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Abstract approved
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In plywood manufacture, the interaction of wood with resin during hot pressing is responsible for the development of glue bond strength and hence panel quality. In this study, temperature and vapor pressure distributions and compaction of laminates were measured during pressing. Analysis of these factors emphasized boards formed under conventional (standard) conditions. However, some laminates were also studied with modified veneer moisture contents and platen pressures.

By analysing data generated from laminates during pressing in the laboratory, the nature of interdepencence between heat transfer, vapor pressure accumulation and board compaction and how they are affected by veneer moisture content and platen pressure were considered.

Complementary to the above work, the rate of strength development of phenol-formaldehyde resin forming a bond between wood wafers was determined. Bonds were formed under a range of steady-state temperatures and immediately tested in shear mode. Curves of bond strength versus pressing time

were derived for each of the eight temperatures used.

The relationship between rate of bond strength development, temperature and pressing time was quantified. At elevated temperatures very rapid resin curing was observed compared to that at lower temperatures. Open assembly time, resin pot life and wood wafer characteristics did not have a significant effects on the rate of curing of the resin under the range of conditions used in this project.

The data generated from both experiments were combined to derive a model for predicting glue bond strength development at various locations in the laminate during hot pressing. The principle for the construction of the model is described as well as factors which should be accounted for in future refinements.

Quantitive analysis of the interaction of these variables will aid in optimising the manufacture of plywood. The use of high MC veneers and selection of appropriate pressing variables depends upon such analysis. The development of new materials and evaluation of new adhesive systems are longer term goals.

Analysis of Processes Operative within Plywood During Hot Pressing

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David Zavala Zavala

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Signature redacted for privacy.

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Signature redacted for privacy.

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Chapter I

Introduction

In years gone by, technical developments in plywood design and manufacture have favored its supremacy over a variety of competing products. In some cases this has been due to economic advantages. However, in order to retain a viable position in the market, alongside highly competitive substitutes (particularly particulate composites), more efficient techniques are required to optimize the manufacture and characteristics of the product at a competitive price. This need is especially evident with the decline in supply of high quality raw material.

It has been pointed out (137, 149) that high quality panel manufacture is still considered an art rather than a science. This statement reflects both the complexity of the process and the attitude of many manufacturers. A large number of variables and possible combinations may be generated in all the main aspects of the system. These are wood characteristics, resin composition and processing parameters. The principle process and raw material variables associated with laminate manufacture are shown as Figure 1.1. The main issues related to each one of these aspects will now be considered here before going on to introduce the primary objectives of the present work.

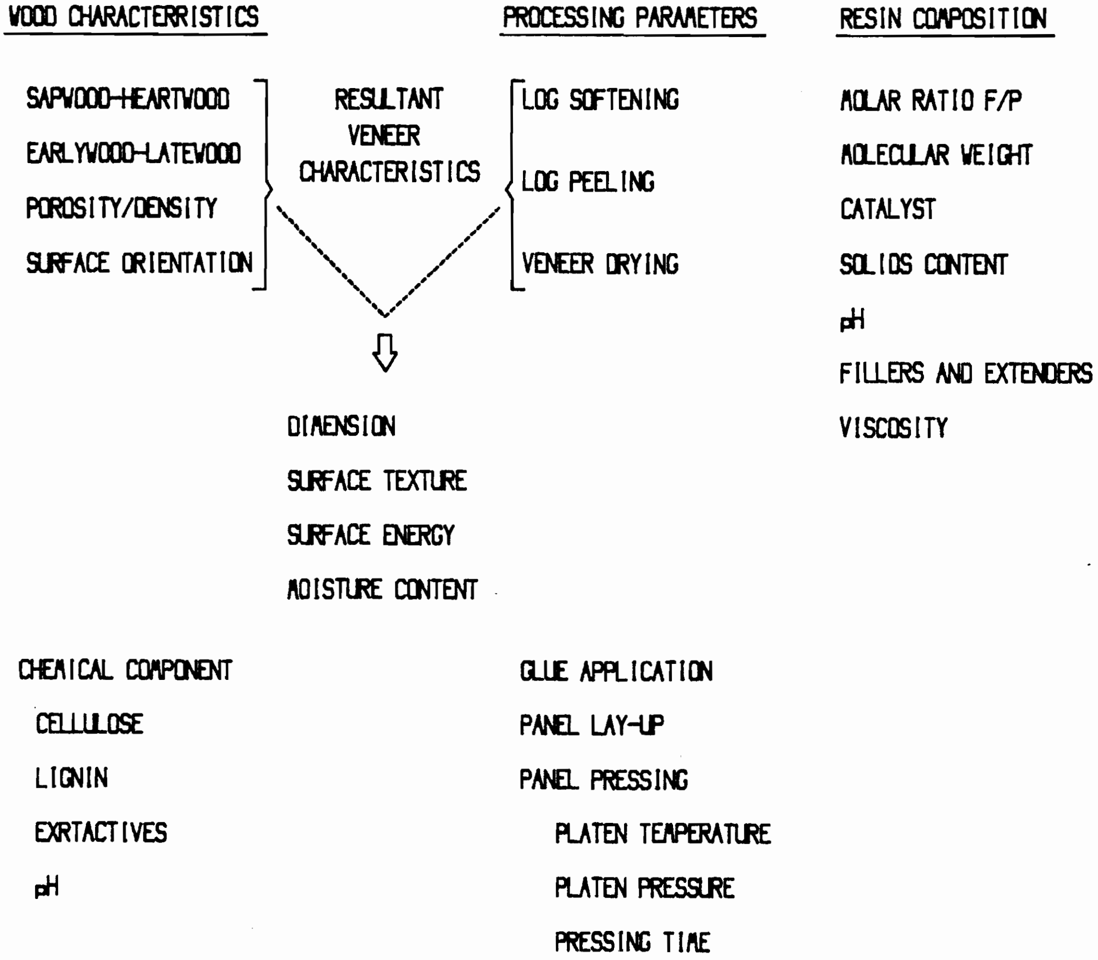


Figure 1.1 A schematic of the principal elements of laminate manufacture.

Wood is a complex material with anisotropic properties and chemical composition that vary greatly both within and between trees. The natural variability of wood is more evident when processing parameters come into play. In laminate production, softening schedules and peeling of the logs, drying the veneer, and assembling and pressing the panels are all affected directly by wood material properties and their variability.

A third component, no less important than wood variation and the processing conditions, is the characteristics of the adhesive system. Presently, the majority of boards manufactured for structural use are bonded with phenolic adhesives. Great potential for the development of alternative bonding systems exists, however. This should be borne in mind throughout any fundamental study of structural composite development.

The characteristics of any glue mix are the result of many factors. In the case of PF systems, this includes the proportions of phenol, formaldehyde, catalyst, fillers and extenders. These components have a direct effect on the final properties of the adhesive and its interaction with wood in the laminate system during pressing (39, 57, 75, 129, 131, 157).

Variability inherent in the wood material properties may not be eliminated. At best, this can be kept within defined ranges. Adhesive formulation and processing parameters therefore remain as the primary factors which are under control to affect product properties.

Glue mix formulations for plywood manufacture are presently selected for specific wood characteristics and pressing conditions by using empirical techniques largely based on trial and error tests (59, 102). The selection is complicated by the varying conditions of temperature, moisture content and compression that prevail within the panel as hot pressing proceeds. Present methods of adhesive specification do not take into account the diversity of such conditions. Among the stages in conventional board manufacture, one of the most important is therefore the pressing stage. This has direct impact on inter-veneer bond formation and quality, and hence overall product performance.

It has been established that for given glue mix formulations and wood characteristics, glue bond strength development associated with polymerization of the adhesive is intimately dependent on the variation of glueline temperature with time (39, 153). Heat is transfered from the platens of the press through the wood in order to reach the gluelines. Moisture moves inside the panel and affects bonding and optimum usage of the pressing equipment and raw material.

Rheological behavior(time dependent deformation under load) of wood material is intimately dependent on moisture content and temperature. This behavior is manifested as compression and resultant densification of the board in response to applied platen loading. Studies have been undertaken (154) to reduce compression losses in commercial boards. This has been achieved by modifying loading cycles and applying a water spray to the board surface immediately after removal from the press. Adhesive dispersion and subsequent bonding between veneers is, however, dependent on the application of compressive loading. The balance between achieving acceptable bonding on the one hand, with the minimum of compression on the other, is an important issue. This sensitivity is heightened with the use of high moisture content veneers.

Objectives of the research

An analysis of factors involved in hot pressing of a panel and their interaction under standard and modified conditions is the basic goal of this study. The effect of high veneer moisture content and different platen pressures on bond strength development and rheological behavior of the panel are specific concerns. It is anticipated that the information generated through this work will contribute to our understanding of the processes involved during pressing of laminates. It will serve as a basis for future research oriented toward the optimization of the system and the development of new material combinations and manufacturing methods.

Due to the complexity of the process and the large number of variables involved during hot pressing, the present work is limited to the study of two of the most important factors affecting glue bond strength development. One goal is to develop numerical techniques which will aid in the optimization of pressing cycles based on the data generated from experimental analysis. Further goals of a longer term nature concern the development of new methods of manufacture and selection of materials. The inclusion of new adhesive systems is a major aspect of this.

To achieve these goals, the following objectives have been established for the present project:

a. To measure temperature and vapor pressure distributions throughout the laminates during pressing in the laboratory. This is with a view to characterizing the conditions under which adhesive cure takes place and also the loads that are placed on those bonds (primarily by vapor pressure) when the press is opened. Additionally, thickness changes of the board during pressing will be analyzed.

b. To obtain data on the steady-state strength development rate characteristics of controlled test bonds when formed under the ranges of instantaneous conditions that are thought to occur within the laboratory board during pressing.

c. To integrate, using numerical methods, data obtained in a.) and b.) above in order to model the development of bond strength throughout the board during pressing.

d. To attempt to predict minimum pressing time on the basis of measured vapor pressure distribution versus accumulated bond strength (note again that initially, residual elasticity as a source of bond loading will not be accounted for).

e. To use the basic understanding gained above to identify approaches to improve the efficiency of board manufacture. This will concentrate on the effects on the system of using high moisture content veneers. Their effect on heat transfer, accumulated vapor pressure, bond strength development and compaction will be factors.

Veneer with moisture content values higher than those traditionally used in plywood manufacture are included in this study to analyze its effect on the system. The economical benefits of incorporating veneers with high moisture contents could result in shorter drying schedules, reduction in veneer shrinkage and degrade, and a moisture content of the complete laminate appropriate for its final end-use destination.

Chapter II

Discussion of literature

2.0 Introduction

Glue bond strength development, as it has been previously mentioned, is dependent upon wood characteristics, adhesive properties and processing parameters. Lying within each of these three components are many factors responsible for the final quality of the laminate.

To analyze the literature in detail for each one of these parameters would be very difficult and would not in any case fulfill the objective of this project. Still, a general description may be warranted in order to place the many contributory aspects which effect bonding during pressing of laminates in context. Emphasis will however be given to the approaches for glue bond strength evaluation and studies related to glue bond strength development during pressing.

2.1. The effect of wood characteristics on adhesion within hot pressed laminates

The effect of different wood characteristics on ultimate bond strength has been investigated by a number of workers (1, 2, 10, 12, 17, 22, 37, 47, 53, 60, 61, 86, 90, 96, 149, 151, 153, 160). Some of the most important wood variables influencing bonding are the following:

- The wood structure (proportion of earlywood to latewood, the density, porosity)
- Chemical composition of wood (cellulose, lignin, extractives, pH)
- Surface texture
- Surface energy (related to inactivation)
- Moisture content of the wood

Optimum wood characteristics for high quality bonding have been pursued by the analysis of these variables. Some of the more important among these will be considered here in turn.

2.1.1. Effect of wood porosity, density, earlywood and latewood on bonding characteristics

The anatomical differences between earlywood and latewood have been some of the main sources of problems associated with glue bonding of some species (10, 61, 63, 65, 90, 92). It has been pointed out that in general, delamination problems are more pronounced when bonding latewood to latewood than when gluing earlywoood to earlywood.

Some of the different bonding characteristics are attributed to density differences between the two types of wood, (8, 75). It is contended that the higher density of the latewood results in more variation in swelling and shrinkage. This leads to higher stresses on the adhesive bond both during resin curing and when the panel is put into its final use. The earlywood is also favored for its greater accessibility due to the larger voids of the fiber lumens. This, in turn, generates a larger active surface available for bonding (8, 75, 97, 105, 153).

In peeling veneer, summerwood tends to separate between cells or in the outer portion of the cell wall. This tends to expose surfaces rich in lignin. Springwood tends to separate, on the other hand, across the cell wall thus exposing the inner surface of the lumen which has the highest hemicellulose and lowest lignin content. Springwood areas with exposed lumens may present 2 to 3 times as many reactive sites for a given area, as well as a greater surface area than summerwood, (42, 75).

Evidently, a porous surface provides more sites for the adhesive to bond to. Furthermore, the greater the chemical reactivity of a wood surface, the more readily an adhesive will spread and wet it. If the lumen is not encrusted with extractives, its polar cellulosic polymers are easily wetted and spread by the adhesive (153). It should be stressed, however, that rough surfaces do not in general lead to good bonding. In many instances, rough surfaces imply damaged wood fibers which do not efficiently transmit load to the sound fibers below.

2.1.2. The effect of chemical components lying on the veneer surfaces

It has already been indicated that the chemical characteristics of the veneer surface play a major role in bonding. Of primary concern are the proportions of cellulose, lignin, and extractives, and the pH (1, 53, 60, 112, 135, 138, 149, 150).

Cellulosic polymers, the major component of the fiber wall (65-75 % by weight), are highly polar and have high surface energies that attract and bond to adhesives. Lignin (20-30 % of the cell wall) may be slightly polar, forming lower energy surfaces which are less attractive for gluing when adsorption is the major cause of adhesion. Extractives (0-10 %) may be polar molecules like the sugars, but other extractives are non-polar as oleoresins and fatty acids. When the non-polar extractives coat the wood surface, the surface energy is reduced and, as a consequence, its attraction to the adhesives (44, 145, 150).

The negative effect of fatty acids on bonding has been reported by several workers (60, 112, 138, 149, 150). Studies have been carried out on the various ways extractives could interfere with the formation of the glue-wood interface. They may form a barrier at the interface that may prevent wetting or cause mechanical weakness, thus changing adhesive properties and altering the normal flow and spreading of adhesive on the wood surface. They may also affect polymerization of adhesive at the interface.

The effect of the proportion of sapwood and heartwood on bonding is associated with the pH and the buffering capacity of the wood. These two characteristics are controlled primarily by the extractives which are found mainly in the heartwood zone. The pH and the buffering of wood affects gluing with crosslinking adhesives, accelerating or retarding the hardening of the resin (1, 53, 135, 150). To overcome this effect, acid catalysts are sometimes added to the adhesive for less acidic woods, lowering the glueline pH The amount of catalyst to be added depends on how strongly wood buffers the glueline pH.

2.1.3. Surface texture, surface inactivation, and veneer moisture content

Surface inactivation is the result of chemical reactions of the components on the veneer surface due to high temperatures of dry air in the veneer dryers. Decomposition of the wood by heat occurs at significant rates at temperatures above about 300 °F and causes hydroxyl groups to be condensed to form less polar ether linkages between the molecules. This reduction in polarity causes the wood surface to be less attracted to adhesives (29, 51, 149).

Veneer overheated during drying usually becomes surface inactivated. The magnitude and effect of surface inactivation is a function of time, temperature, moisture content and species. Most species of wood will tolerate a minute or two of surface temperature above 400 °F without being inactivated. But, these same species may withstand 20 minutes at 300 °F (29, 50, 51, 149).

Another effect of high temperatures is the melting of the extractives, coating the veneer surface, causing it to be less polar, and thus less wettable by adhesives. It has been observed (29) that even when glue had good contact with the veneer, a lack of chemical adhesion occurred due to oxidation of veneer surface. Redrying veneers obviously may increase the severity of surface inactivation (29, 31, 36, 51, 60, 101, 136, 149).

The texture of the veneer is a function of the wood characteristics and the processing parameters used in its production. Deep lathe checks on the face of the veneer, torn grain, and rough surface will be the result of poor cutting conditions. The difference in structure between the earlywood and latewood which determines the lumen size of the fibers, also affects surface roughness at the microscopic level.

The texture of veneer is important in bonding for its effect on the amount of glue required to fill the gaps to produce good contact between veneers. Platen pressure required to form good contact between the veneers and the adhesive are evidently also dependent. Compression losses may result from this interaction.

A rough surface with deep lathe checks requires more adhesive, which can be regarded as excessive waste of resin. The adhesive should also have good gap filling characteristics. Veneer peeled with a smooth surface has already many fibers cut open which provide sufficient roughness to give excellent adhesive bonds (23, 37, 47, 48, 65, 133).

The moisture in the veneer and the moisture from the glue mix affects both the depth of the adhesive penetration and the curing time of aqueous adhesives. Excessively damp veneer also produces "wash out" and steam blisters (blows). Applying pressure to such gluelines may cause deep adhesive penetration (22, 27, 98, 101, 144).

On the other hand, if the amount of adhesive is small relative to the amount of dry veneer (less than 5 % moisture), the veneer may absorb so much water that a dry immobile adhesive film forms prior to assembly of the veneer to be bonded (149).

Values of wood moisture content generally accepted as being appropriate for bonding varies with the type of adhesive and the bonding process. Processes involving elevated temperatures are generally thought to require a veneer moisture content less than 8 % because the moisture is thought to retard heating of the glueline and lead to excessive penetration. Suggested veneer moisture contents range from 2 to 5 % (101, 149). Evidently, these guidelines are based on empirical methods. Future work will attempt to establish more specific information on the effect of moisture content on adhesion. The conditions under which the adhesive cures varies throughout the panel with time as a result of heat and mass transfer.

2.2. The effect of resin composition on adhesion within the laminate

The most common resin presently used in the production of structural plywood is phenol formaldehyde. The relatively low cost of PF when compared with resorcinol, its appropriateness for exterior use and low emissions of formaldehyde when compared with urea justify this popularity.

Phenol formaldehyde resins are formed by polycondensation reactions between phenol and formaldehyde in the presence of a suitable catalyst. This can be a one or two stage process. For plywoood production, the one stage resin or resol is commonly used (140).

The main factors influencing resin properties related to bonding behavior include the percentage of solids content, resin pH, effect of molar ratio, fillers, extenders, and catalysts (24, 38, 39, 57, 63, 75, 102, 106, 131, 148, 157, 165). These variables may be manipulated to achieve specific resin properties. The tailoring of the adhesive to suite given wood characteristics to optimize bonding efficiency is common practice (7, 59). Such selection is, however, based largely on empirical or trial and error experience of the resin chemist and mill operator.

2.2.1. The effect of resin solids content

Resin solids content is generally thought to affect the rate of cure of the glue mix. Increasing the solids content leads to a decrease in the gel time of the resin. Veneer that absorbs water from the glueline too quickly will have limited glue transfer and penetration, and consequently the bonding characteristics will diminish (49, 63, 106).

2.2.2. The effect of resin pH

Resin viscosity increases as more acid is added. When the pH of the glue mix is reduced, the gel time decreases and the resin solids may tend to precipitate out of solution and cannot be redissolved without increasing the pH. The high pH of typical phenolic adhesive mixes may have a deleterious effect on the adhesive itself. This may be due to the increase in viscosity, the decrease in pot life, and the shorter assembly time tolerance (17, 106, 111).

2.2.3. Effect of molar ratio (formaldehide to phenol)

This ratio has been a major variable used to control phenolic resin properties, specifically the molecular weight distribution. Within certain limits, the greater the proportion of formaldehyde, the higher the molecular weight and the more reactive the resin. But on the other hand, if too much formaldehyde is added to the resin, the undesirable odor is detected and the resulting resin may become too brittle (58, 59, 102, 106, 117, 140, 152).

It has been pointed out (38, 39, 85, 129), that resin with a molar ratio of f/p less than 1.4 may not be suitable for bonding plywood. The size of the molecules is one factor which affects the penetration of resin into a wood substrate. Relatively low molecular weights may lead to resin overpenetration. This may produce starved gluelines which cause weak bonding (39, 50).

With a molecular ratio of 2.0, most adhesives achieve complete cross-linking and additional formaldehyde has only a minor influence on the cured resin (39). The most common molar ratio for phenolic resins used in wood composites ranges from 1.8 to 2.2 (24).

2.2.4. The effect of fillers and extenders

Fillers and extenders are added to reduce the cost of the mixed glue (reduction of solids) improve the application of the adhesive, improve prepressing, control penetration of the adhesive into the veneer, and improve the allowable assembly time and bonding quality of the mixed adhesive (75, 77, 110, 111, 131, 148).

The most common fillers and extenders are wheat flour and corncob flour. The former improves the water holding capacity of the adhesive thus avoiding dry out. Furafil or corncob flour extender increases the viscosity of the adhesive mix, makes the cured adhesive film less brittle and improves its gapfilling characteristics. In addition, walnut shell flour may also be used to impart water holding capacity and improve viscosity (77, 115).

2.2.5. The effect of catalysts

The catalysts for making resols are usually caustic soda and ammonia. Barium hydroxide, potassium hydroxide and sodium carbonate are also used on occasion (57, 157).

Caustic soda induces a faster reaction than ammonia and in general gives fast-curing resins. It is mainly used for making liquid resins and it is preferred over the others for its high solubility and low cost. Sodium hydroxide is usually commercialized as 50% aqueous solution (106).

The amount of catalyst in a phenolic resin is generally specified as some percentage of the phenolic charge. The proportion of caustic soda used varies between 0.1% to 1.0% of the weight of phenol (147). When the catalyst level is low, the reaction rate and the molecular weight distribution will be different than when the catalyst level is high (59, 118). As total NaOH content is increased, gel-times and nonvolatile contents also increase. Thus, an optimum amount of NaOH is needed to keep the resin soluble and low in viscosity, but not so much as to increase resin gel-times and glueline cure time excessively. Sodium hydroxide additions decrease viscosity drastically at first, then gradually, after that, viscosity will increase when still more NaOH is added.

2.3. The effect of platen pressure, platen temperature, and pressing time on adhesion within the laminate

The most critical stage of laminate formation is the pressing of the boards. During hot pressing, the interaction of temperature, pressure and pressing time is critical for the formation of the laminates.

Phenolic adhesives cure at elevated temperatures - having activation energies in the order of 50 KJ/mol (67). For bonding of veneer, moderate pressures to achieve good contact between the adhesive and wood are also required. The time necessary to cure the glue to an appropriate level may range from a few minutes at 150°C to 24 hours at 50°C. The characteristics of the adhesive and the heat transmission of the adherend are the determinant factors (32, 57, 76, 87). The relationship between temperature and bonding rate is a major emphasis of the present work and will, therefore, be considered in greater detail in chapters IV, VI and VII. Each of these factors (pressure and temperature) will be considered here in general terms however.

2.3.1. The effect of platen pressure

The principal function of platen pressure in bonding is to force all areas of the veneer surfaces together uniformly so that the adhesive can flow and wet all areas of the bond line. If the veneer surfaces were smooth and uniform in thickness, they may be bonded with pressures not greater than 50 psi (78). Another function of pressure is to hold the veneer together during the adhesive curing process, especially when the vapor pressure in the glueline is increasing and would separate the veneer assembly. As will be demonstrated later in this research, the destructive influence of accumulated vapor pressures within the panel have to be countered by the platens.

As a rule of thumb for plywood, it is suggested to use as much pressure as the veneer can withstand without significant crushing of the wood structure. This maximum pressure depends on the density of the wood used and the combined effect that moisture content and temperature have on the strength of the veneer. Higher pressures of 1 to 5 MPa (150 to 250 psi) are used on dense hardwoods such as oak or maple, while lower pressures are used on the lighter softwoods (6, 36, 49, 78).

2.3.2. The effect of platen temperature

Wood is a relatively poor heat conductor. In order to achieve acceptable rates of cure at the center of the panel, it is necessary to apply platens at significantly elevated temperatures. The minimum pressing time will depend on the integral effect of time and temperature during the heating-up process. The controlling factors include the reactivity of the adhesive (activation energy), the temperature recovery capacity of the heated platens, the mass and thermal diffusivity of the assembly to be heated and the distance from the platens to the deepest glueline (76, 118, 125).

For hot-pressed plywood, platen temperatures range from 120 to 150°C and press times will vary from 1 to 2 minutes for 6 mm thick assemblies (2 mm to the deepest glueline). Three to four minutes are used for 12 mm assemblies (4 mm to deepest glueline), and up to 10 minutes or more for thicker assemblies (25 mm or more). The primary processes which affect the thermodynamic conditions under which the adhesive cures are dependent on heat and mass transfer.

2.4. The effect of heat and mass transfer during hot pressing

The rate of cure of thermosetting resins is dependent on temperature, and the temperature in the inner portion of the panel during hot pressing is a function of heat and mass transfer. Heat transfer is associated with wood characteristics and with pressing parameters. The thermal conductivity of wood is related to density, moisture content, fibrillar orientation, direction of heat flow (radial, tangential or longitudinal direction), and structural irregularities (checks, knots) (80, 83, 126, 132, 142, 147). The processing factors in laminate manufacture associated with heat and mass transfer are the platen pressure, platen temperature, and pressing time (26).

It has been pointed out (54, 130) that in flakeboard manufacture, heat transfer during hot pressing is mainly by convection and conduction. The convection effect is related to phase change and subsequent movement of vapor from the surface to the inner portions of the panel. It is highly likely that a similar combination of processes is operative in laminate pressing, though their relative magnitudes may differ significantly.

At the beginning of the pressing cycle, the panel surface equals the platen temperature, and the rate of heat transfer from the platen to the wood is governed by the temperature gradient immediately below the wood surface. However, as pressing continues, the rate at which heat moves through the board from the surface is primarily a function of moisture content. The moisture in the outer layers is converted to steam within seconds after the press closes (phase change). The vapor pressure gradient in the air voids at the surface rises accordingly. Thus a vapor pressure gradient is established from board surface to the inner portion of the laminate in response to the temperature gradient. It is the pressure gradient that causes water vapor in the form of steam to flow toward the inner portion of the laminate. It was further concluded (132) that only live steam penetration to the center of the board could cause such rapid temperature rises, and that it seems unlikely that moisture flows in the liquid state.

The positive effect of moisture content on the rate of heat transfer may, however, become a negative aspect in the rate of curing of the resin. This may be especially true if the amount of moisture exceeds certain limits (37, 81, 101, 149). Furthermore, the additional increment of stress produced by vapor in the board during pressing accounts for another negative effect of excessive moisture. The strength of the glue should overcome a higher vapor stress to avoid blows during press opening. Vapor pressures have been measured within panels in the present project. These methods are described in chapter IV.

It was also pointed out (132) that heat conduction is dependent, in part, on the platen pressure. The higher pressures give more intimate contact between components, thus enhancing heat conduction. Radiation, on the other hand, may contribute only slightly to heat flow across air voids in a particleboard; its effect can be considered insignificant.

The concept most commonly related to the rate of polymerization of the resin is the effect of temperature as it has been previously mentioned (13, 57, 76, 87). Temperature in the panel during hot pressing is measured mainly with thermocouples (15, 36, 125). For this project thermocouples were used to record temperature distributions throughout the board during hot pressing. This is described in chapter IV.

2.5. A review of approaches used to assess adhesive cure within the panel

Techniques for measuring bond quality through assessment of the degree of cure of the glue have relied largely on indirect approaches. Three broad types of procedure seem to be most widely adopted: percentage of wood failure, spectroscopic analysis and differential thermal analysis. Each one of these will briefly be critically considered in turn before going on to introduce the more direct method of adhesive characterization adopted in the present work.

2.5.1. Percentage of wood failure

One of the most common methods of glue bond strength assessment deals with the interaction of wood failure with glue bonding. When this interaction is used, the efficiency of bonding is indicated by the percentage of wood failure caused during delamination of the joint by some mechanical testing (8, 33, 37, 42, 50, 91, 158). This concept is so traditionally accepted that most of the specifications of good quality plywood are based on percent of wood failure (American and Canadian Standards). Some other standards, however, (German) require only a certain level of plywood shear strength, (37). In exterior type panels, for example, the specimens taken from the board should average 85% wood failure or greater. At least 75% of the panels represented by the test pieces should give 80% wood failure or better

(37, 50).

Another aspect of the wood-failure concept is for differentiation between the adhesive and cohesive strains in a panel. When wood is strong and glue is adequately cured, the percent of wood failure, as previously stated, is an important measurement of adhesive strength; and low wood failure indicates poor glue-wood adhesion. When wood failure is high, the adhesive force is equal to or higher than the cohesive strength of wood, and this indicates good wood-glue adhesion (29).

The validity of using percentage of wood failure alone as an indicator of bond strength has been questioned in many cases (33). The effect of different wood characteristics is said to be of prime importance on the percent of wood failure method (53). Different test specimens, species, panels, and different classes of adhesives are some factors affecting the percentage of wood failure as an estimate of bond quality (30, 87, 99). For example, panels with torn and crushed veneer surfaces show higher wood failure because of the damage of the earlywood than those with clean cut veneer surfaces. When different species are tested, the weaker woods should have low breaking loads and high percent wood failures, whereas the stronger wood should have higher breaking loads and lower percent wood failures. Stronger woods might fail within the springwood fraction. As a result, the percent of wood failure may reflect the percent of springwood in the specimen (65, 99).

Another approach to avoid the wood failure anomalies as a measurement of bond strength is the interpretation of the shear strength values of the panels (33, 37, 99). Apparently by this procedure, the veneer surface characteristics and the adhesive are taken into account in assessing bonding efficiency. For example, the effect of different lathe-check depths on percentage of wood failure was not significant, but for shear strength it was an important source of strength variation. For every reduction of 1% in lathe-check depth there was a shear strength increase of about 1.2 psi. Moreover, the orientation of these lathe-checks was also considered an important cause of shear strength reduction (37). It has been suggested that, in general, any imperfections in core veneers will cause a reduction of tensile shear resistance in plywood (37).

As already stated, these techniques provide no indication of rates of strength development but only final board performance. Certain chemical techniques may be used to indirectly monitor adhesive cure as it progresses. Some of these are considered below.

2.5.2. Spectroscopic analysis

Spectroscopic analysis has been used to determine the degree of cross-linking of thermosetting adhesives. The ratio of intensities of ultraviolet absorption bands of phenol formaldehyde resin at 287 and 302 mu wavelengths correlate well with the degree of cure of the glue mix (27). This technique has been applied to measure the effect of temperature and pressing time on the degree of cure of the resin at different moisture contents and different molar ratios. It has been pointed out (27) that the water, either from the resin or produced from the condensation reaction, may retard the initial cure of the glueline and hence prolong the curing time when the curing temperature is lower than the boiling point of water. Furthermore, it was suggested that the critical temperature for bond formation in gluelines lies between 100 and 110 °C. As a result of these observations, it was concluded that the 5 minutes and 140 °C setting used in industrial plywood manufacturing could not cause complete cure of the glue.

Using spectroscopic analysis, a well defined relationship was found between curing rate, temperature and moisture content. The curing rate increased with an increase of temperature and decreased with an increase of moisture content (32). The curing time for veneer with moisture contents of 7 to 12 percent was 12 and 15 minutes respectively, to reach 80% degree of cure at 120 °C. At 140 °C, curing times are 6 to 11 minutes respectively.

The effect of molar ratio on the degree of cure of phenolic resin has also been analyzed by spectroscopic techniques. It was found that the decrease in ultraviolet intensity ratio was associated with an increase in molar ratio, reflecting the extent of cross-linking reactions of phenolic resins. At molar ratios of 1 to 1.2 (formaldehyde to phenol), insufficient formaldehyde is present to complete cross-linking and insolubilization of the resin results (97).

Again, these techniques, useful as they may be to the resin chemist, do not enable a direct understanding of bond strength development rates to be achieved. These rates are required for the work in hand.

2.5.3. Differential thermal analysis

Thermograms obtained through Differential Thermal Analysis (DTA) have provided another indirect method to evaluate resin cure (18, 30, 32, 74, 82, 97, 116, 156). It has been pointed out that phenolic resins show two endothermic peaks, one in the region of 122 to 135 °C and the second in the region of 145 to 170 °C.

The first endothermic peak is said to be caused either by the heat of water evaporation or by an endothermic reaction of the adhesive polymerization. In either case, it is considered to be important to initial curing of the resin. The second endothermic region is related to the final curing of the resin. At the maximum level of the first peak, the degree of cure (cross linking) is estimated to be 60%. At 150 to 168 °C, the temperature before and after the second endothermic reaction, the degree of cure is from 92% to 100% respectively (30). It was suggested (39), that bonding between veneers starts to occur at 140 °C. At 150 °C, the strength of the bond as expressed in wood failure percentage is still below 80%. When the glueline temperature reached 160 °C, strength, as indicated by wood failure, is fully developed. Furthermore, it has been emphasized (32) that at 160 °C the adhesive cures rapidly regardless of the high moisture content of the specimens. Experience gained by directly testing strength development of urea formaldehyde thermosetting resins (14, 66), suggests that the above conclusions may be an oversimplification of the process. It is not reasonable to state adhesive cure solely in terms of curing temperature; duration of cure at that temperature is also a factor. This issue will be further considered when describing methods to be used in the present study.

2.5.4. Other testing methods

A range of other approaches have been used. Some of these will be described below.

THERMAL SOFTENING TEMPERATURES: Attempts have been made to relate the thermal softening temperature of the resin with its degree of polymerization (35, 41, 117). It has been stated (35) that the amorphous polymers at low temperatures are similar to crystalline polymers in a glassy state. When the temperature is elevated to the point where micro-Brownian motion takes place, the configurational change of a polymer molecule decreases sharply over the specific temperature or glass transition temperature. Because of the difficulty to determine an accurate glass transition temperature due to the broad range of temperatures that the glass transition of molecular polymers take place, the thermal softening temperature has been used.

By measuring the compressibility of a small column of adhesive powder under constant load during heating, the adhesive softening temperature is measured at the temperature at which reduction in column height of the adhesive was initiated (41). However, softening temperature does not reflect the degree of adhesion between adhesive and wood, instead, only one of the properties of the adhesive.

X-RAY FLUORESCENCE ANALYSIS: The degree of cure of phenolic resins has also been measured by the amount of bromination determined by x-ray fluorescence analysis. It was found (34) that the x-ray procedure would be more suitable at high degree of cure when there is little or no water-soluble fraction. When this is not the case, the ultraviolet method should be preferred.

VIBRATIONAL METHOD: During cure, an adhesive undergoes physical, mechanical, and chemical changes. Measurements of mechanical changes by vibrational methods have also been analyzed to determine the transitional stages of the glue during polymerization in a glueline (108). The free vibrational properties indicate that bond strength starts to develop at the gel transition. The strength continues to increase during the rubbery state but decreases sharply at the glass transition.

DYNAMIC MECHANICAL THERMAL ANALYSIS: The value of storage and loss moduli and damping capacity, which are highly correlated with temperature, are determined by dynamic testing to characterize polymers.

A dynamic instrument based on the aforementioned relationship has been developed to carry out dynamic mechanical thermal analysis -"DMTA" (155). The instrument introduces to the sample a forced vibration at different frequencies. The relative amount of damping or energy loss is found by the extent to which the cyclic strain lags behind the applied stress wave. The DMTA senses any change in molecular mobility in the sample to be tested as the temperature is raised or lowered.

2.5.5. Drawbacks of the testing techniques described when used in the present study

Correlation of literature references of bonding strength behavior is rather difficult because of the inconsistent results. Some possible reasons for this discrepancy could be the use of different resin components and reaction process, and the use of different methods of sample preparation and instrumentation.

Disadvantages of the indirect methods for bond strength development determination have been pointed out (14). Some of the indirect methods involve the introduction of additives and tracers into the resin which may affect the curing process. It is considered that glue mix prepared under experimental conditions may differ in its properties from those formed in commercial practice. In some testing methods of adhesives the polymerization is halted by cooling. Such cooling may introduce unknown changes either in the chemical reaction of the resin or as stresses into the bond. Methods involving physical and mechanical properties related to gelation assume a relationship between rate of curing before and after gelation. This has not been proved and indeed seems unlikely in the light of subsequent studies (66).

To overcome these disadvantages in assessing bond strength development, a direct mechanical testing technique has been used to determine tensile strength values (14). Small wood to wood test bonds are formed and tested to destruction under carefully controlled conditions. The use of thin wood wafers enables heat to be transferred rapidly to the glueline. Each test bond is formed in a specially manufactured jig mounted on the universal strength testing machine (instron). The bond is cured under near constant temperature conditions. When the desired pressing time (between 10 and 600 seconds) has elapsed, the joint is immediately pulled apart by reversal of loading. This procedure is repeated with temperature and pressing time as main variables. Activation energy values for strength development were demonstrated to be useful in evaluating the effect on bonding of different resin components, and wood moisture content on activation energy for strength development (66).

Since the philosophy involved in the direct tensile method aforementioned has been proven to be successful for bond strength assessment of UF resin, an approach involving a similar principle, but different design of equipment technique, will be applied in this research project to assess FP bond development. The principle of the technique will be outlined in sections to follow.

Chapter III

The Research Strategy

3.0 Introduction

In plywood manufacture it is vital that portions of the laminate do not delaminate when the load applied by the heated platens is released at the end of the pressing cycle. To prevent this failure, inter-veneer bonds must have developed enough strength to withstand internal stresses. These stresses result both from residual elasticity of the veneers and from the pressure of water vapor accumulated within the board. Consequently, one of the prime factors affecting the attainment of acceptable physical properties for the panel must be how the adhesive bonds develop strength during pressing. This is a major emphasis of the present work.

Traditionally, pressing parameters and raw material combinations have been selected mainly on a trial and error basis. Resin chemists working in cooperation with the technical personnel of the mills have usually undertaken these tasks. This approach has been followed partly because of the complexity of the factors involved in achieving optimum bonding conditions within the panel, and also due to the lack of appropriate techniques to evaluate the effect of pressing conditions on bonding.

In attempting to optimize pressing cycles, it is of prime importance to go beyond the empirical approaches so often used in the past. It is necessary to tackle the problem by attempting to understand the nature and interaction of fundamental physical processes operative within the system during pressing.

This more basic and quantitative approach is appropriate, not only for optimizing plywood, but also for new product development. It is therefore proposed to outline these basic process areas and their interactive nature at this stage, before going on to describe the actual approaches to be used in the present work.

