. Regression plot for MOR and MOE for FFA Vintorg from *E. regnans*.

4.4. Discussion

4.4.1. Effect of type and amount of resin in Vintorg on its mechanical properties

MOE

The results show that the MOE of FFA and MF Vintorg samples from *P. radiata* tend to increase gradually with duration of soaking in either resin while the MOE of the Vintorg samples from *E. regnans* have a tendency to increase to a maximum after 5 minutes of soaking in FFA resin and after 20 minutes of soaking in MF resin and then gradually decrease with increase in duration of soaking. The MOE values of FFA and MF Vintorg samples were also same or higher than that of natural wood.

The general tendency of MOE to increase with duration of soaking in either resin could be due to the plasticising effect of the resins, moisture and heat on the wood. However, the plasticising effect of the resins appears to be effective only up to a certain limit for *E. regnans*. The apparently quicker attainment of the highest MOE by FFAVintorg from *E. regnans* (after 5 minutes of soaking in FFA resin) than MF Vintorg from the same species (20 minutes of soaking in MF resin) is probably due to the lower viscosity of FFA resin. The lower viscosity of FFA resin could have resulted in Torgvin samples treated with this resin reaching the optimum amount of resin required to obtain a maximum plastic yield within a shorter period of time than the samples treated with MF resin.

The higher increase in the MOE values of MF and FFA Vintorg samples from *P. radiata* than those of the Vintorg samples from *E. regnans* produced with the same resin, as compared to the natural wood from each species, could be due to the fact that the two species were subjected to the same amount of pressure during the manufacture of Vintorg, though they are of different specific gravity. The pressure required to obtain a maximum plastic yield increases with an increase in specific gravity (Vick, 1999).

MOR

The general increase in MOR of Vintorg with duration of soaking of *P. radiata* Torgvin in FFA and MF resins could be due to the increase in the density of Vintorg with an increase in resin uptake. The apparently unclear trend in MOR of Vintorg in *E. regnans* samples could probably be due to the differences in density of wood in the Torgvin samples used in the study (Appendix A-19). This could explain the apparently higher MOR values for *E. regnans* samples soaked in MF resin for 60 minutes (0.73 gcm^{-3}) than those soaked for 5 (0.71 gcm^{-3}) and 20 minutes (0.7 gcm^{-3})**.** It is an established fact that MOR is positively correlated with wood density (Green *et al*., 1999; Bootle, 1983; Winandy and Rowell, 1984).

The significantly lower MOR values of FFA and MF Vintorg samples as compared to the natural wood controls could be due to four reasons. Firstly, the high reduction in the initial MOR due to microwave treatment. Microwave treatment of wood could have resulted in hydrolytic degradation of its cell wall. The percentage reduction in MOR of *P. radiata* samples (71 to 74 %, Table 4-4) due to microwave modification is higher but more uniform than that reported by Vinden and Torgovnikov (2000) of 6-68 %. The higher reduction in the MOR of *P. radiata* (71 to74 %) as a result of microwave treatment than *E. regnans* (28.2 to 65.3 %, Table 4-4) could explain the lower degree of restoration of the MOR in some of the *P. radiata* Vintorg samples (13.5 % for FFA Vintorg and 29.3 % for MF Vintorg, Table 4-6) than for *E.* regnans (48.3 % for FFA Vintorg and 51.8 % for MF Vintorg, Table 4-6). The higher degree of increase in the MOR (Table 4-6) of some of the *P. radiata* (102.2 % for FFA Vintorg and 169.6 for MF Vintorg) than *E. regnans* (76.6 % for FFA Vintorg and 17.4 % for MF Vintorg**)** could be due to the higher degree of increase in the density of *P.radiata* (up to 64.3 %) than *E. regnans* (up to 28.6 %) during the manufacture of MF Vintorg and up to 66.7 % and 42.9 % respectively in the case of FFA Vintorg (Table 4-10).

Secondly, the reduction in MOR could be due to the chemically modified wood (Vintorg) samples possibly having fewer fibres per centimeter than the unmodified wood (Rowell, 1996) as a result of the increase in the cell wall volume during the treatment. As samples of

equal cross-sections were used in the mechanical tests, it is likely that there were fewer fibres to test in the Vintorg samples as compared to the natural wood controls.

Thirdly, the lower MOR of Vintorg could be because of possible altered composition effects of the resin treatment on wood. Formaldehyde-treatment of wood, has been reported to reduce bending strength by up to 50% (Rowell, 1996). The reduction in formaldehyde-treated wood is due to embrittlement in the wood that may result from the short cross-linking unit (O-C-O) formed between formaldehyde and fibrils in the cell wall (Matsuda, 1996; Rowell 1984 and 1996). The reduction in the MOR of FFA Vintorg samples could possibly be due to an increased brittleness of wood due to the resin and a possibility of degradation of the carbohydrates by maleic acid (catalyst).

Finally, the pre-heating of Torgvin samples and hot pressing of the resin treated Torgvin samples at 120ºC for 1 hour and 130 ºC for 2 ½ hours, respectively, (Section 3.2.2) could have resulted in a further hydrolytic degradation of cell wall of the microwave modified wood.

Surface hardness of Vintorg

The results also show that surface hardness of Vintorg increased with duration of soaking in either resin for each species. The higher values of surface hardness of Vintorg as compared to the natural wood controls is consistent with what others have found on wood treated with various impregnants (Kollmann *et al*., 1975). The high variations in the surface hardness of Vintorg samples as compared to those of the natural wood could be due to varying effects of microwave treatment on the wood samples. This varied from 9.8 to 59.3 % for *P. radiata* and 3.8 to 224 % for *E. regnans* (Table 4-4).

The higher range in the effect of microwave treatment on the percentage decrease of surface hardness of *E. regnans* than that of *P. radiata* could explain the higher range in the percentage increase in the surface hardness of Vintorg samples manufactured from *E. regnans* using either resin. The lower percentage increase in surface hardness of FFA and MF Vintorg from *E. regnans* than the Vintorg from *P. radiata* produced with the same resins, as compared to the natural wood from each species could be due to the fact that the two species were subjected to the same amount of pressure during the manufacture of Vintorg, though they are of different specific gravity. The pressure required to obtain a maximum compression increases with an increase in specific gravity (Vick, 1999).

It is evident from the results that Torgvin samples from each species treated for 20 minutes with either resin result in Vintorg samples that are more uniform in surface hardness than those from the other treatments. This appears to indicate that 20 minutes of soaking of Torgvin from each species in either resin would be sufficient for an optimum quantity of either resin to penetrate the Torgvin samples and result in an increase in surface hardness of the Vintorg produced.