3.1 Processes operative within laminates during pressing

The overall pressing arrangement is represented schematically in Figure 3.1. The laminate, consisting of wood, adhesive and water is acted upon by the platens of the hot press. These impart both the physical compression and the source of heat to the system.

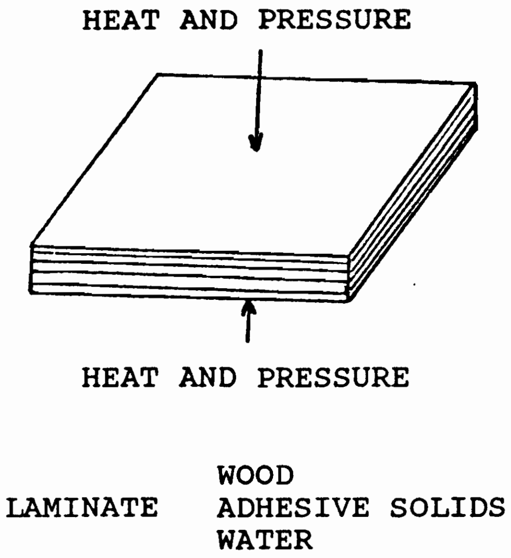


Figure 3.1. The basic pressing arrangement represented schematically.

The processes operative within the material may be divided into three broad categories: heat and mass transfer, rheological behavior and adhesion between the veneers. The validity of these sub-divisions becomes more evident when tackling the system experimentally.

a). Heat and mass transfer:

Conductive heat transfer from the platens to the face and back veneers causes bound water to undergo phase change. Vapor pressure and temperature gradients are therefore established in a direction perpendicular to the laminate surface. Simultaneous transfer of both heat energy and water (in vapor form) results. Gradients of temperature, moisture content and vapor pressure are established in the three dimensions of the laminate.

Horizontal (in plane) gradients are primarily the result of the escape of vapor through the edges of the board where only the partial pressure of water vapor in the atmosphere prevails. Changes in temperature and moisture content distribution during pressing are the main aspects considered in this study. This emphasis results from our concern with the rate of polymerization of the adhesive and resultant bond strength development. Heat and mass transfer is a complex area which is receiving analytical attention elsewhere (67).

b). Rheological behavior:

Densification occurs within the cross section of the laminate during pressing. The rate of this compaction depends upon the combined effect that heat and moisture have on the viscoelastic properties of wood material together with the magnitude of applied platen load. This interaction affects the strength properties and the final dimensions of the laminate, as well as the behavior of the whole system during pressing.

c). Bond strength development:

The rate at which glue-veneer interfaces develop bond strength is an important factor in controlling the integrity of the panel when the press is opened. These rates depend largely on the thermosetting adhesive's response to temperature and moisture content values. Upon press opening, inter-veneer bonds have to counter destructive loads resulting both from residual elasticity of the veneer and residual internal vapor pressure.

Polymerization of the resin leads to strength development of inter-veneer bonds, while vapor pressure is generated within the panel from the phase change of moisture resident in the veneer. This moisture comes in part from the partially dried veneers and that added with the adhesive solution. A numerical approach to these factors - the positive effect of the accumulated strength of the glue bond and the destructive effect of vapor - is essential for pressing cycle optimization. Residual elasticity's role in effecting the balance is difficult to evaluate. It is certainly likely to be less significant in this laminate (veneer) system than in other particulate type composites where free thickness changes are restrained by flake overlapping. In this initial study, no attempt will therefore be made to numerically account for the effect of residual elasticity on the behavior of the system.

The main processes and their main interactions are represented in Figure 3.2.

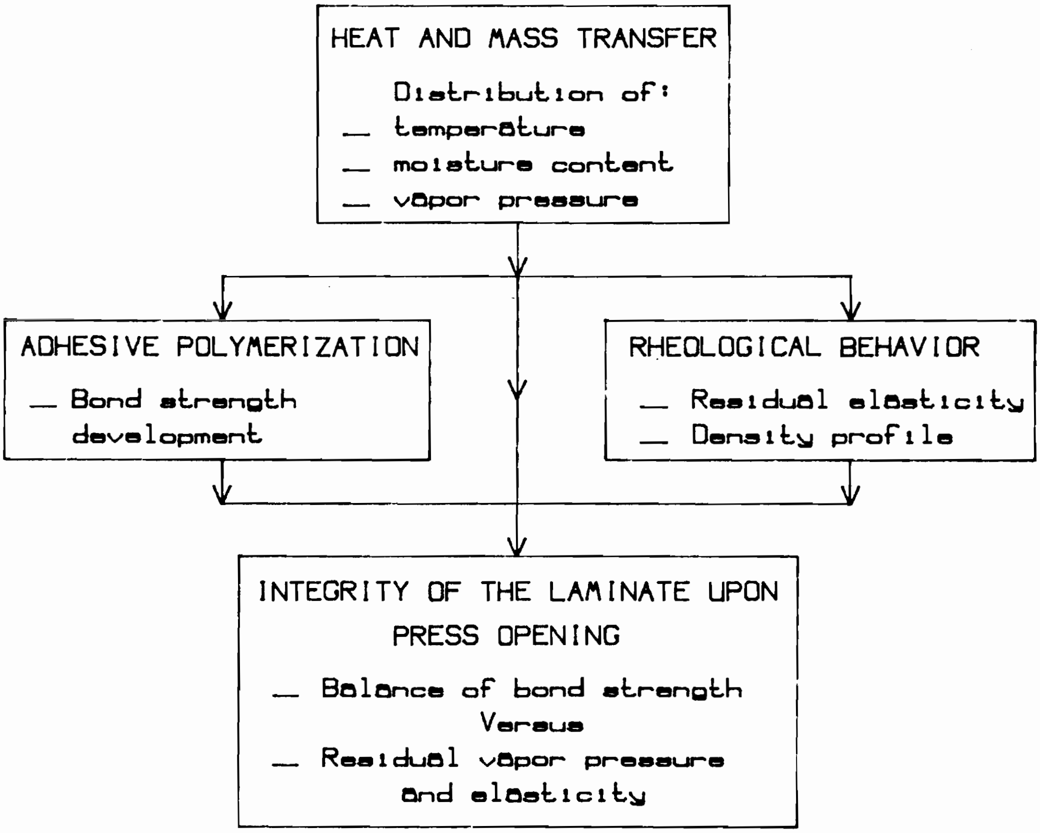


Figure 3.2. Effect of heat and mass transfer on polymerization of resin and rheological behavior, and some of their interactions.

In summary, heat and mass transfer depends on conduction, phase change, and vapor convection. Temperature and moisture content affect the viscoelastic properties of the laminate material. The rate of bond strength development depends primarily on temperature and moisture content. It is the effect of temperature on bonding in the system which will be given the greater attention in the present work. The analysis of the effect of moisture content on the rate of polymerization of the resin requires the development of further experimental methods for its investigation. These are underway in complementary projects at Oregon State University.

3.2. The principles underlying the experimental approaches

To achieve the goals of this project, two different testing approaches are involved. Firstly, heat transfer and compression that occurs during the pressing of actual panels in the laboratory were investigated using a range of different veneer moisture content and platen pressure values. Secondly, glue bond strength development rates were investigated as functions of temperature. This involved forming test bonds between carefully prepared small wood wafers under the range of conditions recorded during panel pressing. Detailed descriptions of these approaches appear in chapters IV and VI, respectively. The underlying experimental principles for each will, however, be summarized in turn here. Prior to this, attempts will be made to justify decisions regarding the selection of primary raw material and processing variables used in the study.

3.2.1. Species and adhesive selection

Wood species and resin type are common to both experimental sections and will therefore be considered here, before going on to each experimental portion in turn.

a). Wood species selection:

Douglas-fir (Pseudotsuga menziesii (Mirb. Franco) veneer was used in this project since it represents one of the major species utilized by the plywood industry in the Northwest USA. By choosing this species it was intended that the results generated from this project would be of immediate benefits to the established industry. Moreover, it will also enable some ready comparison with the results of empirical data already available in the literature. The coarseness and variability of the material does, however, present some experimental difficulties. There was some debate when planning this project regarding the use of a species with significantly less variability (eg cottonwood).

b). Adhesive selection:

Thermosetting adhesives are the most widely used resin type for laminate manufacture. From the thermosetting group, phenol formaldehyde is one of the most common resins for exterior type panels because it produces bonds that withstand exterior conditions as compared with urea formaldehyde. It also enjoys a price advantage over resorcinol resin. A phenolic resin system will therefore be used in the present project. Many of the analytical techniques may, however, be modified with a range of new and alternative adhesive systems in the future.

c). Resin composition:

It was pointed out in chapters I and II that the properties of the resin are dependent on the proportion of its different components. For this project, however, only one type of resin was used. By maintaining the resin characteristics constant it is expected to reduce the number of possible combinations of factors that could be varied during laminate manufacture. This is in order to simplify the analysis of data for better understanding of the system.

3.2.2. Methods used to characterize laminates during hot pressing

Five ply panels were pressed under laboratory conditions. Internal temperature and vapor pressure and compression of the laminate were measured throughout pressing. Initial veneer moisture content and corresponding required pressing loads were varied.

Distribution of temperatures within the panel were measured with thermocouples positioned in a range of vertical and horizontal locations. These lay within the four gluelines and their outputs were monitored throughout the pressing time of the board.

Vapor pressure was measured using fine hypodermic tubes which were embedded in the panel prior to lay up, and externally connected to fluid pressure transducers. This enabled pressures at the ends of the tubes (within the panel) to be monitored. Detailed description of this procedure appears in chapter IV. Two vapor pressure measurements were recorded for each board pressed.

Compaction of the panel as a result of platen pressure was measured throughout pressing.

Glue mix was spread on the veneers once the thermocouples and the hypodermic tubes were afixed to the appropriate plies. Temperature and vapor pressure data was collected and stored during the pressing cycle with the aid of a microcomputer.

The sequence of the activities for data collection during pressing of the laminate involved the following:

- Preparation and conditioning of veneer
- Placement of probes
- Glue spreading
- Lay up
- Pressing and data collection
- Data manipulation (temperature, vapor pressure, and compaction vs. time).

Justification for selection of primary material and manufacturing variables are provided below. Experimental details will, however, be dealt with in chapters IV and VI.

a). Veneer dimensions:

Although the most common veneer thickness produced in industrial operations is 1/10 inch, it was decided to use 1/8 inch thick veneer. This decision was influenced by practical factors related to vapor pressure measurements.

The length and width of the veneer samples (2'x2') were determined by the dimensions of the platens of the experimental press. It is reasonable to expect differences in behavior between the laboratory panel and the industrial laminate to be caused by size difference. Laboratory results will therefore need to be adjusted for comparison with industrial laminate production. This difference primarily relates to the pressures of accumulated vapor which are dependent on the distance from the center to the edges of the panel. The relationships are not likely to be linear (67).

b). Veneer quality:

High grade veneer was used to minimize variability of results. This was necessary to highlight trends in the parameters of interest.

c). Veneer moisture content:

Three values of veneer moisture content were chosen: 6%, 12%, and 16%. Veneers with moisture contents higher than that traditionally used in plywood manufacture were included in this study to analyze its effect on the system, (primarily heat transfer, rheology and internal vapor pressure). The economical benefits of incorporating high moisture content veneer in the system could be reflected in shorter drying schedules, reduction of shrinkage and degrade, and the moisture content of the final laminate being near that of its final destination.

d). Number of plies in the panels:

The number of plies, 5, was selected according to the most common type of structural panels produced by the industry. It was also expected that within the cross-section of a 5 ply panel the distribution of temperature and vapor pressure would be well defined.

e). Glue spread rate:

The rate of glue applied to the veneer was selected according to the specifications of the resin manufacturer for industrial operations: 60 lb/M.sq.ft.DGL for the 300°F platen temperature. The proportion of glue usually changes slightly in response to platen temperature and pressing time: varying from 50 to 67 pounds for 1/8 inch core.

f). Platen temperature:

The platen temperature applied to the laminate was 300 °F. This temperature was constant throughout the experiment and was selected based on the indications of the resin manufacturer. Future analysis should include investigation of this important variable.

g). Pressing time:

The pressing time suggested by the resin manufacturer for industrial operations for similar types of laminate is between 4 1/2 and 6 minutes. This depends on platen temperature and the glue spread rate. In response to the objectives of this project however, the pressing times chosen were 600 and 1000 seconds. These were selected in order to obtain well defined trend of temperature and vapor pressure distribution within the panel, as well as board compaction. It was found through experimental trials that for "standard" industrial pressing times (300 seconds), vapor pressures and temperatures were still rising. Without using the longer pressing times specified here, important information regarding the behavior of these parameters would not have been collected.

h). Platen pressure:

The platen pressure normaly applied in industrial production of Douglas fir plywood is 175 psi. This pressure was applied here to the board established as a standard in the present study. Additionally, two other pressures were analyzed, 100 and 125 psi. These pressures were selected for two reasons: 1). To avoid excessive compaction of the laminates with the higher veneer moisture contents. From preliminary trials it was found that with platen pressures higher than 125 psi the compaction of the boards was very drastic. 2). With a pressure lower than 100 psi, a weak veneer-glue interface may result. It has been reported that even lower pressures could be used, but this may be so with smooth veneer (78).

3.2.3. Bond strength development evaluation - experimental principles

Due to the difficulty of directly measuring the strength development of inter-veneer bonds during pressing of the laminate, an alternative approach was followed.

Lap shear joints between wood wafers were formed and tested to establish the strength development characteristics of PF resin to wood bonds. The aim was to maintain curing conditions constant in a number of test bonds and to break these in shear after a range of pressing times. This enabled accumulated strength vs. time curves to be constructed for the corresponding temperatures. Then, repetition of this procedure using a range of temperatures enabled a set of such strength development lines for the gluebond to be constructed. Constant curing conditions for selected temperatures are obtained by the rapid transfer of heat to the glueline of the thin wood wafers. Near steady-state temperature conditions are therefore achieved during pressing. The range of steady-state temperatures investigated encompassed that known from the board pressing study to occur in the core of the panel during pressing.

The wood specimens were prepared from clear Douglas-fir strips measuring 150x20x1.5 mm. They were machined and conditioned prior to the beginning of testing. Each test bond was formed in an electrically heated jig which was mounted on a universal testing machine. When the appropriate pressing time elapsed, the lap joint formed was pulled apart in tension and its strength recorded. The bond was therefore tested hot. A diagram of a glued wood wafer sample is shown below in Figure 3.3.

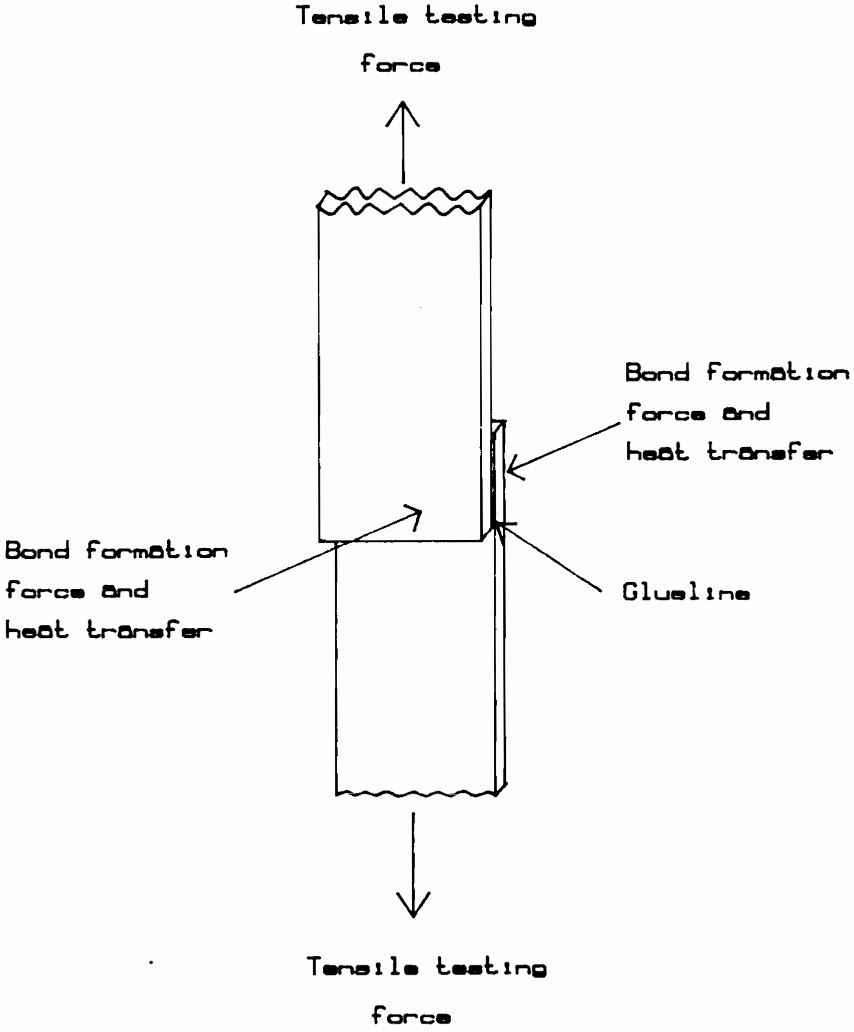


Figure 3.3. Schematic representation of joined wood wafers for glue bonding evaluation.

The activities involved for data collection of glue strength evaluation consisted of:

- Wood wafer preparation
- Glue spreading
- Bond formation and immediate strength testing
- Production of a strength vs time relationship for each of the temperatures tested.

The use of this derived data for bonds formed under near steady-state temperatures is considered below.

3.2.4. Integrating processes related to the pressing cycle

By integrating the information collected throughout the two experimental approaches described, attempts will be made to develop a quantitative understanding of the balance of destructive forces and cohesion within the laminate. This approach is the first step towards the development of rigorous approaches to press cycle optimization and minimization of pressing times.

By comparing the stress resulting from internal vapor pressure with the accumulated strength of the glue bond, a minimum pressing time of the board may be projected. This may be defined in terms of the time at which the strength valueof the glue bond just overpasses the stress value of internal vapor. Any increase in time beyond this period may assure a higher bond strength value and perhaps a decline in vapor stress. Thus, the possibility of blows or delaminations will decrease at the expense of reduced press output per unit of time.

The natural variability in localized values of pressure and bonding in the mill situation does, of course, also have to be considered when selecting minimum press times on the basis of such theoretical numerical approaches. This variability, both within and between panels, will result primarily from irregular moisture distributions within the veneers leaving the dryer, together with variability in the physical properties of the veneer.

The reliability of these approaches and possible extension of the methods will be discussed later in the thesis.

Chapter IV

Measurements on boards during pressing in the laboratory: Experimental methods

4.0 Introduction

Three basic factors were investigated during board pressing. These were temperature and vapor pressure distributions within the panel, and compaction (thickness reduction) of the laminate during the pressing cycle.

The trends of these factors were measured initially for what was established as a "standard board":

- Veneer moisture content --------------------- 6%
- Glue spread rate of ---------- 60 lb/M bd.ft.DGL
- Platen pressure of -------------------- 175 psi
- Platen temperature of ----------------- 300 °F.

By keeping these parameters constant it was intended to gain a basic understanding of the interdependence of measured variables for the typical system while limiting replications to a manageable level. This approach was adopted due to the complexity of the system; only a limited number of variables can be efficiently investigated in a study of this size. Identifying a standard set of material and pressing values, and then varying selected ones in turn, while keeping the remainder constant, seems to be the only way to tackle such a complex system.

A description of the different steps required to achieve the stated goal follows. Firstly, a general description of material preparation and panel pressing is outlined. The procedures for data collection of each one of the parameters of interest are then considered in turn. Data reduction, prior to analysis of the processes operative within the laminate, is the subject of chapter V.

4.1. Panel manufacture

The activities required for collection of data for characterization of the laminates during hot pressing involved the production and preparation of veneer, formulation and application of adhesive, configuration of the panel and finally hot pressing of the laminate. A description of methods used for panel manufacture follows. All techniques associated with the collection of data during the pressing stage (including probes and their positioning) will, however, be dealt with in subsequent sections.

4.1.1. Production of veneer

All veneer for the project was produced from a specially selected log with a regular and concentric growth ring distribution, cylindrical form and relatively free from external defects. Prior to peeling, the log was softened in a steam bath chamber according to the softening schedules of the mill. The log was then peeled with a newly ground knife and special care was taken in setting the lathe knife and bar to produce smooth veneer during peeling.

The cooperation of Sun Studs, Inc. for donating the log and producing the veneer at their mill in Roseburg, OR. is appreciated. The assistance of the mill personnel in selecting and peeling the log so carefully to produce the veneer with the specified characteristics played an important role in reducing the variability in experimental results.

4.1.2. Preparation of veneer

Veneer in 8x4 feet (nominal) sheets was shipped from the mill to the Forest Research Laboratory. The green veneer was close stacked and covered with plastic to minimize water loss. The stack of veneer was sprayed with water every other day to keep it wet. While still green, 2x2 foot samples were obtained from the original sheets of veneer by cutting around defects with a hand-held circular saw.

The veneer samples were carefully stacked using 1/2 x 1 1/2 x 48 inch stickers between every two pieces of veneer, as depicted in Figure 4.1.

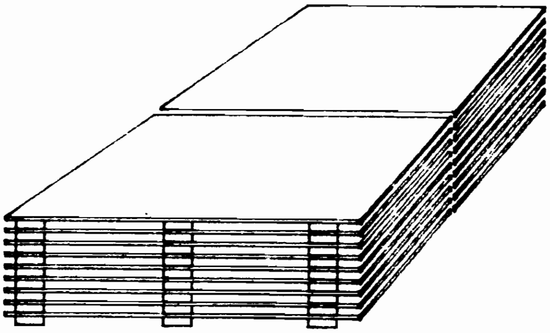


Figure 4.1. Configuration of stacked veneer samples.

Three stacks were formed, placing each in different conditioning rooms with relative humidity and temperature values adjusted to maintain 6%, 12%, and 16% nominal equilibrium moisture contents (EMC). The variation in moisture content of the veneer after equilibrium was reached and the number of veneer samples for each selected moisture content is specified in Table 4.1.

No. of veneer samples	Nominal moisture content	Moisture content variation between samples
200	6 %	6.1 % - 6.5 %
120	12 %	12.03 % - 12.42 %
60	16 %	15.08 % - 15.9 %

Table 4.1. Number of samples for the selected veneer moisture contents and their variability.

4.1.3. Formulation and application of adhesive

Glue-mixing:

The phenol formaldehyde resin (Cascophen 3128-M) with original solids content of 41%, was kindly donated by Chembond Inc (Springfield, OR). In the final adhesive, solids content was reduced to 28% according to the specifications of the resin manufacturer. For the preparation of the adhesive the following components were used in the specified sequence and mixing time according to the suggestions of the resin manufacturer. These are outlined in Table 4.2.

Component	Percentage of total (by weight)	Mixing time
Water at 90°F	16.09	Short mixing
Resin	6.90	
Gluefil	4.60	5 minutes
Wheat flour	6.90	
Resin	11.50	Short stir
50% Caustic solution	3.45	10 minutes
Resin (41% solids	50.56	10 minutes

Table 4.2. Components and mixing time for the adhesive.

Each one of these components was carefully measured and added at specified elapsed mixing times. Great care was taken to follow set routines for adhesive preparation so that variations between batches was kept to a minimum. The amount of glue mix prepared per batch was 2.5 pounds. With this quantity there was enough adhesive for the manufacture of four panels within a 5 hours working period. Within this period, no significant change in adhesive properties (particularly viscosity) was detectable.

The glue was applied to the veneer with a hand roller. This procedure proved to be efficient for achieving uniformity in the amount of glue being applied. A mechanical roll spreader was used initially. Difficulties were, however, encountered when pressure and temperature probes were incorporated. Considerable time was devoted to developing techniques and personal skill to achieve uniformity of spread with the hand roller. This was considered a critical factor in the project, not only because of the direct effect of resin solids on bonding but also because of the major contribution to overall panel moisture content made by the adhesive.

4.1.4. Lay-up and panel pressing

Adjacent plies were layed up within each panel in a mutually perpendicular arrangement. Care was taken to ensure that the tight side of the face and back plies were outermost in each panel.

Following glue application, an open assembly time of ten minutes was included according to the specifications of the resin manufacturer. During this time a 20 pound load was applied to the configured panel to keep the veneers together and to encourage distribution of the adhesive.

Before putting the panel in the hot press, the press was briefly closed. This was necessary for pre-setting of the data collection system used to record compaction of the panel during pressing.

Once the different sensing devices were connected to their corresponding terminals, closing of the press followed, together with the initialization of data collection. Each board was pressed for either 600 or 1000 seconds.

4.2. Measurements on panels during pressing

Measurement methods for each one of the parameters of interest for this project will be described in turn.

4.2.1. Measuring temperature distributions in the panel during pressing

Heat plays a very important role in affecting the rate of polymerization of the adhesive. This is the main reason that temperature has been measured during pressing at different locations within the board.

The temperature distributions in the panel were measured in both the horizontal (in panel plane) and vertical (perpendicular to panel plane) axes. Probes were positioned at 3, 6, 9, and 12 inches from the edge of the two foot square board in each glueline. The locations are shown schematically as Figure 4.2.

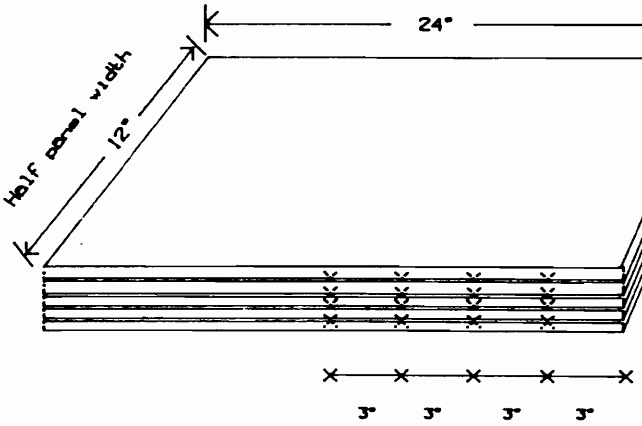


Figure 4.2. Positions of thermocouples within the laminate. (Cross cut at the middle of the panel).

Probe positions were selected in order to obtain sufficient information to enable non-linear gradients in both planes (vertical and horizontal) to be resolved.

The number of probes inserted in each panel was limited by experimental constraints of the apparatus. A total of seven channels were available for data collection -four of them were devoted to temperature measurement.

Emphasis for the temperature gradient analysis was given to panels with 6% MC veneer (the "standard" value). A preliminary analysis of temperature variation due to changes in veneer MC and platen pressure was, however, also included. The experimental techniques of measurement for these panels did not differ from those for the standard panels.

PTFE insulated copper-constantan fine gauge thermocouple wire (0.010" wire; 0.017" with insulator) was used to record the temperature in the gluelines. The fine gauge was chosen to minimize the effect of the probe on panel behavior. The junctions of the probes were formed with high-temperature soft solder with flux and an electric soldering iron. Care was taken to produce a small soldered junction to minimize response time (heat capacity) of the probe.

Approximately 200 thermocouples with lengths ranging from 12 to 18 inches were produced. The greater number were 18 inches in length and were used to record temperatures at the innermost portion of the board. The shorter lengths were used for temperature measurement in the horizontal direction in different gluelines.

The junctions were carefully fixed to the plies where the glueline temperatures were to be recorded. They were retained with a very small metal staple. Miniature thermocouple connectors (with appropriate metal contacts) were used to connect the free ends of the wires to the recording system.

Once the thermocouples completed their function, they were discarded with the boards, except for the male connector part which was reused.

The general arrangement of a thermocouple within the panel is depicted in Figure 4.3.

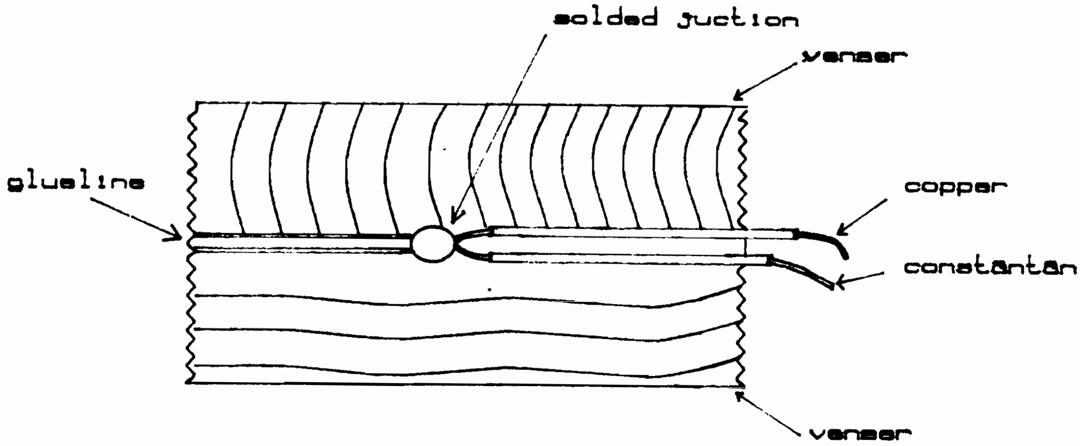


Figure 4.3. Cross-sectional diagram of a thermocouple within a panel.

Each thermocouple was scanned by the computer every 0.8 seconds. The electrical signal generated by the thermocouple was sent to the analog to digital convertor and compared to an electronic reference (cold) junction resident in the circuit board. The digitized signal was stored on a floppy disc for future analysis and interpretation. Details of this data collection system will be provided in section 4.2.4. to follow.

A typical graphical representation of the temperature versus time relationship in a four glueline "standard" panel is shown as Figure 4.4. This information is provided here merely to demonstrate the nature of information gained during the procedure. Reduction of the raw temperature data is described in Chapter V.

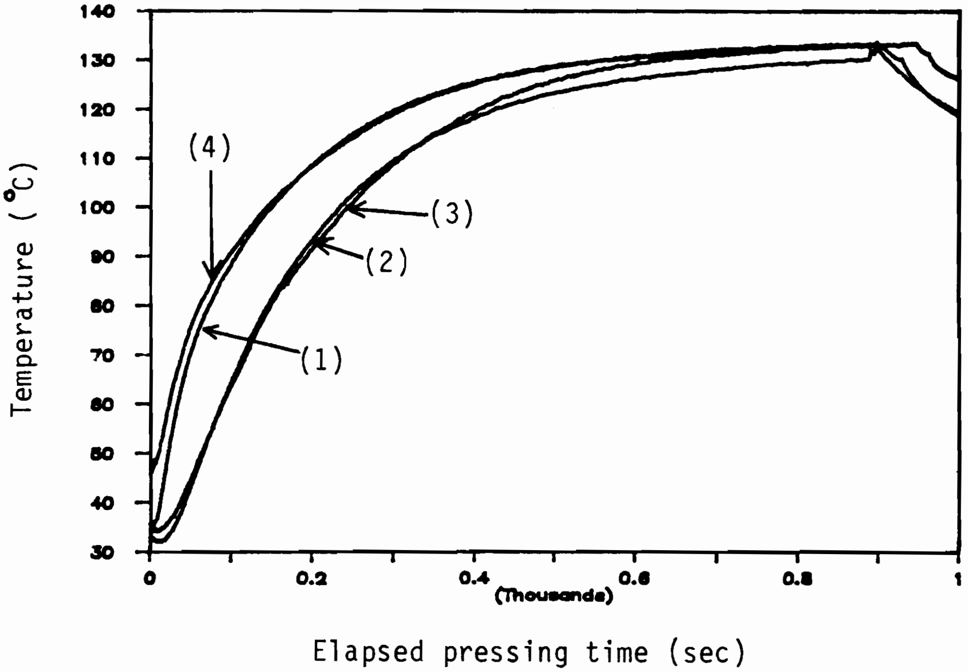


Figure 4.4. Typical temperature distributions in "standard" board during pressing. (Numbers refer to vertical location).

Platen temperature calibration:

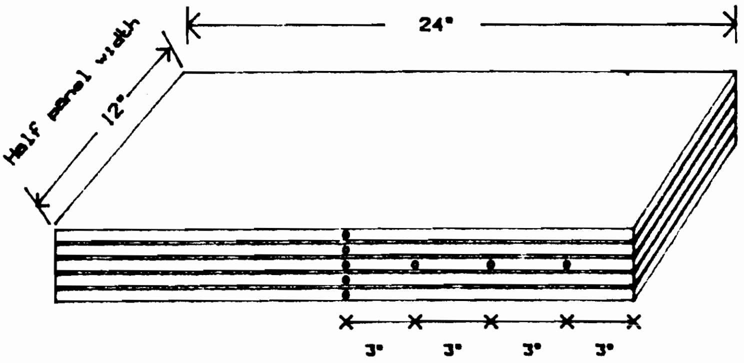
Prior to panel manufacture, tests were conducted to investigate the accuracy of platen temperature control. The temperature of the platens of the press is monitored by thermocouples embedded in each of the platens. This was compared with the actual surface temperature recorded with thermocouples positioned at the interface between the platens. No significant difference was found, however, between the gauge temperature and the platen temperature.

4.2.2. Measuring vapor pressures in the panel during pressing

One of the factors interfering with bond strength development during hot pressing is the possible negative effect that moisture has on the gluelines. Additionally, the phase change of this adsorbed moisture due to heat transfer from the platens, generates vapor pressure within the panel and resultant destructive stresses on the glueline when the press is opened.

Hypodermic tubes connected to remote gas pressure transducers were used in this project to measure vapor pressure within the panel. Distributions were measured in the vertical and horizontal planes of the boards. In the horizontal direction, however, measurements were limited to the core ply. The number of pressure transducers available was limited to two.

The hypodermic tubes were located in the center of the faces of the veneers to record the vertical distribution of vapor pressure in the board. When measuring horizontal vapor pressure distributions, the hypodermic tubes were embedded within the cross section of the core ply at distances of 3, 6, 9, and 12 inches from the edge of the board. Horizontal vapor pressure distributions were determined only for the 6% MC boards. Figure 4.5 shows the locations of the open ends of the hypodermic tubes where vapor pressure measurements were taken.



4.5. Schematic representation of the panel showing locations of hypodermic tubes. (Only half the panel is shown in order to expose locations within the cross-section).

The effect of veneer grain direction on vapor pressure distributions was also investigated. For selected veneers, the ends of the hypodermic tubes formed lines oriented along and perpendicular to the grain.

To enhance our understanding of vapor pressure distributions, a preliminary analysis was carried out using veneer with 12% and 16% MC. This was combined with 3 different platen pressures. (Section 3.3.2. contains discussion of how these pressures were selected). Again, the reduction of this derived data is described in Chapter V.

Principle for vapor pressure measurement:

Two vapor pressure transducers with sensitivities of 1.46 mV/PSIG and 1.48 mV/PSIG were used to record vapor pressures in the boards at the locations specified.

Stainless steel tubing of 0.9144 mm external diameter and 0.508 mm internal diameter was used to convey the vapor from within the panel to the pressure transducers. The selection of tube diameter was based on the following considerations:

a) Dead volume: This is the space in the tube which has to be filled with vapor to affect measurement at the transducer. The accuracy of vapor pressure measurement depends on the amount of vapor produced in the board versus dead volume in which to accomplish pressure changes by ingress or outgress of vapor from the end of the tube. The dead volume did not significantly affect the accuracy of the measurements because it was kept to a minimum by filling the tube with silicon oil.

b) The effect of the tube on the physical behavior of board during pressing: The diameter of the tube was kept to a minimum and only two tubes were used in each panel.

c) Previous experience of vapor pressure measurements in flakeboards (67).

Approximately 100 tubes were manufactured in four different lengths of 8, 10, 14, and 18 inches. The greatest number were 18 inches long because of the larger number of observations made in the central portion of the panel.

The transducers were piezoresistive and had a stainless steel diaphragm. To protect this membrane from moisture and heat, a 4 mm diameter "U" tube filled with low viscosity silicone oil served as a protective barrier between the vapor and the diaphragm as well as minimizing dead volume. This did not impair the transmission of pressure to the transducers. The arrangement of tube with transducer is represented as Figure 4.6.

The U tubes and the pressure transducers were mounted on a specially made adjustable aluminum frame. This frame allowed the transducers to be moved back and forth, up and down, and sideways so that alignment of the transducers with probes could be achieved. This assembly was clamped onto the frame of the hot press.

Output from the transducers were connected to the data collection system responsible for transforming the electrical signal into digital form.

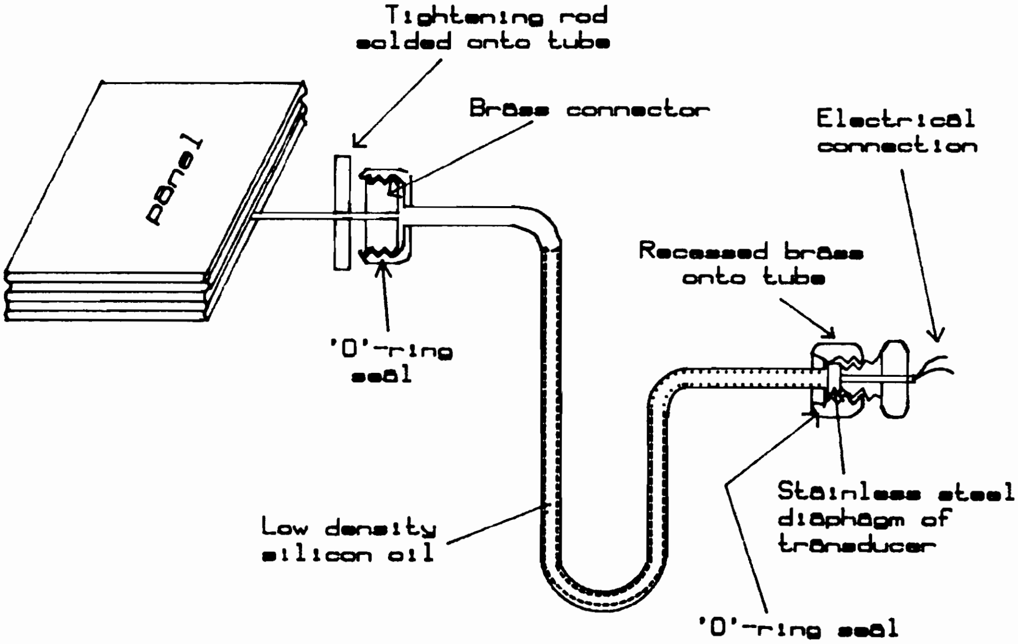


Figure 4.6. Configuration of a hypodermic tube and vapor pressure transducer.

Installing the probes:

The hypodermic tubes were positioned in the cross-section of the veneers to protect them from blocking with adhesive. Therefore, the vapor pressure was measured at either side of the glueline instead of doing it at the glueline itself. By interpolating the values between locations, a very good approximation of estimated vapor pressure at the glueline was obtained. A diagram with the location of the tubes in the cross-section of the veneer is depicted in Figure 4.7.

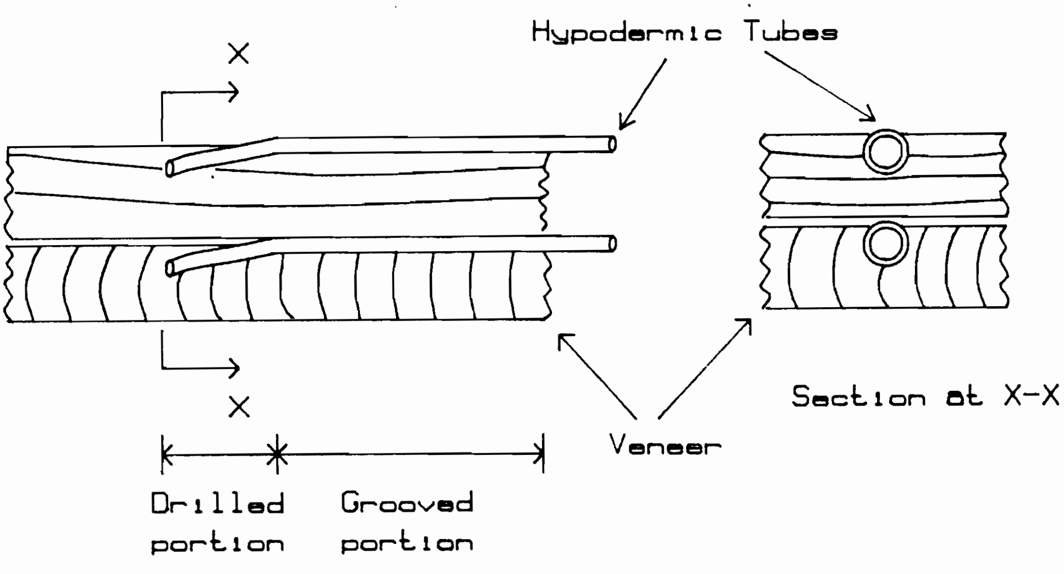


Figure 4.7. Cross-section through veneer with hypodermic tubes in position.

Preparing the veneer for pressure measurement:

Grooves were made in the veneer in order to avoid vapor pressure leakage alongside the tubes during pressing of the panel. The 1.5 mm deep groove had just enough space to hold the hypodermic tube. A power router with specially selected bit was used to perform this task. The grooves ranged in length; the ends being 12, 9, 6, and 3 inches from the edge of the veneers toward the center. At the end of the groove a continuation hole was drilled with a flexible metal rod, producing a 2 mm diameter hole. The diagram in Figure 4.7 shows the characteristics of the grooves in the veneer.

Grooves were always made in the tight side of the veneer. This was to avoid the possible effect of lathe checks on resin penetration to the hole where the end of the tube was located. Workability of grooving and drilling was also easier in this face.

Half of the veneer prepared to hold the hypodermic tubes was grooved along the direction of the grain and the other half perpendicular to the grain. Adjacent plies were layed up perpendicular to each other with respect to grain direction and the probes were always placed in adjacent plies.

Once the grooving was completed, the veneer samples were returned to their respective conditioning rooms until formation and testing of the boards was performed.

Prior to board pressing, the end of the hypodermic tube to be embedded in the veneer was wrapped with cotton to achieve a tight fit between the tube diameter and the hole. This prevented possible leakage of resin into the tube.

The hypodermic tubes were discarded (left inside the board) once the vapor pressure was recorded. The brass connectors were the only reuseable parts and were removed from the panel to be soldered to a new tube.

Data collection:

The recording procedure of vapor pressure in the veneer plies was similar to the one outlined for the measurement of temperature. Vapor pressure acting on the silicone oil meniscus resulted in deflection of the transducer diaphragm and thence changes in electrical resistance of the Wheatstone bridge circuit. The IOV dc excitation then resulted in the generation of a proportional electrical voltage. This output was scanned by the computer every 0.8 seconds. The analog signals were transformed into digital form by the convertor and stored in floppy disks.

A graphical representation of vapor pressure with pressing time in each one of the five plies of a standard board is shown in Figure 4.8. Again, this is given only as an indication of the type of data generated. The means of reducing data and subsequent discussion of results appears in Chapter V.

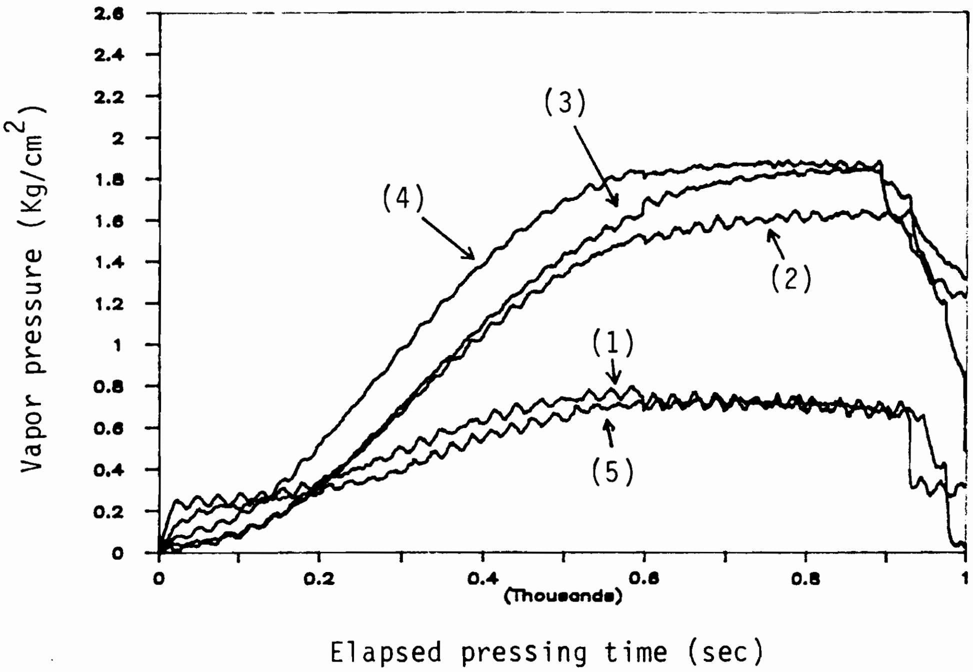


Figure 4.8. Typical vapor pressure distribution in "standard" boards. (Numbers refer to vertical locations of the probes).

Sources of error in the system:

Considerable variability among the results of replications were detected in pressure measurements. This prompted very careful consideration of the accuracy of the measuring system. Of primary concern were factors associated with leakage from around the tubing, dead volumes in the system, and inconsistency in the performance of the pressure transducers themselves. After careful control of veneer grooving and drilling was achieved, vapor escape past the tube was eliminated.

Previous work (67) using this approach for pressure measurement suggests that the effect of the dead volume of the tube and connecting system should be minimized. It was found, however, that having filled the larger voids with incompressible liquid (silicone oil), the volume occupied by the small bore of the capillary tubing itself did not have a significant effect on measured pressures. In any case, this volume did not vary significantly from board to board and would not, therefore, affect variability in pressures among boards.

Due to variations in vapor pressure recorded by the two transducers in preliminary trials of boards pressed, the pressure transducers were individually calibrated using a "dead weight gauge tester". The corresponding data is graphically represented in Figure 4.9. From the calibration analysis, some other sources of variation in vapor pressure measurement in the panel during pressing were detected and eliminated. Values for output at zero gauge pressure and linear sensitivity were derived.

Variability in vapor pressure within the board is most likely to be due to variability in permeability and localized moisture contents of the veneers. Permeability is a parameter which varies over a very wide range in response to relatively small differences in anatomical structure.

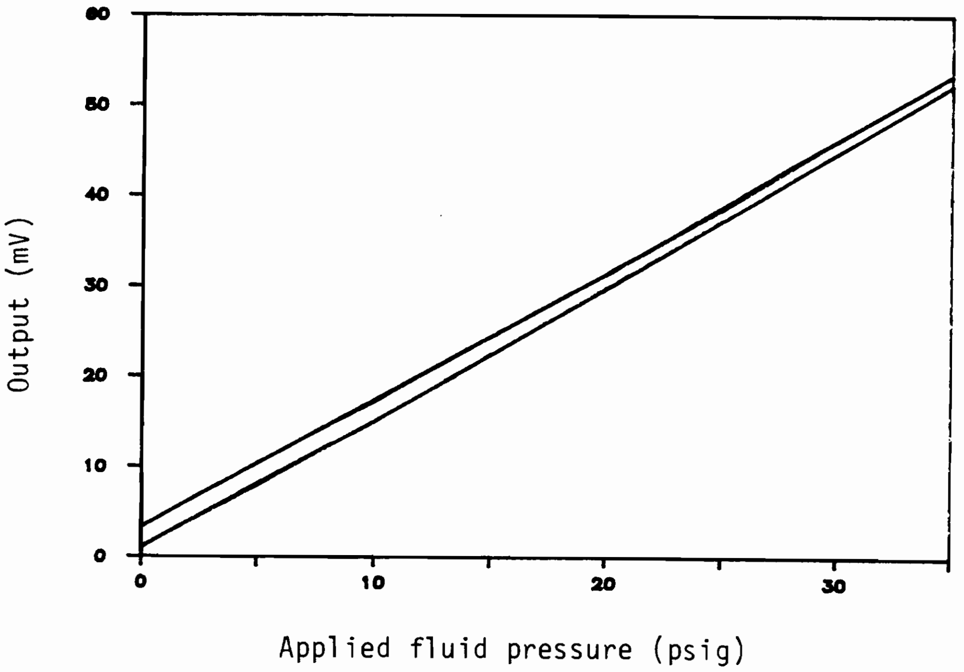


Figure 4.9. Calibration curves for the two gas pressure transducers.

4.2.3. Measuring the variation in panel thickness during pressing

Board compaction during pressing is associated with the viscoelastic behavior of wood, which in turn is related to temperature, moisture content, and platen pressure. This was infered by monitoring platen separation throughout the pressing cycle with a Linear Variable Differential Transducer (LVDT). Total compaction was also determined by direct measurements of veneer thickness prior to pressing, and also measurements of the board once it was removed from the press and allowed to cool.

Rheological behavior of the laminate is an important issue but is not the primary focus of this research.

Future work will concern more rigorous approaches to studying the mechanisms of compaction. These are, however, largely dependent on heat and mass transfer, one of the issues of immediate concern here. In addition, a number of researchers have explored this area in some depth from an empirical point of view (45, 154). This has primarily been derived by volumetric recovery of the material.

The effects of veneer MC and platen pressure on board compaction, as well as their interactions, are further analyzed in sections to follow.

Measurement principle:

An alternating current LVDT, with a range of 1 inch displacement was used to record board compaction. The LVDT was rigidly mounted on one corner of the hot press frame. Care was taken to position the device at a sufficient distance from the hot platens to avoid damage by heat and to maintain retention of accuracy.

As press closure progressed, platen position was monitored once platen separation reached 22 mm. The original thickness of the standard board prior to pressing never exceeded 18 mm. This enabled thickness to be monitored throughout the pressing cycle. The time when the LVDT started generating information was just a few seconds before the upper platen made direct contact with the top veneer of the laminate.

Again, the frequency of scanning for thickness variation of the board by the computer was 0.8 seconds and the information recorded was also stored in floppy disks.

A typical compaction versus pressing time curve is shown in Figure 4.10. Brief discussion of these data appears in Chapter V.

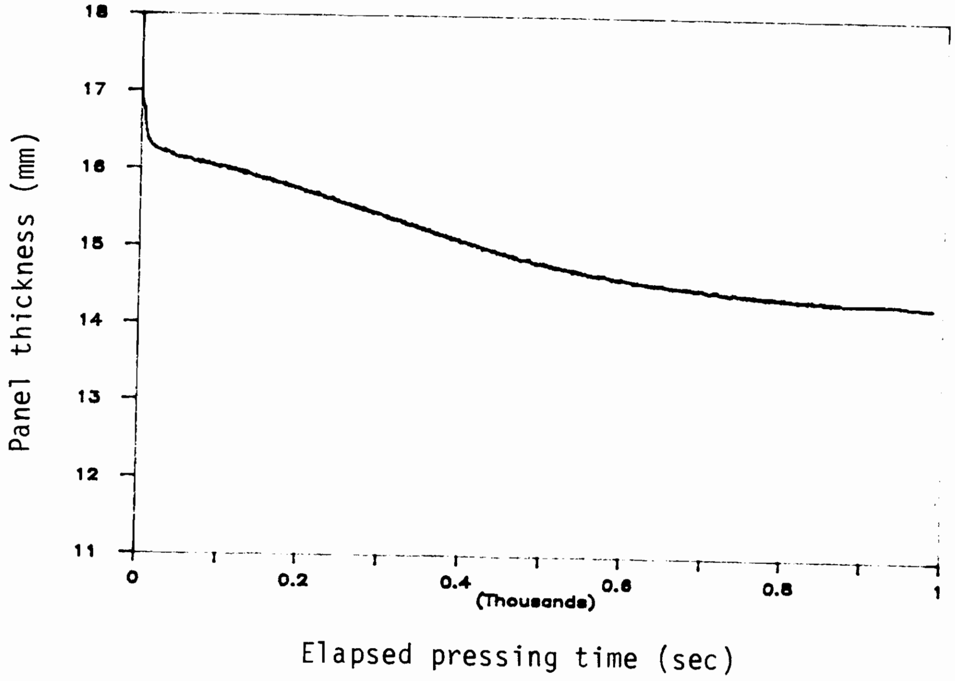


Figure 4.10. Compaction of a standard board during hot pressing.

4.2.4. The data collection system

The following issues were of primary concern for the selection and configuration of the data collection system:

Frequency of scanning:

Appropriate frequencies for sequentially scanning each of the probes is dependent in part on the rates at which the variables to be monitored change. A balance between the frequency of scanning and the rate of change of the variable must be established in order to derive trends in the parameters measured while avoiding the generation of unmanageable quantities of data.

A variable which undergoes progressive changes, for example, requires a lower scanning frequency to enable trends to be accurately detected than does a variable which exhibits sudden discontinuities. The three parameters measured in the present project exhibit different rates of change. Temperature changed quite rapidly during the first 200 seconds of pressing time, followed by compaction. Vapor pressure showed very little variation within that period. It is after the 200 seconds when vapor pressure underwent somewhat faster changes. This information is outlined in Chapter V.

The maximum speed of the processor in the data collection system limits the frequency of scanning. In the event, 0.8 seconds dwell time on each one of the transducers was used. This proved to be most adequate for obtaining well defined trends for the variables of interest.

Capacity of data storage of the computer system and the disket:

The internal memory of the computer and the floppy disk space were also important factors in affecting the allowable rate of operation of the scanner and the duration of data collection (pressing time). The capacity of the computer memory (640 Kbytes) was adequate to collect information from the board for pressing times up to 1000 seconds. The data collected from the board during that period of time was equivalent to 86 Kbytes, which required nearly a 1/4 of the space available in an ordinary 360 Kbytes disket. The format of a typical array and the type of data collected is shown in Table 4.3. The information generated was arranged in 8 columns with 1250 rows. The first 4 columns correspond to temperatures of the gluelines, the next 2 columns represent vapor pressure, the 7 th corresponds to compaction. The 8 th column represents the pressing time.

Temp Chan 1	Temp Chan 2	Temp Chan 3	Temp Chan 4	Vap Pres Chan 5	Vap Pres Chan 6	Compact Chan 7	Pressing Time
32.89	27.74	29.38	35.69	0	0	22.27	0.8
32.88	27.95	29.6	35.9	-0.1033	-0.0611	22.27	1.6
32.88	27.72	29.36	35.9	-0.1653	-0.1426	22.27	2.4
32.86	27.7	29.34	36.35	-0.2272	-0.2445	22.27	3.2
32.86	27.93	29.58	38.44	-0.2479	-0.0815	16.765	4
30.77	28.42	30.07	39.38	0.1859	0	16.482	4.8
31.02	28.68	30.09	40.1	0.2479	0.1426	16.308	5.6
69.69	43.07	45.83	77.39	0.4545	0.3464	16.069	58.4
70.13	43.3	46.06	77.61	0.4338	0.3057	16.069	59.2
70.58	43.99	46.74	77.83	0.4545	0.3057	16.058	60
106.92	87.81	88.88	107.75	2.4169	2.3231	15.535	180
107.34	87.81	88.88	108.17	2.4995	2.3435	15.557	180.8
107.56	88.26	89.33	108.19	2.4995	2.3638	15.525	181.6
116.07	102.3	102.93	115.03	4.1934	3.9533	15.198	240
116.29	102.31	103.16	115.26	4.1521	3.8311	15.187	240.8
116.31	102.75	103.59	115.28	4.1314	3.8514	15.209	241.6
121.84	112.15	112.98	120.2	6.1145	5.8077	14.839	300
122.07	112.58	113.2	120.43	6.2178	5.8485	14.85	300.8
122.27	112.58	113.2	120.22	6.1971	5.8892	14.817	301.6
125.93	118.97	119.79	122.25	7.8084	7.5195	14.491	360
125.5	118.95	120.19	122.03	7.8291	7.5399	14.469	360.8
125.52	119.18	120.2	122.25	7.8084	7.5195	14.491	361.6
128.16	124.09	125.11	122.87	9.3783	9.272	14.186	420
128.15	124.28	125.3	122.65	9.3577	9.2516	14.143	420.8
128.38	124.31	125.54	122.68	9.3164	9.1905	14.132	421.6
137.3	134.09	136.9	124.16	13.4685	13.857	13.033	990.4
137.5	134.29	136.9	123.75	13.3239	13.6329	13.055	996
137.5	134.09	136.9	123.75	13.2825	13.5921	13.044	996.8
137.29	134.28	137.29	123.74	13.2412	13.4902	13.033	997.6
137.69	134.28	137.09	123.74	13.1586	13.4699	13.033	998.4
137.49	134.08	137.09	123.74	13.1793	13.4087	13.022	999.2
137.49	134.08	137.09	123.53	13.1379	13.4087	13.033	1000

Table 4.3. Type of data collected during hot pressing of standard boards.

Accuracy of measurements by the system:

The accuracy of the system depends in part on the ranges of signal sizes to be accommodated by the system. The sensitivities of the three types of transducers are listed in Table 4.4.

Type of sensor	Sensitivity units	Sensitivity mV	Maximum output recorded mV	Maximum output recorded Equivalence
Thermocouple	1 °F	0.0225	6.647	300 °F
	1 °C	0.0445	6.702	150 °C
Vapor press.	1 psig	1.46	58.4	40 psi
	1 psig	1.48	59.2	40 psi
LVDT	1 mm	787.4	4724.4	6 mm
	1 in	20000.0	4725.0	0.236 in

Table 4.4. Sensitivity and maximum output produced in mV by different transducers and their equivalence in corresponding units.

The large signal produced by the vapor pressure transducers and the linear variable differential transducer were reduced with resistances. In this way the output from the thermocouples and transducers were similar, and an identical gain value could be used on the analog to digital conversion unit ("Data Translation" board -the trade name of the manufacturer) for all signals. Conversion of recorded electrical signals (mV or V) into scientific units (°C, N/mm, mm), is also important for accuracy. In the case of temperature, accuracy of ± 0.1 °C was imparted by the analog to digital convertor; this is slightly better than the nearest accuracy attainable with thermocouples and was therefore appropriate.

Number of channels:

It is not possible to have many probes in the panel because of possible interference with its natural behavior during pressing. On the other hand, there must be enough to get as much information as possible from each one of the panels pressed.

The number of probes was limited by the data collection system; only 8 channels were available. With these channels, 4 probes for temperature, 2 for vapor pressure and 1 for compaction were used. The 8th channel was used to integrate within the system the cold junction reference required for the thermocouples to generate temperature values. To record more information from each panel, perhaps 11 channels would have been a better number. In this way, 3 more probes for vapor pressure determination would be available. Vapor pressure was one of the most important variables measured in this project. In addition, inferences could have been made on the basis of comparing data for one board alone. Problems due to variability in measured values among boards could then be partially overcome.

"Basic" computer program:

Control of the data collection system was achieved by means of a computer program using the Basic language. Three major components constituted the program: a). The frequency of scanning of the probes, b). Data translation, involving the conversion of electrical signal into scientific units -analog to digital conversion-. c). Data storage, according to specifications for future data analysis. A listing of the program is included in Appendix A.

A block diagram representing the different components of the data collection system is depicted in Figure 4.11.

The characteristics of the data collection system in terms of automation and efficiency were advantages that provided a lot of flexibility for handling the data during the analysis. Graph plotting, data reduction, and combination of data from different boards were some of the most obvious advantages.

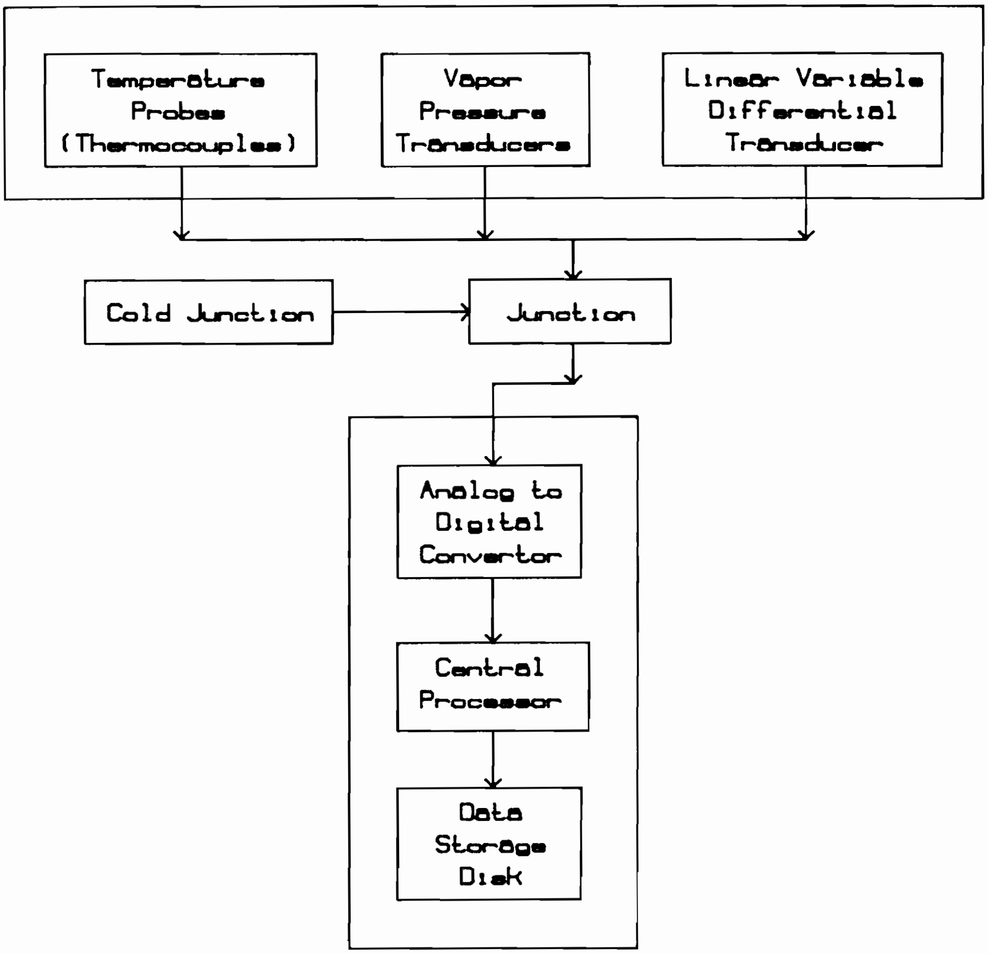


Figure 4.11. Configuration of the data collection system.

Chapter V

Reduction and discussion of data collected during panel pressing

5.0 Introduction

Through the ATDC and with the aid of the microcomputer instructed by a program written in BASIC, values generated by each one of the sensor devices were collected every 0.8 seconds. After transformation, this information was stored on a disket - vertical columns of numbers corresponding to each of the ATDC channels. The first four columns corresponded to temperatures, the next two were devoted to vapor pressures and the seventh contained board compaction data. An eighth column was used to contain elapsed pressing time. The eight channel of the ATDC was used to collect cold reference junction values but these were used during temperature data conversion prior to storage and were therefore not retained. When 600 second pressing times were selected, 750 rows of numbers were generated for each column and with 1000 seconds pressing time 1250 observations were recorded in each column. The type of information collected is specified in Table 4.3.

The first approach for handling the raw data for each board was to reduce it into a more concise form. Graphical means of data presentation are appropriate when trying to interpret such information and then to relate parameters of interest. As a first step temperature was plotted against time for each one of the probe positions. A similar approach was followed for vapor pressure distribution and board compaction. Derived curves with time as the independent variable therefore consisted of 750 or 1250 data points which could satisfactorily be connected by straight lines. The numerical approaches used to combine replicative curves and derive the most pertinent trends are discussed below.

5.1. Data reduction

A total of 48 panels were pressed for data collection. The number of replications for each parameter measured under the different sets of pressing conditions is outlined in Table 5.1. The replications for vapor pressure and temperature are indicated by the ply and glueline location in the board according to the scheme of Figure 5.1. A numerical system has been used to identify these plies and gluelines. Ascending code numbers correspond to plies and gluelines of the panel in the press working from top to bottom. The column corresponding to the board compaction data represents the total number of boards measured under each specific pressing condition.

Moisture Content (%)	Probe Location	Platen Pressure (Psi)	Parameters and # of Boards Measured		
			Vapor Pressure	Temperature	Compaction
5	Vertical	175	Ply 1 => 3 Ply 2 => 6 Ply 3 => 6 Ply 4 => 6 Ply 5 => 3	GL 1 => 8 GL 2 => 8 GL 3 => 8 GL 4 => 8	8
		125	Ply 1 => 1 Ply 2 => 2 Ply 3 => 2 Ply 4 => 2 Ply 5 => 1	GL 1 => 4 GL 2 => 4 GL 3 => 4 GL 4 => 4	4
5	Horizontal	175	Loc A => 4 Loc B => 8 Loc C => 8 Loc D => 8	GL 1 => 4 GL 2 => 3 GL 3 => 4 GL 4 => 4	18
12	Vertical	175	Ply 1 => 1 Ply 2 => 2 Ply 3 => 3 Ply 4 => 3 Ply 5 => 1	GL 1 => 5 GL 2 => 5 GL 3 => 5 GL 4 => 5	5
		125	Ply 1 => 2 Ply 2 => 4 Ply 3 => 4 Ply 4 => 4 Ply 5 => 2	GL 1 => 8 GL 2 => 8 GL 3 => 8 GL 4 => 8	8
16	Vertical	100	Ply 1 => 2 Ply 2 => 2 Ply 3 => 2 Ply 4 => 2 Ply 5 => 2	GL 1 => 3 GL 2 => 3 GL 3 => 3 GL 4 => 3	5

Note: PLY corresponds to veneer number
LOC corresponds to horizontal location number
GL corresponds to glueline number

Table 5.1. Replications of vapor pressure, temperature and compaction under different sets of pressing conditions.

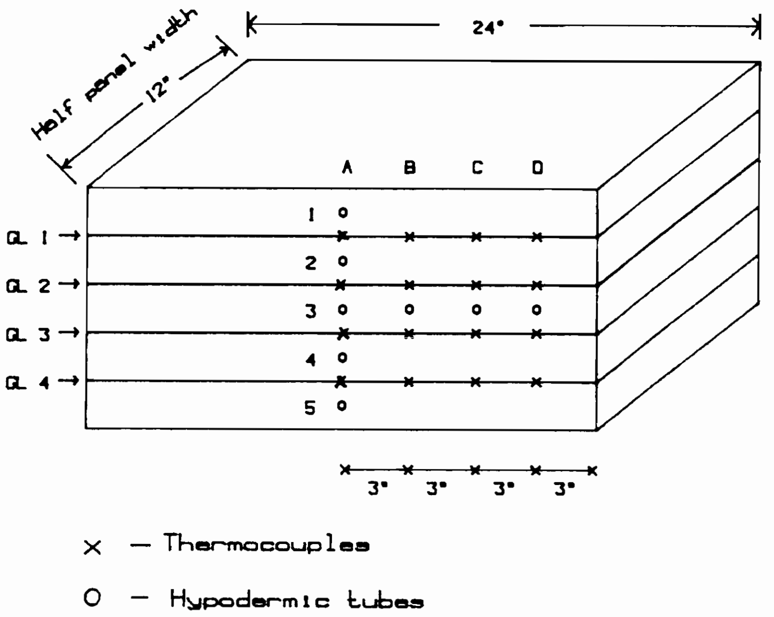


Figure 5.1. Probe locations for temperature and vapor pressure measurements within the laminate. (Only one half of the panel is shown to enable probe locations within the vertical cross-section to be displayed).

To analyze the data collected from these panels, the use of two different approaches has been considered. The first alternative was to derive regression models for temperature, vapor pressure and board compaction versus time from the set of graphs corresponding to boards pressed under similar conditions (replications). The second alternative was to determine data points by averaging observations for each replication at corresponding elapsed times. Repetition of this procedure after small time increments would enable averaged curves for the whole period to be derived.

Due to the irregular and complex shape of the curves, it was decided to adopt the second (averaging) approach.

The method of numerical data reduction used for each of the variables investigated will now be outlined in turn before going on to discuss the implications of these reduced data in Section 5.2 to follow. In general, graphs for each of these variables will be grouped together following each sub-section.

5.1.1. Reduction of vapor pressure data

The number of replications of vapor pressure measurements for each one of the plies of the different sets of pressing conditions is indicated in Table 5.1. In the standard boards, sets of probes were positioned to form lines in the horizontal and vertical planes. In the vertical (cross sectional) direction, measurements were made within the 5 plies of the laminate. By plotting and combining vapor pressure versus pressing time curves for each of the replications at each location, 5 sets of graphs were derived corresponding to the 5 plies of the laminate. All graphs concerning vapor pressure have been grouped together at the end of this Section (5.1.1).
A set of original curves for the boards pressed at 175 psi are shown as Figures 5.3, 5.5, 5.7, 5.9 and 5.11. A corresponding set of averaged curves were derived by taking the mean from the replications for each specific location. These average curves are shown as Figures 5.4, 5.6, 5.8, 5.10 and 5.12. By integrating these average curves in a single graph, the vapor pressure distribution for the

standard board was derived. This is shown as Figure 5.13.

By following a similar procedure, vapor pressure versus time curves were also derived for boards pressed at 125 psi. Only the final graph representing the reduced vapor pressure distribution for the vertical direction of boards pressed at 125 psi is shown here (as Figure 5.14). The original replication curves are not included - their variability is, however, similar to that for the boards pressed at 175 psi.

The distribution of vapor pressure in the horizontal direction for boards pressed at 175 psi was measured at four locations equally spaced between the center and edge of the core ply. The number of replications for each location is also indicated in Table 5.1. A similar procedure as the one outlined for the distribution in the vertical direction was followed here to derive averaged distributions for the horizontal direction of the laminates. This is presented as Figure 5.15.

The marked difference between the longitudinal and radial permeability of wood is likely to lead to differing horizontal (and associated vertical) vapor pressure gradients between adjacent plies. To investigate this hypothesis, horizontal pressure distributions were measured in the core veneer for locations running both normal and parallel to the longitudinal grain direction. These positions are shown in the diagram of the core ply below, (Figure 5.2).

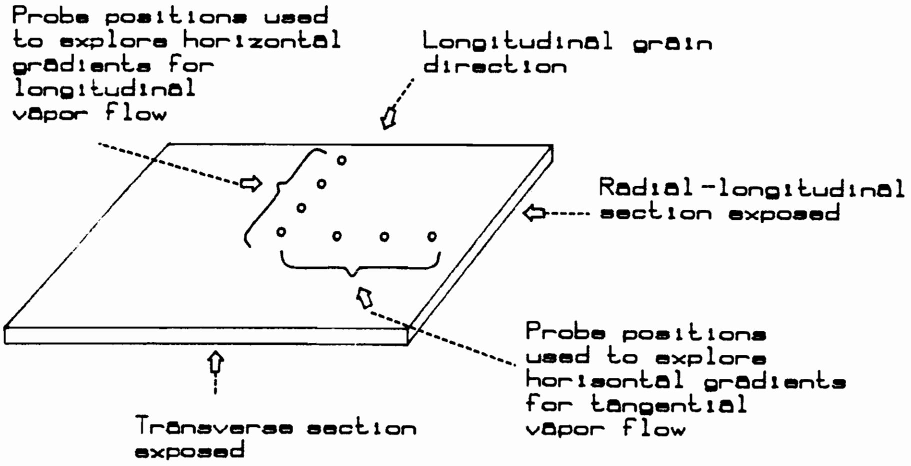


Figure 5.2. The core ply with the position of probes used to explore horizontal vapor pressure distributions resulting from anisotropy of wood.

Horizontal vapor pressure distribution in relation to the perpendicular direction of the grain is depicted as Figure 5.16. Similarly, the distribution of vapor pressure with respect to positions running parallel to the grain is shown in Figure 5.17.

The reduced curves for vapor pressure distribution versus time for boards with 12% and 16% veneer moisture content, pressed at the platen pressures specified in Table 5.1, were also derived using similar averaging techniques. The corresponding graphs are represented in Figures 5.18 to 5.20.

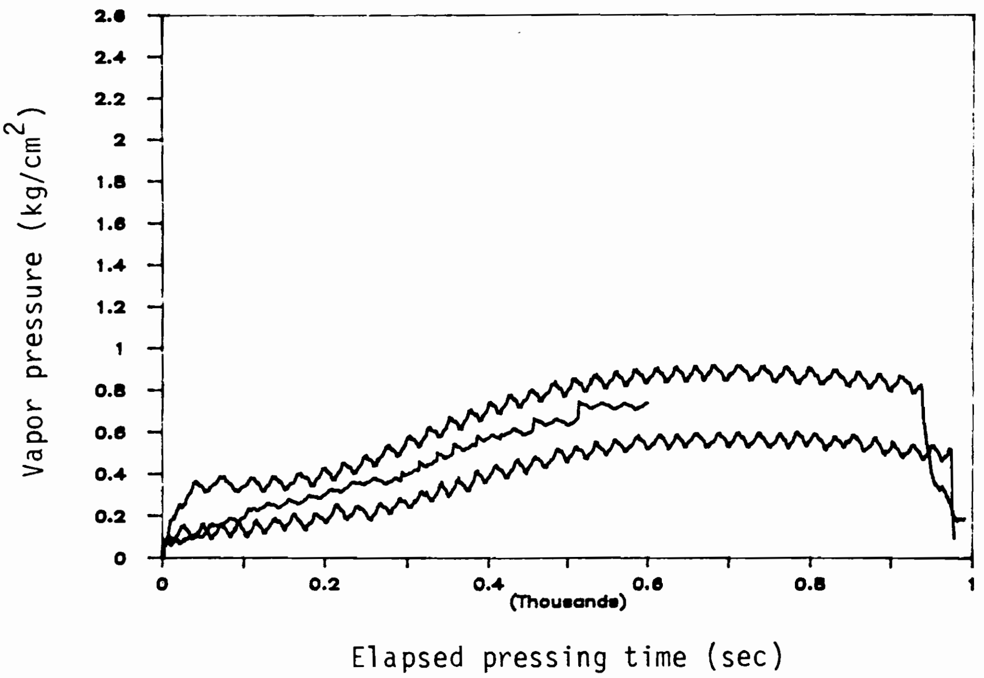


Figure 5.3. Three replications of vapor pressure in location # 1 of a standard board (at the center of the upper veneer).

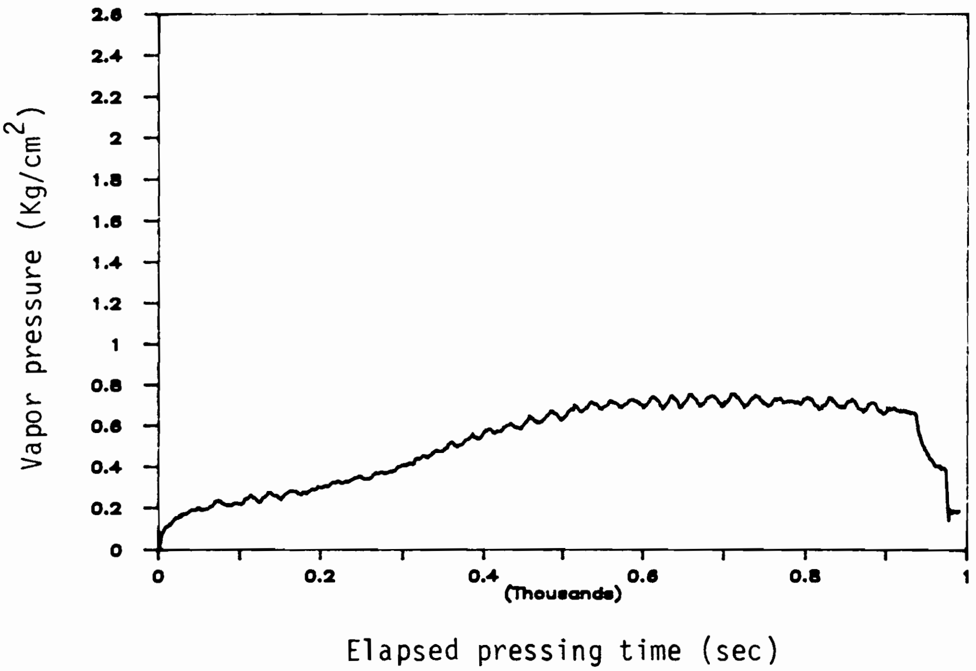


Figure 5.4. Trend of average vapor pressure in location # 1 of standard panel (at the center of the upper veneer). - Corresponding to fig. 5.3.