FFA and MF Vintorg from *E. regnans*

The generally lower MOR and surface hardness values in the case of *E. regnans* for FFA Vintorg as compared to MF Vintorg might be attributable to differences in bonding and cross-linking of wood with the different resins. MF resin is classified as a conventional bonding system while FFA resin as a non-conventional one (Zavarin, 1984). In conventional bonding the wood surface represents, or is thought to represent, a secondary reaction partner only, with covalent bonding restricted mainly to cross-linking reactions of the bonding agents (Schmidt, 1948; Allan, 1971; and Ramiah, 1970 cited in Zavarin (1984)). The non-conventional bonding systems form covalent bonds with the wood surfaces. The chemical composition of the wood surface is therefore a function of the conditions and methods of surface formation and may be different from the chemical composition of the bulk of the wood. The percentages of lignin, hemi-cellulose and cellulose are therefore greatly influenced by wood surface formation. An increase in temperature, for example, results in an easier separation, followed by breaking of wood fibres from the parent wood. Oxidative bonding i.e. lignin to lignin or lignin to cellulose bonding results in a significantly higher bonding strength than acidic bonding. The presence of maleic acid in FFA resin possibly resulted in a higher presence of acidic bonding than the oxidative bonding. There is also a possibility of preferential participation of lignin in bond formation with maleic acid than cellulose.

Comparison of FFA and MF Vintorg with ISO Vintorg

The higher MOR of isocyanate Vintorg and natural wood from the same species as compared to the Vintorg from the other resins could have been due to the fact that isocyanate is a tougher adhesive than the two other resins. The adhesive properties of isocyanate resin are based on the reactivity of the N.C.O. groups, and covalent bonds taking the form of urethane bridges are formed with the hydroxyl groups of the cellulose of the wood (Dinwoodie, 1978). This chemical bonding between isocyanate and the wood, results in an extremely strong bond. 'Tough glues' produce joints with high strains at the breaking stresses so that when over loaded the failure is induced in the wood and not in the glue lines (Kollmann *et al.*, 1975).

The mathematical relationship between the stress σ applied ($Kpcm^{-2}$) and modulus of elasticity *E* ($Kpcm^{-2}$) of wood (w) and the glue (g) is:

$$(\sigma / E)_w = (\sigma / E)_g \qquad \textit{(Eq.4-1).}$$

By introducing the breaking stresses in wood (σ_{wb}) and in the glue line (σ_{gb}) in equation (4-1) the following relationship is obtained:

$$(\sigma / E)_{wb} \leq (\sigma / E)_{gb} \qquad \textit{(Eq.4- 2).}$$

The modulus of elasticity of the fully hardened glue should therefore always be lower than that of the material glued. As the MOE for isocyanate Vintorg from *P. radiata* was relatively lower than that of natural wood, it could therefore have been possibly due to increased rigidity of the isocyanate Vintorg as compared to the natural wood from the same species. The insignificant difference in MOE of the isocyanate Vintorg and MF Vintorg tallies with the findings of Ayarkwa *et al.*,(2000). They found that MF and isocyanate resins were nearly equivalent in finger joint bending strength though isocyanate resin was superior in tension. They further reported that the performance of the adhesives related to the wood density. MF resin was found to perform better in medium and high-density hardwoods than in low-density wood. This could explain the lower MOE values of MF Vintorg from *P. radiata* as compared to those of FFA Vintorg from the same species.

Correlation of the properties of Vintorg

The low coefficients of determination obtained (sections 4.3.5 and 4.3.6) suggest that resin uptake and density of Vintorg can explain only a small percentage of the variability in the mechanical properties of Vintorg.

The strong correlation between MOE and MOR of Vintorg suggest that MOE values of Vintorg can be used for a non-destructive estimation of the MOR of Vintorg. Non-destructive tests of a material are based on a known relationship between its strength and some other property that can be evaluated without damaging the material. MOE of Vintorg can be determined without destroying the material and therefore the significant correlation between MOE and MOR of Vintorg can be used as a convenient relationship for this purpose.

4.4 Conclusions

- MOE and surface hardness of Vintorg tended to increase with duration of soaking.
- MOR of Vintorg was affected more by density of wood in the Vintorg than the amount of resin in the samples.
- The mechanical properties of Vintorg had weak to modest correlation with density of Vintorg and generally no correlation with resin uptake except for a modest one in the case of MOE of FFA, implying that the third hypothesis was disproved. It is therefore not possible to predict the mechanical properties of Vintorg from resin uptake and nominal density values.
- Vintorg is the same or higher in MOE, much higher in density but lower in MOR than natural wood from the same species, irrespective of wood species, resin type or soaking time but is higher in surface hardness than natural wood from the same species irrespective of resin type and soaking time only in the case of *P. radiata.*
- *E. regnans* Vintorg is lower in surface hardness than natural wood from the same species irrespective of resin type except for higher soaking times (60 minutes or more) in the case of MF resin and a short soaking time (1 minute) with FFA resin.
- FFA and MF Vintorg are the same or higher in MOE but lower in MOR than isocyanate Vintorg from the same species irrespective of wood species and duration of soaking, is the same or higher in surface hardness in the case of *P. radiata* but same or lower in the case of *E. regnans.*
- The density of Vintorg from *P. radiata* is lower than or the same as that of isocyanate Vintorg from the same species irrespective of resin type and duration of soaking.
- MF Vintog from *E. regnans* has density similar to that of isocyanate Vintorg from the same species irrespective of resin type and duration of soaking.
- FFA Vintorg from *E. regnans* is the same or higher in density than isocyanate Vintorg irrespective of resin type and duration of soaking.

- Isocyanate Vintorg is higher in MOR, surface hardness and density than natural wood from the same species, the same or higher in MOE than natural wood for *E. regnans* but lower in MOE than natural wood in the case of *P. radiata*.

CHAPTER 5:

5 GENERAL DISCUSSION AND CONCLUSIONS

5.1 Objective

To discuss the results and consider the implications of the findings for the purposes of industrial application and further research.

5.2 General discussion

Current wood processing technologies have a number of disadvantages emanating from the variable nature of wood. Characteristics of wood may vary between species, between trees and within a tree. Microwave modification of wood can be used to overcome a number of these problems. By applying intensive microwave radiation, it is possible to modify the structure of wood, minimizing variability and providing improved physical properties and technological attributes. Microwave modification of wood therefore has the potential of enhancing existing processes and making possible the development of new products from wood.