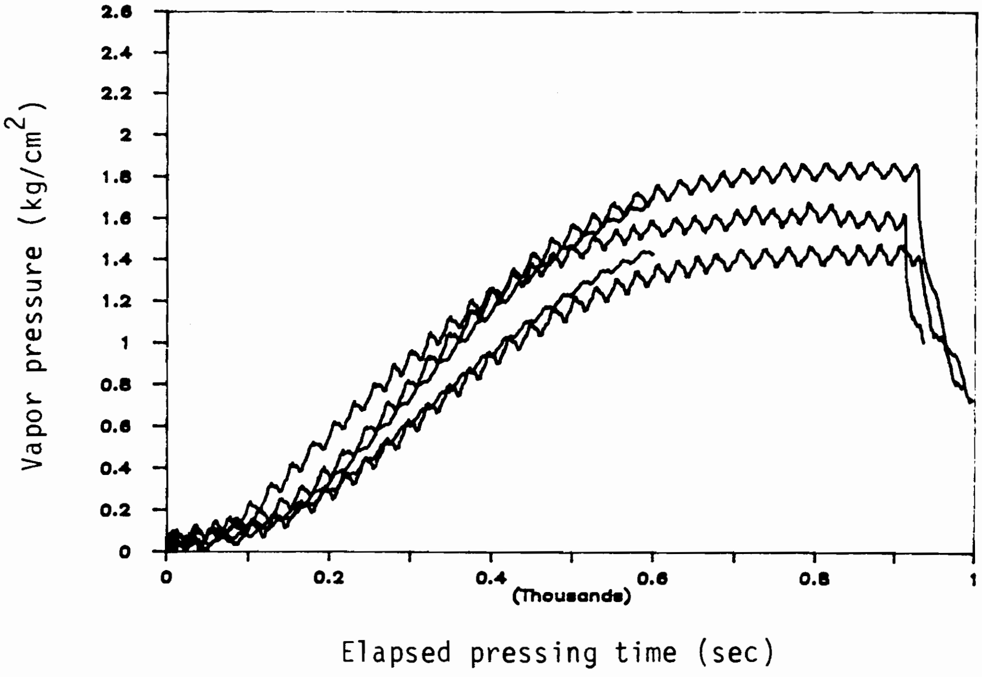


Figure 5.5. Five replications of vapor pressure in location # 2.

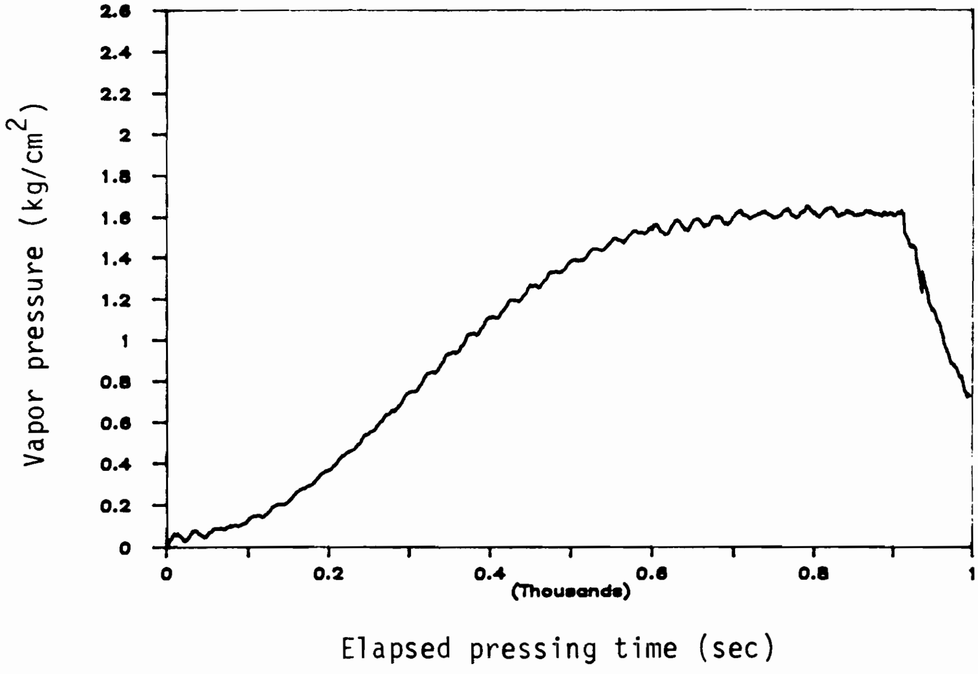


Figure 5.6. Trend of average vapor pressure in location # 2. (Corresponding to fig. 5.5)

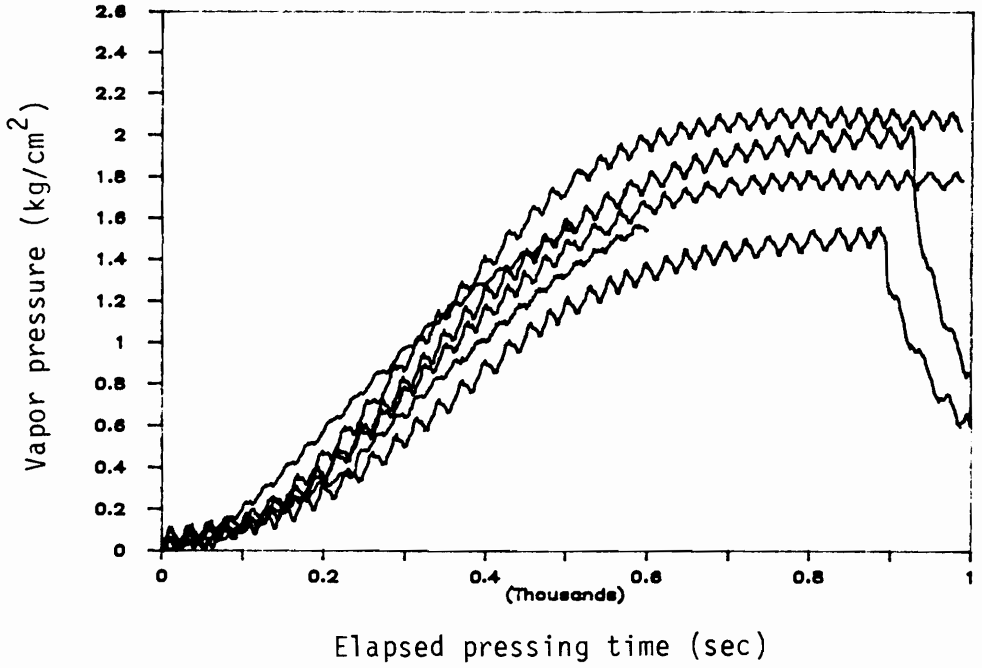


Figure 5.7. Six replications of vapor pressure in location # 3.

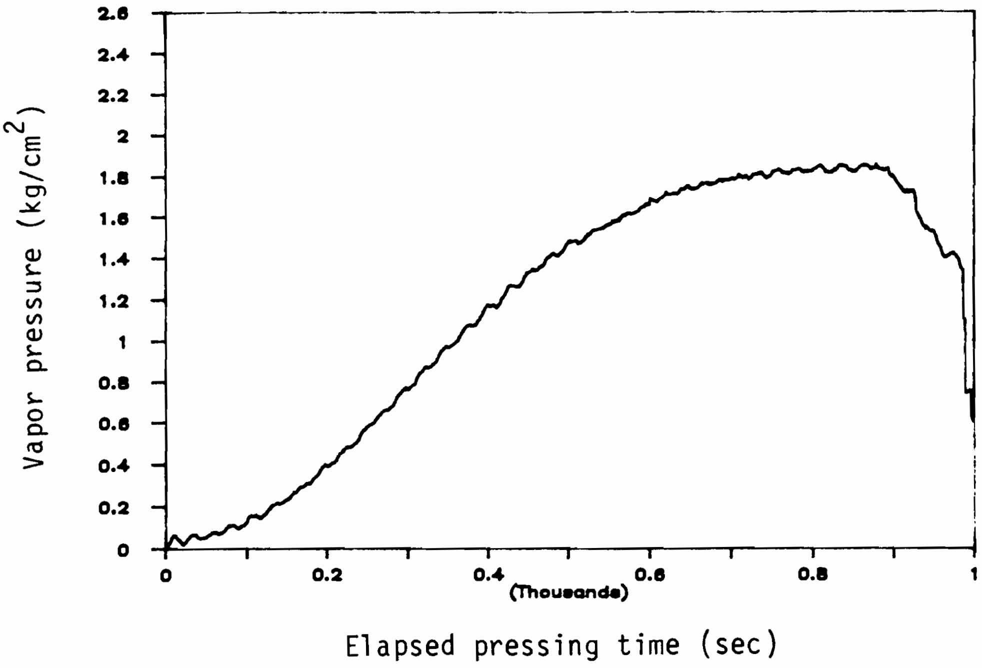


Figure 5.8. Trend of average vapor pressure in location # 3. (Corresponding to fig. 5.7)

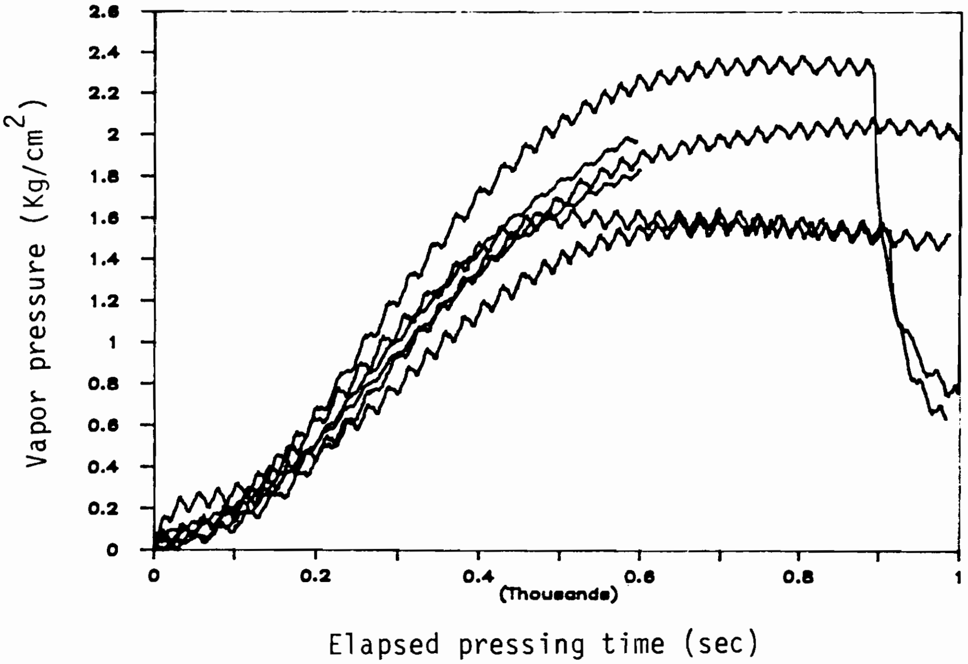


Figure 5.9. Six replications of vapor pressure in location # 4.

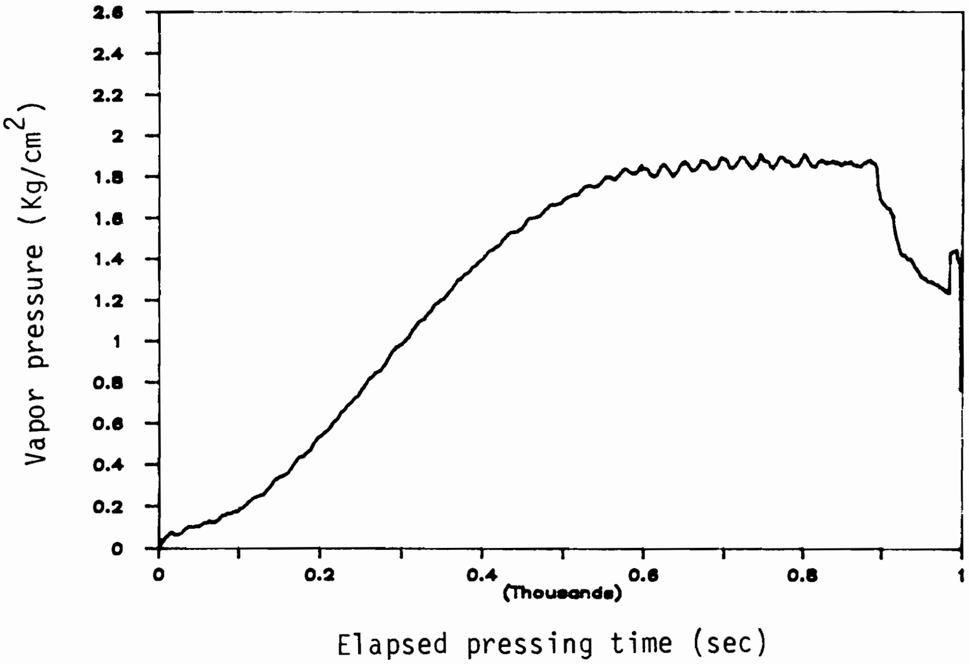


Figure 5.10. Average trend of vapor pressure in location # 4. (Corresponding to fig. 5.9)

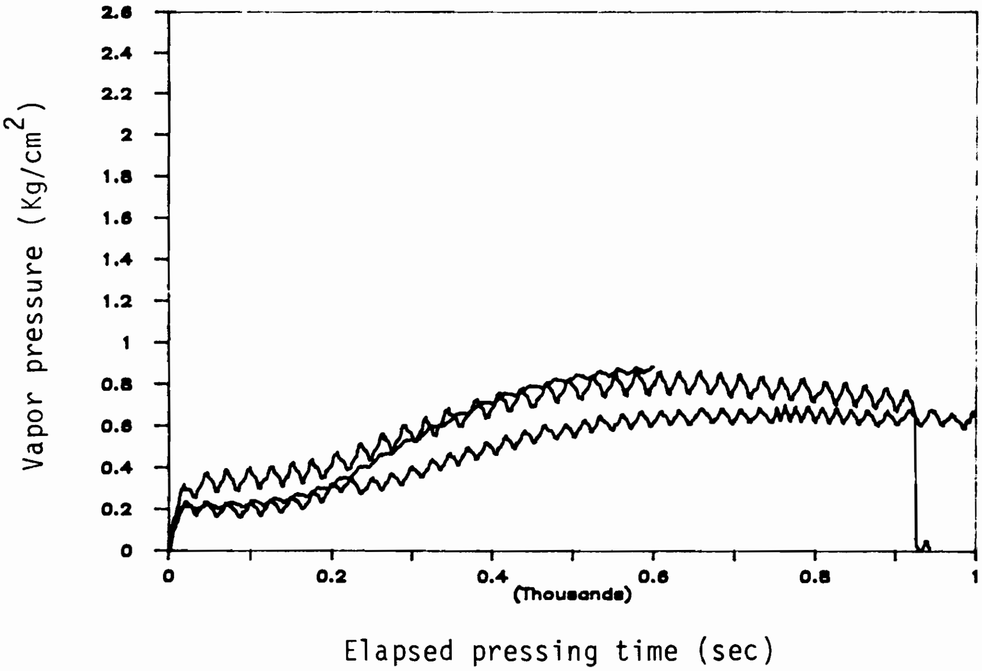


Figure 5.11. Three replications of vapor pressure in location # 5.

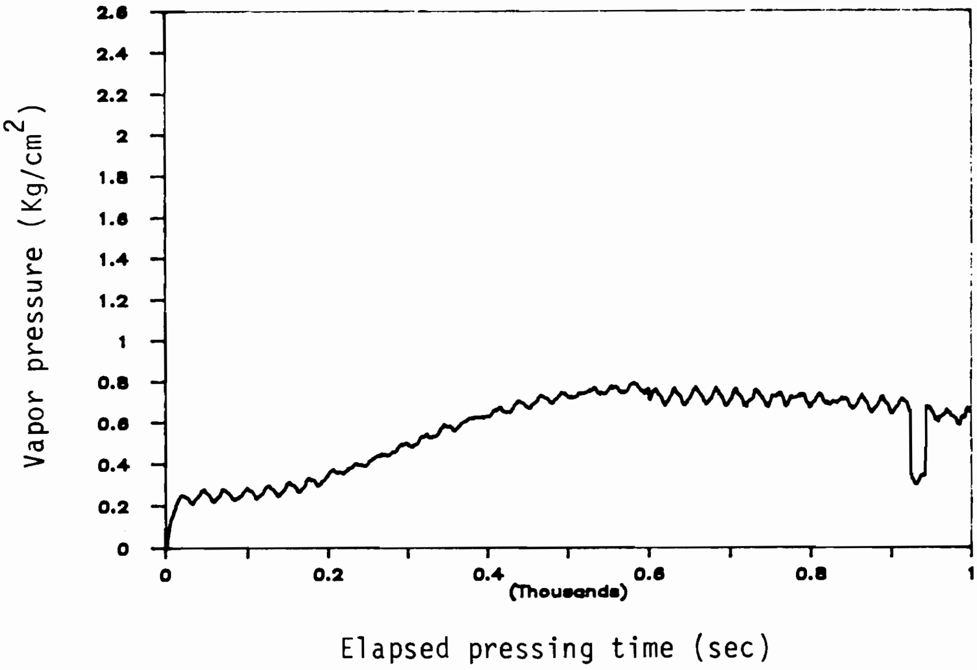


Figure 5.12. Average trend of vapor pressure in location # 5. (Corresponding to fig. 5.11)

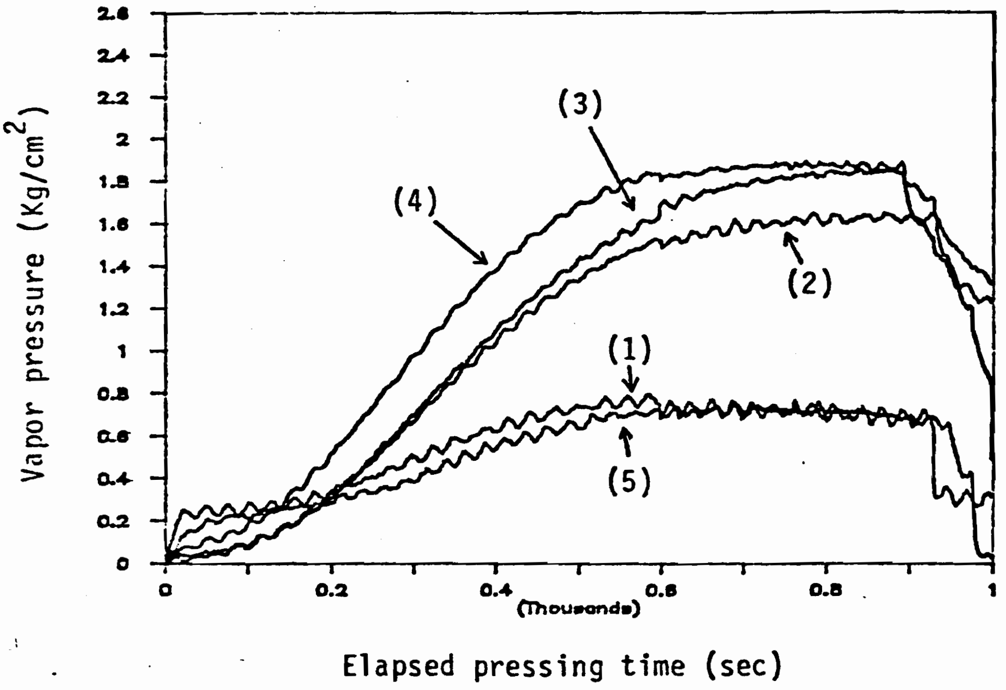


Figure 5.13. Average vapor pressure versus time curves for boards pressed under standard conditions. (Curves are presented for the center of each of the five plies. Code numbers refer to vertical locations within the panel).

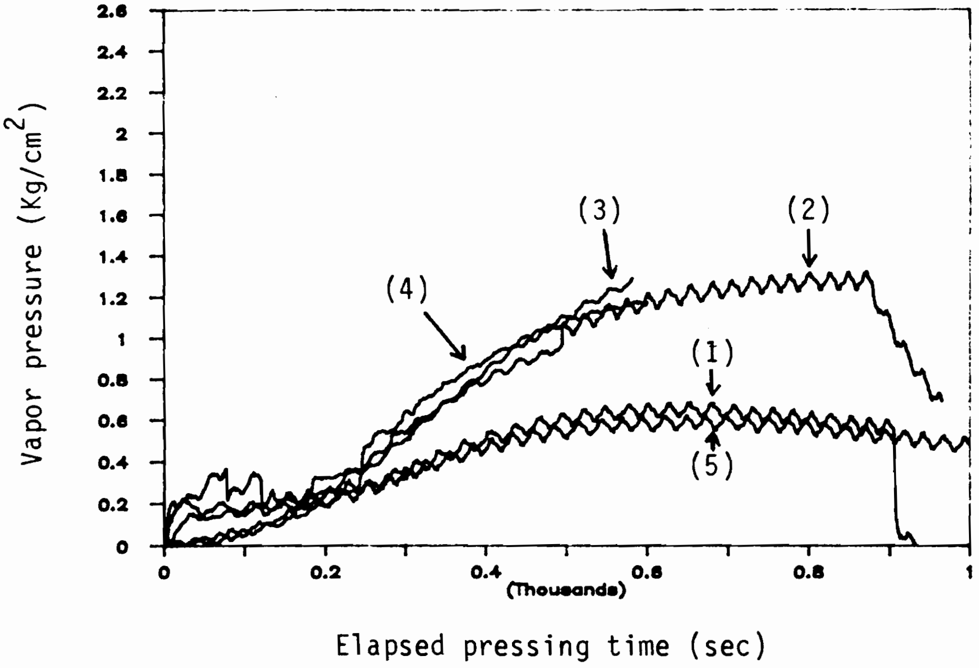


Figure 5.14. Average vapor pressure curves for boards with 6% MC veneer, pressed at 125 psi.

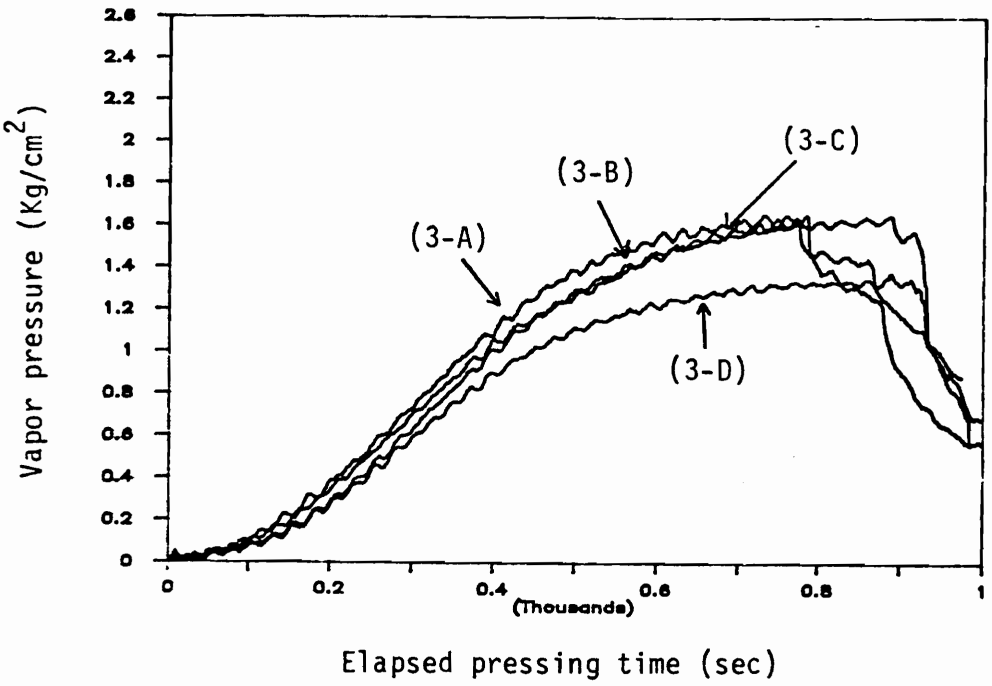


Figure 5.15. Average vapor pressure curves in four locations from the center to the edge of the core ply in standard boards. Code numbers and letters refer to vertical and horizontal positions in the panel respectively.

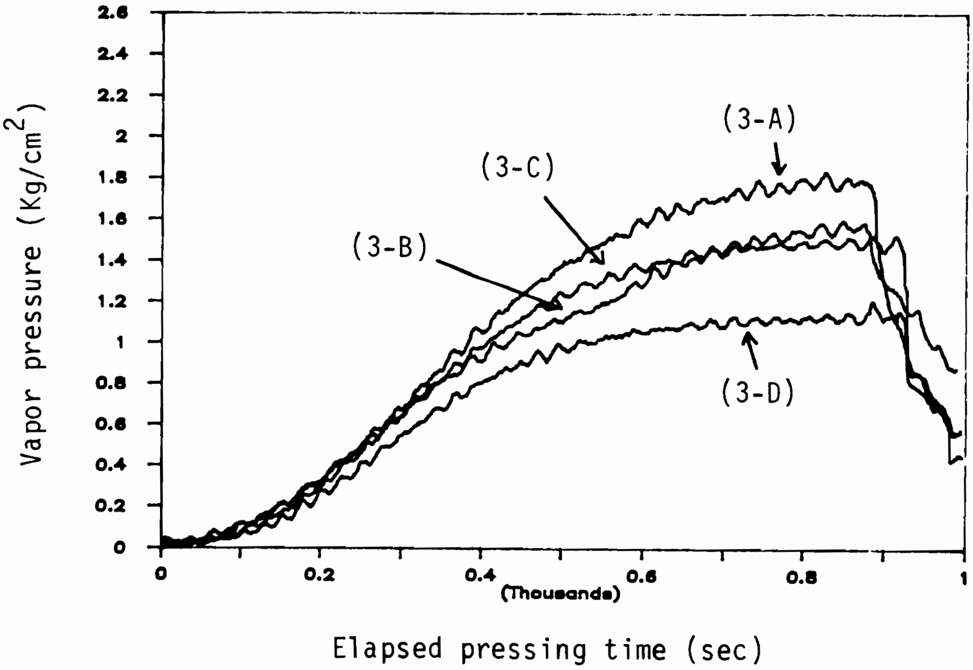


Figure 5.16. Average curves for vapor pressure distribution perpendicular to the grain in four locations of the core ply.

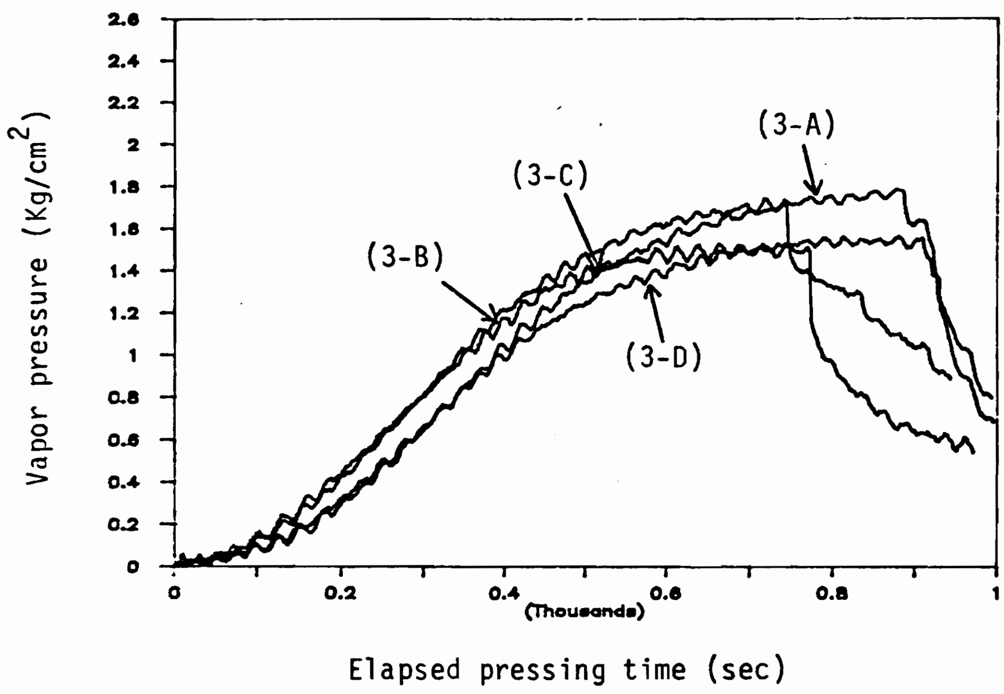


Figure 5.17. Average curves for vapor pressure distribution parallel to the grain in four locations of the core ply.

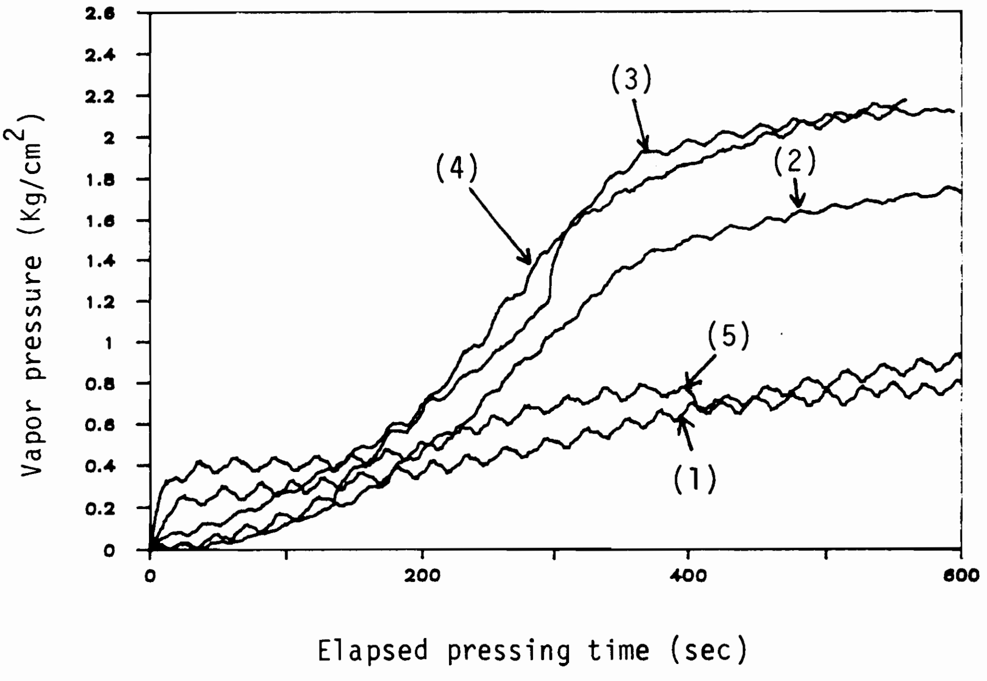


Figure 5.18. Average vapor pressure curves for boards with 12% MC veneer and 175 psi platen pressure.

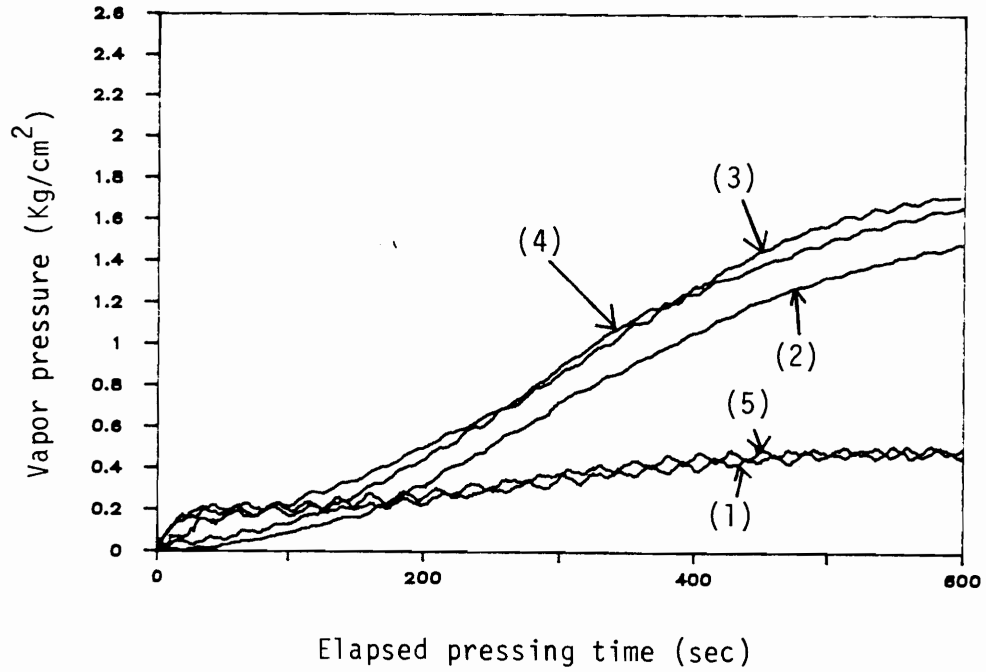


Figure 5.19. Average vapor pressure curves for boards with 12% MC veneer pressed at 125 psi.

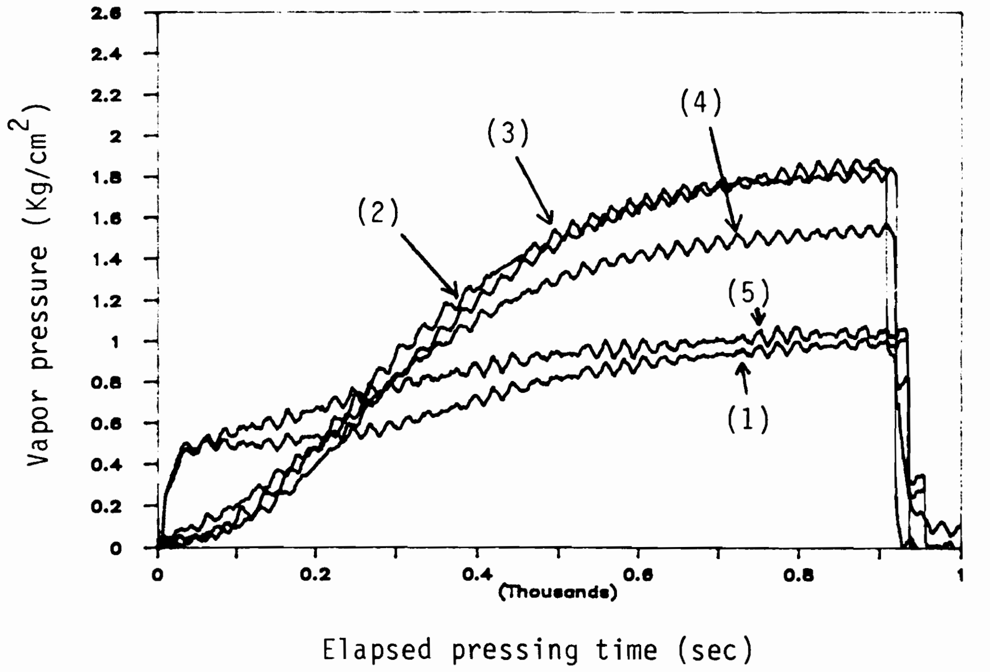


Figure 5.20. Average vapor pressure curves for boards with 16% MC veneer pressed at 100 psi.

5.1.2. Reduction of temperature data

The number of replications for temperature measurements for each set of pressing conditions is also outlined in Table 5.1. A similar approach to the one previously described for vapor pressure was also used when reducing sets of replications for temperature. Not all the replications were, however, used to derive the final average temperature distribution curves. Significantly lower levels of variability among replications were evident for temperature than those for vapor pressure. This trend can be observed in Figure 5.21, where a set of original temperature versus time curves for one location of the standard board has been plotted. The average from these replications is shown in Figure 5.22. Corresponding averaged curves for the standard board and also for boards pressed at 125 psi are depicted in Figures 5.23 and 5.24.

Sets of graphs of time versus temperature curves for each one of the four horizontal locations for each one of two gluelines are shown in Figures 5.25 and 5.26. Evidently, gradients of temperature in the horizontal plane are not large as can be observed in the aforementioned figures. Further analysis of these trends will appear in the discussion Section to follow (5.2).

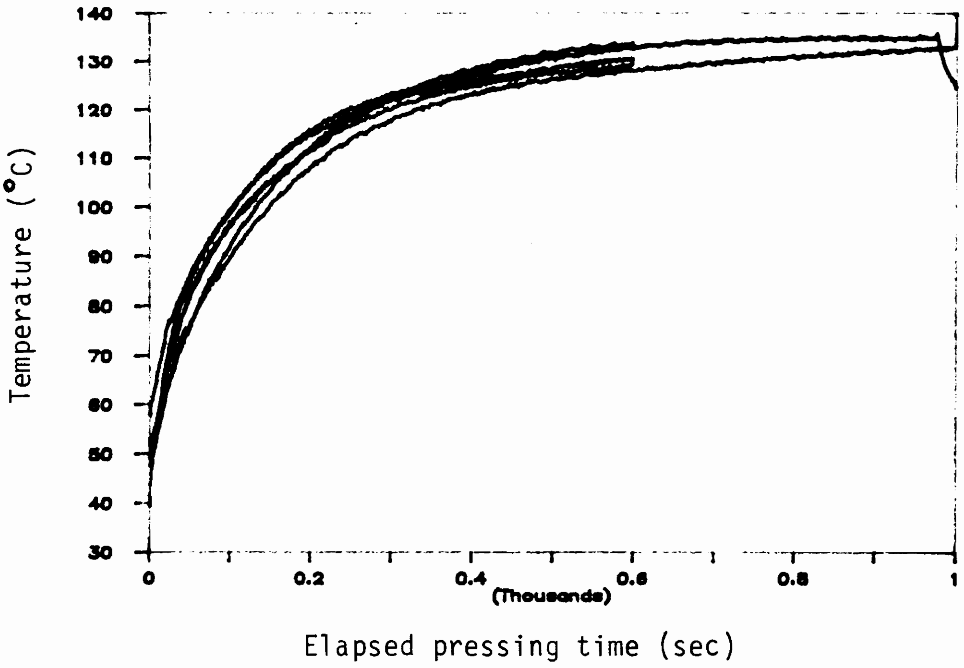


Figure 5.21. Five replications of temperature curves for location # 4 in the center of the standard board.

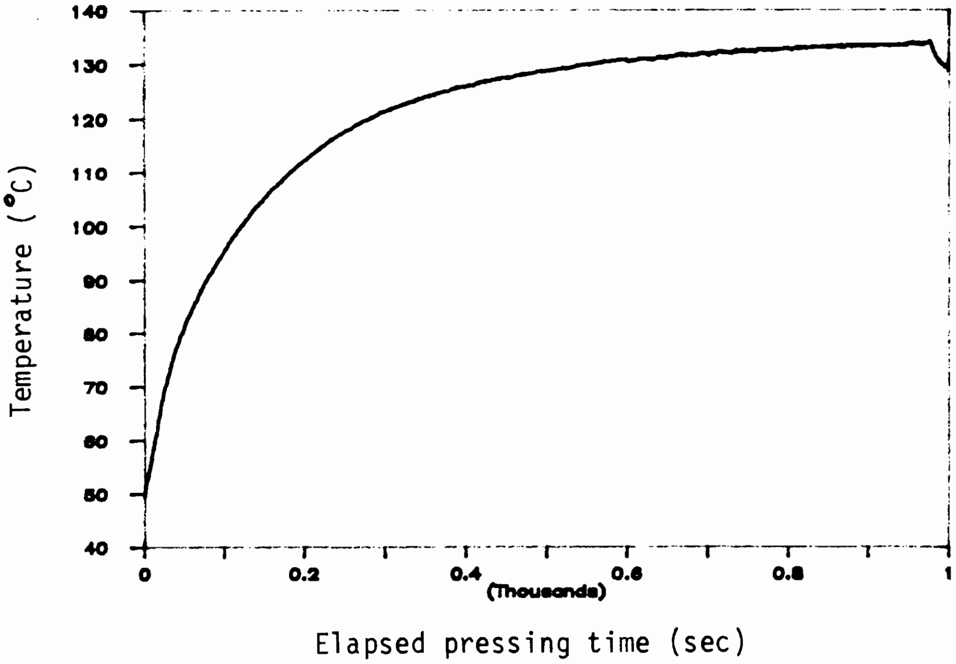


Figure 5.22. Average temperature curve for location # 4 in the center the standard boards. (Derived from fig. 5.21)

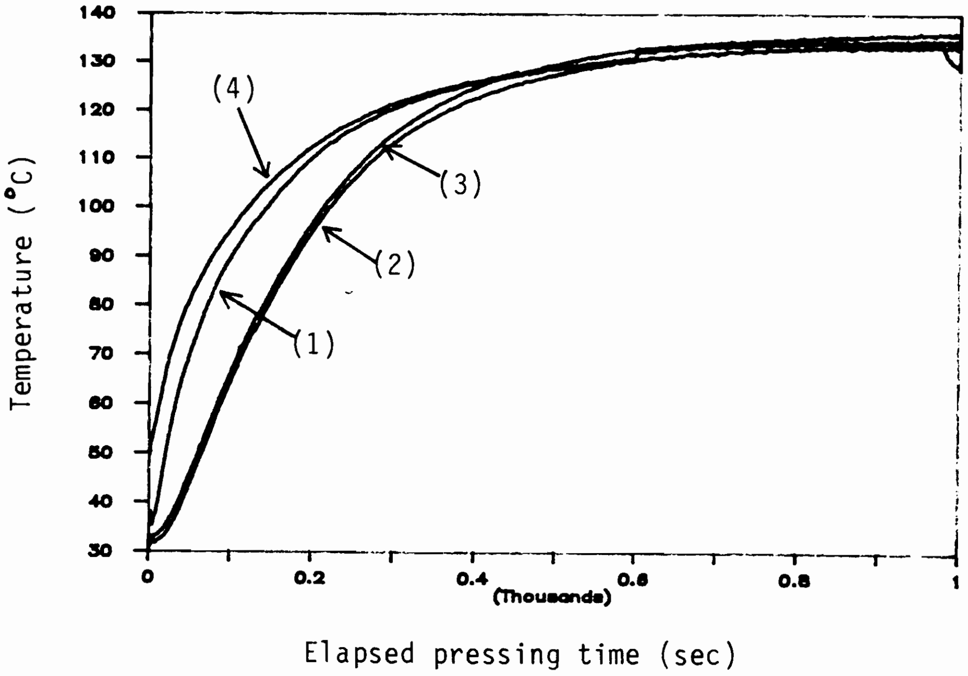


Figure 5.23. Average temperature distribution curves at the center of standard boards. Numbers refer to vertical position.

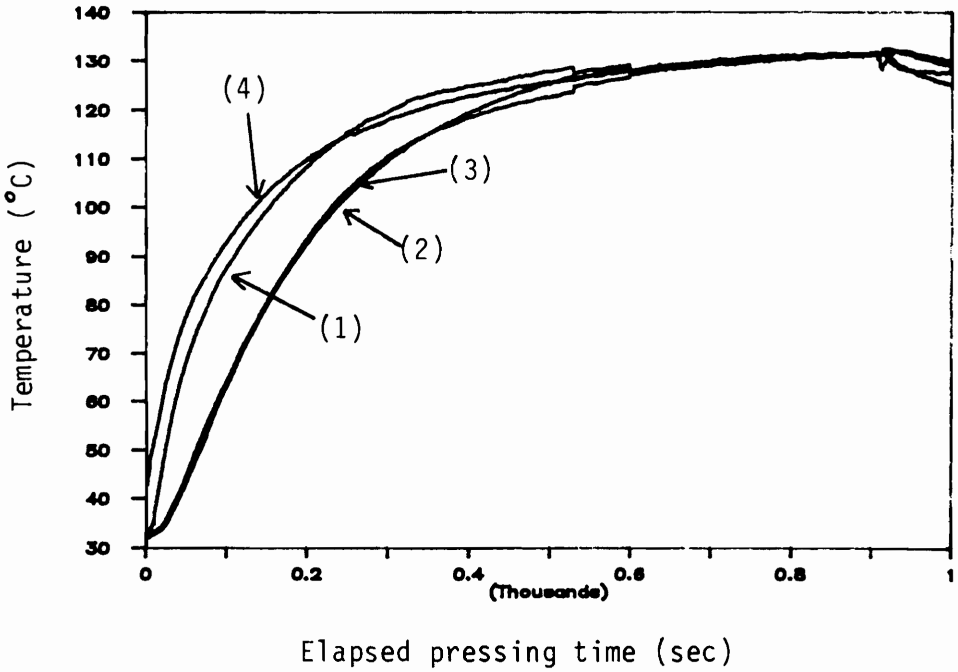


Figure 5.24. Average temperature distribution curves for boards with 6% MC veneer pressed at 125 psi.

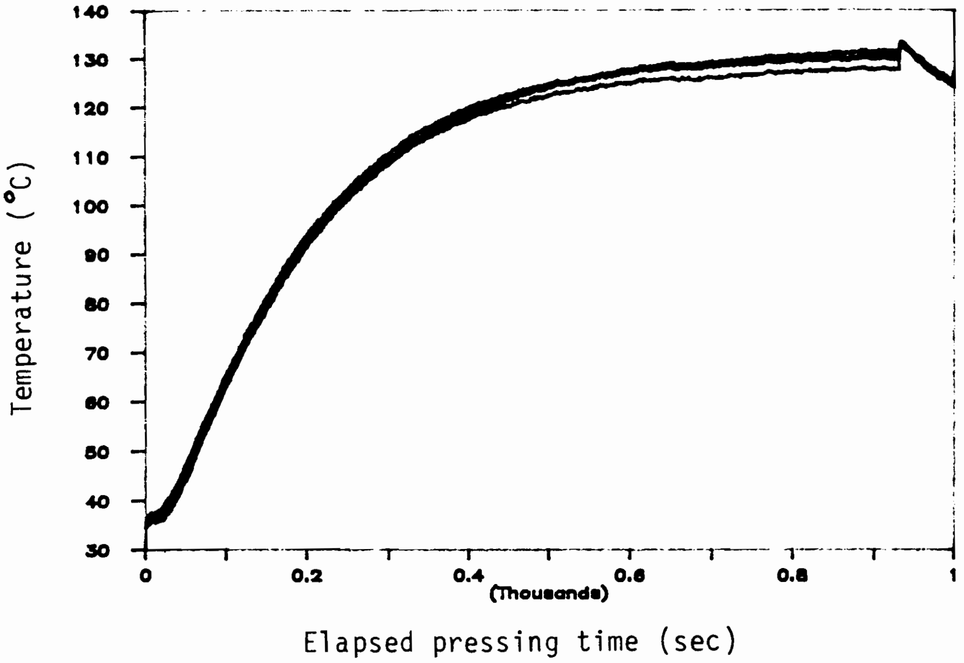


Figure 5.25. Temperature distribution in four horizontal locations of glueline 3.

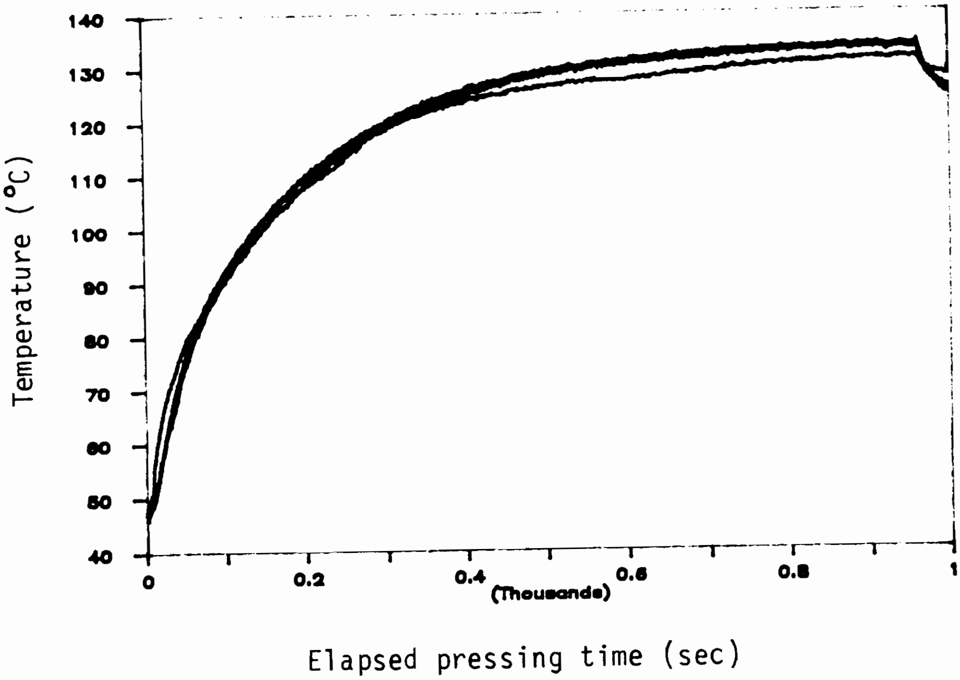


Figure 5.26. Temperature distribution in four horizontal locations of glueline 4.

5.1.3. Reduction of data for board compaction

The number of replications for board compaction under the different sets of pressing conditions was relatively large, since compaction was recorded for every board pressed. This was especially true for the standard boards (27 replications). The variability among replications, on the other hand, was relatively small. This can be observed in Figure 5.27, which depicts some typical compression curves for boards pressed under standard conditions. Due to inevitable random differences among the compression curves from 600 to 1000 seconds, it was decided to use only the replications of boards pressed for 1000 seconds to obtain the average curve. This avoided the production of a discontinuity in the averaged curves at 600 seconds pressing time. The derived average compression curve for standard boards is depicted in Figure 5.28, and the average curve for boards pressed at 125 psi is shown in Figure 5.29. By using a similar approach, the average compression curves for the different conditions used (moisture contents of 12 and 16% and loads of 100, 125 and 175 psi) were derived. These are depicted in Figures 5.30 through 5.32.

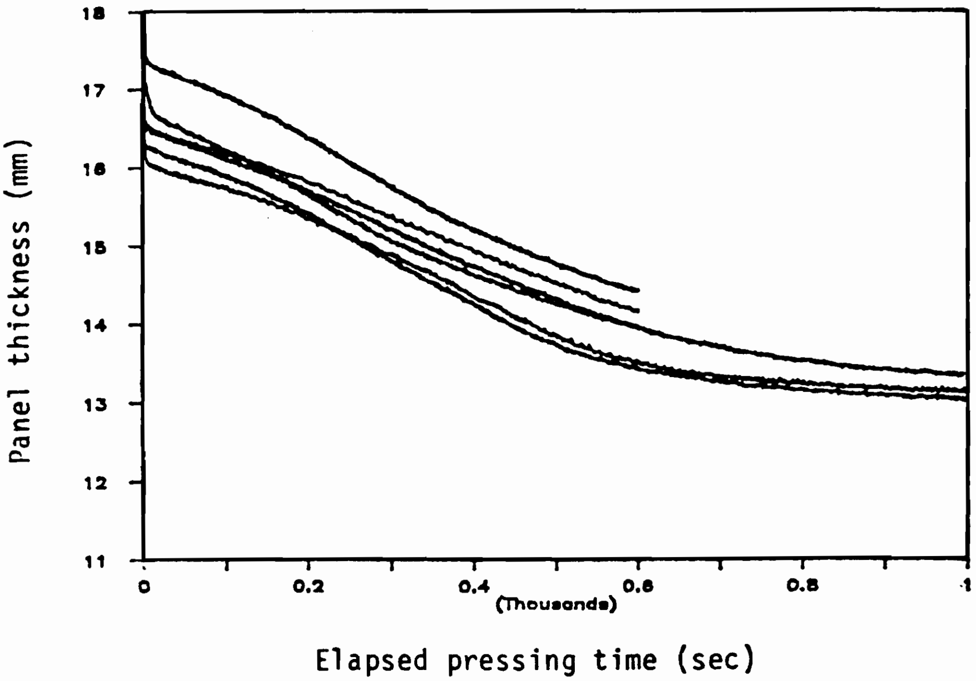


Figure 5.27. Typical replications of standard board compaction.

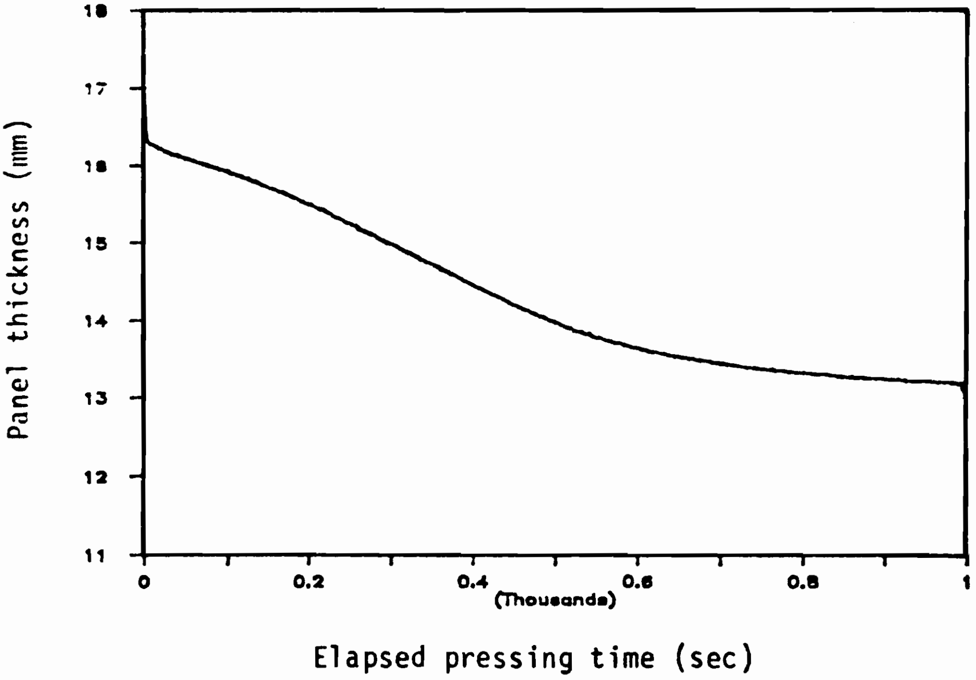


Figure 5.28. Averaged compaction curve of boards pressed under standard conditions.

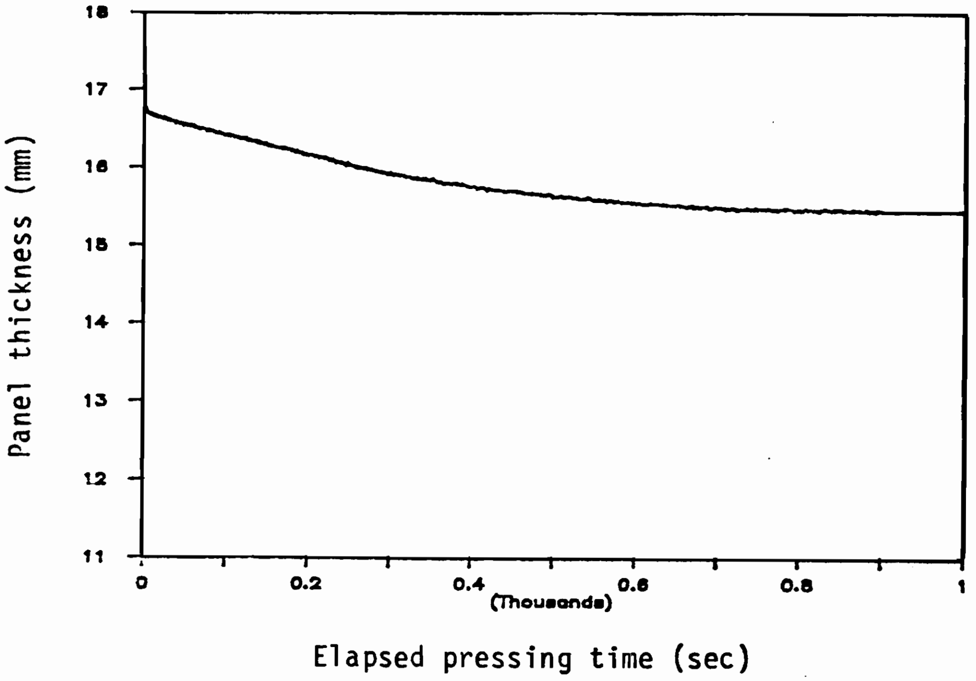


Figure 5.29. Average compaction curve of boards pressed at 125 psi with 6% MC veneer.

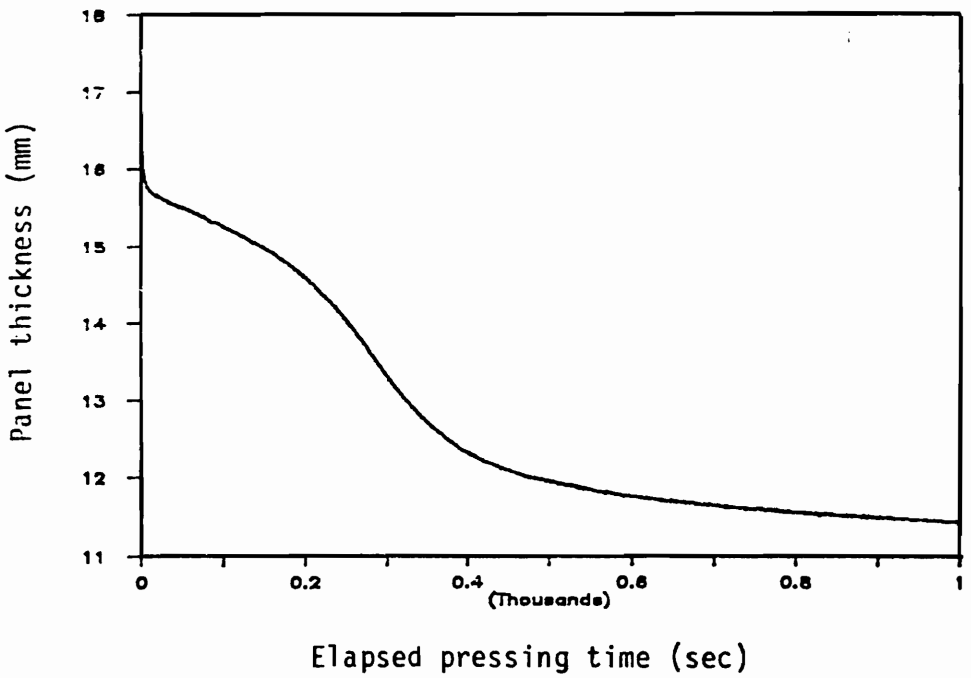


Figure 5.30. Averaged compaction curve of boards pressed at 175 psi with 12% MC veneer.

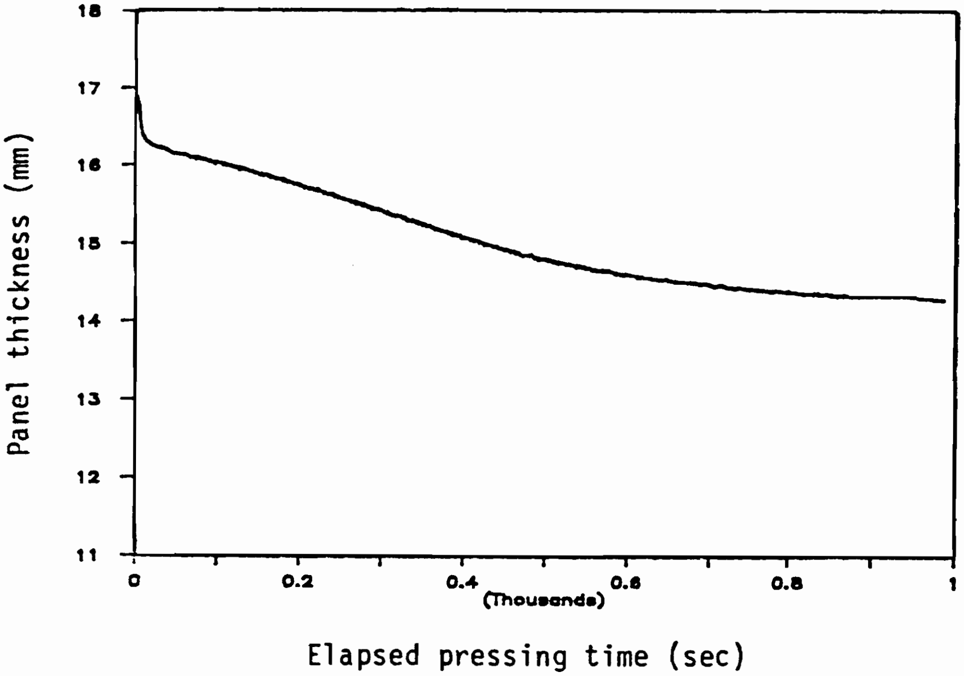


Figure 5.31. Average compaction curve of boards pressed at 125 psi with 12% MC veneer.

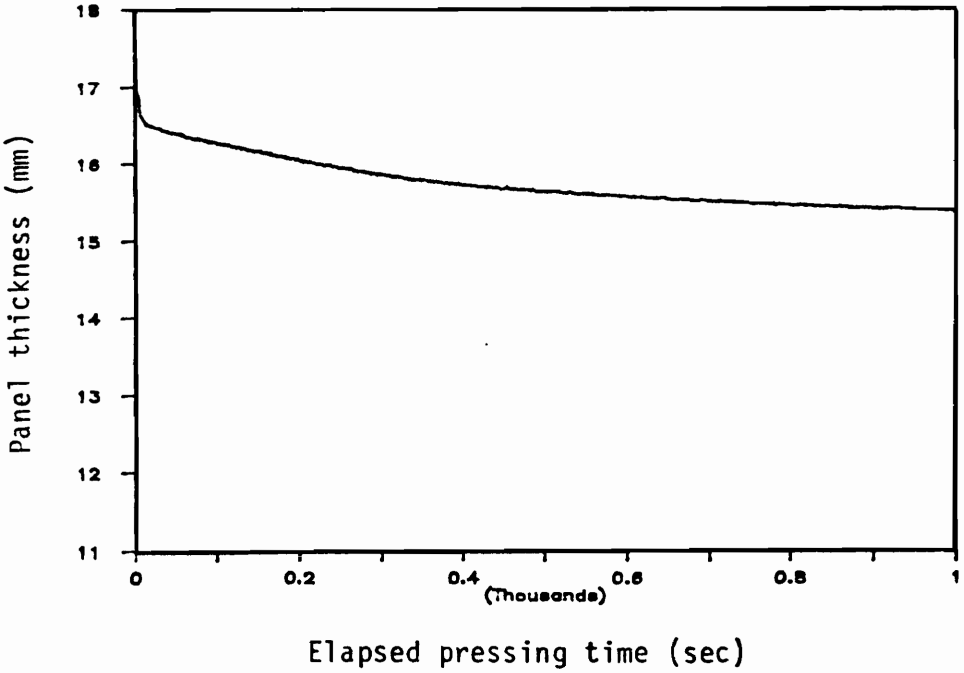


Figure 5.32. Average compaction curve of boards pressed at 100 psi with 16% MC veneer.

5.2. Discussion of board pressing curves

5.2.0. Introduction

It has already been pointed out in Chapter II that heat and mass transfer processes are highly interactive. Temperature and vapor pressure gradients are very interdependent. Similarly, the nature of board compaction depends upon the effects that temperature and moisture content together have on the viscoelastic properties of wood. For the purposes of discussion, however, each of the three measured variables - temperature, vapor pressure and compaction - will mainly be considered separately.

The initial analysis of board behavior is emphasized for panels pressed under standard conditions. Time dependent trends are considered for different locations within the board in both the vertical and horizontal planes. Following this, vertical (cross-sectional) distributions in relation to changes in platen pressure and veneer moisture will be considered.

5.2.1. The variation in temperature within the panel during pressing

The temperatures of the gluelines themselves were recorded by positioning thermocouple junctions between veneers. This is in contrast to vapor pressure measurements where probes terminated within the cross-section of the veneer. Four temperature locations in the vertical plane were therefore recorded while there were five vapor pressure positions.

Distributions of temperature will now be considered for horizontal and vertical directions in turn.

5.2.1.1. Temperature distribution in the horizontal plane

Distributions of temperature in the horizontal plane were measured since horizontal vapor movement could be expected to have an effect on localized equilibrium combinations of temperature with moisture content and relative humidity. This has been found to be the case with flakeboards (67). In the event, however, no such trend was detected for temperatures in the laminate investigated here. Probes were positioned in the locations previously shown in Figure 5.1.

Families of such time versus temperature curves are shown in Figures 5.25 and 5.26 in Section 5.1.2. Due to this lack of horizontal gradient, all curves within any given vertical position have been combined. This has enabled a reliable distribution of temperatures in the vertical direction to be derived.

The absence of any significant difference in temperature in the horizontal plane suggests that conductive heat transfer dominates in this veneer system. It was considered important to investigate this hypothesis, however, because the existence of horizontal temperature differences would have a serious impact on the relative rates of bond strength development across the panel. Account would then have been taken of these differences when modeling bond strength development.

5.2.1.2. Temperature distribution in the vertical plane

By combining all the curves measured for similar vertical positions (at all horizontal locations), well defined trends in cross-sectional behavior can be detected. Figure 5.33 shows curves for the temperature of the four gluelines of the standard panel during pressing.

As may be expected, the lower glueline (# 4) was the first to display temperature rise. Indeed, data collection could not begin until the panel had been positioned in the press and electrical connections made. The inevitable delay meant that the temperature rise of glueline # 4 had already begun. The rapidity of this rise is likely to be the combined result of both conductive heat transfer and the convection of water vapor. The rapid evaporation of water in the surface veneer creates a vapor pressure gradient which leads to moisture and associated energy (latent heat) transfer towards the first glueline.

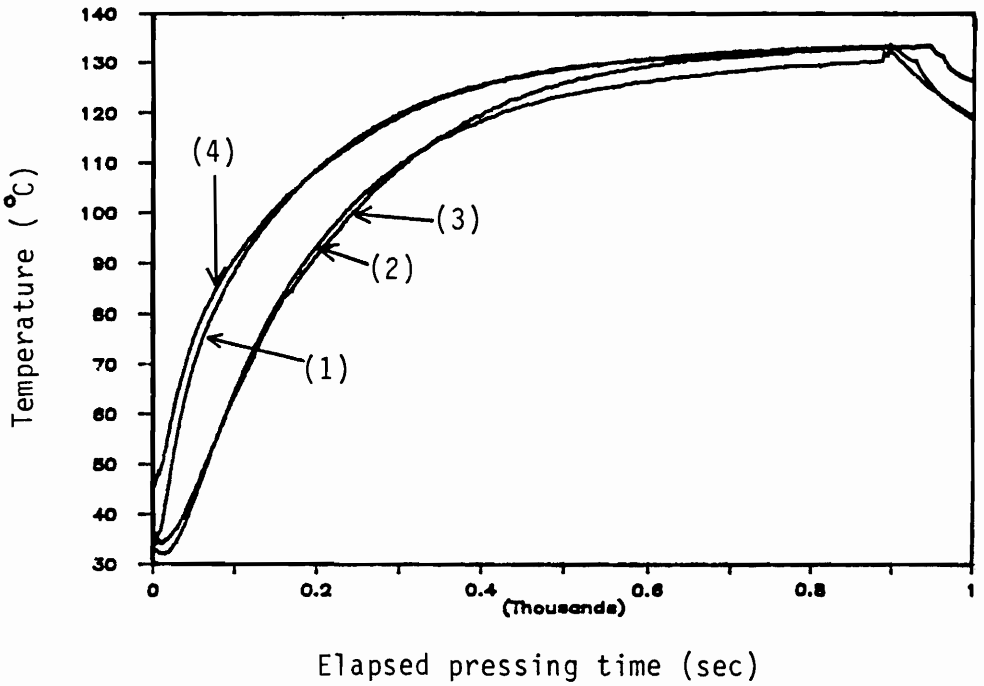


Figure 5.33. Temperature versus time curves for the four gluelines of the standard panel. Derived by assuming no horizontal gradient and therefore combining all curves.

Similar processes become operative once contact is made between the upper platen and the panel. From then on, heat is transferred almost symmetrically into the panel. The intimate contact between platen and veneers that results from the application of platen pressure also leads to a significant increase in heat transfer to the lower veneer. Probe # 1 therefore displays similar behavior to # 4 though in a slighty delayed fashion.

The temperature of the inner gluelines (probes # 2 and 3) experience delayed temperature rise, as would be expected. As the pressing period progresses, this differential reaches a maximum at about 100 seconds, after which the temperatures converge. The differential between surface and core plies has a very significant impact on adhesion kinetics and thence the production efficiency of the whole process. An attempt to quantify these effects of temperature on bonding will be described in Chapter VII.

It has already been pointed out that the rates of heat transfer and resultant temperature rise are dependent on the combined processes of conduction and convection (after phase change). Thermal conductivity and specific heat are both almost directly proportional to moisture content and temperature (54, 82, 130). Moisture content and temperature are themselves changing throughout the panel during pressing. Heat transfer rates are therefore affected by the complex interaction of dependent variables. It does, however, appear that the rates of temperature rise are consistent with the results of analysis of other workers which account only for conductive transfer.

Phase change and resultant convective transfer certainly plays a role, but less so than in wet formed hardboard, particleboards and flakeboards. The related issue of internal vapor pressures will be considered in sections to follow.

5.2.2. The variation of vapor pressure within the panel during pressing

One of the most important and original aspects in this project was the measurement of vapor pressure distribution throughout the laminate. Stresses due to localized vapor pressure at the gluelines must be countered by the accumulated strength of the glue-bond to secure a stable laminate at the moment that the press is opened. Furthermore, the movement of water within the panel during pressing is principally the result of vaporization and subsequent vapor movement in response to pressure gradients. This moisture plays an important role in affecting bonding and panel compaction.

It was evident from the vapor pressure versus time curves for individual replications (Figures 5.3, 5.5, 5.7, 5.9, and 5.11) that the development and/or escape of vapor in the system is highly variable, both within and between panels. This is likely to be directly attributable to the natural variability of wood. Such variability is less evident as the sub-division of the wood material used to form the composite increases - as is the case with flakeboards and fiberboards.

Upon averaging the vapor pressure curves for plywood, relatively well defined trends for the different locations are evident. However, the high variability does make rigorous numerical analysis difficult. The following discussion of this veneer based system will therefore be rather qualitative in nature.

Before relating curves, the form common to them all will be considered. The distribution of vapor pressure will then be discussed - first in terms of the vertical (cross sectional) direction, followed by horizontal trends and how they vary with time. This will initially be for the standard board.

5.2.2.1. The vapor pressure versus time curve

For the purpose of discussion, typical vapor pressure versus time curves are presented below as Figure 5.34.

Small and quite regular cyclical fluctuations in pressure are evident in this figure. These have a period of about 30 seconds and amplitude of about 0.1 kg/cm^2. As would be expected, they are more clearly visible on the curves for individual (not averaged) data than in Figure 5.13 which is based on superimposed sets of raw data.

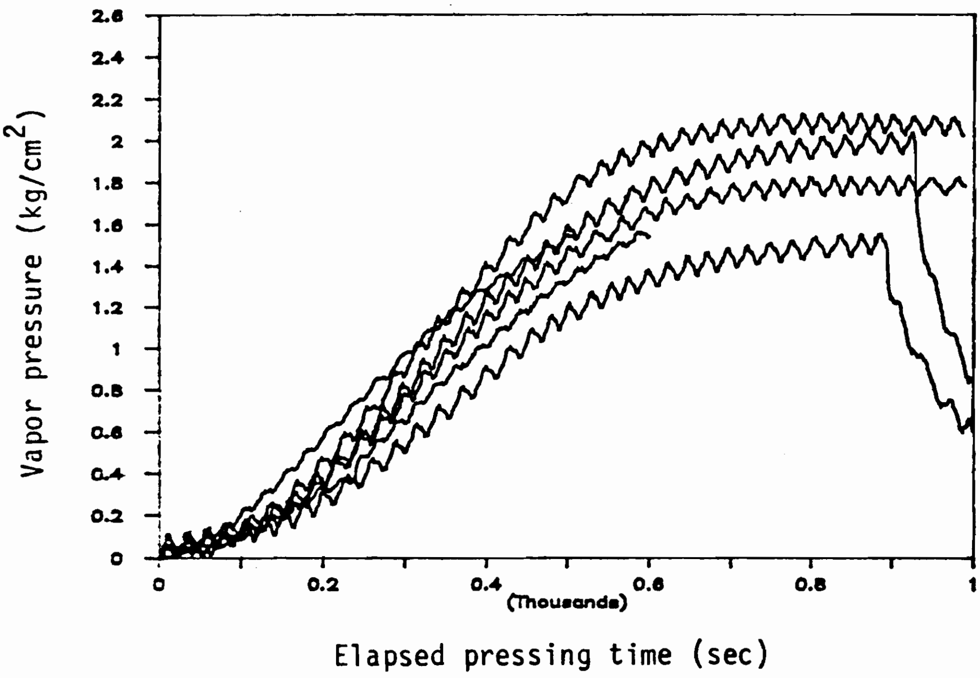


figure 5.34. A typical set of individual vapor pressure versus time curves (for standard boards at the central/core position).

The cause of these fluctuations is not clear. Several attempts were made to trace their origin, but without success. Possible explanations include the following:

- Cyclical fluctuations in hydraulic ram pressure. No corresponding effect could, however, be detected in the platen separation versus time curves.
- Cyclical fluctuations in platen temperature resulting from instability in the superheated steam control system. Again, this seems unlikely since no significant variation could be detected in platen temperature when a thermocouple was placed in contact with the surfaces.
- The cyclical accumulation and dissipation of gas or vapor within the measuring system itself - possibly as a result of capillary condensation within the hypodermic tubes. This seems unlikely since the fluctuations are present even before the veneer and probe have reached temperatures approaching 100 °C.
- Electrical interference of either the power supply, transducer itself or output signal transmitted to the data collection system. This is possibly the most likely cause, though still after a number of tests the exact origin could not be traced.

In addition to the above, it may be that this is a real effect in that excess vapor pressures do indeed accumulate locally within the material and periodically dissipate within the fine structure. Such effects were not, however, detected by Humphrey (67), when making similar measurements on flakeboards. The nature of the bonding systems differ considerably, however. The presence of a continuous glueline in plywood may lead to very different localized concentrations of bound water and vapor. In the absence of more detailed and fundamental understanding of these mechanisms it is considered dangerous to make more hypotheses here.

Data collection commenced some little time (about 15 seconds) after the panel was positioned in the open press. Pressures accumulated until the press was opened. At this stage, escape of vapor to the atmosphere was possible through the surfaces of the panel as well as its edges, and rapid falls may be seen. It is interesting to note, however, that some time elapses before vapor pressures dissipate completely. This supports the assertion that permeability in the vertical (cross-sectional) direction of this type of panel is relatively low compared with particulate composites like flakeboard. Here, gradients in the vertical direction are very small during pressing and vapor pressures fall almost instantaneously when the press is opened.

The retention of vapor pressures in plywood may have significance in terms of the duration of loads on the glue-bonds when the press is opened. It may therefore also influence the optimum rates for press opening if the dissipation of vapor pressure prior to complete platen removal is a goal.

5.2.2.2. Vapor pressure distribution in the vertical plane

Probes were positioned within the cross-section of the five veneers. When investigating cross-sectional (vertical) distributions, emphasis was given to the central position in the horizontal plane. This is where the greatest pressures occurred and may therefore be limiting when considering criteria for press opening.

Figure 5.35 (reproduced below) displays the variation in measured vapor pressure for the vertical positions.