Microwave modification of wood has resulted in the production of some new products, namely Torgvin and Vintorg. Torgvin is microwave-modified timber with a higher permeability to liquids and more flexible, but of lower density and lower mechanical properties than untreated wood from the same species. Vintorg is the product that results from impregnation of Torgvin with resins followed by compression to the original dimensions. Vintorg production results in the restoration of the original properties (MOR) and increases some of them (dimensional stability, density, surface hardness and modulus of elasticity). The initial trials of Vintorg production employed isocyanate as the resin. However, isocyanate has some drawbacks (e.g. may have some carcinogenic effects and has a high viscosity, more than 200 cps and is expensive) so that it would be advantageous if other resins without these undesirable features could be used to manufacture Vintorg equal to isocyanate Vintorg.

Melamine formaldehyde and furfuryl alcohol resin were identified as potential substitutes of isocyanate resin in the manufacture of Vintorg. These resins seem attractive as they are less hazardous and have a lower viscosity.

A review of literature on microwave and resin modification of timber showed that very little research has been carried out in this area. The production of Vintorg is still in its infancy and

not much studied. It was, however, evident that the properties of Vintorg could be influenced by a number of factors. These include: degree of microwave modification, resin type, method of resin treatment, concentration of adhesive, pH of adhesive or wood, type of catalyst, chemical reactivity of the adhesive, temperature and duration of curing of adhesive, moisture content of wood, amount of pressure and duration of pressing of the bonded wood. There was no information from the literature review on Vintorg manufactured using resins other than isocyanate. It was therefore not known whether it would be possible to manufacture Vintorg using other resins with mechanical properties equal to or greater than the unmodified wood and equal to isocyanate Vintorg, nor was it known how wood species and resin levels would affect the properties of the Vintorg produced.

The research therefore aimed to evaluate Vintorg manufactured from heartwood of *E. regnans* and *P. radiata* treated with furfuryl alcohol (FFA) and/or melamine formaldehyde (MF) resins as a substitute for isocyanate and to determine the correlation and regressions of resin uptake and density of Vintorg on mechanical properties of Vintorg.

The effect of wood species, resin type and duration of soaking on resin uptake and loss during the manufacture of Vintorg was investigated. The results showed that wood species and duration of soaking have significant effects on the resin uptake and loss during the manufacture of Vintorg. Resin type did not have any significant effect on resin uptake by Torgvin but had a greater influence on the amount of resin loss than wood species and duration of soaking The results also showed that it is possible to manufacture Vintorg after relatively short duration soaking, 20 minutes or less.

The ranking of the two species in terms of the mean resin uptake and resin loss varied with resin type. *P. radiata* on one hand had higher mean FFA resin uptakes and higher relative amount of the FFA resin lost than *E. regnans*. On the other hand, *E. regnans* had a significantly higher mean initial MF resin uptake and amount of MF resin lost than *P.radiata*. However, the final MF resin uptakes, though higher for *E. regnans*, were not significantly different.

The effect of wood species, resin type and duration of soaking on the expected increase in density and decrease in cross-sectional area of Torgvin during the manufacture of Vintorg was also assessed. It was found that wood species, duration of soaking and resin type had significant effects on the increase in the density of Torgvin during the manufacture of Vintorg. There appeared to be a higher overall increase in density of *E. regnans* Torgvin than

that in *P. radiata.* Melamine formaldehyde resin tended to have a higher overall effect on the increase in the density of the Torgvin samples than furfuryl alcohol resin**.**

The density and the mechanical properties of Vintorg manufactured from the *P. radiata* tand *E.regnans* MF and FFA resins were evaluated and compared to those of natural wood and isocyante Vintorg. MOE and surface hardness of Vintorg tended to increase with duration of soaking. The results indicate that Vintorg is the same or higher in MOE, much higher in density but lower in MOR than natural wood from the same species, irrespective of wood species, resin type or soaking time and is higher in surface hardness than natural wood from the same species irrespective of resin type and soaking time only in the case of *P. radiata.* It was interesting to note that surface hardness of Vintorg was lower in *E. regnans* as compared to natural wood from the same species.

The higher MOE of Vintorg than natural wood from the same species is presumably due to the plasticing effect of the resins on wood. The lower MOR of Vintorg from the two resins could be due to the fact that treatment of wood with either resin causes embrittlement of the wood. The higher MOR of isocyanate Vintorg than natural wood is because it is a tough adhesive. The increases in density of Vintorg were found to be more of a mathematical effect resulting from the increase in mass of wood due to the resin and reduction in cross-sectional dimensions due to pressing of the resin treated samples.

Comparisons of the mechanical properties of Vintorg with those of isocyanate revealed some interesting results. FFA and MF Vintorg were found to be the same or higher in MOE but lower in MOR than isocyanateVintorg from the same species irrespective of wood species and duration of soaking, the same or higher in surface hardness in the case of P. *radiata* but the same or lower in the case of *E. regnans.*

5.3 Conclusions

The general conclusions from this study are as follows:

1. Wood species, resin type and duration of soaking have significant effects on the resin uptake by Torgvin and the resulting expected increase in density.

2. Vintorg can be manufactured to a higher density than natural wood from the same species using either resin irrespective of duration of soaking.

3. The density of Vintorg and resin uptake can explain only a small percentage of the variability in the mechanical properties of Vintorg and may not be suitable as a predictor of the mechanical properties of Vintorg.

4. Vintorg can be made from *P. radiata* and *E. regnans* to the same or higher levels of MOE of natural wood with FFA or MF resin.

5. Vintorg can be made be made from *P. radiata* with FFA or MF resin to the same or higher surface hardness than natural wood.

6. The MOR of Vintorg manufactured from *E. regnans* and *P. radiata* is lower than that of isocyanate Vintorg and natural wood from the same species.

7. It may be possible to substitute MF or FFA resins for isocyanate resin in the production of Vintorg provided that a way is devised to ensure that the MOR of the resultant Vintorg from these resins is at least the same or higher than that of original wood.

Recommendations

Further research needs to be done to establish an optimum microwave regime that would still ensure sufficient permeability of wood to resins without significantly lowering MOR. Research on other resins should also be carried out with a view of developing environmentally friendly resin systems with low viscosity and tough enough to manufacture Vintorg that is similar to isocyanate Vintorg, consequently, and superior to natural wood in terms of the mechanical properties.

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APPENDIX

Appendix 1. Methods of analysis.

Moisture content

The moisture content of the samples was determined by oven drying the samples at 105 ^{o}C for 24 hrs. The samples were weighed before and after drying.