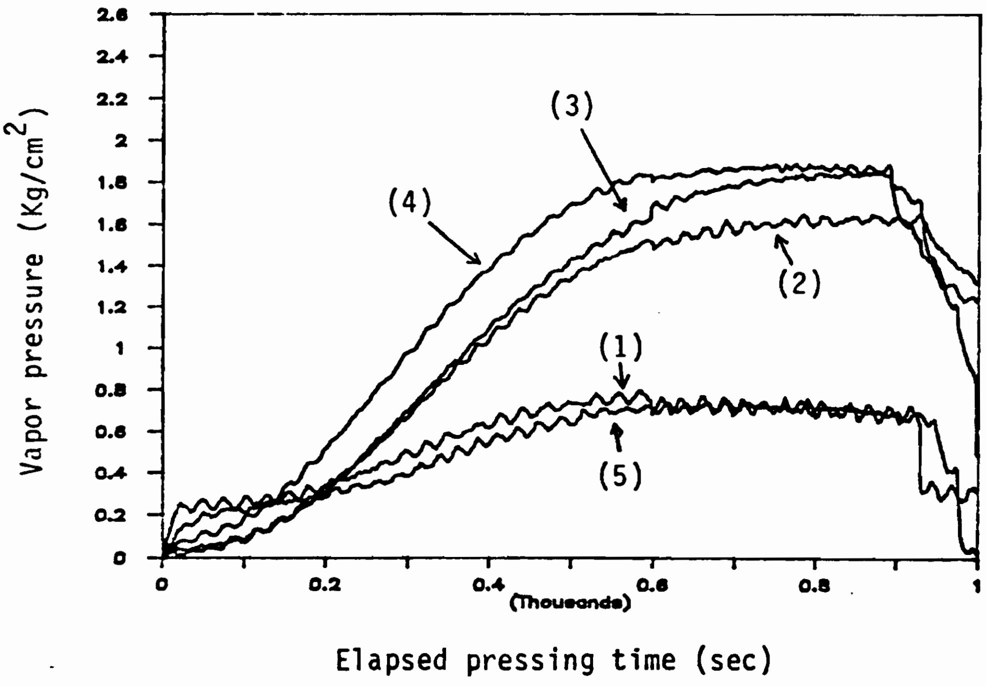


Figure 5.35. Average vapor pressure distribution curves for boards pressed under standard conditions.

Significantly differing pressures are evident among the veneers at any one vertical location. As may be expected, initially vapor pressure rises the most rapidly within the lowest veneer (# 5) which is in contact with the lower platen. Sufficient energy is transmitted into the surface material to rapidly convert adsorbed water to vapor. Migration towards the core of the board, in response to a pressure gradient, will then follow.

The above process increases in rate as the press closes and similar behavior is initiated at the uppermost veneer (# 1). Migration is complicated by the presence of the gluelines between veneers. Here a barrier to vapor movement may exist, though there is also a ready supply of liquid water for secondary vaporization. The overall effects of the glueline and its changing properties as curing takes place are difficult to quantify and should receive more attention in future research.

Pressures at the surface veneers soon level off as the supply of adsorbed water decreases. A plateau stage is then reached. At the same time, however, pressures in the inner plies (2, 3 and 4) begin to rise and eventually far exceed those at the surfaces. This gradient reversal was not anticipated based on previous work. It is likely the result of the relatively low radial permeability of wood combined with the presence of high moisture content gluelines near the core layer of the panel.

To demonstrate this gradient reversal, distribution of vapor pressure at various stages of the pressing cycle are shown as Figure 5.36 below. These have been derived from the time versus vapor pressure curves of Figure 5.35.

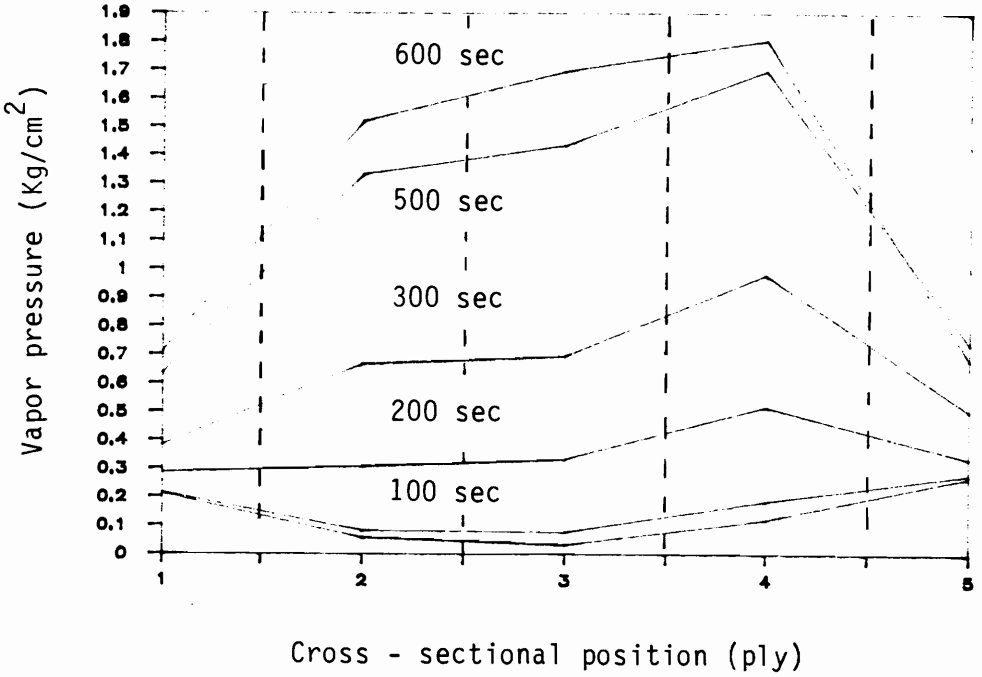


Figure 5.36 Vertical pressure distribution at various stages in the pressing cycle. Derived from Figure 5.35. (Assuming a constant veneer thickness of 3.17 mm). - Broken lines represent glueline positions.

The presence of the highest vapor pressures in the core layer is significant because this is where glue-bonds are likely to be weakest. This is both because of the slow temperature rises there, and also because moisture contents are likely to be higher as a result of vertical migration of vapor. (Moisture above certain levels is thought to limit strength development of PF adhesive).

Evidently, vapor pressures will decline eventually as moisture is lost from the panel. This stage was not, however, reached after the one thousand seconds of pressing time used in these experiments. In all industrial panels it is likely that pressures at the core will always be rising throughout the pressing cycle.

The effect of panel size on accumulated pressures has not been investigated here. It is, however, likely to play an important role in enabling laboratory derived results to be applied to the industrial situation. The repetition of some of these small scale measurements of vapor pressure and temperature for larger panels is given high priority therefore.

5.2.2.3. Vapor pressure distributions in the horizontal direction

Variability among vapor pressures measured in the horizontal direction at any one of the four locations was greater than that observed in the vertical direction. The vapor pressure curves did, however, exhibit similar overall trends as those in the vertical direction.

Since the panel is built up of veneers which are oriented in alternating directions at all horizontal positions except the center (centroid), vapor pressures would be expected to differ. This is due to the differing resistance to the lateral escape of vapor to the edge of the panel offered by the veneers. Horizontal gradients will therefore be considered separately relative to grain orientation.

Effect of grain direction on vapor pressure distribution:

From the horizontal vapor pressure distribution, it was possible to analyze the effect of veneer orientation in relation to vapor pressure diffusion along and perpendicular to the grain. From the analysis of Figure 5.16, it seems apparent that vapor pressure perpendicular to the grain tends to decrease very little toward the edges. In the case of vapor pressure parallel to the direction to the grain, there does not appear to be any significant change with horizontal position, and the variation between replications is also smaller. This can be observed in Figure 5.17.

A general conclusion is that averaged vapor pressures tends to be higher in the parallel direction than in the perpendicular direction of the grain. The levels of variability exhibited among the replications does not allow further quantitative analysis to be given. Evidently, the differences in vapor pressure due to grain orientation are not very pronounced and would require more experimentation to quantify accurately.

5.2.3. Board compaction during pressing

A general trend of compaction curves for standard boards is shown in Figure 5.27. From the analysis of these graphs, it seems apparent that the rate of board compaction is quite drastic within the first 400 seconds of pressing time. Beyond 600 seconds the rate of board compaction diminishes, and beyond that period it is almost nil.

Compression losses for the standard board reached up to 20% of the original board thickness when pressed for 1000 seconds. The compression, however, is similar to values reported in the literature for only 5 minutes pressing time. In this study, a range from 6% to 10% compression loss was found when 5 minutes pressing time had elapsed. In the literature, a range from 4% to 11% compression has been reported (45, 154).

The topic of viscoelastic behavior of the panel was not the main emphasis of the present work. It should, however, be given considerable emphasis in future work.

5.2.4. Effect of modifying selected standard pressing conditions on board behavior

Temperature gradients, vapor pressure distribution and board compaction using veneer with 12% and 16% MC., combined with platen pressures of 100, 125, and 175 psi, will now be considered.

To compare the changes in trends of these parameters with the specified pressing variables, a further combination of data was performed from the averages previously derived for the corresponding replications of temperature, vapor pressure and compaction.

5.2.4.1. Effect of veneer moisture content and related platen pressure on temperature distribution

Temperature changes in different gluelines were considered as a function of veneer MC and platen pressure. Figures 5.23 and 5.24 were used for this. The two curves representing the outer gluelines were reduced into a single average curve. The same procedure was applied with the two inner plies. Figure 5.37 represents the temperature changes as a function of platen pressure for 6% MC veneer.

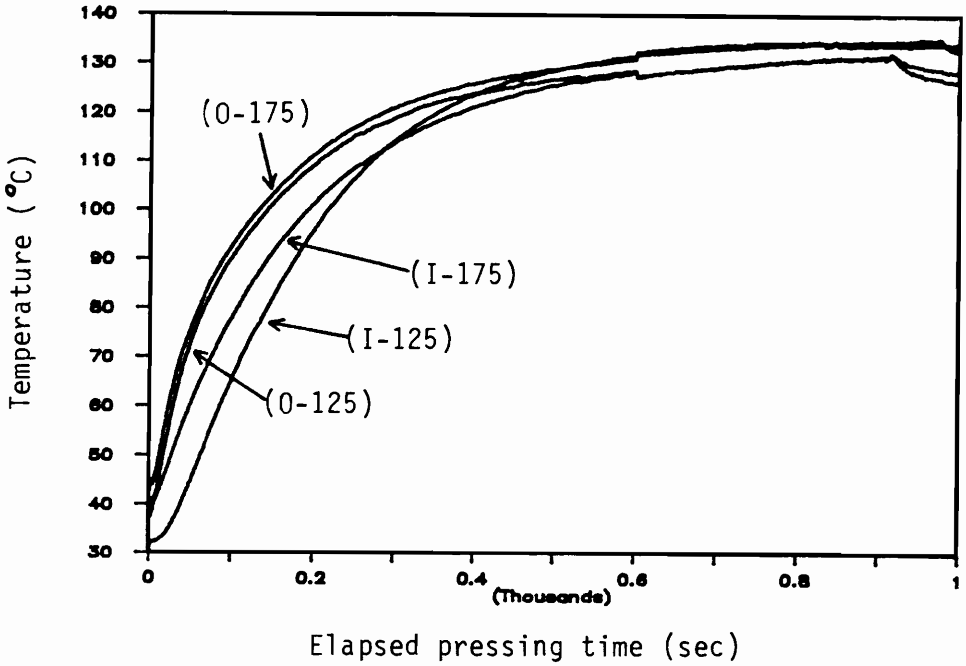


Figure 5.37. Effect of platen pressure on temperature distribution of boards with 6% MC veneer. (I stands for inner glueline, O stands for outer glueline; 175 and 125 are platen pressures in psi).

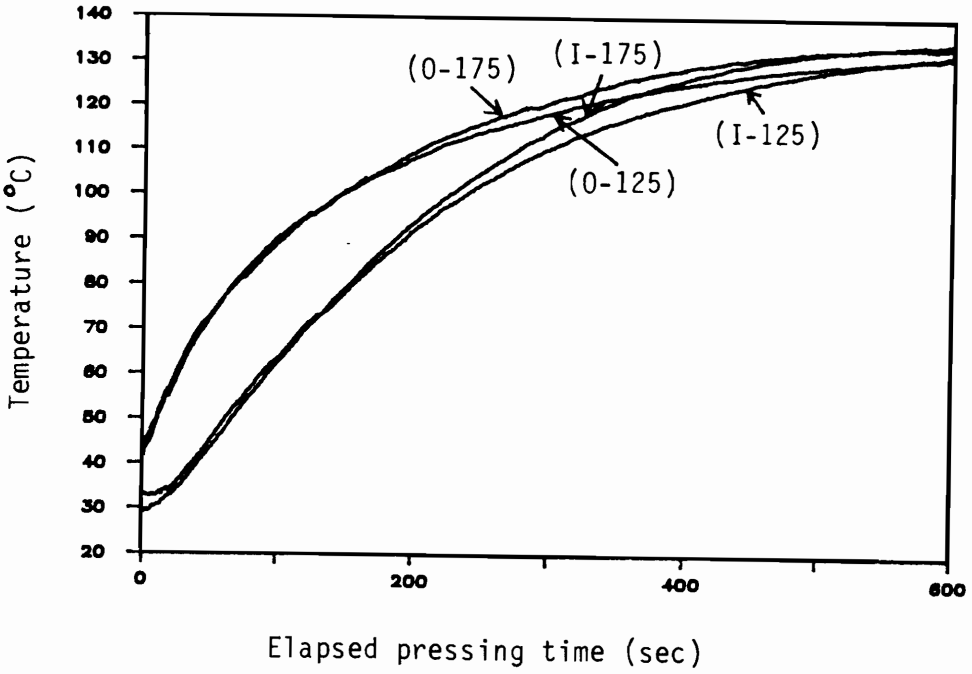


Figure 5.38. Effect of platen pressure on temperature distribution of boards with 12% MC veneer.

From the trend of the curves in Figure 5.37, it seems apparent that the effect of platen pressure on temperature for gluelines with 6% MC veneer is almost the same as that for platen pressures of either 125 psi or 175 psi.

In the case of 12% MC veneer, the platen pressure seems to have a lager effect on heat transfer. This can be observed in Figure 5.38. The temperature values for the 175 psi platen pressure in general are higher than those for 125 psi. This difference tends to increase with pressing time, generating a larger differential as pressing time progresses.

Two general conclusions can be drawn from the previous analysis: 1). The rate of heat transfer is not significlantly affected by platen pressure when low MC veneer is used. If the MC of the veneer increases, together with an increment in platen pressure, the rate of heat transfer also increases. 2). For the same platen pressure, the higher the moisture content, the higher the rate of heat transfer, especially if the platen pressure is high.

In general, for specific platen pressures and temperatures, heat transfer increases with veneer MC. As a result, veneer with high MC will show higher rates of heat transfer, reflected in higher temperatures for similar pressing times.

By increasing the platen pressure, the board is subjected to compaction, which also increases with MC and temperature. This is due to plastization of wood, (moisture and temperature together accelerate plastization, and this results in higher compaction). The compacted board material is denser, with higher thermal conductivity coefficients, reflected again in faster rates of temperature rise for the same pressing time.

5.2.4.2. Effect of veneer MC and platen pressure on vapor pressure distributions

From the analysis of the trend of vapor pressure for the sets of derived average curves specified in Figures 5.13, 5.14, 5.18, 5.19 and 5.20, it seems evident that vapor pressure is very closely related to veneer MC and platen pressure. In general, the higher the veneer MC, the higher the vapor pressure, especially for the core and inner plies. The outer plies seem to be less affected by MC variation for either 6% or 12% MC.

By comparing the effect of similar veneer MC with different platen pressures, a higher vapor pressure trend is evident for the higher platen pressure for both 6% and 12% MC veneer.

From a similar analysis of the vapor pressure curves in relation to similar platen pressures, it can be concluded that vapor pressure increases with veneer MC, especially in the core and inner plies.

5.2.4.3. Effect of veneer MC and platen pressure on board compaction

A set of graphs were obtained for each specific veneer MC for boards tested with different platen pressures. From these graphs, it is evident that compaction increases with veneer MC for the same platen pressure. This can be observed in Figures 5.28 and 5.30.

To compare the effect of different platen pressures combined with different veneer MC values on board compaction, an average graph was obtained for each set of conditions. This graph is represented in Figure 5.39. It is apparent that platen pressure most significantly affects board compaction for panels with similar veneer moisture content. If veneer MC increases but platen pressure is diminished, board compaction in general tends to decrease. This trend is evident for the 16% MC veneer pressed at 100 psi, as shown in Figure 5.39.

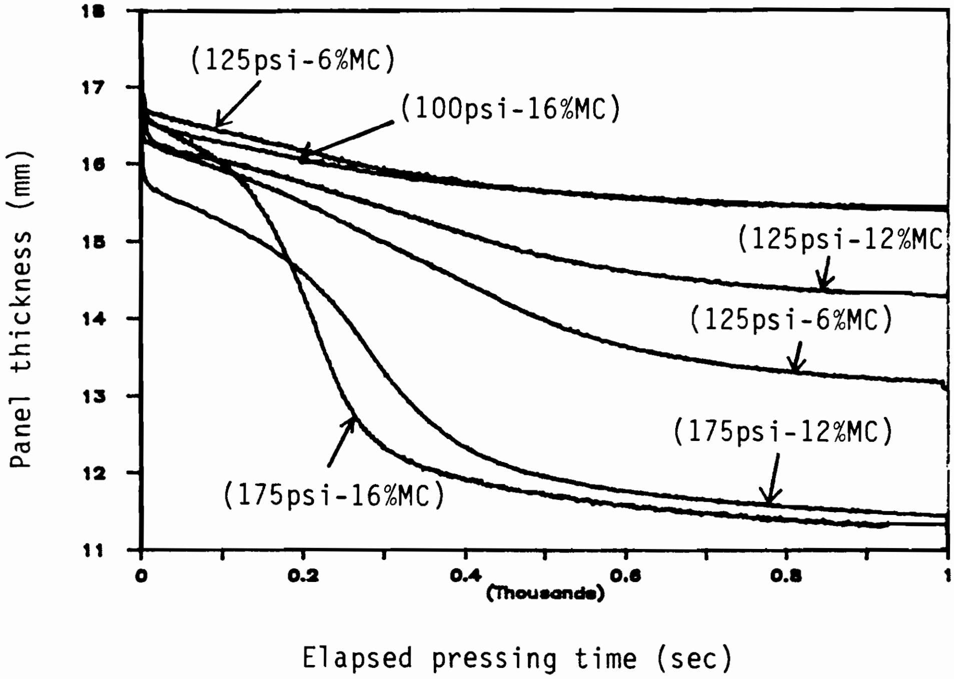


Figure 5.39. Average compaction curves for boards pressed under different conditions of platen pressure and moisture content.

5.2.4.4 Conclusion to results for non-standard panels

It has been pointed out (78) that good contact between plies during pressing can be achieved with platen pressures as low as 50 psi. With such low pressures the compression problem could be eliminated for any kind of veneer MC. In industrial plywood production, however, the surface texture of the veneer must also be considered to achieve this close contact between veneer and adhesive.

On the other hand, the rate of heat transfer is associated with MC and platen pressure. If the veneer MC is only 6%, no apparent difference is observed in the rate of heat transfer to the gluelines at either 125 or 175 psi platen pressure. As the veneer MC increases, the rate of heat transfer also increases with higher platen pressures. In boards with 12% MC veneer pressed at 175 psi, higher temperatures were recorded than for boards pressed at 125 psi. This difference can be observed in Figure 5.38.

Chapter VI

Measuring bond strength development characteristics

6.0. Introduction

Understanding the way glue bonds develop strength during hot pressing is a fundamental need for achieving an optimum pressing cycle without diminishing the quality of the final laminate. The physical-mechanical characteristics of phenolic resin-to-wood bonds increases with polymerization, and the rate of polymerization increases with temperature.

A number of approaches to infer the rate of polymerization of the resin have been investigated based on different testing techniques. Some of the most common procedures, as already pointed out in the literature review chapter, include:

- The percentage of wood failure
- Spectroscopic analysis
- Thermal differential analysis
- Thermal softening temperatures
- X-ray fluorescence analysis
- Vibrational methods
- Dynamic mechanical thermal analysis.

Some of the major limitations of these approaches are:

- The introduction of additives and tracers into the resin that may affect its properties.
- In some, polymerization reactions are halted

by rapid cooling that may generate results different from the real values.

- Assumptions of the rate of curing before and after gelation which are still unproven.

To overcome some of the limitations of these techniques an alternative approach has been used in this project. Its principle is based on making instantaneous measurements of bond strength between wood wafers formed under steady-state temperature conditions. Steady-state temperature is achieved at the glueline by raising the temperature of the bonding surfaces quickly. The rapid transfer of heat energy from the wood to the glueline is possible through the used of thin wood wafers. Repetition of this process, but for different pressing times enables bond strength curves to be constructed for each selected temperature.

Specially designed and manufactured electrically heated blocks mounted on a universal testing machine were used here to provide the source of heat and pressure needed to form the resin-wood bonds. These bonds were tested to destruction in shear mode immediately after a specified pressing time interval had elapsed at a selected temperature. In order to achieve an instantaneous measurement of bond strength, the elongation of the testing assembly during the transition from the compressive mode to the shear mode was kept to a minimum.

The "steady-state" bonding data are used to model the real board behavior during pressing. For each "steady state" temperature selected, a set of strength values were determined at different pressing time intervals. When the strength values for a given temperature are plotted against pressing time, a well defined relationship is observed. This may be seen for each temperature investigated. From the slope of the strength versus time curves for each temperature, a secondary relationship may be derived between rates of strength development and temperature. This relationship may be used with the temperature versus time curves measured in the gluelines of the laminates. By using numerical methods, bond strength development at specific locations within the board may be predicted. The integration of the data and the detailed principles of the procedure are described in chapter VII.

When characterizating boards during pressing, emphasis was given to temperature and vapor pressure distributions within and among the gluelines during pressing; and it is temperature that is accounted for in the model for prediction of bonding. There are, however, many secondary aspects that may also influence bonding. These include platen pressure, glue characteristics (spread rate, open assembly time, resin pot life etc.), veneer characteristics (moisture content, surface texture, surface age, wood type etc). Some of these factors have been analyzed in a superficial manner with the present technique. This has only been in order to determine the nature of their effect on glue bond strength development. This evaluation is important because it makes possible the segregation of variables that may otherwise interfere with the uniformity of testing conditions between samples and the detection of well defined effects of temperature on bonding Kinetics - our primary concern.

6.1. Materials and equipment

Evaluation of resin polymerization with the present approach is intended to eliminate some of the major problems of the techniques previously mentioned. The design of the apparatus and the characteristics of the wafers are the main key to successfully attaining this goal.

6.1.1. Apparatus and testing equipment

Glue bond formation between matched pairs of wafers was achieved using a specially designed electrically heated jig. The two jig blocks for pressing and heating the wafers measured 4 x 4 cm each, but the actual wafer contact area (overlap area) was 3.2 cm^2. Pressure was applied by the jig platens to the wafers by a pneumatic piston connected to a control valve. Heating for the platens was achieved with electric coils wrapped around the jig platens. Power to the windings was supplied and controlled by three term proportional controllers responding to the output of thermocouples embedded in the platens. The platens could operate up to 150 °C with variation of 1 °C. Each platen was controlled by a separate device to achieve this accuracy. A diagram of the jig is depicted in Figure 6.1.

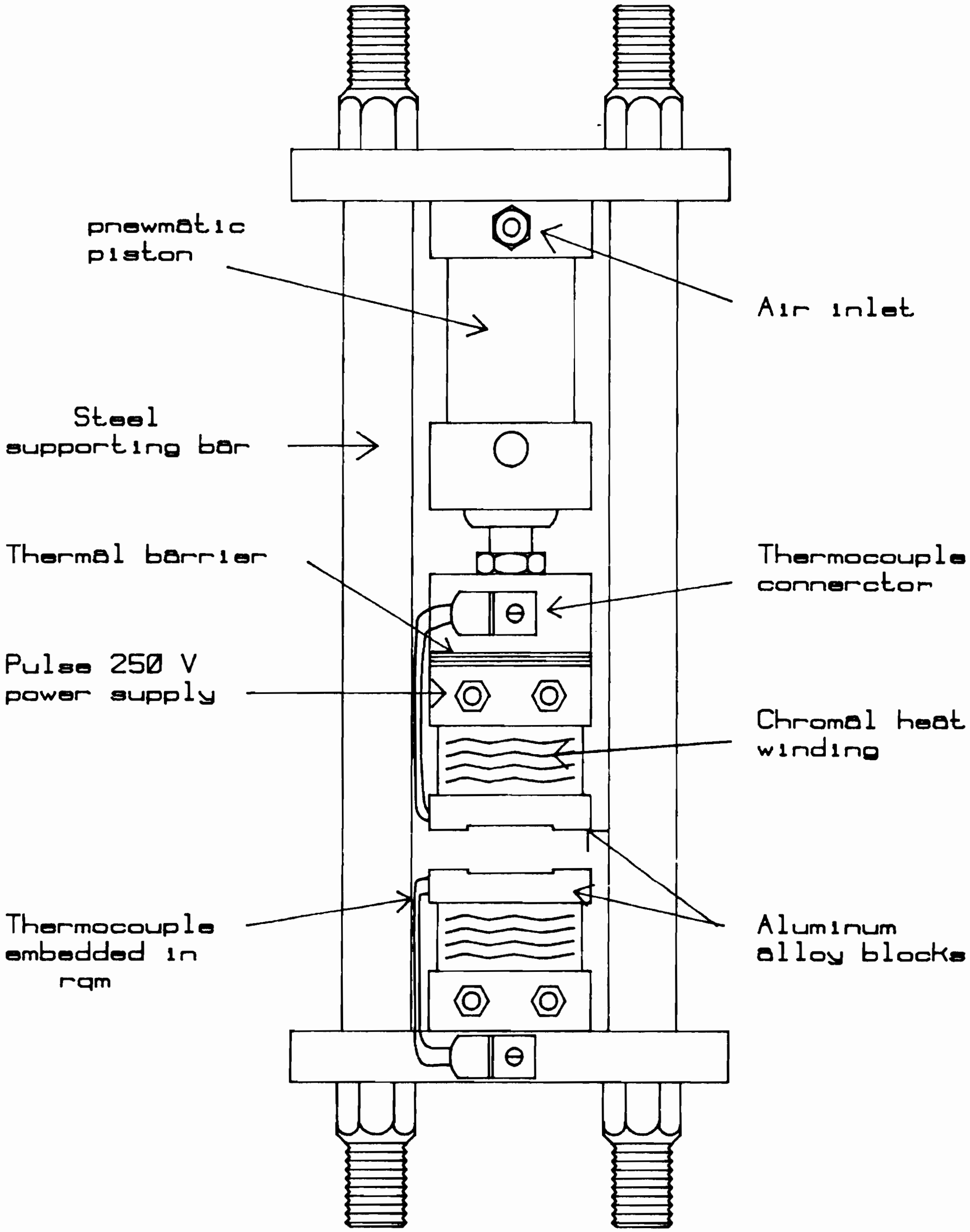
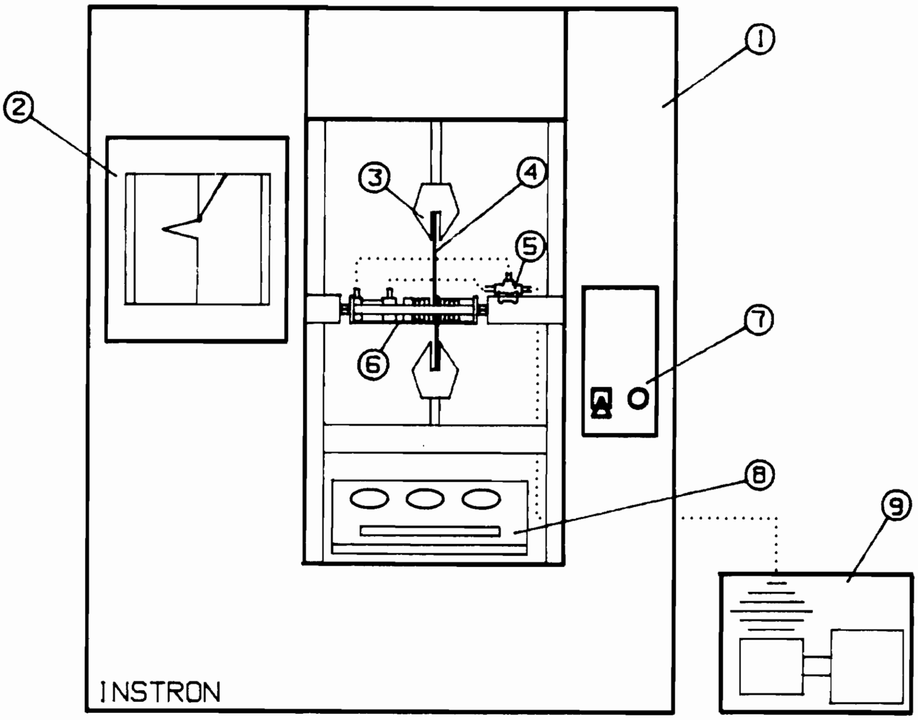


Figure 6.1. Schematic diagram of the jig for test bond formation.

The jig and a Universal Testing Machine constitutes the main components for bond formation and subsequent shear strength evaluation of the wafers. A general arrangement of the testing equipment is shown in Figure 6.2.



1 Testing frame
2 Chart recorder
3 Pneumatic clamps
4 Wafer
5 Air supply valve
6 Testing jig
7 Cross-head controller
8 Temperature controllers
9 Air pressure controller

Figure 6.2. General overview of the testing arrangement

6.1.2. Wood wafer characteristics

Veneer specimens were cut from a 150 mm x 150 mm x 1.6 m vertical grain, coastal Douglas-fir block. Veneers with tangential surface were sliced off this cant using the parallel or end slicing technique. This method effectively eliminated lathe checks and produced thin material of high surface quality. This high surface quality of the wafers, when compared to the industrially produced veneer, enabled the effect of surface variation on bond strength evaluation to be minimized. Tangential surface veneer was used for bond strength evaluation because it corresponds to rotary cut veneer used by the laminate industry. However, the wafer bonding process differed from industrial veneer bonding for laminate production. For bonding evaluation, two wafers were overlapped with the grain parallel to each other, while in laminate production adjacent veneers are normally bonded with the grain perperdicular to each other.

The veneers were placed in a room of controlled temperature and relative humidity and were allowed to stabilize at 9% moisture content. This value was selected as a compromise between the 6% and 12% moisture content values used in the board pressing part of the study. The effect of moisture content on bond strength development was not accounted for in glue bonding evaluation, but it should be considered in future studies.

After the veneer reached the specified moisture content, 1500 wafer samples of 1 mm x 20 mm x 150 mm were accurately prepared, with the 150 mm dimension along the grain, as shown in Figure 6.3. The wafer thickness was a compromise between that allowing an acceptable rate of heat transfer through the wafers to the glueline and their tensile strength. Thinner wafers would have a better rate of heat transfer, but they would also limit the range of bond strengths that could be investigated.

A preliminary segregation by early wood, late wood, and a combination of ealy-late wood in the bonding vicinity was conducted. This was done to investigate the possible effect of wood structure on bond strength development. This evaluation was considered important since the main objective of this study was to quantify the effect of temperature on bond strength development rates. Any other factor which may interfere with this goal was to be avoided. Figure 6.3. represents examples of wood wafers with different type of wood characteristics at the bonding area.

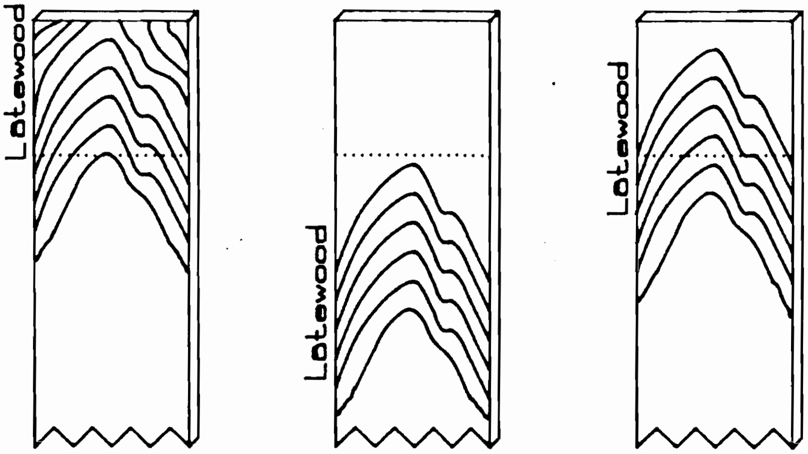


Figure 6.3. The criteria for wafer segregation by wood type prior to bonding.

6.1.3. Glue mix formulation

The glue mix was prepared according to the manufacturers specifications. The characteristics of the glue were similar to those for board manufacture:

68.97% resin
16.09% water
4.6% glufil
6.9% wheat flour and
3.45% sodium hydroxide.

The solids content of the original resin was 41% and of the glue mix was 28.27%.

The glue spread rate and the open assembly time were different than the ones used in board characterization. These parameters were adjusted according to the requirements of the present technique for bonding of wafers. This was principally in response to the difference in surface texture and absorbency exhibited for the two types of surfaces.

6.2. Experimental approach

A general description of the experimental sequence for bond strength evaluation was already described in Section 3.3.3 of Chapter III. The basis for the selection of specific values of the different variables tested are outlined in the following sections.

6.2.1. The selection of platen temperatures and bond pressing times

The maximum platen temperature used for laminate formation was 300 °F, (149 °C). The temperatures selected for bond strength evaluation should cover the range of temperatures recorded in critical gluelines during board characterization. The temperature of the innermost gluelines did not attain platen temperature, as can be observed in Figures 5.21 to 5.26 in Chapter V. The maximum pressing time of the laminate was 1000 seconds. For bond strength evaluation, however, long pressing periods could only be applied when low platen temperatures were used. With high temperatures, rapid increases in strength of the bonds develop which quickly surpass the tensile strength of the wafers.

From preliminary trials using jig platen temperatures of 70 °C, 100 °C, and 125 °C, and based on bonding results at different pressing time intervals, it was decided to test at a range of temperatures from 70 °C to 130 °C (150 °F to 266 °F). Intervals of 10 °C were used for temperatures lower than 110 °C, and 5 °C intervals for the higher temperatures.

The pressing time intervals for each temperature were selected in response to the rate of glue bond strength development. For the range of temperatures from 70 °C to 100 °C, pressing time intervals of 30 seconds were chosen. For the temperatures from 110 °C to 130 °C, the pressing time intervals were of 10 seconds. These intervals enabled well defined trends in bonding to be ascertained when the results were plotted. This information is presented in Table 6.1.

Temperature in °C	Range of pressing time intervals in seconds
70	30 -- 480
80	30 -- 420
90	30 -- 360
100	30 -- 310
105	30 -- 120
110	10 -- 80
120	10 -- 45
130	10 -- 30

Table 6.1. Jig platens temperature and pressing time ranges for bond strength evaluation.

The pressing time was counted from the moment the jig platens made contact with the wafers to the time the platen pressure was released and tensile loading was initiated. Time to failure of the bond varied slightly as a function of bond strength and individual wafer stiffness. This time was, however, small and ranged between approximately 2 to 5 seconds.

6.2.2. The selection of platen pressure

Even though platen pressure used in board manufacture was usually 175 psi, a constant pressure of 60 psi was selected for bond strength evaluation. The intrinsic characteristics of the bonds differed in many respects from actual veneer pressing.

It has been pointed out (31, 51, 78, 86) that the main function of platen pressure is to bring into close contact the adhesive with the veneer. It has also been stated that with smooth veneer, 50 psi is often sufficient to achieve good wood-adhesive contact. Using 60 psi seems to be more than enough to achieve this goal when smooth wood wafers are used. With 60 psi, a lot of the glue was squeezed out of the glueline at the time the platen pressure was applied to the wafers. This situation would not, evidently, have applied if porous and rough surfaces were being used.

6.2.3. Glue application and the selection of spread rate

A uniform film of glue mix was applied with a small paint brush to one end of the wafers, covering a surface area of at least 3.7 cm^2 (20 x 19 mm). This was the surface area that made direct contact with the jig platens to form the bonding between the wafers and the resin.

The amount of glue spread varied little from one wafer to another. The proportion of glue applied to the wafers was lower than the amount of glue used when pressing boards. The primary reasons have already been mentioned:

1). The wafers used had smoother surfaces than veneer

2). The effect of the jig platens squeezing out the excessive resin from the wafers glueline at the time that the pressure was applied.

It would have been of interest to evaluate the effect of different proportions of resin in bonding characteristics. However, due to priorities of the research, it was not possible to do this at this time. In future work, the effect of platen pressure and adhesive spread rate could usefully be investigated using this technique.

6.2.4. Open assembly time and resin pot life

Two other possible external sources of variation that may interfere with the evaluation of the real effect of temperature on glue bond strength development rates are the open assembly time (OAT) and the resin pot life (RPL).

The effect of OAT on glue bonding has been recognized (3, 24, 25, 58, 113, 139, 141). If the OAT is too long, a chance of glue dry out is possible. On the other hand, if the OAT is too short, excessive moisture in the glueline can cause wash out of the glue, producing starved gluelines. The maximum OAT recommended by the resin manufacturer was 18 minutes for the resin used for pressing whole panels. In this case an OAT of 10 minutes was used, and about 2 minutes was used for bonding evaluation. The later value was adopted to eliminate any possible effect on glue bonding evaluation due to OAT variation from sample to sample and its selection was supported from the results of experimental evaluation of the effect of OAT on bond strength development as described in Section 6.3.1 to follow.

Resin pot life (the time the resin was mixed to the last sample tested) was limited to 6 hours. The maximum RPL used was similar in both parts of the experiment: board characterization and bond strength evaluation. The effect of RPL on bonding characteristics is analyzed in Section 6.3.2 to follow.

6.2.5. Testing procedure

Adhesive was applied with a small paint brush to the area of one of the wafers to be joined. After glue application and within 2 minutes of OAT, both wafers were placed on the testing machine with specially prepared grips and then put into contact with the platens of the jig. Immediately after the wafers made contact with the platens a pressure of 60 psi was applied through the pneumatic piston of the jig. The control of the pressure was achieved with pneumatic valves and a regulator. The desired pressure was maintained until the required test duration had elapsed. Immediately after the platen pressure was released, the cross-head of the testing machine was raised at a suitable speed (5 cm/min) until the bond failed in shear mode. The cross head speed was selected to achieve a rapid measurement of bond strength and to reduce time variability of bond formation between tests.

At a given temperature a number of tests were conducted at progressively longer curing periods. This testing sequence is represented schematically in Figure 6.4.

The small but significant heat capacity of the wood wafer specimens, combined with the low thermal conductivity of wood and endothermic nature of part of the curing process and evaporation of adsorbed water, all combine to produce an unavoidable time lag in raising the temperature of the glueline to that of the Jig platens. This affects the curing rate in the initial stages of pressing. The magnitude of the temperature lag was measured by inserting a thermocouple into the glueline between wood wafers at each curing temperature.

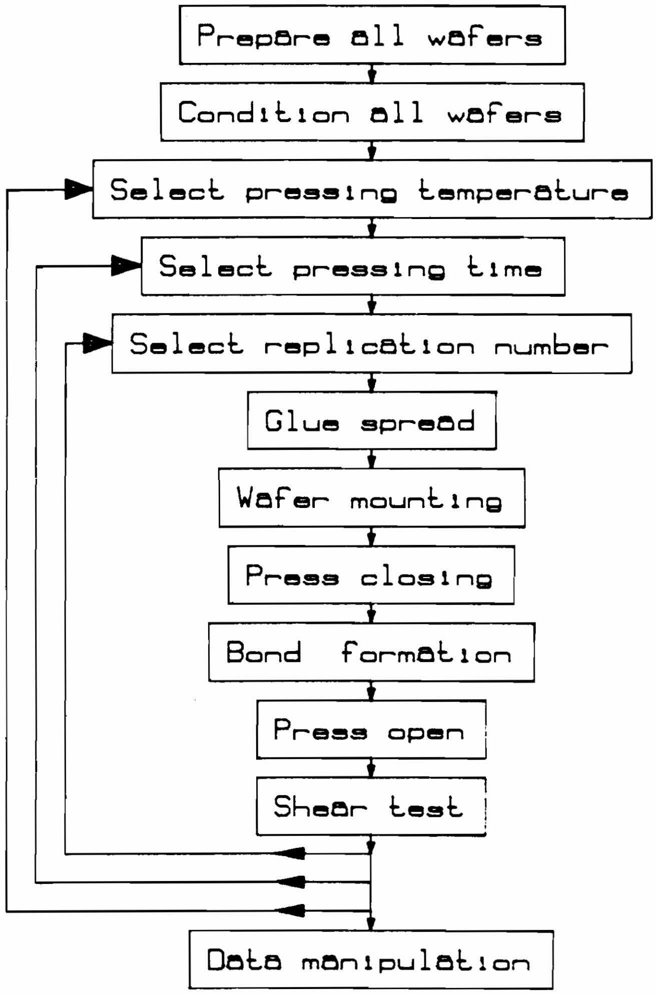


Figure 6.4. Testing sequence for evaluation of glue bond strength development.

6.3. Analysis of data

It has already been emphasized that the experimental work was concentrated on the evaluation of glue bond strength as a function of temperature for a specific set of bonding conditions. Additionally, the effect of OAT and RPL on glue bond strength was evaluated. This was mainly to determine any possible effect on the corresponding values of bond strength for each temperature tested. The effect of wood characteristics on bonding was partially considered. This concerned the effects of early wood, late wood, and early-late wood interactions at bonding surfaces. These again were primarily secondary investigations designed to evaluate and, if necessary, reduce the variability in bond strength data. Each of these sections will be considered in turn.

6.3.1. Open assembly time

A range of 0 to 40 minutes OAT were investigated with 5 minute intervals between each, using a jig platen temperature of 105 °C combined with 60 seconds pressing time.Thesedata are plotted as Figure 6.5.Evidently, a clearly defined effect of OAT on bonding is not immediately evident.

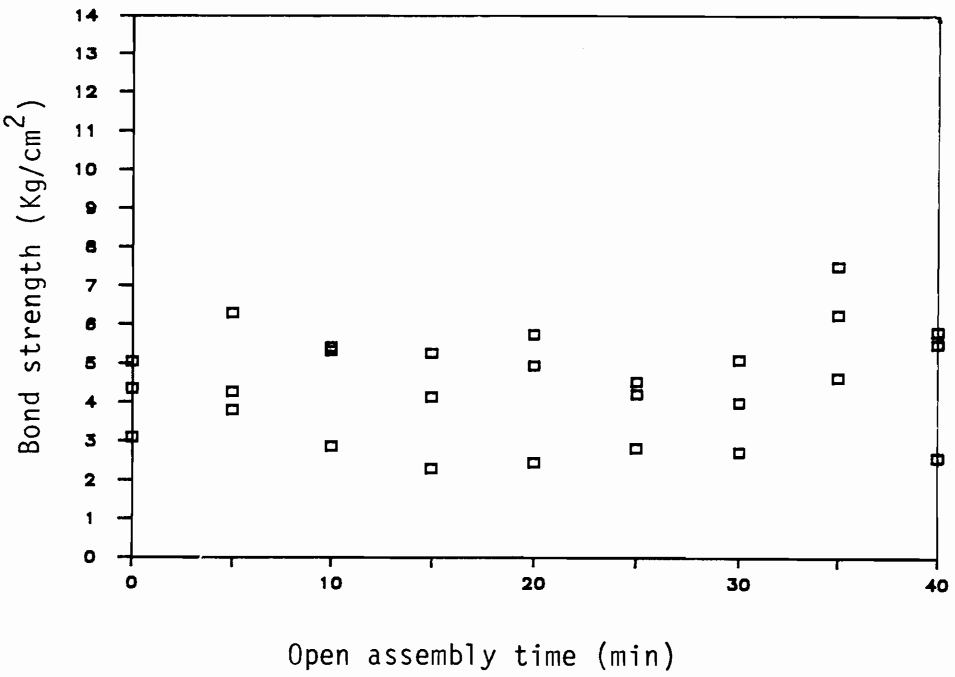


Figure 6.5. Relationship of glue bond strength with different open assembly times.

An analysis of variance to test for significant differences among the means for the different groups of OAT tested was carried out (Appendix B). This supports the conclusion drawn from the graphical representation: no significant difference exists among mean strength values of the different OAT values.

6.3.2. Resin pot life

A preliminary analysis of the effect of resin pot life on glue bond strength was performed. The RPL range investigated covered a 22 hour period. Jig platen temperature and pressing time were kept constant at 105 °C and 60 seconds, respectively.

A graphical representation (Figure 6.6) of the results shows no apparent differences among the observations for different pot life values and this was supported by an analysis of variance (Appendix B). Although the time intervals selected are not uniform beyond 4.4 hours, still the latest glue bond strength values present a similar trend as those obtained during the first hours of the resin pot life. In the event, a maximum RPL of 6 hours was used in the experiment.

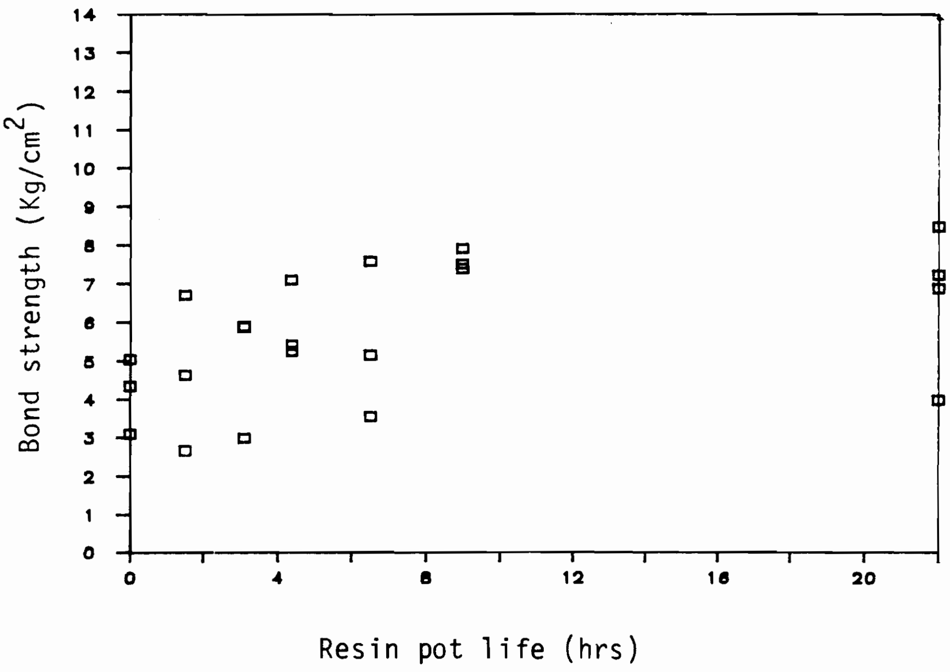


Figure 6.6. The effect of resin pot life on subsequent bond strength development.

6.3.3. Heat transfer from the platens to the glueline

In this analysis, the temperature of the jig platens has been assumed to be identical to the temperature of the glueline itself. The time required for the wafers to reach the platen temperature has been neglected. For a selection of specially formed bonds, the temperature of the gluelines were measured with thermocouples and recorded using a continues strip chart. Time versus temperature curves for all the jig temperatures used are presented as Figure 6.7. It is evident that for the lower jig platen temperatures, (70 °C to 105 °C) the time elapsing before the glueline reaches the platen temperature is relatively short - within 25 seconds.

For jig platen temperatures from 110 °C to 130 °C, two peaks in the glueline were observed. A plateau was reached within a relatively short time interval, (15 seconds). After this rapid increase in temperature, longer times were required for the glueline to reach the target temperature.

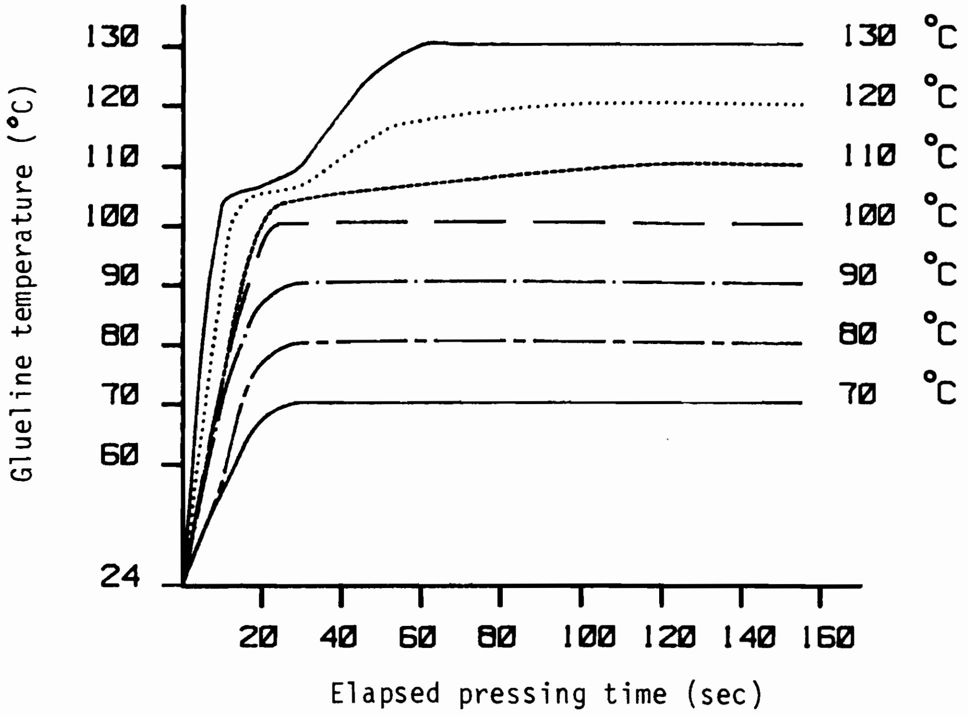


Figure 6.7. Glueline temperature versus time curves for jig platen temperatures used.

This information is very important for the correct interpretation of the bonding results. Evidently, the wafers' heating time values affect the analysis of the strength versus time curves. It seems apparent that at lower jig platen temperatures, relatively little time elapses before the glueline approaches the platen temperature. Furthermore, the possible effect of these short lived differentials between platen and glueline temperatures are less critical for the lower temperatures. Sufficient time is available beyond this stage for well defined trends to become evident.

Similar conclusions cannot, however, be drawn from the tests made at higher temperatures. The strength of the glue bonds surpassed that of the wafers in a very short time, (90 seconds at the most). This made it impossible to carry out tests when steady temperatures had been reached. Platen temperatures have been adopted in this initial analysis for simplicity. Future refinement of the technique could involve iteractive correction for this unsteady state behavior at the beginning of each test.

6.3.4. Wood wafer characteristics

The evaluation of the effect of wood variation on glue bond strength development was performed at platen temperatures of 100 °C and 110 °C. For each selected temperature, two samples of each type of wood: early, late, and mix - were tested. Pressing time intervals were selected on the basis of rate of polymerization for each temperature. Bond strength values measured for the different types of wood and the corresponding platen temperatures and pressing times are listed in Table 6.2.

Platen Temperature 100 °C				Platen Temperature 110 °C			
Press Time (sec)	Shear Strength (Kg/cm^2)			Press Time (sec)	Shear Strength (Kg/cm^2)		
	Early	Late	Mix		Early	Late	Mix
30	0.19	0.14	0.14	10	0.30	0.19	0.30
30	0.16	0.16	0.11	10	0.30	0.19	0.19
60	1.38	1.84	1.27	20	0.30	0.32	0.30
60	0.57	1.30	1.27	20	1.38	0.84	0.19
90	2.73	2.49	3.57	30	5.00	5.70	3.00
90	4.38	1.30	2.65	30	5.27	2.19	3.65
120	7.22	4.38	4.35	40	5.54	7.16	3.57
120	5.62	3.95	5.1	40	3.92	3.81	7.43
150	6.14	5.65	7.05	45	7.05	7.41	5.97
150	6.08	6.84	8.54	45	5.97	5.97	8.16
180	6.11	4.73	7.43	50	8.78	11.03	7.05
180	6.11	7.14	9.08	50	11.16	10.08	5.97
210	8.68	11.65	16.08	60	8.51	11.95	6.86
210	15.76	9.76	14.62	60	15.03	17.08	7.59
240	11.11	14.95	12.32	70	15.46	13.27	16.35
240	15.19	15.51	10.84	70	11.95	15.24	18.19

Table 6.2. Glue bond strength values as a function of wood type, platen temperature and pressing time.

Bond strength values for the three different wafer surface types are depicted in Figure 6.8 for platen temperature of 100 °C.

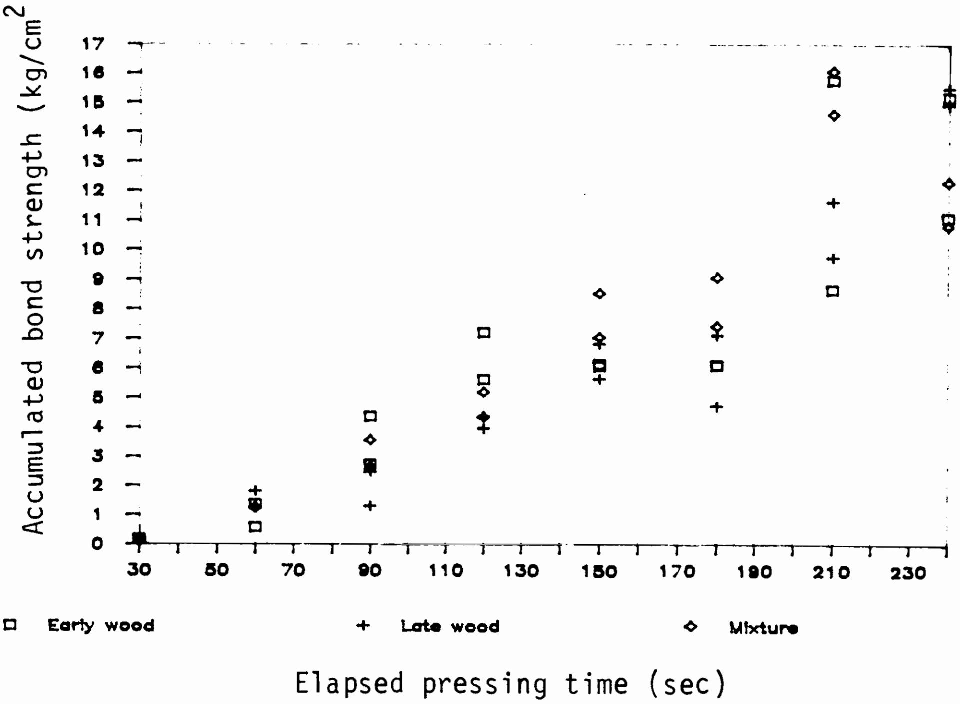


Figure 6.8. Glue bond strength development as a function of wood wafer surface characteristics.

An analysis of variance was performed for differences in bonding among the three types of surfaces for each one of the two temperatures tested (Appendix B). No significant difference was found among means. Care was still taken to randomly distribute wafer types in the actual bonding study.

An additional evaluation to test for the effect of the combined interaction of wood type and temperature on bond strength was also performed by a 2 x 2 x 3 factorial analysis (Appendix B). To apply the factorial analysis to this experiment, the data congruent to both temperatures, (100 °C and 110 °C) were selected. These corresponded to elapsed times of 30 and 60 seconds.

From the ANOVA, it was found that the interaction of woodtype with temperature was not significant (Appendix B). As expected, the interaction of time with temperature was highly significant at either 5% or 1% level. The effect of wood type shows some significant effect at the 1 % level, but not at the 5 % level.

Although the present results show no strong evidence of significant differences among wood type, it is likely that with refinament and reduction of variability of the materials and methods, differences in bonding due to wood characteristics may be detected. There is considerable potential to use the present technique for evaluation of many factors affecting bonding.

6.3.5. Glue bond strength evaluation at different pressing temperatures

An example of the information collected from each set temperature is displayed in table 6.3.

Sample Number	Shear Strength (kg/cm^2)	Pressing Time (Seconds)
1	0.22	30
2	0.16	30
1	0.57	60
2	0.32	60
3	0.84	60
4	2.14	60
1	3.92	120
2	3.00	120
3	4.14	120
4	3.54	120
⋮	⋮	⋮
1	8.51	360
2	7.59	360
3	6.70	360
4	7.65	360

Table 6.3. Typical glue bond shear strength values for jig platen temperature of 80 °C at different pressing time intervals.

A minimum of four bonds were tested for each combination of temperature and time. The upper limit of pressing time for each temperature was dictated by the strength of the wood wafers. During the testing procedure, the type of failure was recorded; differentiating between bond failure, wood failure, and both wood and bond failure. The complete set of data partly displayed in Table 6.7 is plotted as Figure 6.9.

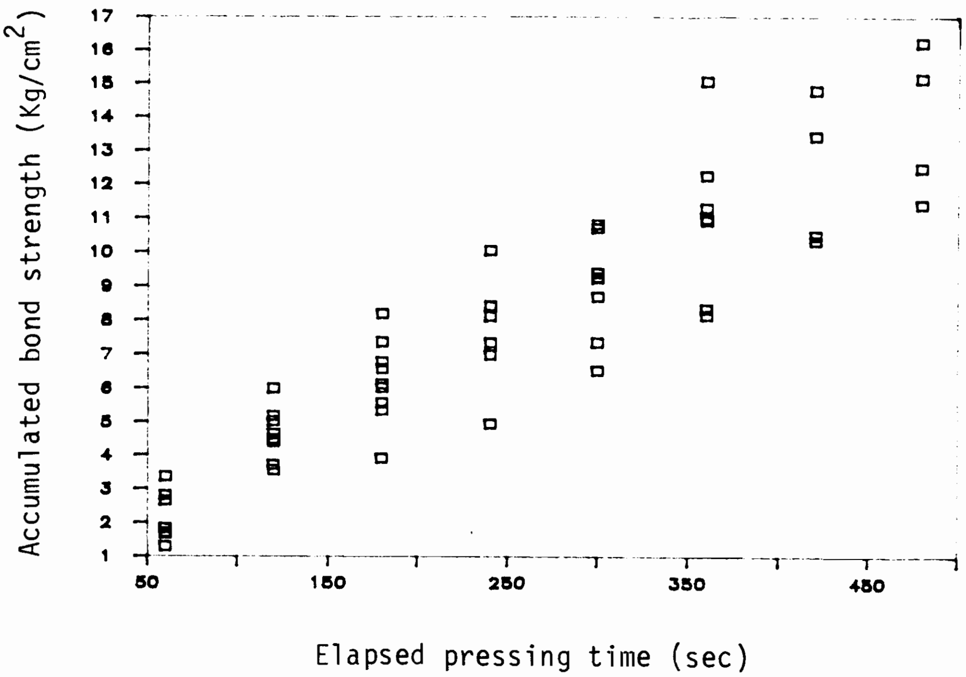


Figure 6.9. A family of glue bond strength values for different pressing times at constant platen temperature of 80 °C.

Bonds formed at lower temperatures generally display wider variations in accumulated strength. However, when the mean strength values for each elapsed time are calculated, a well defined trend of bond strength development is evident. Such a graph derived from the same data as that used for Figure 6.9 is shown as Figure 6.10.

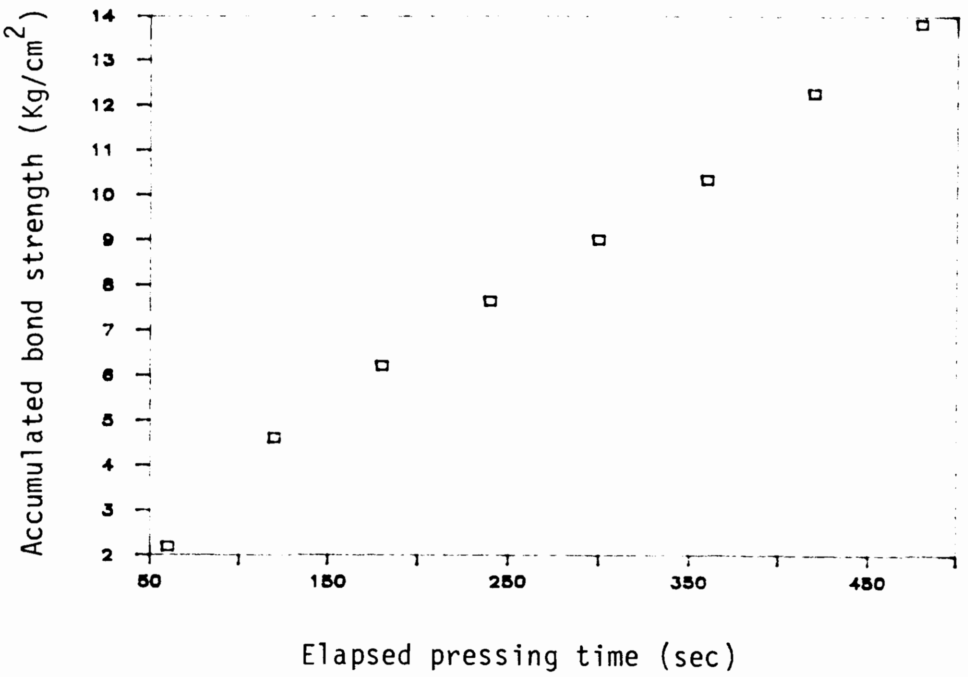


Figure 6.10. Averaged bond strength values versus time measured at 80 °C platen temperature.

6.3.6. Regression models for bond strength development with time

Separate regression equations are required for each of the temperatures used. Following this, a further model to relate the above rates of bonding to glueline temperature is also outlined. The latter model, when combined with the distribution of temperatures in the glueline recorded during pressing of the boards, may then be used to simulate glue bond strength development within boards as pressing proceeds.

Several regression models were employed to determine the best fit for the distribution of the measured bond strength values. These included Logarithmic, Power, Exponential and Linear functions. The linear model fitted better than the other three, especially for the higher temperatures. For the temperatures with large variation of the glue bond strength values, two linear regression models were determined; the first one included all the observations collected, and in the second observations that were questionable due to non-typical behavior were eliminated. The second model improved substantially the R value, but not much change was observed in the coefficient of the independent variable, the primary value of interest. The latter conclusion was significant because these coefficients were used as the basis for subsequent numerical simulation purposes. This information is outlined in Table 6.4.

Platen Temperature (°C)	Number of Obs	Statistic R^2 Values	Regression Models
70	56	0.685	Y = 1.253 + 0.0193X
	53	0.749	Y = 0.898 + 0.0216X
	44	0.845	Y = 0.702 + 0.0218X
80	55	0.854	Y = 1.019 + 0.0270X
	54	0.867	Y = 1.076 + 0.0266X
90	49	0.629	Y = 0.939 + 0.0310X
	40	0.824	Y = 0.041 + 0.0368X
100	84	0.739	Y = -1.266 + 0.055X
	74	0.857	Y = -1.708 + 0.057X
	65	0.917	Y = -1.370 + 0.052X
105	15	0.896	Y = -2.869 + 0.143X
	14	0.913	Y = -4.231 + 0.158X
110	54	0.774	Y = -3.536 + 0.251X
	45	0.855	Y = -2.745 + 0.222X
120	39	0.846	Y = -3.385 + 0.477X
	38	0.847	Y = -3.947 + 0.496X
130	23	0.92	Y = -3.740 + 0.681X
	22	0.94	Y = -4.782 + 0.729X

Table 6.4. Regression equations for glue bond strength (Y) as a function of time (X).

6.3.7. Determination of the regression model to relate rates of glue bond strength development with temperature.

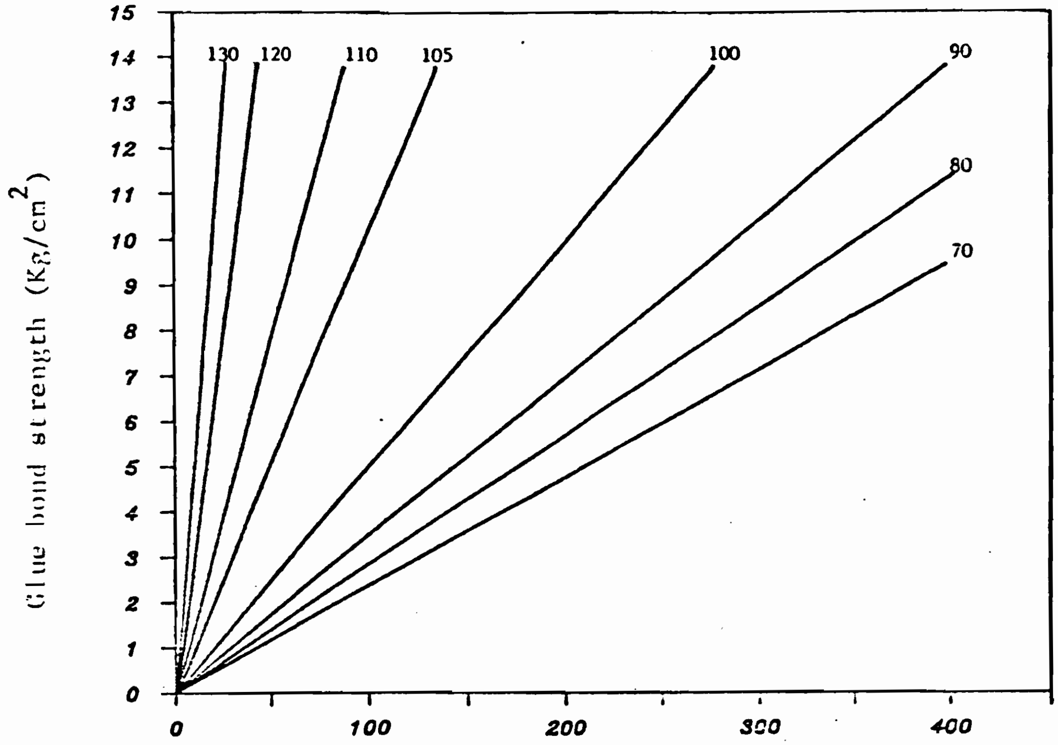
The above type of regression models for cumulative glue bond strength development with time have been obtained for all temperatures tested. The rates of glue bond strength development used in the present regression were derived from the coefficients in the strength versus time equations.

The corresponding values of the coefficients are listed in Table 6.5.

Platen Temperature (Centigrade)	Number of Observations	Rate Strength Development (Kg/cm^2/sec)
70	56	0.019
70	53	0.021
70	44	0.021
80	55	0.027
80	54	0.026
90	49	0.031
90	40	0.036
100	84	0.055
100	74	0.057
100	65	0.052
105	15	0.143
105	14	0.158
110	54	0.251
110	45	0.222
120	39	0.477
120	38	0.496
130	23	0.681
130	22	0.729

Table 6.5. Rates of glue bond strength development for different temperatures. (Derived from regression models in section 6.3.6).

A well defined trend in the rate of glue bond strength development with temperature is evident in the graphical representation of the family of strength development curves in Figure 6.11. It should be noted that intercept values have been removed so that all curves pass through the origin. It is the rate (slope) of the strength development which is relevant here. Differences in intercept are solely the result of non-steady temperatures at the early stages of test bond formation.



Elapsed pressing time (sec)

Figure 6.11. Regression lines of glue bond strength development for different platen temperatures. (Intercept values are removed to highlitht gradient differences).

A range of different regression models to correlate the rates of strength development with temperature were investigated. The following exponential equation provided a good fit:

$$\text{Ln } Y = \text{Ln } 0.0001325 + 0.065 X$$

A correlation coefficient of .904 was derived. This equation may now be used to provide bonding rates for given temperature values. The regression equation is plotted in Figure 6.12 together with the data upon which it is based. More than one point for each temperature value is included. These correspond to the regression equation for differing number of observations.

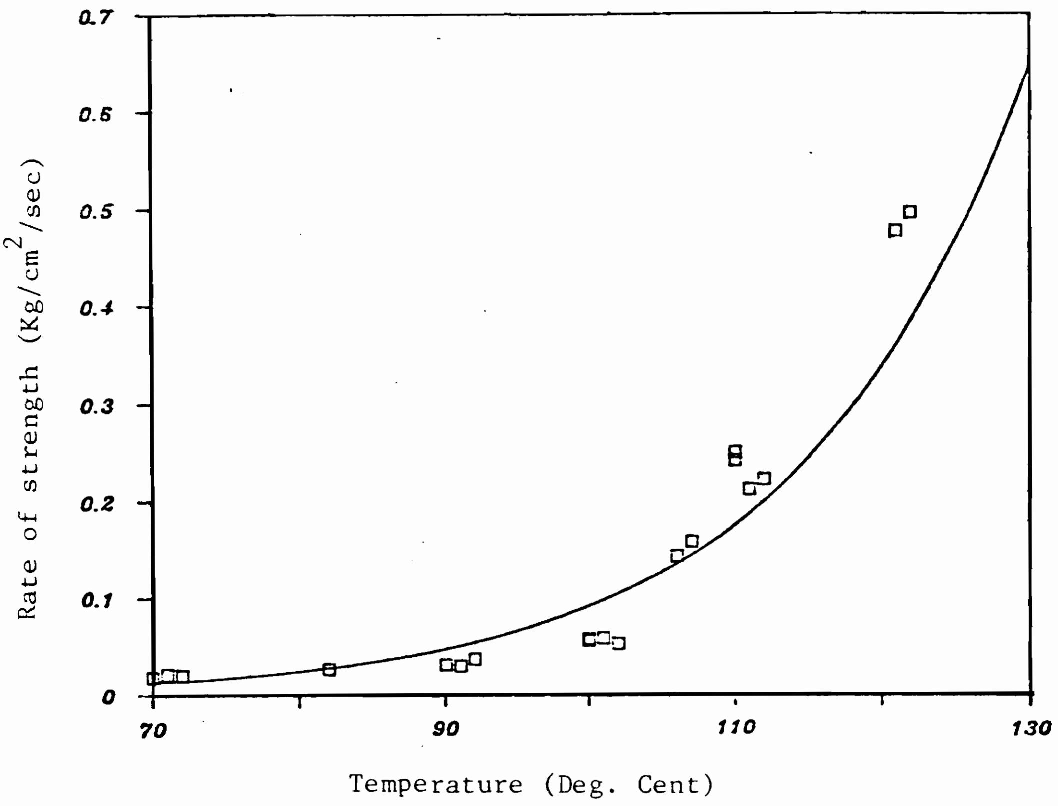


Figure 6.12. Predicted rate of glue bond strength development at different pressing time intervals.

This relationship may now be used as the basis for the model prediction of strength development in bonds formed under the known, though changing, temperature conditions within the panel during pressing.

Chapter VII

The physical interaction of bonding and vapor pressure within the panel

7.0 Introduction

Pressing cycles are usually developed to optimize production by decreasing the pressing time to a level where the glue bond is strong enough to hold the veneers together. This is both to ensure panel integrity as the press is opened, and also to ensure that the panel will fulfill specific quality standards for service.

The physical factors (stresses and strengths) interacting during pressing should be balanced at the time that the press is opened. The destructive stresses, due to internal vapor pressure and residual elasticity of the veneer system, should be exceeded by the strengths of the glue bonds between veneers. The interaction of these factors has already been symbolized schematically in Figure 3.2 of Chapter III.

This Chapter is primarily concerned with initial attempts to develop numerical methods to predict bonding throughout the panel as pressing proceeds. Subsequent attention is given to the balance between bonding and vapor pressure. This will start first with a consideration of the information needed for such modeling. The modeling approach itself will then be presented. The balance of destructive versus constructive forces will then be tackled numerically before the implications of the results are addressed.

7.1. Data required for the modeling of the system

One major objective of the two experimental studies previously described: 1). pressing panels in the laboratory and 2). evaluating bonding kinetics of the PF resins, was to generate adequate information to enable aspects of the pressing cycle to be modeled numerically. These approaches could eventually be employed for boards under industrial production conditions. They also shed light on the nature of the system and the relative importance of the fundamental processes operative.

No method has been found to reliably measure strength development of bonds between veneers during pressing of the actual laminate. The bonding rates derived indirectly by the wafer method (Chapter VI) are therefore to be used to predict the behavior of gluelines within the board. The range of temperatures investigated indirectly were therefore selected in the light of the range of temperature conditions known to occur in the panel. Glue bond strength development mappings for the laminate were therefore derived based on the behavior of bonds between wafers. Glue bond strength versus time curves for each one of the temperatures tested enable the relationship between bonding rates and temperature to be developed. This is represented by the regression equation derived in Chapter VI.

$$\text{Ln } Y = \text{Ln } 0.0001325 + 0.065\ X$$

By combining predicted bond strength values with measured vapor stress values for corresponding positions in the laminate, the balance of forces in the system may be quantified as pressing proceeds. The numerical approach necessary for the modeling will now be presented. Assumptions made and resultant inadequacies of the approach in its present early form will also be discussed.

7.1.1. The numerical prediction of bonding in the laminate

The approach used here is an adaptation of one previously used to predict bonding kinetics of UF resins (14). The apparatus used to characterize bonding under steady-state temperature conditions, and also the panel system being simulated differed, however. Previous work was concerned with flakeboard pressing rather than the present laminated panel.

Starting with a known temperature versus time curve for a specific glueline location, construction of a corresponding bonding curve commences by dividing the pressing period into small time increments. If these increments are sufficiently small relative to the rates of change in temperature, then temperature, and thus resultant bonding rates, remain approximately constant for their duration. By assuming zero strength at the beginning of the first time increment and by applying the principle of superposition, then a bonding curve may be constructed. This procedure will now be described and some of the limitations of the technique in its present form highlighted.

Below is an enlarged portion of a hypothetical time versus temperature curve (Figure 7.1) with two time increments. It should be noted that rates of change in temperature have been exaggerated to demonstrate the technique. Time increments of 0.8 seconds were used in the actual construction. Changes in gradient between successive increments were therefore very small. The sequence of computations is outlined below.

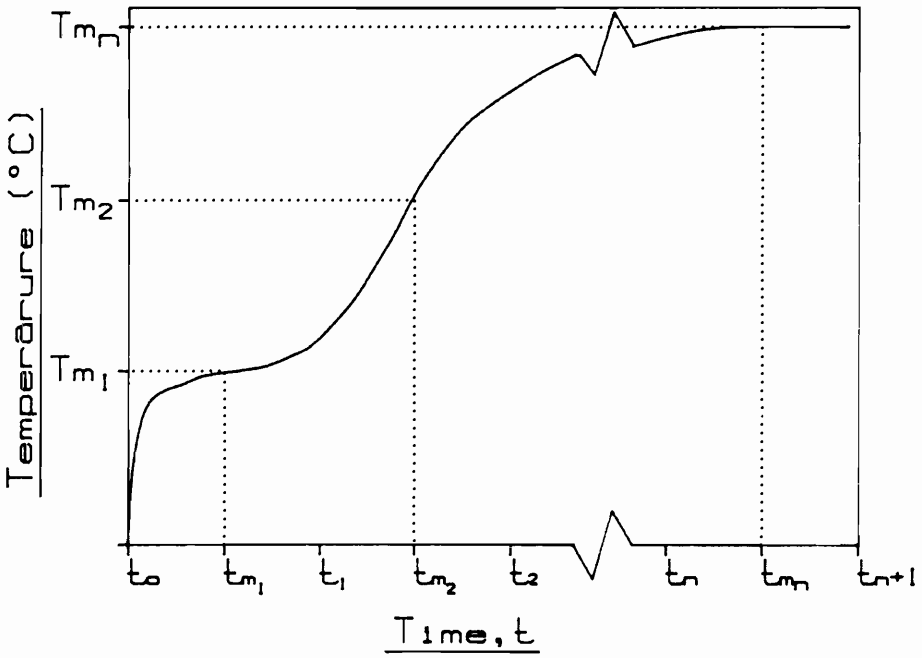


Figure 7.1. A hypothetical time versus temperature curve with two time increments superimposed.

For any given time increment:

1. For specific time intervals (tn to tn+1), there is a corresponding temperature range (Tn to Tn+1)
2. A mean temperature value (Tm) can be extracted from the curve. This may be calculated in two ways:
   a). With the tm value which is determined by the following relationship
   $$tm = \frac{tn+1 - tn}{2} + tn$$
   the corresponding Tm value may be found.
   b). With the temperature values corresponding to the beginning and end of the increment (tn and tn+1)
   $$Tm = \frac{Tn+1 - Tn}{2} + Tn$$
   In either case, the Tm values obtained will be similar since the time increments selected were very small.
3. In the event, option b) was employed. Having derived a mean temperature value (Tm) for the time increment in question, a rate of strength development value can be found. This can be determined directly from the regression equation ($\mathrm{Ln}\ Y = \mathrm{Ln}\ Bo + B1\ X$), relating temperature to bonding rate. Here, X represents the Tm value for the selected time interval, Y is the bonding rate and Bo and B1, are system constants. In the absence of such a relationship, rates could be extracted from a two dimensional array relating temperature to bonding

rate.