Calculation

$$\% \text{ Moisture content} = \frac{(\text{mass before drying} - \text{mass after drying}) \times 100}{\text{Mass after drying}}$$

Nominal density

$$\text{Nominal density} = \frac{\text{Nominal mass} \times 100}{\text{Nominal volume}}$$

Appendix 2. Machines used

Figure A2-1 below shows a Baioni press used for the pressing of the resin treated samples and curing of the resin during the manufacture of Vintorg at the School of Forestry.

Fig. A2-1. Baioni press used for pressing of samples during the manufacture of Vintorg.

Fig. A2-2. Hounsfield Strength Testing Machine (10 K) used for determination of strength properties of samples.

Appendix 3. Manufacture of isocyanate Vintorg.

The process was similar to that used to manufacture Vintorg using the other two resins except for the method of treatment. Pressure treatment method was used for treating the Torgvin samples with isocyanate resin.

Pressure treatment method.

The treatment of the wood samples was conducted in the University of Melbourne laboratory wood treatment plant located at the School of Forestry, Creswick (Figure A3-1). A modified Bethel treatment method with the following schedule was used was used:

Evacuation of timber – 84 KPa (gauge) over 5 min

Hold at 84 KPa (Gauge) 15 min

Applcation of pressure of 600-700 Kpa (gauge) over 30 min

Release pressure for 10 sec.

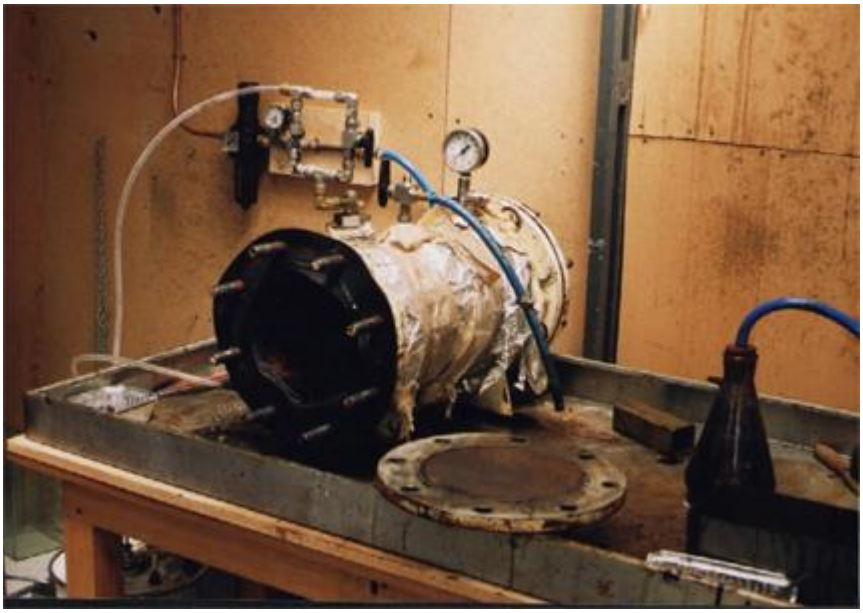

Fig A3-1. Laboratoray pressure treatment plant.

Appendix 4. Summary of some results.

Table A-1: FFA Resin uptake by Torgvin from *P. radiata* and *E. regnans* during the manufacture of Vintorg.

Species	Duration of soaking (Min)	Wood density (kgm^{-3})	M.C of Torgvin (%)	Maximum possible resin uptake (kgm^{-3})			Initial resin uptake (kgm^{-3})		
				Mean	S.d	C.V %	Mean	S.d	C.V%
Pinus radiata	1	497	9.3	561.3	49.8	8.9	104.7	20.5	19.6
	5	474	8.0	589.4	30.7	5.2	141.8	34.9	24.6
	10	471	9.3	584.3	75.5	13	162	40.3	24.9
	20	483	8.5	578.2	33.6	5.8	166.3	40.9	24.5
	Mean	479	8.7	-	-	-	-	-	-
Eucalyptus regnans	1	669	9.9	565.7	36.2	6.4	58.5	14.0	23.8
	5	661	11.1	563.4	28.8	5.1	81.2	15.9	19.5
	10	681	10.7	547.6	34.5	6.3	91.2	9.1	10.0
	20	649	11.0	565.1	52.2	9.2	100.2	14.6	14.5
	Mean	665	11.0	-	-	-	-	-	-

Species	Duration of soaking (Min)	Final resin uptake (kgm^{-3})			Percentage saturation of Torgvin with resin (%)		
		Mean	S.d	C.V %	Mean	S.d	C.V %
Pinus radiata	1	62.8	19.6	31.2	18.8	4.3	22.8
	5	65.7	17.8	27.1	24.1	6.3	25.9
	10	106	31.8	30.1	28.0	7.1	25.5
	20	105.8	24.0	27.7	28.8	6.7	23.2
	-	-	-	-	-	-	-
Eucalyptus regnans	1	25.7	10.5	40.9	10.3	2.1	20.7
	5	41.5	15.0	36.1	14.3	2.4	16.7
	10	47.6	8.9	18.7	16.7	1.1	6.7
	20	52.4	10.1	19.2	17.8	3.0	16.6
	-	-	-	-	-	-	-

Species	Duration of soaking (Min)	Percentage saturation of Vintorg with resin (%)			Relative measure of resin loss (RMRL)(%)		
		Mean	S.d	C.V %	Mean	S.d	C.V %
Pinus radiata	1	11.3	3.5	31.1	42.0	16.2	38.5
	5	11.1	2.9	26.4	64.3	16.3	23.9
	10	18.1	5.2	28.5	56.3	15.5	27.5
	20	18.1	3.9	21.6	61.0	23.0	37.7
	-	-	-	-	-	-	-
Eucalyptus regnans	1	4.5	1.7	38.3	32.9	7.4	22.5
	5	7.3	2.4	33.6	40.3	7.5	18.7
	10	8.7	1.4	16.3	43.6	10.7	24.4
	20	9.3	1.5	16.6	47.8	8.2	17.2
	-	-	-	-	-	-	-

Table A-2: MF Resin uptake by Torgvin of *P. radiata* and *E. regnans* during the manufacture of Vintorg.