4. By ploting the rate of strength the development values for the subsequent intervals in a time-strength relationship, a succession of small straight lines with specific slope (rate of strength) are generated.
5. The accumulation of bond strength can be predicted by summating incremental strength values corresponding to the pressing time increments. In general, accumulated strength will be equal to the strength at the beginning of the time interval in question (t1) plus the incremental change in strength during that increment.

Bonding corresponding to the time increments shown on Figure 7.1 are presented below as Figure 7.2.

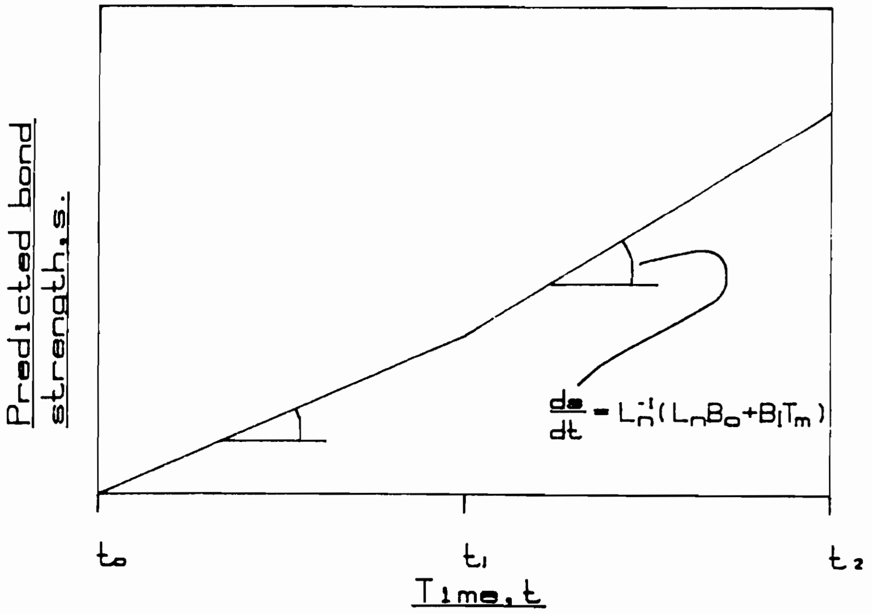


Figure 7.2 Bonding corresponding to two specific time increments (t1 and t2) shown as Figure 7.1.

Evidently, for the first time increment, the initial strength will be zero. This provides the starting point for the construction. All subsequent points of the curve are based solely on derived gradients for each time increment.

This operation can efficiently be carried out on the computer. Time increments of 0.8 were used throughout. This was primarily because laboratory collection of temperature in plywood gluelines was at this rate. The frequency was certainly high enough to avoid any significant inaccuracy in predicted curves due to linearization of the time versus temperature curve.

Following the approach described, the predicted strength values were calculated for laminates pressed under selected conditions. A sample of intermediate data generated by the computer for boards pressed for 600 seconds at 175 psi with 12% MC veneer is shown as Table 7.1. Ploting the strength values against time, the predicted strength curve shown as Figure 7.3 was generated.

Following the same approach, the corresponding predicted bonding curves for boards with 6% MC veneer are presented as Figure 7.4. The accuracy and usefulness of these predicted curves will be considered in Section 7.2 to follow.

Elapsed time (sec)	Tm(1+4) (C)	Tm(2+3) (C)	Strength Change (1+4)	Strength Change (2+3)	Cumulative Strength (1+4)	Cumulative Strength (2+3)
					0	0
0.8	44.41	33.07	0.0019	0.0009	0.0019	0.0009
1.6	44.77	33.26	0.0020	0.0009	0.0039	0.0019
2.4	45.29	32.92	0.0020	0.0009	0.0060	0.0028
3.2	45.53	33.04	0.0021	0.0009	0.0080	0.0037
4	45.88	32.87	0.0021	0.0009	0.0102	0.0046
60	77.12	49.60	0.0164	0.0027	0.5487	0.1080
60.8	77.51	50.01	0.0168	0.0028	0.5655	0.1108
61.6	77.78	50.46	0.0171	0.0029	0.5826	0.1136
120	94.47	70.65	0.0509	0.0107	2.8909	0.5515
120.8	94.68	71.03	0.0516	0.0110	2.9425	0.5625
121.6	94.76	71.12	0.0519	0.0111	2.9944	0.5736
180	105.89	88.31	0.1074	0.0340	8.7086	2.0711
180.8	105.89	88.63	0.1074	0.0348	8.8160	2.1058
181.6	106.19	88.67	0.1095	0.0348	8.9256	2.1407
240	115.21	103.00	0.1975	0.0889	20.0022	6.4888
240.8	115.11	103.21	0.1962	0.0901	20.1984	6.5789
241.6	115.37	103.43	0.1996	0.0915	20.3980	6.6704
300	120.92	114.53	0.2868	0.1889	38.2328	16.5981
300.8	121.08	114.69	0.2899	0.1909	38.5227	16.7890
301.6	121.29	114.75	0.2940	0.1917	38.8167	16.9807
360	126.51	122.74	0.4134	0.3230	64.2463	35.6358
360.8	126.25	122.83	0.4064	0.3251	64.6527	35.9609
361.6	126.42	122.86	0.4110	0.3256	65.0638	36.2865
420	129.51	127.73	0.5029	0.4477	98.6465	64.6415
420.8	129.63	127.85	0.5070	0.4514	99.1535	65.0929
421.6	129.68	127.90	0.5087	0.4529	99.6622	65.5458
480	131.78	131.27	0.5833	0.5644	139.95301	103.1075
480.8	131.83	131.32	0.5853	0.5663	140.53831	103.6738
481.6	131.82	131.27	0.5849	0.5642	141.12331	104.2380
540	133.21	133.41	0.6406	0.6490	186.25351	148.8334
540.8	133.31	133.36	0.6448	0.6469	186.89831	149.4803
541.6	133.30	133.46	0.6446	0.6510	187.54291	150.1313
598.4	133.65	134.51	0.6593	0.6973	233.78512	197.8263
599.2	133.52	134.38	0.6539	0.6914	234.43902	198.5177
600	133.62	134.38	0.6581	0.6914	235.09712	199.2090

Table 7.1 Intermediate data for predicting bonding curves for outer (locations 1 and 4) and inner (locations 2 and 3) gluelines of laminates pressed for 600 seconds, at 175 psi, with 12% MC veneer.

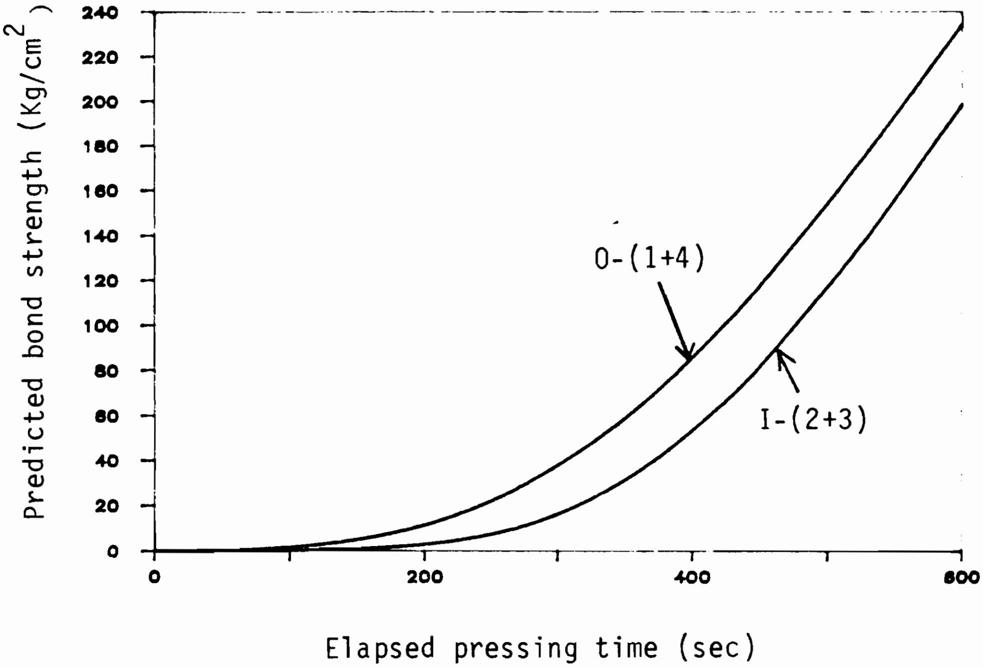


Figure 7.3 Predicted glue bond strength curves for the two inner and two outer gluelines of the laminates with 12% MC veneer.

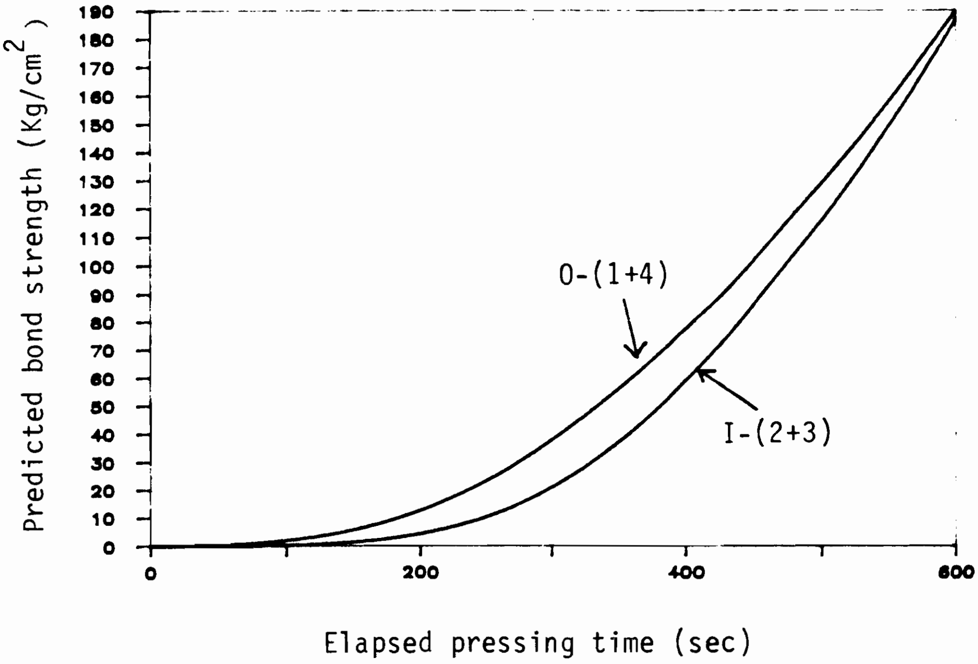


Figure 7.4 Predicted glue bond strength curves for the two inner and two outer gluelines of the laminates with 6% MC veneer.

7.2. The interaction of predicted bonding with measured vapor pressure curves

It has already been suggested that the interaction of the vapor pressure curves with the modeled bonding curves in Figures 7.3 and 7.4 could provide criteria for opening of the press. It is expected that once bonding exceeds vapor pressures throughout the board the strength developed by the glue overcomes the stress produced by the vapor in the glueline. In theory, at this stage, opening of the press could be safely performed with no risk of delamination or blows. It is further expected that beyond these pressing times, the longer the laminate remains in the press the stronger the bonds become. Evidently however, variability within the system does not enable press cycles to be designed to operate within such fine limits. Even with the highly controlled methods and raw material selection used in the present study, variability was significant. This variability will be present both in the rates of bonding throughout the panel and the values of vapor pressure that load the bonds.

Evidently, there are deficiencies in one or both of the data (pressure and bonding curves). When boards were pressed at the higher two moisture content values, blowing occurred. This was in spite of the fact that predicted strength values of the bonds were very high. It is clear, therefore, that although the approach has potential as a means of numerically tackling the system, it requires refinement before practical uses may be found. The implications of these results and possible means of refinement will therefore be given here.

Three primary limitations of the approach described for glue bond strength determination and subsequent integration with vapor pressure curves may be identified. 1). Predicted bond strength values were developed by assuming that the rate of polymerization of the resin in the wafers followed similar trends as the resin in the laminate during hot pressing.

This assumption is known not to be entirely well founded since the nature of the materials and conditions under which they cured differ. The following aspects are particularly relevant: moisture content in the gluelines, wood surface characteristics, quantity of glue applied, vapor pressure build up, and parity between the testing mode used for bonding evaluation and actual loading in the panel.

The effect of MC on the rate of curing of resin is one of the major factors affecting glue bonding. It has been suggested (27, 32, 100) that the higher the MC, the lower the rate of resin polymerization. From the analysis of the information generated in this project, it is expected that even if the original MC of the wafers was similar to the MC of the veneer, the MC of the two types of gluelines may differ as curing proceeds. This may be due to:

a). A higher proportion of wood which contains adsorbed water available to generate vapor (or MC per unit area) in the laminate. This is principally in the core layers as vapor migrates away from the platens.

b). Differing proportions of glue to wood. This affects the quantity of moisture present during the curing reaction.

c). Effect of destructive forces in the board due to the spring back of the veneer in the laminate once the platen pressure is removed.

d). Also regarding the wafer tests, destructive forces due to the stress of vapor accumulated within the glueline are not taken into account. This factor is, however, likely to be insignificant. The test bonds were small in area and the escape of vapor relatively unimpaired.

None of the above were taken into account when determining rates of glue bond strength during laminate pressing. It is the goal of future research to take account of the effect of changing moisture content on resin cure. Attempts should also therefore be made to determine moisture values within the laminate.

2). Due to the rapid rates of glue bond strength development predicted by the derived model, it seems evident that some other factors have to be taken into account. A more precise model is needed to represent the real pressing process, especially during the last period of the pressing cycle. It should be realized, however, that the lower predicted bonding levels are the more important since they are likely to limit press opening. Inaccuracies in the prediction of higher strengths are not necessarily a limitation in the analysis. Indeed, such an inaccuracy is an inevitable consequence of the modeling method since the theory in its present form provides no upper limit on strength development - even though in reality, polymerization must eventually slow down and wood failures also occur. This does not negate the fact that in its present form, the simulation produces bonding values which far exceed realistic values even after relatively short pressing times.

3). For the prediction of pressing cycles, the bond strength values in the wafers were determined in a shear mode. The destructive forces in the laminate during pressing (generated by vapor pressure and spring back of the veneer) are, however, more likely to occur in a mixture of modes; perhaps tension forces in major proportion, with smaller effects resulting from shear modes. Priority is therefore given to establishing a relationship between these two modes so that the balance between bonding and vapor pressure may be more realistically quantified.

If one temporarily assumes that bond strength predictions are adequate, and that the factors interfering with the rate of polymerization of the resin do not have a major effect on bond strength development, then the question arises as to whether the measured vapor pressure in the veneers represents the real effect of vapor pressure in the gluelines. It should be pointed out, however, that vapor pressures at the center of the veneers are likely, if anything, to be lower than those at the gluelines themselves. Here there is an excess of water and the escape of vapor may be impaired by the presence of the void-filling polymer. Over estimation of the vapor pressures at the glueline therefore seems unlikely.

When veneer with 12% MC was used to form laminates pressed at 175 psi for 600 seconds, all the boards failed immediately after the press was opened. For this type of panel it was necessary to increase the pressing time up to 1000 seconds to avoid delamination.

The effect of moisture or water vapor on the rate of resin polymerization and again the inefficiency of the pressing cycle model, was also realized when boards with 16% MC were pressed for 1000 seconds with either 100 or 175 psi. In both cases the boards failed immediately after the press was opened.

Chapter VIII

Conclusions and suggestions for future work

8.0. Introduction

The principal conclusions of this research will be dealt with according to the three main components of the project: Characterization of boards during pressing, evaluation of glue bond strength development and integration of numerical data. This will be followed by a brief discussion of potential application and suggestions for future work.

8.1 Characterization of boards during pressing

The conclusions of this part of the research work are presented according to the results obtained by pressing standard boards and boards formed under modified veneer MC and pressing conditions.

The standard panel:

1. Temperature gradients in the cross-section of the board (between the two outer and two inner gluelines) are most pronounced during the first 400 seconds pressing time. After that period, the four glueline temperatures began to converge

2. In the horizontal direction of the board, no significant difference in temperature is observed within

the same glueline.

3. Vapor pressure varies throughout the board in both the horizontal and cross-sectional directions. In the cross-sectional direction, the core and inner plies exhibit similar vapor pressure, while those in the surface veneers are significantly different.

4. During the first 300 seconds of pressing time, the vapor pressure in the three inner plies is very low and steady. Beyond that stage a rapid rise occurs up to 600 seconds. After that period, the pressure levels off and would, given sufficient time, eventually decline as drying of the panel takes place.

5. In the face and back plies, vapor pressure increases very fast within the first 30 seconds of pressing time. It then continues rising at a very low rate up to 500 seconds, after that period no change is observed. Vapor pressure in the outer plies is higher than in the inner plies only for the first 200 seconds. Beyond that period, vapor pressure rises very fast in the inner plies while in the outer no significant change is observed.

6. Vapor pressure in the horizontal direction within the same ply varies in response to grain direction and resultant effects on the pathways available for the escape of vapor. Vapor pressure is higher in the central location of the board and decreases toward the edges when it is measured perpendicular to the grain. Vapor pressure parallel to the grain is, however, very similar between

locations at any point within the same ply.

7. The following factors are therefore important in affecting the behavior of the panel upon press opening:

- high concentration of moisture that accumulates in the core layers which interferes with bonding
- the high vapor pressure exercising destructive stresses in the bonding area
- polymerization due to the lower rate of heat transfer at the center of the panel.

It can therefore be concluded that the inner plies of the boards are more vulnerable to blows and delaminations.

8. In standard boards, a drastic thickness reduction is observed during the first 400 seconds of pressing time. This early compaction is dominated by elastic deformation. It subsequently levels off beyond that period as viscous deformation progresses at rates dictated by the combined effects of temperature and MC. Beyond 600 seconds, this becomes almost imperceptible.

9. A total compression loss of 6 to 10% of the original board thickness dimension was recorded for the first 300 seconds of pressing time. This is similar to the figures reported by other workers for the same type of boards.

Boards with high moisture content veneer:

1. The rate of heat transfer (temperature rise) is affected by both veneer MC and platen pressure. At low MC, (eg 6%) temperature trends for both 125 and 175 psi

are similar, while at 12% MC a different trend in temperature is observed between 125 and 175 psi. In this case, a higher rate of heat transfer was registered for the higher platen pressure.

2. It may be concluded that the rate of heat transfer is not affected by platen pressure when low MC veneer is used. On the other hand, if the veneer MC is increased, a higher rate of heat transfer is observed for the higher platen pressures.

3. As would be expected, vapor pressures tend to increase with veneer moisture content, especially in the core and inner plies. The outer plies are less affected by MC variation within the range of 5 to 12%.

4. Compaction of the board is directly related to veneer MC and platen pressure. Board compaction increases with veneer MC for a fixed platen pressure. Similarly, increasing platen pressure for a fixed veneer MC, leads to an increase in compaction.

5. If veneer MC is increased but platen pressure is diminished, then board compaction tends to decrease. Accordingly, high MC veneer can be used without compaction problems by reducing platen pressure, but a slight reduction in heat transfer may be expected. This highlights the need for accurate and responsive computer control of platen position and load.

8.2. Glue bond strength development

The following conclusions are based on the wafer technique used in this research to measure PF resin to wood strength development characteristics.

1. Open assembly time had no significant effect on bond strength development when it was kept within 40 minutes. Similarly, resin pot life does not affect glue bond strength development for a period of up to 9 hours. Furthermore, the method in its present form did not expose significant differences in strength development characteristics when bonds between earlywood, latewood or mixture of both were tested. With refinement, however, it is considered that the approach could have usefulness to investigate such important effect.

2.The rate of resin polymerization reflected as the rate of glue bond strength development is directly related to temperature and time. Bonds formed at low temperature requires long curing periods while at high temperature (130 C) the resin polymerizes very quickly, soon developing strength that surpasses that of the wafers themselves. Wafer cross-sectional dimensions therefore limit the applicability of the technique; the evaluation of higher degrees of resin polymerization and the resultant bond strength, is not therefore possible.

3. Wafer bonding does not accurately represent the conditions under which bonds are formed in plywood during

pressing. This is due to differences in wood characteristics, glue spread rate, platen pressure, MC in the glueline, and vapor pressure accumulation in the glueline.

4. Even if the bonding characteristics determined with the wafer technique differ from those in the board, the wafer technique can still be usefully used to evaluate different types of adhesive systems. Their bonding characteristics may be compared with those for standard phenolic resin. This comparison is possible because the evaluation can be performed with the same sets of conditions for all the resins.

8.3. Prediction of pressing cycles

Optimization of pressing cycles depends in part on the interaction of stresses at specific locations within the panel, particularly when the press is opened. These principally concern bond strength, vapor pressure and, to a lesser extent, residual elasticity. Any additional increments in pressing time beyond the stage at which bonding exceeds the destructive forces would lead to higher rates of resin polymerization, thus diminishing the risk of blows when the press is opened. The selection of actual pressing times would have to take account both of the theoretical minimum and additional time to accommodate the effects of variability. This is principally the veneer properties, condition and process control.

The minimum pressing time derived from the combination of bonding characteristics by the wafer method with vapor stress inside the board do not presently provide meaningful results. Panels remain unstable for times far in excess of those predicted by the present analysis. This result is, however, proving useful in highlighting the importance of moisture in the bonding process.

Below, therefore, are some of the factors that may interfere with the effectiveness of the model in its present form:

a). A possible difference between the real stress of the vapor pressure in the glueline of the board and the stress of the vapor pressure measured with the method described in this research.

b). Bond strength characteristics were determined in shear while the destructive forces on the gluelines in the panel are likely to be mainly in tension perpendicular.

c). As implied above, bonding is not only dependent on temperature; MC also plays an important role in the curing of the resin. However, the effect of MC on this curing was not quatified or accounted for in the model.

8.4. Suggestions for future research

The research described in this thesis has provided new insight to the processes operative within laminated panels during pressing. This particulary relates to the accumulation and dissipation of water vapor. There is, however, potential to pursue many aspects in considerably more depth. The more important among these are:

a). To develop a greater understanding of the conditions under which the adhesive bonds have to cure within the panel during pressing. This would involve a fundamental study of the movement (dynamics) of adhesive and associated water in the vicinity of the bond. This involves the effect of water vapor gradients across the glueline on its integrity and associated moisture movement. It could involve a combination of experimental and fundamentally based computer simulation techniques.

b). To modify methods of adhesive test bond characterization (wafer method) to reflect the increased understanding gained by the above analysis. This would primarily involve a numerical study of the combined effect of both MC and temperature on bonding.

c). To extend the numerical methods for bonding prediction used in this thesis to account for the above effects of moisture. The resulting predictions could open the way to practically useful pressing optimization techniques.

d). To further explore the use of high MC veneer in plywood manufacture. The use of responsive platen control to avoid excessive compression loss while achieving good bonding is necessary for this. Further work to develop appropriate pressing cycles and possibly evaluate alternative/new bonding systems could be based on the approaches described in the present research.

e). The wafer method of adhesive characterization could be adapted and simplified to be used as a standard tool for the evaluation of new adhesive systems.

In addition to the above applications specific to plywood, the approaches described here could aid in the development of new composite systems - possibly incorporating combinations of veneers, flakes and even non-wood components. Quantifying the transfer of heat and water in the system and the kinetics of adhesion are important aspects of such product development.

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APPENDICES

APPENDIX A

Computer program in "Basic" for collection of temperature, vapor pressure and compaction data during hot pressing of boards.

```
10 '    C O L L E C T . B A S
20 '    ********************
21 '
22 '    This program collects data using the Data Translation 2805 board.
23 '    It is based on the program MANEP07.BAS.
24 '
25 '
80 '
90 'define constants
100 '
110 DEFINT A-Z
120 BASE.ADDRESS       =&H2EC
130 COMMAND.REGISTER   =BASE.ADDRESS+1
140 STATUS.REGISTER    =BASE.ADDRESS+1
150 DATA.REGISTER      =BASE.ADDRESS
170 COMMAND.WAIT       =&H4
180 WRITE.WAIT         =&H2
190 READ.WAIT          =&H5
200 '
210 CCLEAR             =&H1
220 CCLOCK             =&H3
230 CSAD               =&HD
240 CRAD               =&HE
250 CSTOP              =&HF
260 PERIOD#            =40000!
270 '
280 BASE.FACTOR#       =4096
285 BASE.CHANNELS      =16
290 GAIN(0)            =1
291 GAIN(1)            =10
292 GAIN(2)            =100
293 GAIN(3)            =500
300 '
310 'stop and clear the dt2801 series board
320 '
330 OUT COMMAND.REGISTER, CSTOP
340 TEMP = INP(DATA.REGISTER)
350 WAIT STATUS.REGISTER, COMMAND.WAIT
360 OUT COMMAND.REGISTER, CCLEAR
1000 '
1010 'set clock rate
1020 '
1030 'wait until the dt2801 board ready flag is set, then write the
1040 'set clock period command byte to the command register
1050 '
1060 WAIT STATUS.REGISTER, COMMAND.WAIT
1070 OUT COMMAND.REGISTER, CCLOCK
1080 '
1090 'divide period# into high and low bytes and write both bytes to the data
1100 'in register, waiting for a clear data in full flag before each write.
1110 '
1130 PERIODH =INT(PERIOD#/256)
```

```
1140 PERIODL = PERIOD# - PERIODH*256
1150 WAIT STATUS.REGISTER , WRITE.WAIT,WRITE.WAIT
1160 OUT DATA.REGISTER, PERIODL
1170 WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
1180 OUT DATA.REGISTER, PERIODH
1190 '
1191 PRINT "RUN NUMBER (ONE ... ...) EQUALS ?";
1192 INPUT NRUN$
1193 PRINT "PRESSING TIME (SECONDS) EQUALS ?";
1194 INPUT TTIME#
1270 ADGAIN =3
1271 PRINT "NUMBER OF T/C EQUALS ?";
1272 INPUT NTHERM
1273 PRINT "NUMBER OF PRESSURE TRANSDUCERS EQUALS ?";
1274 INPUT NPT
1275 PRINT "NUMBER OF DISPLACEMENT TRANSDUCERS EQUALS ?";
1276 INPUT NLVDT
1277 PRINT "AUTOMATIC PRESSURE ZERO SET @ FIRST CYCLE (1=YES, 2=NO)";
1278 INPUT PCHECK
1280 PRINT "A/D START channel ( 1 TO 7 )";
1282 INPUT N
1285 ADSCHANNEL = N-1
1290 IF ADSCHANNEL<0 THEN GOTO 1280
1300 IF ADSCHANNEL > (BASE.CHANNELS-1) THEN GOTO 1280
1310 '
1320 PRINT "A/D END CHANNEL ( 1 TO 7 )";
1325 INPUT ADECHANNEL
1330 IF ADECHANNEL <0 THEN GOTO 1320
1340 IF ADECHANNEL >(BASE.CHANNELS-1) THEN GOTO 1320
1341 PRINT "DO WE NEED PLATEN OPENING ZERO CHECK (1 = YES, 2 = NO)";
1342 INPUT CHECK
1344 IF CHECK > 1 GOTO 1355
1345 PRINT "CLOSE THE PRESS, READ LVDT OUTPUT & TYPE VALUE (mV)";
1346 INPUT LVREF#
1347 PRINT "OPEN THE PRESS, INSERT BOARD & PRESS RETURN TO BEGIN SCANNING";
1348 INPUT L
1349 GOTO 1360
1350 '
1355 LVREF! = 0!
1356 PRINT "PRESS RETURN TO BEGIN SCANNING";
1357 INPUT L
1360 NCHAN = ADECHANNEL - ADSCHANNEL + 1
1370 IF NCHAN < 1 THEN NCHAN = NCHAN + BASE.CHANNELS
1380 NCONVERSIONS# = TTIME#/.1
1400 '
1410 'DIMENSION ARRAY TO HOLD HIGH AND LOW BYTE OF A/D DATA.
1420 '
1430 DIM ADL(NCONVERSIONS#), ADH(NCONVERSIONS#)
1440 '
1450 'DO A SET A/S PARAMETERS COMMAND TO SET UP THE A/D CONVERTER.
1460 '
1470 'WAIT UNTIL THE DT2801 BOARD READY FLAG IS SET THEN WRITE THE
1480 'SET A/D PARAMETERS COMMAND BYTE TO THE COMMAND REGISTER.
1490 '
1500 WAIT STATUS.REGISTER, COMMAND.WAIT
1510 OUT COMMAND.REGISTER, CSAD
1520 '
1530 'WAIT UNTIL THE DT2801 BOARD DATA IN FULL FLAG IS CLEAR, THEN
1540 'WRITE THE A/D GAIN BYTE TO THE DATA IN REGISTER.
1550 '
1560 WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
1570 OUT DATA.REGISTER, ADGAIN
1580 '
1590 'WAIT, UNTIL THE DT2801 BOARD DATA IN FULL FLAG IS CLEAR, THEN
1600 'WRITE START CHANNEL BYTE TO THE DATA REGISTER.
1610 '
```

```
1620 WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
1630 OUT DATA.REGISTER, ADSCHANNEL
1640 '
1650 'WAIT UNTIL THE DT2801 BOARD DATA IN FULL FLAG IS CLEAR, THEN
1660 'WRITE THE A/D END CHANNEL BYTE TO THE DATA REGISTER.
1670 '
1680 WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
1690 OUT DATA.REGISTER, ADECHANNEL
1700 '
1710 'DIVIDE NCONVERSIONS# INTO HIGH AND LOW BYTES AND WRITE BOTH BYTES
1720 'TO THE DATA IN REGISTER, WAITING FOR A CLEAR DATA IN FULL FLAG
1730 'BEFORE EACH WRITE.
1740 '
1750 NUMBERH= INT(NCONVERSIONS#/256)
1760 NUMBERL= NCONVERSIONS#-NUMBERH*256
1770 WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
1780 OUT DATA.REGISTER, NUMBERL
1790 WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
1800 OUT DATA.REGISTER, NUMBERH
1810 '
1820 'START  THE READ A/D COMMAND.
1830 '
1840 'WAIT UNTIL THE DT2801 BOARD READY FLAG IS SET, THEN  WRITE THE
1850 'A/D COMMAND BYTE TO THE COMMAND REGISTER.
1860 '
1870 WAIT STATUS.REGISTER, COMMAND.WAIT
1880 OUT COMMAND.REGISTER, CRAD
1890 '
1900 'READ THE A/D, HIGH AND LOW BYTES, INTO ARRAYS, WAITING FOR A SET
1910 'DATA OUT READY (OR READY) FLAG BEFORE EACH READ.
1920 '
1921 PRINT "!!!!!DATA COLLECTION STARTED !!!!!!!!!!!!!!!"
1922 BEEP
1930 FOR LOOP = 1 TO NCONVERSIONS#
1940 WAIT STATUS.REGISTER, READ.WAIT
1950 ADL(LOOP) = INP(DATA.REGISTER)
1960 WAIT STATUS.REGISTER, READ.WAIT
1970 ADH(LOOP) = INP(DATA.REGISTER)
1980 NEXT LOOP
1990 '
1991 PRINT "!!!!!!DATA COLLECTION COMPLETE - CONVERSION IN PROGRESS !!!!!!!!"
1992 BEEP
1993 BEEP
2000 'WAIT UNTIL THE DT2801 BOARD READY FLAG IS SET, INDICATING COMMAND
2010 'COMPLETION, THEN CHECK THE STATUS REGISTER ERROR FLAG.
2020 '
2030 WAIT STATUS.REGISTER, COMMAND.WAIT
2040 STATUS = INP(STATUS.REGISTER)
2050 IF (STATUS AND &H80) THEN GOTO 3450
2060 '
2070 'CALCULATE AND PRINT ALL CONVERTED A/D VOLTAGES, FORMATTING THE SPACING
2080 'TO INDICATE FIRST AND LAST CHANNEL READINGS.
2090 '
2110 FACTOR# = (10/BASE.FACTOR#) / GAIN(ADGAIN)
2140 '
2250 'SET VALUES FOR SYSTEM OF THERMOCOUPLES, PRESSURE AND LVDT
2260 'NTHERM=NUMBER OF THERMOCOUPLES
3020 'SENPT=SENSITIVITY OF PRESSURE TRANSDUCERS (PSI/VOLT)
3022 SENPT14! = 10000/(1.46*1.5)
3024 SENPT12! = 10000/(1.48*1.5)
3041 'ZERO14!= ZERO OUTPUT OF PRESSURE TRANS # 14 IN VOLTS
3042 'ZERO12! = ZERO OUTTUT OF PRESSURE TRANS # 12 IN VOLTS
3050 SENLV!=1.11403
3070 NCYCLE=NCONVERSIONS#/NCHAN
3080 OPEN "B:DATA"+NRUN$ FOR OUTPUT AS #1
```

```
3111 IF(PCHECK > 1) THEN GOTO 3120
3112 N = (NTHERM+2)
3113 K=1
3114 GOTO 3462
3115 ZERO14! = V!
3116 N = (NTHERM+3)
3117 K = 2
3118 GOTO 3462
3119 ZERO12! = V!
3120 FOR CYCLEN = 1 TO NCYCLE
3130 'CALCULATE PREVAILING ELAPSED TIME
3140 TIME!=CYCLEN *.1 * NCHAN
3150 'OBTAIN REFERENCE COLD JUNTION VOLTAGE
3155 N =(((CYCLEN-1)*NCHAN)+1)
3156 K = 3
3157 GOTO 3462
3158 VR! = V!
3162 TR!= VR!* 1000! / .5
3164 VREF! = 38.66698 * TR! + 4.373944E-02 * TR!^2 -2.497418E-05*TR!^3
3170 'START LOOP TO CONSIDER EACH CHANNEL
3180 FOR CHANN = 2 TO NCHAN
3190 'OBTAIN VOLTAGE FOR CURRENT CHANNEL
3200 N = (((CYCLEN-1)*NCHAN)+CHANN)
3201 K = 4
3202 GOTO 3462
3203 VN! =V!
3210 'SELECT THERMOCOUPLE CHANNELS
3220 IF (CHANN>NTHERM+1) GOTO 3290
3230 'APPLY COLD JUNTION CORRECTED VOLTAGE (IN MICROVOLTS)
3240 VCOR! = (VN! * 1000000!) + VREF!
3250 'APPLY CUBIC CONVERSION FACTORS TO GET TEMPERATURE
3260 TEMP!=(2.507424E-02*VCOR!)-(4.492068E-07*VCOR!^2!)+(7.994254E-12*VCOR!^3!)
3270 'DEPOSIT RESULTS IN DATA FILE
3280 PRINT #1,USING "####.##,";TEMP!,
3282 PRINT USING "####.##,";TEMP!,
3285 GOTO 3370
3290 L=0
3300 'SELECT PRESSURE CHANNELS
3310 IF (CHANN > NTHERM+NPT+1) GOTO 3340
3320 'CALCULATE PRESSURES
3321 SEN! = SENPT14!
3322 ZERO! = ZERO14!
3323 IF(CHANN > NTHERM + 2)THEN  ZERO! = ZERO12!
3325 IF(CHANN > NTHERM +2) THEN SEN! = SENPT12!
3330 PRES!=(VN!-ZERO!)*SEN!
3331 PRINT #1,USING "###.####,";PRES!,
3332 PRINT USING "###.####,";PRES!,
3335 GOTO 3370
3340 L=0
3350 'CALCULATE LVDT DISPLACEMENT
3360 DISPL!= (VN!*1000! - LVREF!) * SENLV!
3361 PRINT #1,USING "###.###,";DISPL!,
3362 PRINT USING "###.###,";DISPL!,
3370 NEXT CHANN
3380 'RECORD ELAPSED TIME
3390 PRINT #1,USING "####.##,";TIME!,
3391 PRINT USING "####.##,";TIME!,
3392 PRINT #1,
3393 PRINT
3400 NEXT CYCLEN
3417 PRINT "S E Q U E N C E   C O M P L E T E   ! ! !"
3440 GOTO 3480
3450 PRINT
3452 PRINT "BLOW UP IN PROGRAM"
3454 GOTO 3480
3462 DATA VALUE# = ADH(N)*256+ADL(N)
```

```
3464 UNI.VOLTS# = DATA.VALUE#*FACTOR#
3466 BI.VOLTS# = UNI.VOLTS#*2-(10/GAIN(ADGAIN))
3468 V! = BI.VOLTS#
3470 IF(K=1) GOTO 3115
3472 IF(K=2) GOTO 3119
3474 IF(K=3) GOTO 3158
3476 IF(K=4) GOTO 3203
3480 END
Ok
```

APPENDIX B

Analysis of variance Tables for open assembly time, resin pot life and Wood Wafer Characteristics

ANOVA TABLE

Source	DF	SS	MS
OAT	8	11.977	1.497
Error	18	35.055	1.947
Total	26	47.033	

F Value = 0.768 8, 18 DF

Analysis of variance for the effect of open assembly time (OAS) on glue bond strength development.

ANOVA TABLE

Source	DF	SS	MS
RPL	6	26.844	4.474
Error	15	36.995	2.466
Total	21	63.839	

F Value = 1.814 6, 15 DF

Analysis of variance for the effect of resin pot life (RPL) on glue bond strength development.

ANOVA TABLE FOR 110 °C

Source	DF	SS	MS
Wood Type	2	9.879	4.939
Error	45	1258.404	27.964
Total	47	1268.284	

F Value = 0.176 2, 45 DF

Analysis of variance for the effect of wood type on bond strength, using platen temperature of 110 °C.

ANOVA TABLE FOR 100 °C

Source	DF	SS	MS
Wood Type	2	5.076	2.539
Error	45	1103.007	24.511
Total	47	1108.084	

F Value = 0.103 2, 45 DF

Analysis of variance for the effect of wood type on bond strength, using platen temperature of 100 °C.

Source	D.F.	S.S.	M.S.	F
Total	23	512.82		
Block	1	5.41	5.41	1.97
Time	1	87.93	87.93	32.09
Wood	2	24.20	12.10	4.42
Temperature	1	310.32	310.32	113.25
Time x Wood	2	5.46	2.73	0.99
Time x Temp	1	43.96	43.96	16.04
Wood x Temp	2	22.05	11.02	4.02
WoodxTimexTemp	2	8.11	4.06	1.48
Error	11	30.14	2.74	

ANOVA for 2 x 2 x 3 factorial analysis, for pressing time, pressing temperatures and wood type.