Species	Duration of soaking (min)	Wood density kgm^{-3}	M.C (%)	Maximum possible resin uptake (kgm^{-3})			Initial resin uptake (kgm^{-3})		
				Mean	S.d	C.V %	Mean	S.d	C.V %
Pinus radiata	5	509	8.7	535.8	34.2	6.4	101.3	23.1	22.0
	20	489	8.4	557.1	49.9	9.0	141.3	28.9	20.5
	60	483	8.3	561.0	50.2	9.0	160.7	27.3	17.0
	90	507	9.2	538.2	53.8	10.0	183.4	27.5	15.0
	Mean	496	8.7	-	-	-	-	-	-
Eucalyptus regnans	5	737	9.9	532.5	30.9	5.8	132.2	29.5	22.3
	20	720	9.0	550.8	48.5	8.8	132.1	27.0	20.4
	60	716	7.6	570.3	36.3	9.8	176.8	30.5	17.3
	90	719	9.6	546.4	44.7	8.2	199.3	43.1	21.6
	Mean	723	8.7	550.0	41.1	7.5	160.1	43.3	27.1

Species	Duration of soaking (min)	Final resin uptake (kgm^{-3})			Percentage saturation of Torgvin with resin (%)		
		Mean	S.d	C.V %	Mean	S.d	C.V %
Pinus radiata	5	64.4	17.4	27.0	18.9	4.3	22.8
	20	76.2	18.0	23.6	25.4	5.3	20.9
	60	93.7	19.5	20.8	28.7	4.7	16.4
	90	116.1	26.1	22.5	34.3	5.9	17.2
	-	-	-	-	-	-	-
Eucalyptus regnans	5	65.4	15.2	23.2	24.8	5.5	22.2
	20	67.1	18.2	27.1	24.0	4.5	18.8
	60	87.8	22.1	25.2	31.0	5.3	17.1
	90	104.5	47.7	45.6	36.4	6.8	18.7
	-	-	-	-	-	-	

Species	Duration of soaking (min)	Percentage saturation of Vintorg with resin (%)			Relative measure of resin loss (RMRL)(%)		
		Mean	S.d	C.V %	Mean	S.d	C.V %
Pinus radiata	5	12.0	3.4	28.3	36.9	10.9	29.5
	20	13.8	3.7	26.8	65.0	16.5	25.4
	60	16.8	3.5	20.8	67.0	11.3	16.9
	90	21.6	5.1	23.6	67.3	8.1	12.0
	-	-	-	-	-	-	-
Eucalyptus regnans	5	12.3	2.7	22.0	61.7	23.3	37.8
	20	12.0	3.2	26.7	71.4	14.4	20.2
	60	15.3	3.7	24.2	89.0	27.0	30.3
	90	18.9	8.0	42.3	94.8	31.1	32.8
	-	-	-	-	-	-	-

Table A-3. Tukey's Comparisons for treatment pairs resin uptake, and loss for *P. radiata* Torgvin treated with FFA resin.

Response variable	Treatment pairs	Difference of mean	Standard error of difference	T-value	Adjusted P-value
Initial resin uptake (kgm^{-3})	5 -1	37.0	14.2	2.6	0.065
	10-1	57.3	14.2	4.04	0.002
	20-1	56.5	14.2	4.0.	0.002
	10-5	20.3	14.2	1.43	0.493
	20-5	19.5	14.2	1.4	0.524
	20-10	-0.74	14.2	-0.05	1.000
Final resin uptake (kgm^{-3})	5 -1	3.0.	8.9	0.34	0.987
	10-1	43.0	8.9	4.8	0.000
	20-1	40.9	8.9	4.6	0.000
	10-5	40.0	8.9	4.5	0.000
	20-5	37.9	8.9	4.3	0.001

Table A-4. Tukey's Comparisons for treatment pairs for resin uptake and loss for *P. radiata* Torgvin treated with MF resin.

Response variable	Treatment pairs	Difference of mean	Standard error of difference	T-value	Adjusted P-value
Initial resin uptake (kgm^{-3})	20-5	39.9	13.5	3.0	0.030
	60-5	59.4	13.5	4.4	0.001
	90-5	82.0	13.5	6.1	0.000
	60-20	19.7	13.5	1.4	0.484
	90-20	42.1	13.5	3.1	0.021
	90-60	22.7	13.5	1.7	0.353
Final resin uptake (kgm^{-3})	20-5	11.8	9.7	1.2	0.62
	60-5	29.3	9.7	3.0	0.027
	90-5	51.7	9.7	5.3	0.000
	60-20	17.5	9.7	1.8	0.297
	90-20	39.8	9.7	4.1	0.002
	90-60	22.4	9.7	2.3	0.123
Relative amount of resin lost (kgm^{-3})	20-5	30.11	5.4	5.6	0.000
	60-5	28.11	5.4	5.2	0.000
	90-5	30.4	5.4	5.6	0.000
	60-20	-2.0	5.4	-0.37	0.982
	90-20	0.3	5.4	0.05	1.0
	90-60	2.3	5.4	0.42	0.975

Table A-5. Turkey's Comparisons for treatment pairs for resin uptake and loss for *E. regnans* Torgvin treated with FFA resin.

Response variable	Treatment pairs	Difference of mean	Standard error of difference	T-value	Adjusted P-value
Initial resin uptake (kgm^{-3})	5 -1	24.4	4.4	5.6	0.000
	10-1	32.7	4.4	7.4	0.000
	20-1	41.7	4.4	9.5	0.000
	10-5	8.3	4.4	1.9	0.256
	20-5	17.3	4.4	3.9	0.003
	20-10	9.0.	4.4	2.0	0.197
Final resin uptake (kgm^{-3})	5 -1	22.8	4.7	4.8	0.000
	10-1	25.5	4.7	5.4	0.000
	20-1	31.0	4.7	6.6	0.000
	10-5	2.7	4.7	0.57	0.940
	20-5	8.3	4.7	1.8	0.316
	20-10	5.6	4.7	1.2	0.6417
Relative amount of resin lost (kgm^{-3})	5 -1	1.6	3.3	0.48	0.962
	10-1	7.2	3.3	2.2	0.158
	20-1	10.6	3.3	3.2	0.02
	10-5	5.6	3.3	1.7	0.351
	20-5	9.0	3.3	2.7	0.053
	20-10	3.4	3.3	1.02	0.739

Table A-6. Turkey's simultaneous tests for treatment pairs for resin uptake and loss for *E. regnans* Torgvin treated with MF resin.

Response variable	Treatment pairs	Difference of mean	Standard error of difference	T-value	Adjusted P-value
Initial resin uptake (kgm^{-3})	20-5	7.0.	14.1	0.497	0.959
	60-5	41.0	11.5	3.6	0.005
	90-5	79.6	14.1	5.7	0.000
	60-20	34.0	14.1	2.4	0.09
	90-20	72.6	16.2	4.5	0.000
	90-60	38.5	41.1	2.8	0.04
Final resin uptake (kgm^{-3})	20-5	-9.4	9.1	-1.0	0.735
	60-5	14.5	7.5	2.0.	0.222
	90-5	37.2	9.1	4.1	0.001
	60-20	23.9	9.1	2.6	0.056
	90-20	46.6	10.5	4.4	0.000
	90-60	22.7	9.1	2.5	0.08
Relative amount of resin lost (kgm^{-3})	20-5	16.4	9.8	1.7	0.349
	60-5	26.5	78.0	3.3	0.009
	90-5	42.4	9.8	4.3	0.000
	60-20	10.10	9.8	1.03	0.732
	90-20	26.0	11.3	2.3	0.112
	90-60	15.9	9.8	1.6	0.375

Table A-7: Paired t-test results for the difference in cross-sectional area of Torgvin and Vintorg from *P. radiata.*

Resin type	Duration of soaking (min)	Mean difference	Standard deviation	Standard error of mean	T-value	P-value
FFA	1	151.3	46.1	14.6	10.3	0.000
FFA	5	149.1	45.8	14.5	10.3	0.000
FFA	10	130.4	98.3	31.1	4.2	0.002
FFA	20	183.3	30.6	9.7	19.0	0.000
MF	5	126.5	45.4	14.3	8.8	0.000
MF	20	102.8	31.8	10.1	10.2	0.000
MF	60	152.9	78.5	24.8	6.2	0.000
MF	90	154.6	37.9	12.0	12.9	0.000

Table A-8. Paired t-test results for the difference in cross-sectional area of Torgvin and Vintorg from *E. regnans*

Resin type	Duration of soaking (min)	Mean difference	Standard deviation	Standard error mean	T-value	P-value
FFA	1	198.7	78.8	24.9	8.2	0.000
FFA	5	157.1	68.9	21.8	7.2	0.000
FFA	10	221.9	86.1	27.2	8.2.	0.000
FFA	20	173.0	73.1	23.1	7.5	0.000
MF	5	327.3	94.2	29.8	11.0	0.000
MF	20	311.7	87.5	27.7	11.3	0.000
MF	60	297.3	75.6	23.9	10.4	0.000
MF	90	308.5	72.5	22.9	13.5	0.000

Table A-9. Paired t-test results for the difference in nominal density of Vintorg and Torgvin from *P. radiata*.

Resin type	Duration of soaking (min)	Number of samples	Mean difference	Standard deviation	Standard error mean	T-value	P-value
FFA	1	10	0.10	0.03	0.01	10.04	0.000
FFA	5	10	0.10	0.02	0.01	13.5	0.000
FFA	10	10	0.13	0.04	0.01	10.1	0.000
FFA	20	10	0.16	0.05	0.02	10.8	0.000
MF	5	10	0.09	0.02	0.01	12.4	0.000
MF	20	10	0.09	0.02	0.01	15.0	0.000
MF	60	10	0.12	0.04	0.01	10.9	0.000
MF	90	10	0.15	0.03	0.01	16.0	0.000

Table A-10. Paired t-test results for the difference in nominal density of Vintorg and Torgvin from *E. regnans*

Resin type	Duration of soaking (min)	Mean difference	Standard deviation	Standard error mean	T-value	P-value
FFA	1	0.09	0.04	0.01	8.2	0.000
FFA	5	0.1	0.04	0.01	8.5	0.000
FFA	10	0.13	0.03	0.01	13.1	0.000
FFA	20	0.12	0.32	0.01	11.7	0.000
MF	5	0.2	0.05	0.01	13.8	0.000
MF	20	0.17	0.02	0.01	13.6	0.000
MF	60	0.19	0.04	0.01	15.3	0.000
MF	90	0.22	0.06	0.02	11.7	0.000

Table A-11: The percentage decrease in cross-sectional area of Torgvin during the manufacture of FFA Vintorg from *P. radiata* and *E. regnans*.

Species	Duration of soaking (Min)	Cross-sectional area of Torgvin (mm^2)			Cross-sectional area Vintorg (mm 2)			Decrease in cross-sectional area (%)		
		Mean	S.D.	C.V (%)	Mean	S.D.	C.V (%)	Mean	S.D.	C.V (%)
Pinus radiata	1	1796.2	56.1	3.1	1624.6	50.6	3.1	9.9	3.3	33.0
	5	1806.3	35.9	2.0	1655.4	40.9	2.5	8.4	2.3	27.4
	10	1815.9	55.8	3.1	1685.9	67.7	4.0	8.2	2.4	28.8
	20	1806.7	38.9	2.2	1617.4	41.3	2.8	10.5	2.0	19.4
	Mean	1806.3	46.7	2.6	1645.8	50.1	3.1	9.3	2.5	27.2
Eucalyptus regnans	1	1807.3	70.5	3.9	1614.2	68.9	4.3	10.6	4.3	40.1
	5	1792.3	55.0	3.1	1645.1	70.9	4.3	8.9	3.1	35.0
	10	1792.4	67.1	3.7	1564.4	86.7	5.5	12.7	4.6	36.4
	20	1825.3	74.8	4.1	1642.5	63.9	3.9	9.5	3.8	39.8
	Mean	1804.3	66.9	3.7	1616.6	72.6	4.5	10.4	4.0	37.8

Table A-12: The percentage decrease in cross-sectional area of Torgvin during the manufacture of MF Vintorg from *P. radiata* and *E. regnans*.

Species	Duration of soaking (Min)	Cross-sectional area of Torgvin (mm^2)			Cross-sectional area of Vintorg (mm^2)			Decrease in cross - sectional area (%)		
		Mean	S.D.	C.V (%)	Mean	S.D	C.V (%)	Mean	S.D	C.V (%)
Pinus radiata	5	1824.2	58.4	3.2	1697.6	67.9	4.0	6.9	2.5	36.2
	20	1782.4	81.3	4.6	1675.5	79.3	4.7	6.0	1.7	28.0
	60	1783.1	54.8	3.1	1633.6	92.1	5.6	8.4	4.2	50.6
	90	1819.2	49.6	2.7	1669.4	48.3	2.9	8.1	2.2	27.7
	Mean	1802.2	61.0	3.4	1669.1	71.9	4.3	7.4	2.7	35.6
Eucalyptus regnans	5	1779.2	104.2	5.9	1469.2	87.6	6.0	17.2	6.3	36.5
	20	1770.1	70.2	4.0	1475.5	91.2	6.2	16.6	5.4	32.4
	60	1776.5	74.5	4.2	1472.4	62.7	4.3	17.0	4.3	25.1
	90	1784.9	58.8	3.3	1476.4	54.6	3.7	21.7	3.7	21.7
	Mean	1772.7	76.9	4.4	1473.3	74.0	5.1	18.1	4.9	28.9

Table A-13: The percentage increase in density of Torgvin during the manufacture of FFA Vintorg from *P. radiata* and *E. regnans*.

Species	Duration of soaking (min)	Density o f Torgvin (gcm^{-3})			Density of Vintorg (gcm^{-3})			Increase in wood density (%)		
		Mean	S.D.	C.V (%)	Mean	S.D.	C.V (%)	Mean	S.D.	C.V (%)
Pinus radiata	1	0.45	0.04	8.9	0.56	0.05	8.9	26.0	9.5	36.5
	5	0.44	0.03	6.8	0.54	0.03	5.6	24.7	5.0	20.2
	10	0.44	0.06	13.6	0.57	0.07	12.3	33.3	10.0	30.0
	20	0.43	0.06	14.0	0.58	0.04	6.9	34.2	7.3	.21.3
	Mean	0.44	0.05	10.8	0.56	0.05	8.4	29.6	8.0	27.0
Eucalyptus regnans	1	0.61	0.03	4.9	0.70	0.03	4.3	17.0.	6.4	37.2
	5	0.62	0.04	6.5	0.71	0.02	2.8	17.2	7.1	41.3
	10	0.61	0.03	4.9	0.74	0.04	5.4	24.1	5.7	23.7
	20	0.59	0.04	6.8	0.71	0.03	4.2	21.1	5.5	26.1
	Mean	0.60	0.04	5.8	0.72	0.03	4.2	19.9	6.2	32.1

Table A-14: The percentage increase in density of Torgvin during the manufacture of MF Vintorg from *P. radiata* and *E. regnans*.

Species	Duration of soaking (min)	Density of Torgvin (gcm^{-3})			Density of Vintorg (gcm^{-3})			Increase in wood density (%)		
		Mean	S.D.	C.V (%)	Mean	S.D.	C.V (%)	Mean	S.D.	C.V (%)
Pinus radiata	5	0.48	0.03	6.3	0.57	0.04	7.0	19.9	6.8	34.1
	20	0.47	0.04	8.5	0.56	0.06	10.7	22.7	9.1	40.1
	60	0.45	0.04	8.9	0.58	0.05	8.6	31.3	8.9	28.4
	90	0.46	0.05	10.9	0.62	0.05	8.1	33.4	8.2	24.6
	Mean	0.47	0.04	8.7	0.58	0.05	8.6	26.8	8.3	31.8
Eucalyptus regnans	5	0.62	0.04	6.5	0.81	0.03	3.7	33.2	10.5	31.6
	20	0.61	0.03	4.9	0.78	0.04	5.1	30.5	8.2	26.9
	60	0.62	0.03	4.8	0.81	0.03	3.7	35.9	9.5	26.5
	90	0.60	0.04	6.7	0.82	0.04	4.9	39.0	12.8	32.8
	Mean	0.61	0.04	5.7	0.81	0.04	4.4	34.7	10.3	23.3

Table A-15: Effect of resin type on the increase nominal density of Torgvin during the manufacture of Vintorg from *P. radiata* and *E. regnans*.

Species	Resin type	Duration of soaking (min)	Density ofTorgvin (gcm^{-3})			Density of Vintorg (gcm^{-3})			Increase in wood density (%)		
			Mean	S.D.	C.V (%)	Mean	S.D	C.V (%)	Mean	S.D	C.V (%)
Pinus radiata	FFA	5	0.44	0.03	6.8	0.54	0.03	5.6	24.7	5.0	20.2
		20	0.43	0.06	14.0	0.58	0.04	6.9	34.2	7.3	21.3
		Mean	0.44	0.05	10.4	0.56	0.07	6.3	29.5	6.2	20.8
	MF	5	0.48	0.03	6.3	0.57	0.04	7.0	19.94	6.8	34.1
		20	0.47	0.04	8.5	0.56	0.06	10.7	22.7	9.1	40.1
		Mean	0.48	0.04	7.4	0.57	0.05	8.9	21.3	8.0	37.1
Eucalyptus regnans	FFA	5	0.62	0.04	6.5	0.71	0.02	2.8	17.2	7.1	41.3
		20	0.59	0.04	6.8	0.71	0.03	4.2	21.1	5.5	26.1
		Mean	0.61	0.04	6.7	0.71	0.03	3.5	19.2	6.3	33.7
	MF	5	0.62	0.04	6.5	0.81	0.03	3.7	33.2	10.5	31.6
		20	0.61	0.03	4.9	0.78	0.04	5.1	30.5	8.2	26.9
		Mean	0.62	0.04	5.7	0.8	0.04	4.4	31.9	9.4	29.3

Table A-16. Density and mechanical properties of furfuryl alcohol Vintorg and controls from *P. radiata.*

Treatment	MOE (MPa)			MOR (MPa)			Hardness (N)		
	Mean	S.D	C.V	Mean	S.D	C.V	Mean	S.D	C.V
Vintorg - 1 min	7274	3367	46.3	30.7	16.4	53.4	2972	485	16.3
Vintorg - 5 min	7368	2668	36.2	32.9	14.3	43.5	3008	630	20.9
Vintorg- 10 min	7498	1713	22.9	33.2	15.2	45.8	3018	461	15.3
Vintorg -20 min	7739	2171	28.0	40.0.	14.1	35.3	3051	351	11.5
Torgvin	2703	942	34.9	20.7	5.5	26.6	1846	138	7.5
Natural wood	6784	1663	24.5	57.4	9.7	16.9	2595	502	19.3

Treatment	Density of Vintorg (gcm^{-3})			Density of wood (gcm^{-3})		
	Mean	S.D	C.V	Mean	S.D	C.V
Vintorg - 1 min	0.560	0.06	10.7	0.497	0.05	10.2
Vintorg - 5 min	0.540	0.03	5.6	0.474	0.03	6.4
Vintorg- 10 min	0.577	0.08	13.9	0.471	0.08	17.0
Vintorg -20 min	0.580	0.04	6.9	0.476	0.04	8.5
Torgvin	-	-	-	0.47	0.04	8.5
Natural wood	-	-	-	0.520	0.07	13.5

Table A-17. Density and mechanical properties of melamine formaldehyde Vintorg and controls from *P. radiata*.

Treatment	MOE (MPa)			MOR (MPa)			Hardness (N)		
	Mean	S.D	C.V	Mean	S.D	C.V	Mean	S.D	C.V
Vintorg - 5 min	6056	961	15.7	47.5	11.9	25.1	2968.1	474.6	16.0
Vintorg - 20 min	6264	1304	20.8	43.5	7.0	16.1	2975.1	239.5	8.1
Vintorg - 60 min	6576	697	10.6	43.5	11.9	27.4	2989.7	378.8	12.7
Vintorg - 90 min	6989	882	12.6	46.2	9.0	19.5	3301.1	373.5	11.3
Torgvin	2703	942	34.9	20.7	5.5	26.6	1846	138	7.5
Natural wood	6784	1663	24.5	57.4	9.7	16.9	2595	502	19.3

Treatment	Density of Vintorg (gcm^{-3})			Density of wood (gcm^{-3})		
	Mean	S.D	C.V	Mean	S.D	C.V
Vintorg - 5 min	0.582	0.02	3.4	0.508	0.03	5.9
Vintorg - 20 min	0.577	0.06	10.4	0.482	0.05	10.4
Vintorg - 60 min	0.589	0.06	10.2	0.486	0.05	10.3
Vintorg - 90 min	0.604	0.05	8.3	0.507	0.05	9.9
Torgvin	-	-		0.47	0.04	8.5
Natural wood	-	-		0.520	0.07	13.5

Table A-18. Density and mechanical properties of furfuryl alcohol Vintorg from *E. regnans*.

Material	MOE (MPa)			MOR (MPa)			Hardness (N)		
	Mean	S.D	C.V	Mean	S.D	C.V	Mean	S.D	C.V
Vintorg -1 min	11446	1214	10.6	87.8	17.6	20.0	3296.6	636.5	19.3
Vintorg -5 min	12180	911	7.5	87.2	14.3	16.4	3643.5	436.6	12.0
Vintorg -10 min	11999	1491	12.4	86.1	16.3	18.9	3792.6	206.6	5.4
Vintorg - 20 min	11356	1312	11.6	83.1	12.2	14.7	3233.9	617.8	19.1
Torgvin	5245.6	88.7	16.9	44.2	10.8	24.4	2071	662	32.0
Natural wood	11050	1563	14.1	105.7	7.04	6.7	4468.1	190.1	4.3

Material	Density of Vintorg (gcm^{-3})			Density of wood (gcm^{-3})		
	Mean	S.D	C.V	Mean	S.D	C.V
Vintorg -1 min	0.735	0.03	4.1	0.735	0.03	4.1
Vintorg -5 min	0.758	0.05	6.6	0.721	0.04	5.6
Vintorg -10 min	0.732	0.04	5.5	0.720	0.04	5.6
Vintorg - 20 min	0.722	0.04	5.5	0.719	0.03	4.2
Torgvin	-	-	-	0.643	0.1	9.4
Natural wood	-	-	-	0.662	0.02	3.0

Table A-19. Density and mechanical properties of melamine formaldehyde Vintorg and controls from *E. regnans.*

Material	MOE (MPa)			MOR (MPa)			Hardness (N)		
	Mean	S.D	C.V	Mean	S.D	C.V	Mean	S.D	C.V
Vintorg - 5 min	11374	929	8.2	96.0	8.8	9.2	4193.1	198.6	4.7
Vintorg - 20 min	11285	969	8.6	92.2	11.8	12.8	4021.9	110.3	2.7
Vintorg - 60 min	11609	835	7.2	98.2	9.0	9.2	4325.3	321.2	7.4
Vintorg - 90 min	11513	843	7.3	94.3	8.9	9.4	4384.4	396.2	9.0
Torgvin	5245.6	88.7	16.8	44.2	10.8	24.4	2071	662	32.0
Natural wood	11232	1086	9.7	107.1	7.0	6.5	4468.1	190.1	4.3

Material	Density of Vintorg (gcm^{-3})			Density of wood (gcm^{-3})		
	Mean	S.D	C.V	Mean	S.D	C.V
Vintorg - 5 min	0.807	0.04	5.0	0.710	0.04	5.6
Vintorg - 20 min	0.779	0.04	5.1	0.703	0.04	5.7
Vintorg - 60 min	0.806	0.03	3.7	0.730	0.03	4.1
Vintorg - 90 min	0.830	0.04	4.8	0.723	0.02	2.7
Torgvin	-	-	-	0.643	0.1	9.4
Natural wood	-	-	-	0.662	0.02	3.0

Table A-20. Comparison of the mechanical properties of FFA Vintorg and those of natural wood control samples for *P.radiata.*

Mechanical property	Duration of treatment (min)	Mean difference	Standard deviation	Standard error of mean	T-value	P-Value
MOE (MPa)	1	491	3882	1372	0.36	0.731
	5	584	4554	1610	0.36	0.728
	10	120	3256	1151	0.1	0.920
	20	1485	2820	940	1.6	0.153
MOR (MPa)	1	-39.9	30.4	10.7	-3.7	0.007
	5	-34.3	30.6	10.8	-3.2	0.016
	10	-37.7	32.1	12.1	-3.1	0.021
	20	-21.5	22.0	7.8	-2.8	0.028
Hardness (N)	1	311	575	192	1.6	0.143
	5	413	469	153	2.6	0.030
	10	376	397	132	2.8	0.022
	20	389	331	110	3.5	0.008

Table A-21. Results of the paired t-test for the mechanical properties of MF Vintorg and the natural wood controls for *P. radiata*.

Mechanical property	Duration of treatment	Mean difference	Standard deviation	Standard error of mean	T-value	P-Value
MOE (MPa)	5	3013	1329	470	6.4	0.000
	20	3028	1097	388	7.8	0.000
	60	3552	708	267	13.3	0.000
	90	3850	1233	436	8.8	0.000
MOR (MPa)	5	26.4	13.7	4.9	5.4	0.001
	20	16.9	6.5	2.3	7.4	0.000
	60	24.2	7.7	2.9	8.4	0.000
	90	26.0	10.6	3.8	6.9	0.000
Hardness (N)	5	1062	394	149	7.1	0.000
	20	1036	377	133	7.8	0.000
	60	1088	319	130	8.4	0.000
	90	1493	222.8	84.2	17.7	0.000

Table A-22. Dunnett's test for the Comparison of the mechanical properties of FFA Vintorg and those of natural wood control samples for *E. regnans*.

Mechanical property	Duration of treatment (min)	Difference of means	Standard error of difference	T-value	P-Value
MOE (MPa)	1	716.8	660.9	1.1	0.658
	5	1426.2	660.9	2.2	0.116
	10	1716.1	701.0	2.5	0.061
	20	45	660.9	0.1	1.000
MOR (MPa)	1	-16.3	7.0	-2.4	0.083
	5	-16.6	7.0	-2.4	0.076
	10	-14.2	8.3	-1.7	0.283
	20	-21.0	7.2	-2.9	0.022
Hardness (N)	1	-1192	163.2	-7.3	0.000
	5	-845	163.2	-5.2	0.000
	10	-696	169.2	-4.1	0.000
	20	-1254	163.2	-7.7	0.000